LCLS-II

Production and Performance of LCLS-II Cryomodules

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- What are we building?
  - Cryomodule Deliverables
- How are we building it?
  - The Collaboration
- Cryomodule Testing
  - Performance
  - Challenges
  - Lessons learned
- Summary

Project Collaboration: SLAC couldn't do this without…

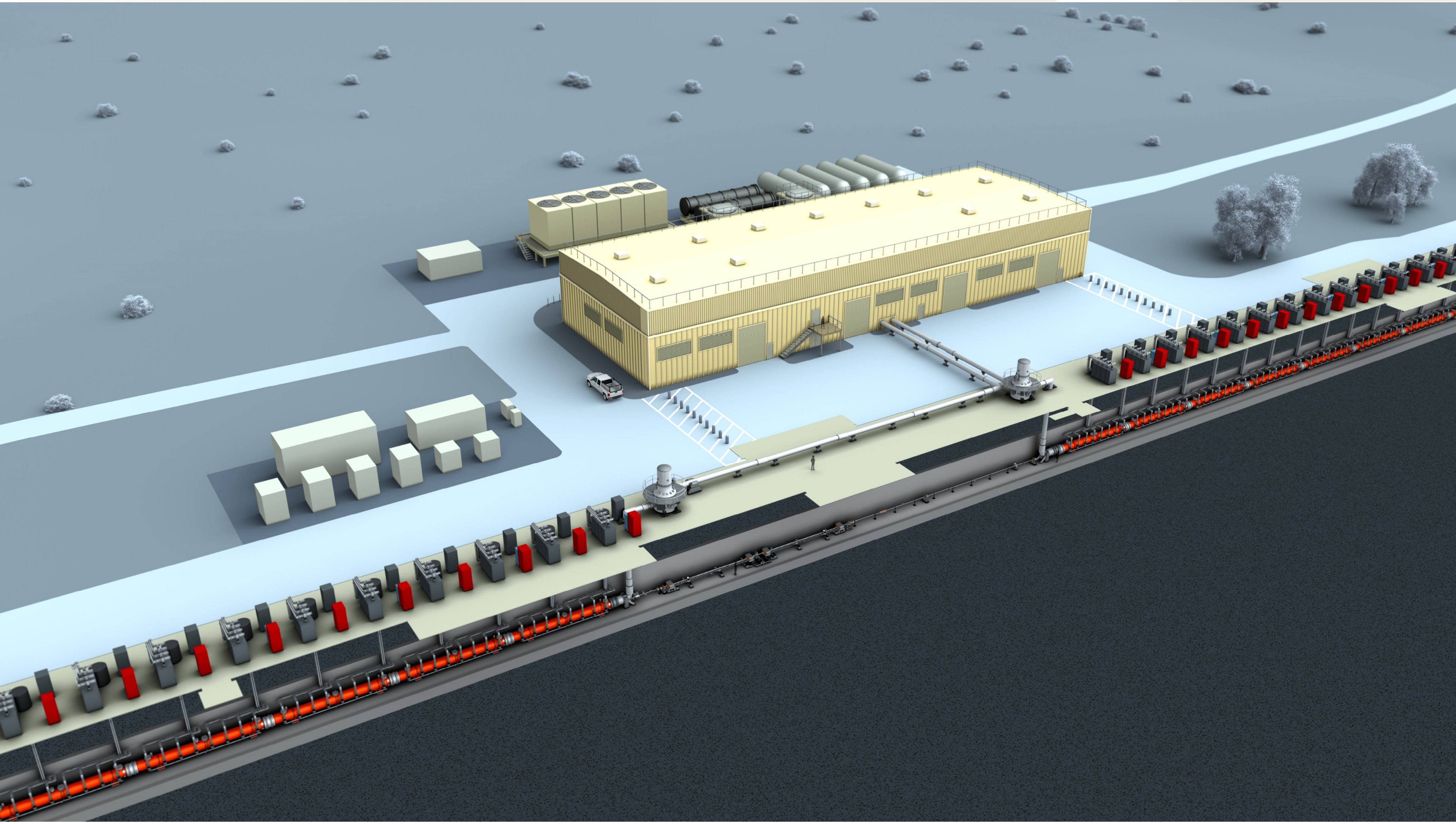
