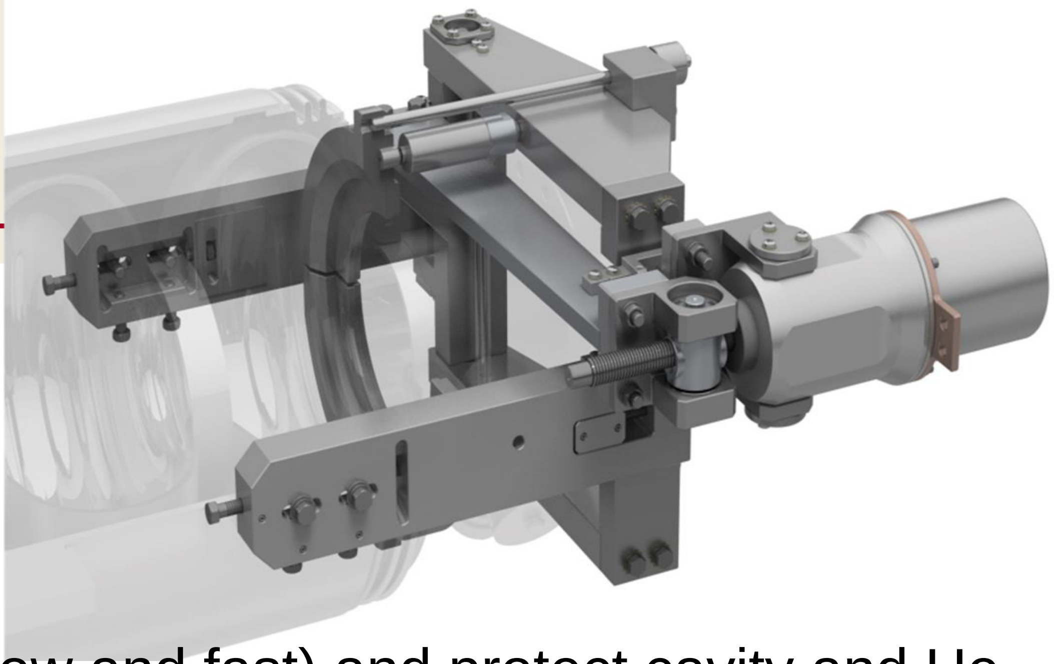
Tuner and coupler testing in cryomodule

Nikolay Solyak
(on behalf of LCLS II team)
LCWS2018, Oct.25, 2018, Arlington

Tuner Functional Specification



Tuner design team:

Y.Pischalnikov, W. Schappert, J.Holzbauer, J.C. Yun, E.Borissov

- Designed for ILC cavity
- Tuner must tune cavity (slow and fast) and protect cavity and He Vessel system during CM production cycle and operation of the accelerator.
- High reliability of tuner components (electromechanical actuator and piezo-actuator); Replaceable through port, if failed.
- Low magnetization to preserve high Q0 of SRF cavity
- Tight requirements for slow/coarse & fast/fine tuning resolution
  → *cavity bandwidth 30 Hz, resonance control <**10Hz)***

Tuner Physics Requirements & lifetime specification

Slow Tuner frequency range	nominal	250 kHz
	max	450 kHz
Slow Tuner dimensional range	nominal	0.75 mm
	max	1.3 mm
Slow Tuner sensitivity		2 Hz/step
Fast Tuner frequency range		1 kHz
Fast Tuner dimensional range		3 um
Fast Tuner tuning resolution		1 Hz
Fast Tuner stroke resolution		3 nm
Fast Tuner response bandwidth		5 kHz
Min. tuner stiffness Min. mechanical resonance		30 kN/mm 5 kHz
Tuner lifetime		20 years
Tuner operating conditions		Ins. vacuum T=20-60K

Y.Pischalnikov, LCLS-II Tuner, FAC review 10/14/15