European XFEL

DESY

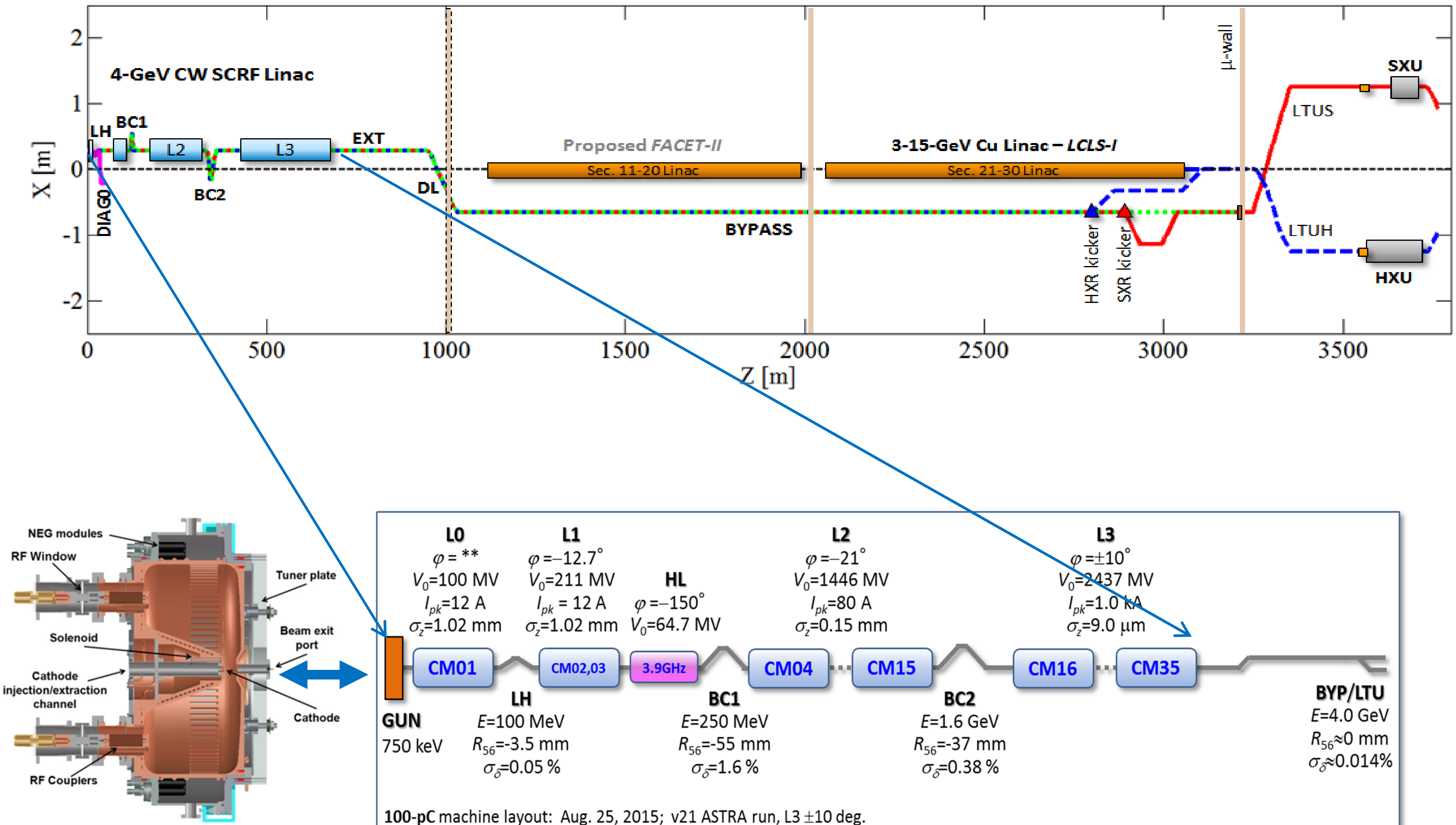
DE LA RECHERCHE À L'INDUSTRIE
cea

LAL
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

The Linac



Linac Layout



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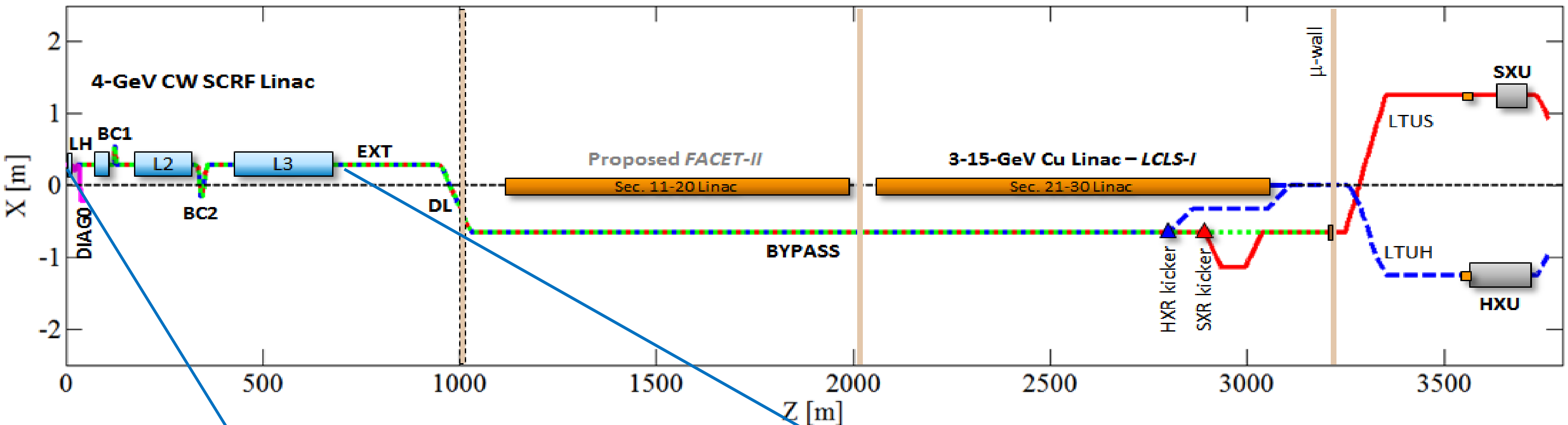
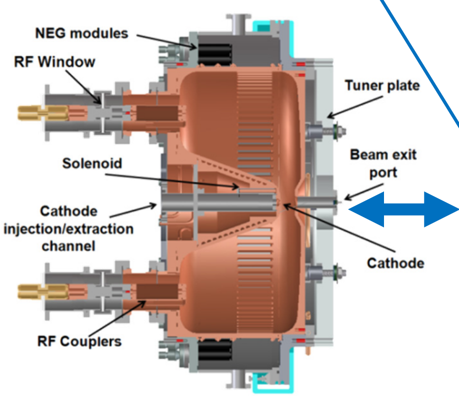
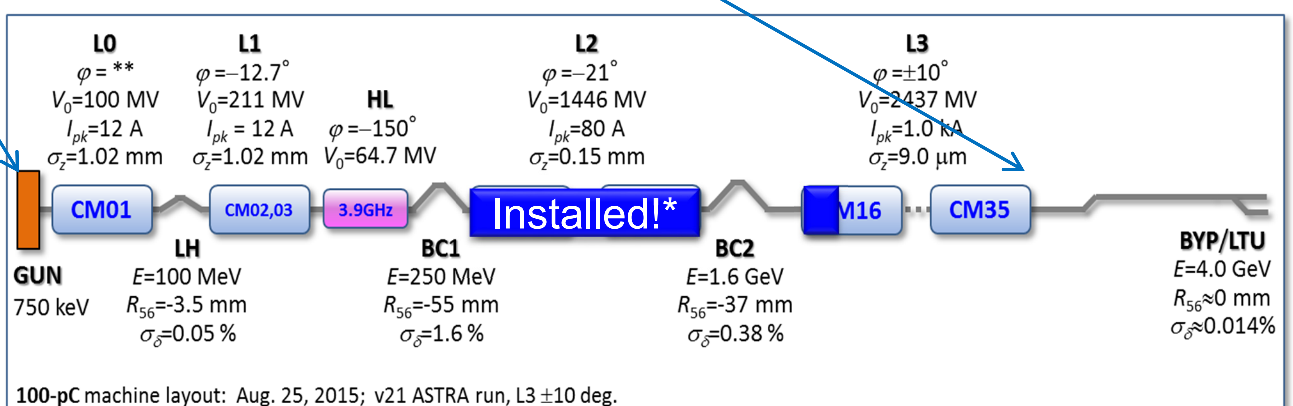
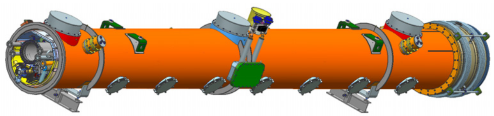




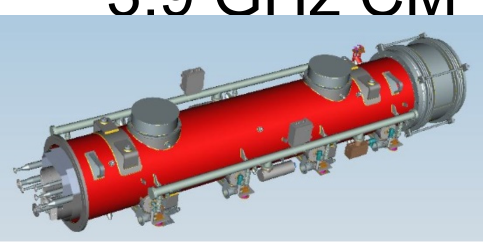


High-level comparison of 1.3 GHz & 3.9 GHz cryomodule

1.3 GHz CM



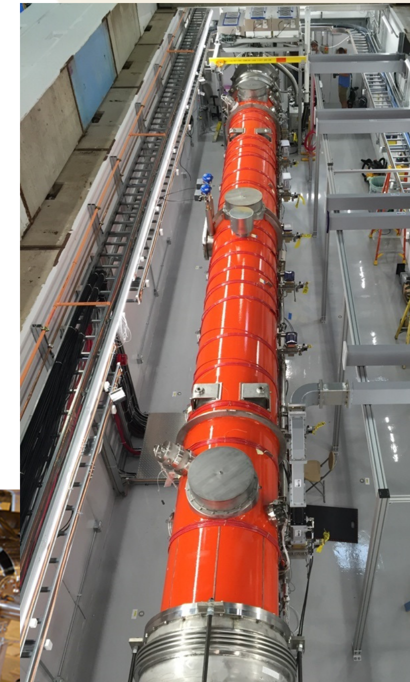
3.9 GHz CM

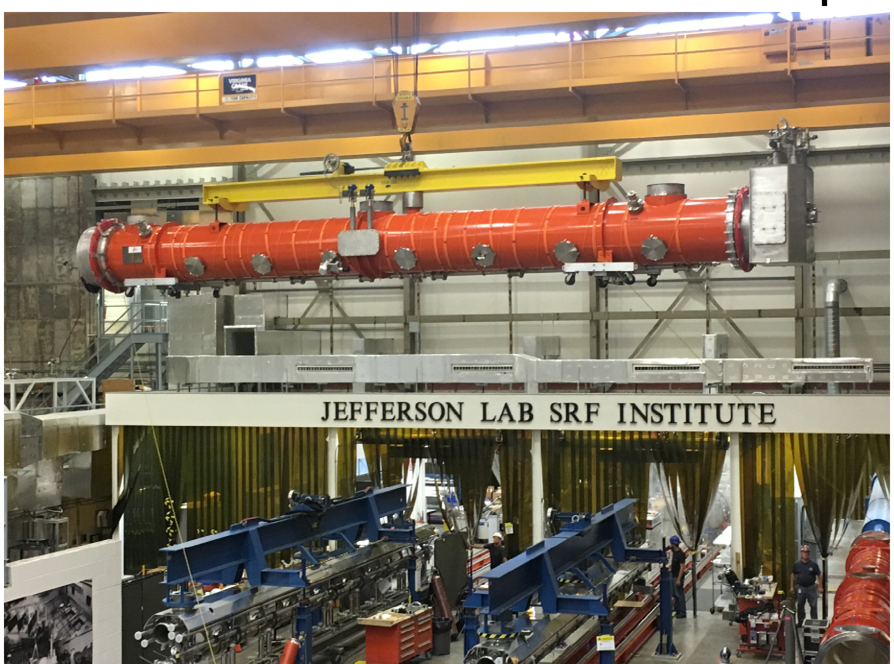


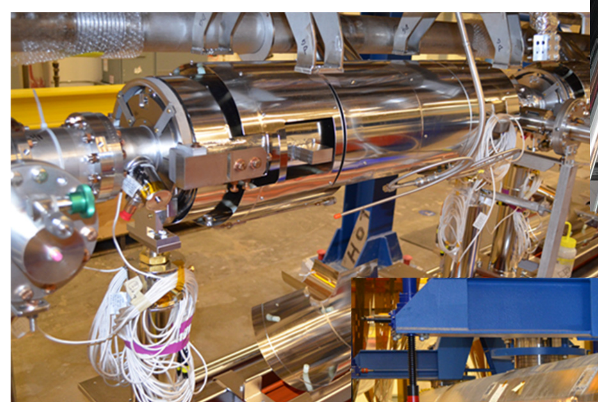
item	1.3 GHz CM	3.9 GHz CM
# installed (built) CM’s	35 (40)	2 (3)
Length/CM	~12.5 m	~7 m
Weight/CM	19,000 lbs	9,700 lbs
#cavities/CM	8	8
Cavity nominal Q0@2K	2.7E10 (N2 doped)	2.0E9 (std process)
Cavity nom. Eacc	16 MV/m	13.4 MV/m
Cavity tuner	End-lever + piezos	Blade + piezos
Cavity magnetic shielding	He vessel external (<5 mG)	He vessel internal & external (<15 mG)
Power couplers	All one side	Alternating sides
Magnet	Split quad+dipole V/H	None
HOM feedthroughs, BPM, cryogenic valves, interconnect & stand	Identical	Identical

LCLS-II Cavity and CM Statistics

- 320 1.3 GHz Cavities required
  - 304 from Vendors, 16 from ILC R&D program
- 304 of 320 cavities qualified to date
- 27 of 40 1.3 GHz cryomodules tested*
- 7 cryomodules currently being assembled
- 9 of 24 3.9 GHz cavities qualified







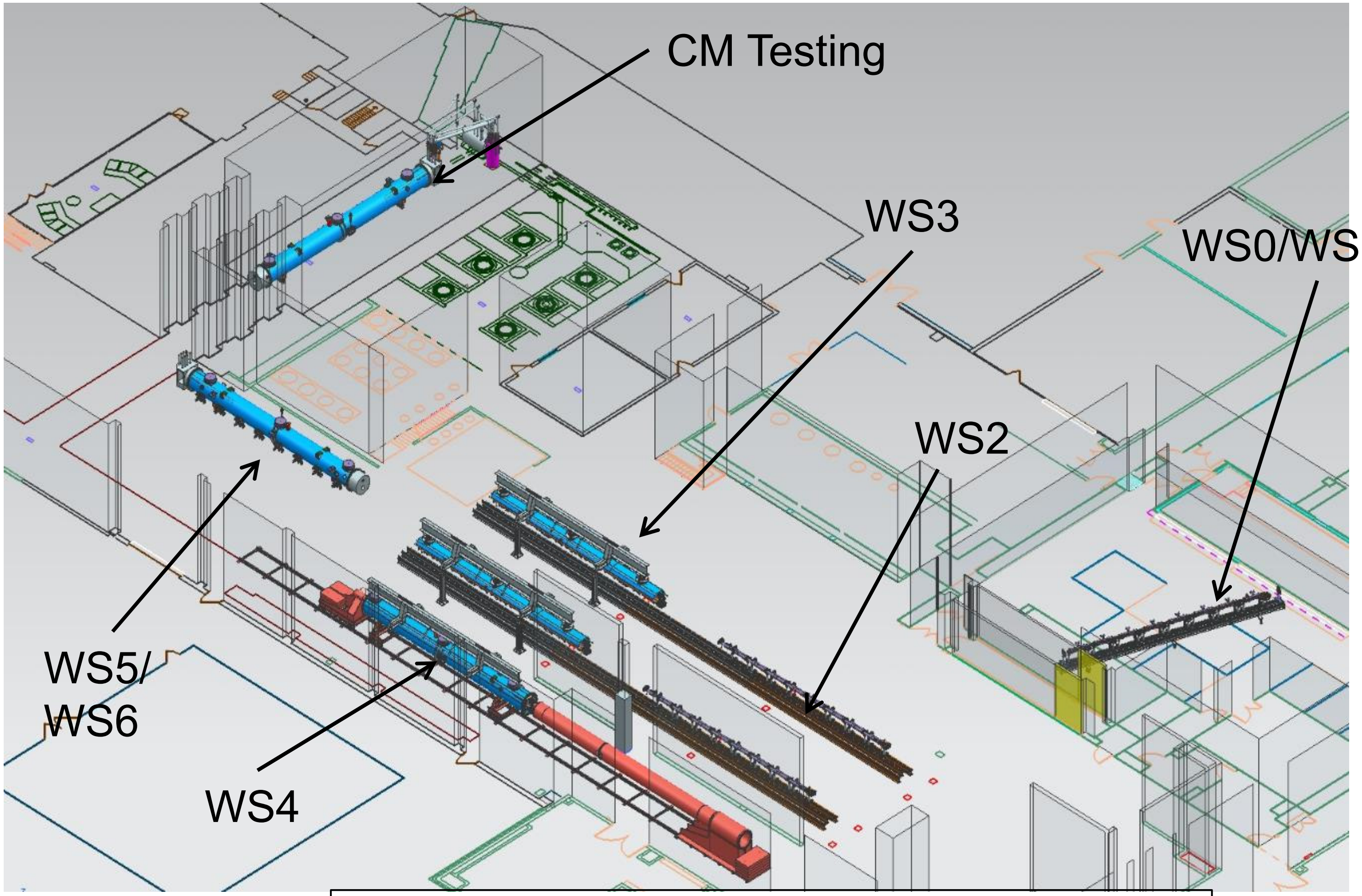
How are we building it?

Overall:

- Jefferson Lab builds and tests 21 – 1.3 GHz cryomodules
- Fermilab builds and tests 19 – 1.3 GHz cryomodules and 3 – 3.9 GHz cryomodules.
- SLAC – receives, inspects and installs the cryomodules
  - CM interconnect welding, RF connection etc.
- Procurements were split ~ 50/50 between JLab and FNAL
- SLAC procured fundamental power couplers

Cryomodule Assembly Sequence

Each Lab has 6 workstations, similar to XFEL



JLab Layout – FNAL has similar layout

JLab Cryomodule Production

FNAL Cryomodule Production

CM performance – what we care about

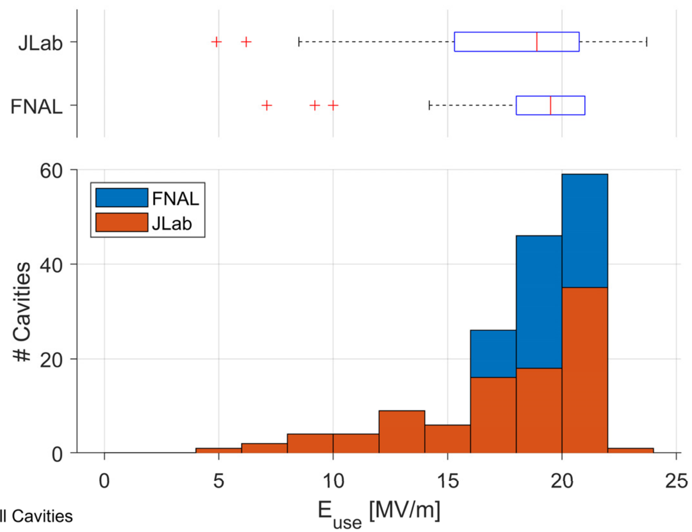
- Happy Users
  - Reliable beam
- How do we give it to them?
  - Cavities deliver on gradient – with comfortable margin
  - Minimal field emission – long term reliability
  - Cryogenic facility runs reliably
    - Cavity Quality factor
  - Cryomodules run reliably
    - Minimal cavity trips/quenches
    - Couplers behave (FPC, PU, HOM)
    - Tuners and piezos work as planned
    - Cables don’t overheat, short out or are wired incorrectly
    - Leaks don’t open up

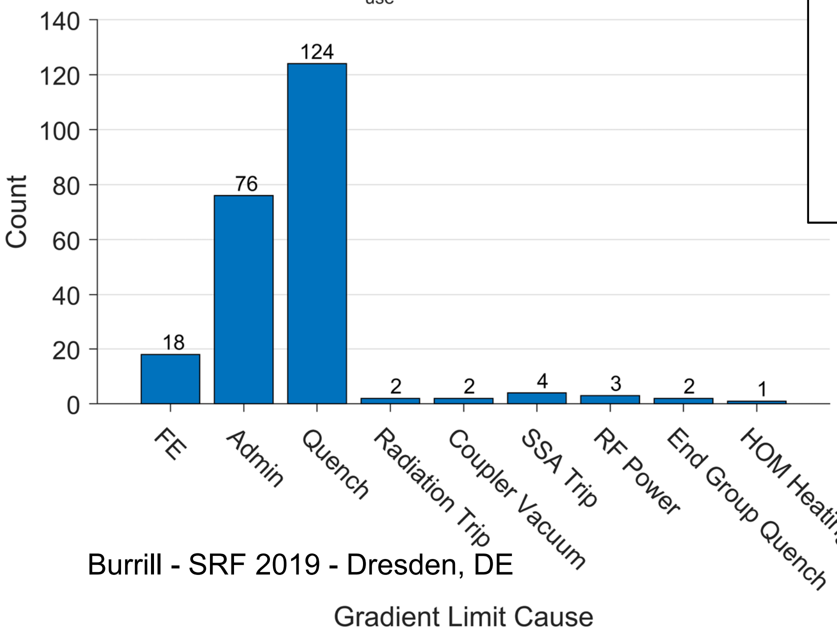
Detailed Cryomodule Acceptance Criteria

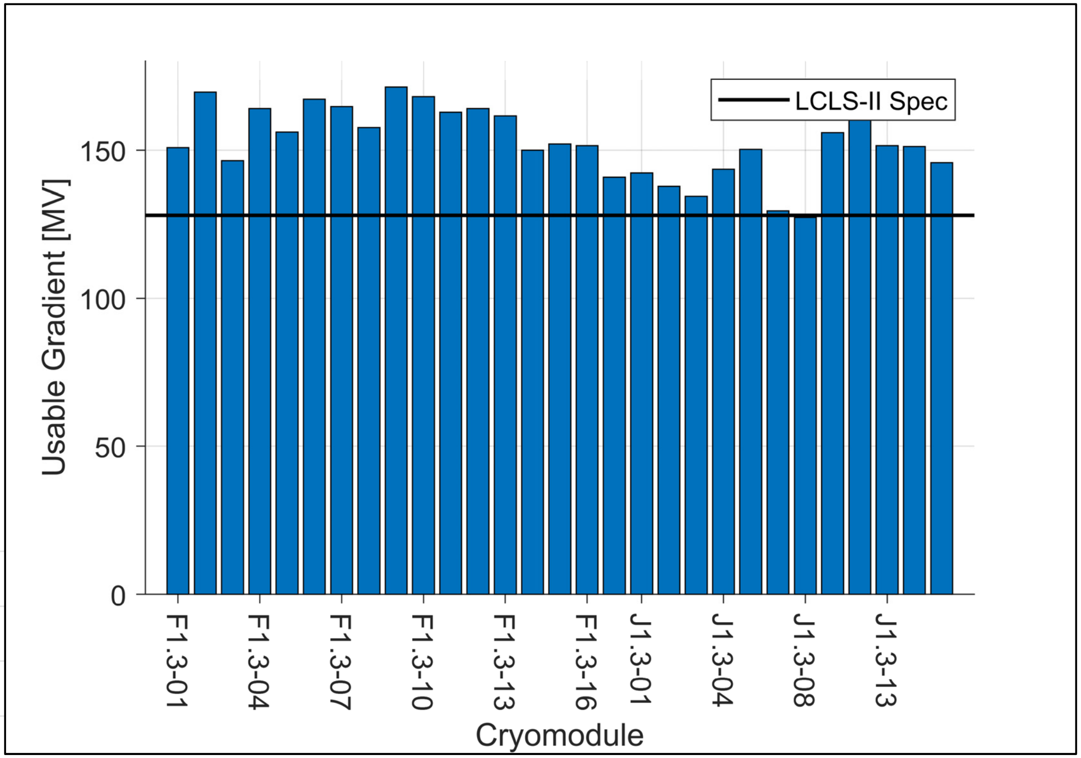
Table 2 Production Cryomodule Minimum Acceptance Criteria

	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 Usable gradient shall be defined as stable operation for at least 1 hour of c.w. operation.
✓	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. If the CM test stand does not support operation of all 8 cavities together then two - 4 cavity runs can be carried out instead.
✓	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		$Q_{ext} \geq 2\times10^{11}$, 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

Cryomodule Performance – Usable Gradient

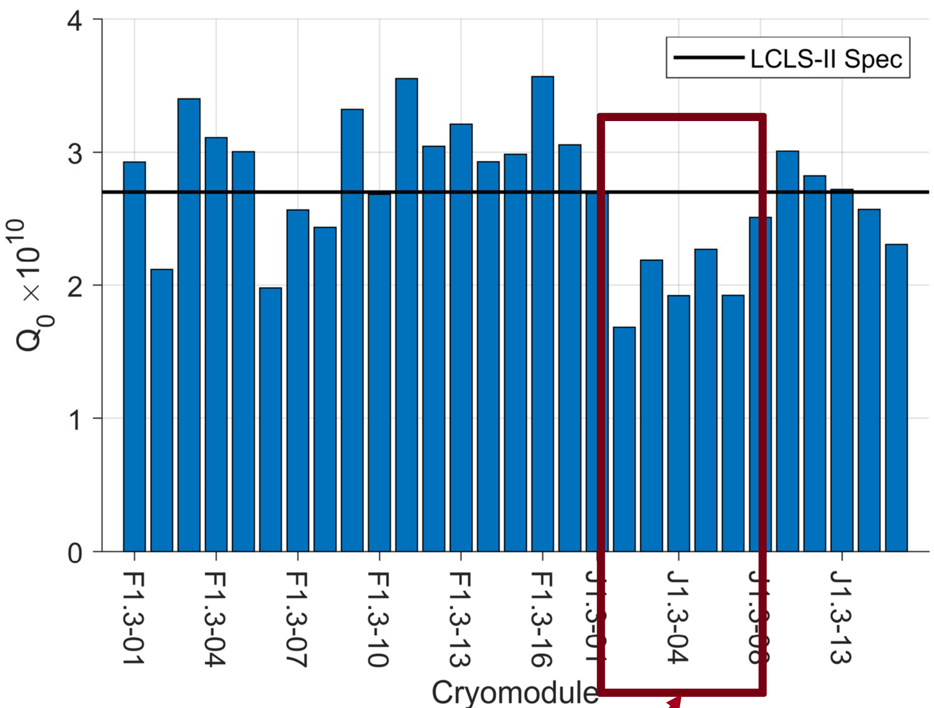




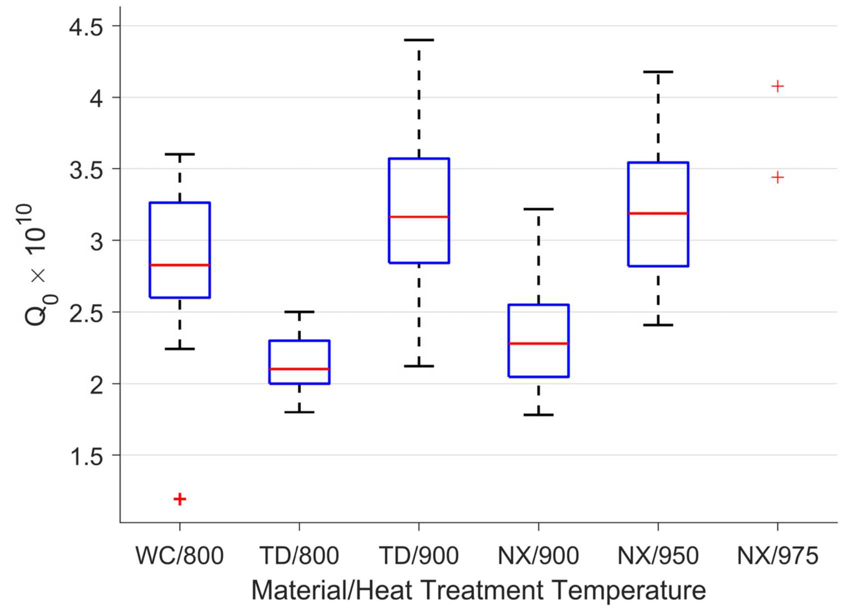


Usable gradient is either:
21 MV/m (admin limit)
FE < 50 mR/hr
Cavity quench

Cryomodule Performance – Quality Factor



Insufficient cooldown rate



Gradient Optimization

Our goal is to build a 4GeV linac operable by one 4 kW cryoplant.

Case	P_{diss}/CM [W]	Extrapolated Total CP Load [kW]
JLab Q's Estimated	72.29	3.52
JLab Q's as Measured	76.92	3.68

Assumptions:
- Gradient limit is 18.2 MV/m
- 7 worst cavities are turned off
- CM02's are not used

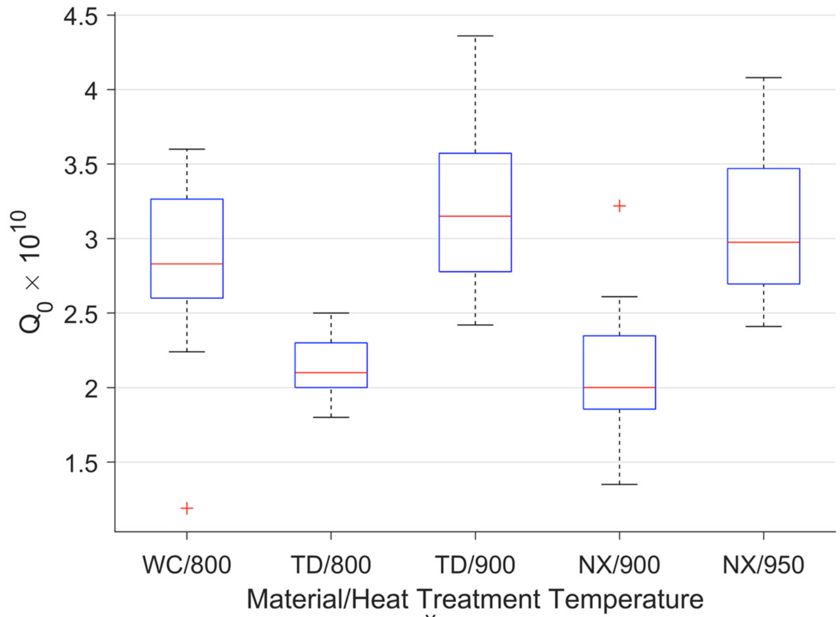
Cryomodule Challenges

1. Maintaining High Q from vertical test to cryomodule
2. Coupler overheating – limited incidents
3. Cavity quench after stable operation for more than 30 minutes
4. Cryomodule test cave differences
5. Shipping cryomodules 5000 km

Maintaining High Q from Vertical Test to Cryomodule

SLAC

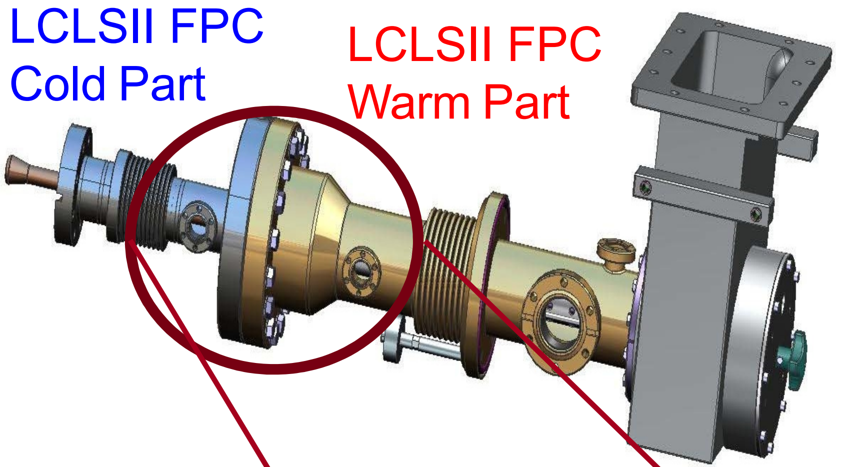
- Flux trapping and thus Q depression varies based on material type and cavity preparation.
- Required “fast” cooldown rate varies based on material
  - 30 g/sec – spec
  - 80 g/sec required for some material
  - Some material simply traps 100% of trapped flux.
- JLab only recently achieved ~30 g/sec cooldown
  - Early JLab CM test had low measured Q due to slow cooldown rate and too warm helium
  - **This does not represent true CM performance**



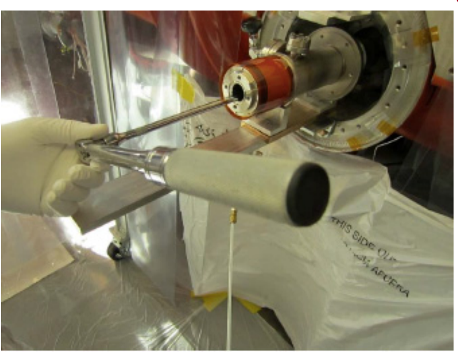
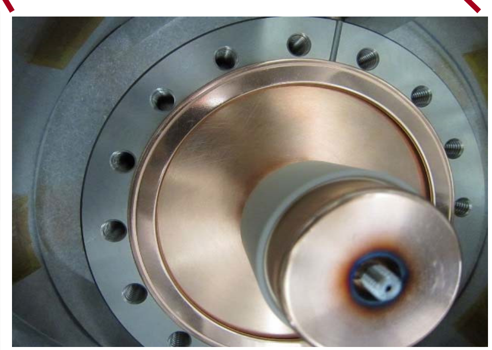
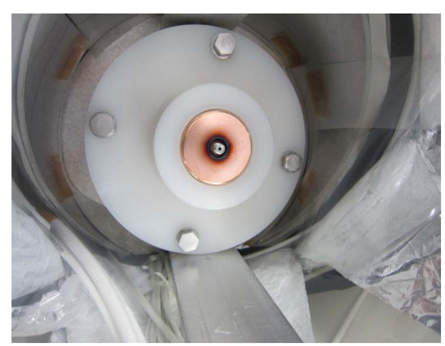
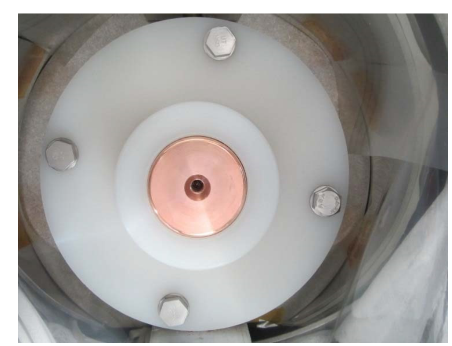
Boxplot by Material Type

- Red line is Median for each type
- Blue box is 25th – 75th quartile
- Whiskers are min and mix
- + and * are outliers

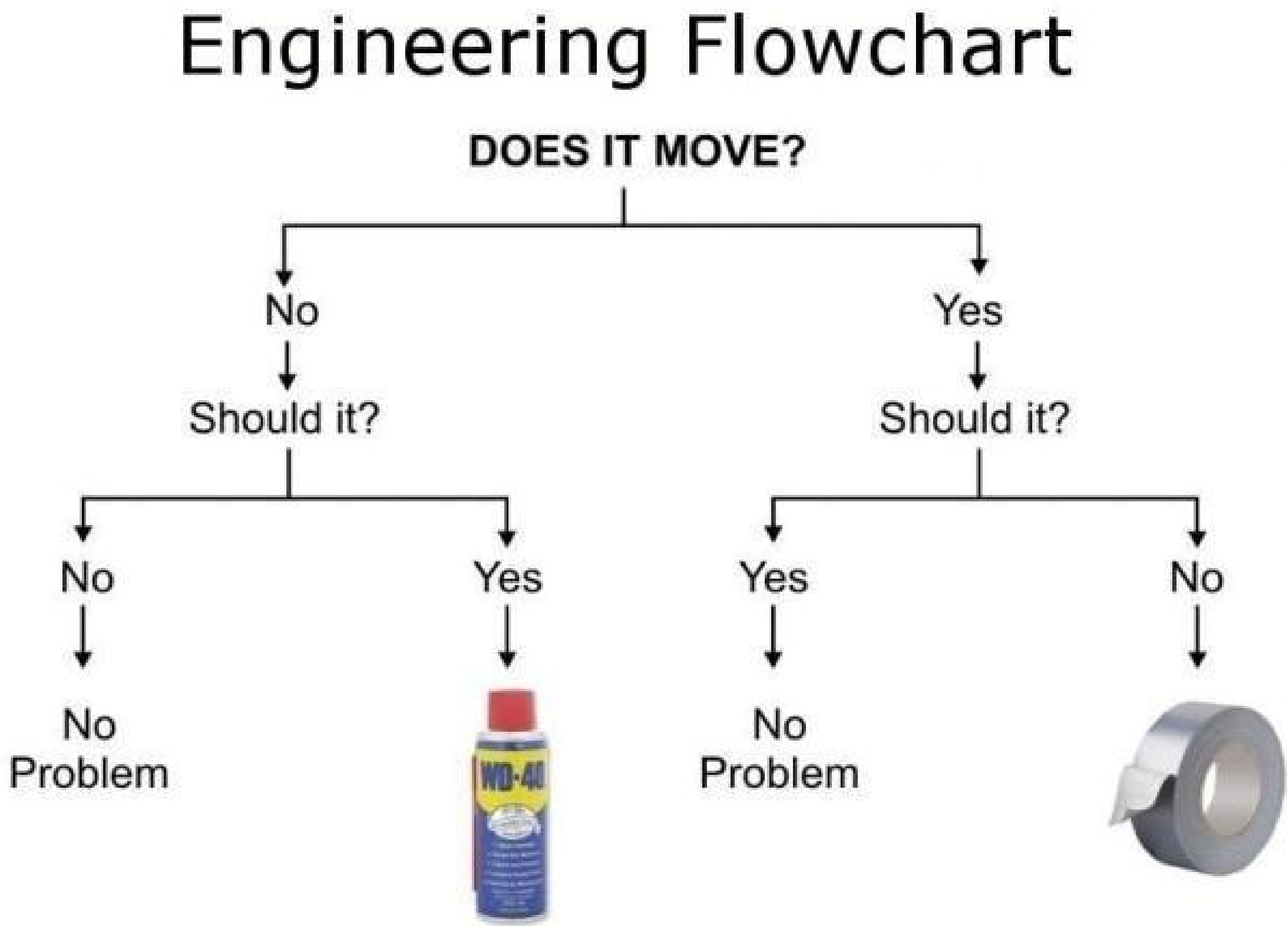
Cryomodule Challenges - Coupler



- 3 couplers have had overheating, or other spurious RF issues
- Cause for 2 cases traced to connection of inner conductor
- Root cause – improperly seated bolt

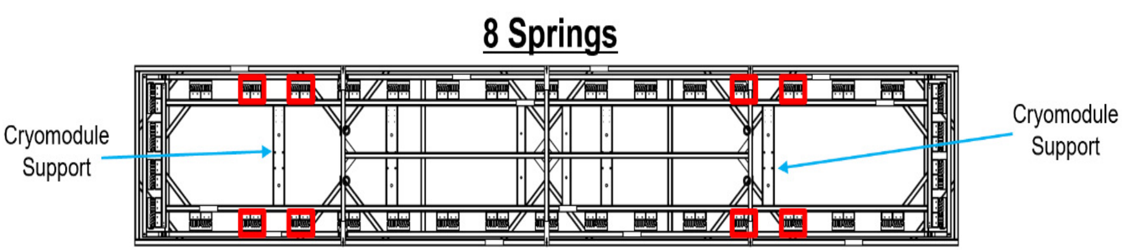
Some of our Challenges…

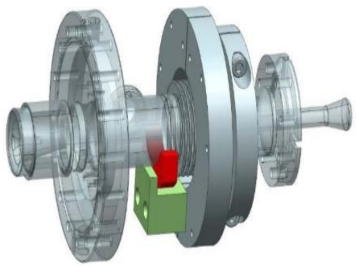


Cryomodule Shipping and Handling

The problem: Cryomodule damage during shipping and handling

- Ensure that the entire design has been fully analyzed before shipping.
  - Just because someone shipped something similar doesn't mean things will be ok
- Prototype – Test – Revise – Test
- Understand the entire processes from the time it leave the test cave until it's ready for operation at the host site
- Ensure the procedures are precise and verify people follow them
- Detailed shipping presentations at TTC 2019 (T. Peterson and others)
  - https://indico.desy.de/indico/event/21337/session/13/contribution/81





Lessons Learned from the Collaboration

- Standardize cryomodule testing across all locations
  - Measurement techniques
  - Radiation detectors
  - Durations for acceptance testing
- Ensure any changes to cryomodule design are pushed out of the engineering software to all concerned parties
- Agree on data packages and format to be transmitted to the host lab

Summary

- 17 Cryomodules are at SLAC!
- LCLS-II is well positioned to operate with average $Q_0 \geq 2.7x10^{10}$ @ 16 MV/m long term.
  - **130 MV Energy gain CW per CM = 80 W to 2K**
- Many issues have been identified along the way but solutions have been found
- Ensure that design changes are properly communicated to all stakeholders
  - Especially those with whom you don't routinely interact
- Learn from those who have gone before you

LCLS-II

The End

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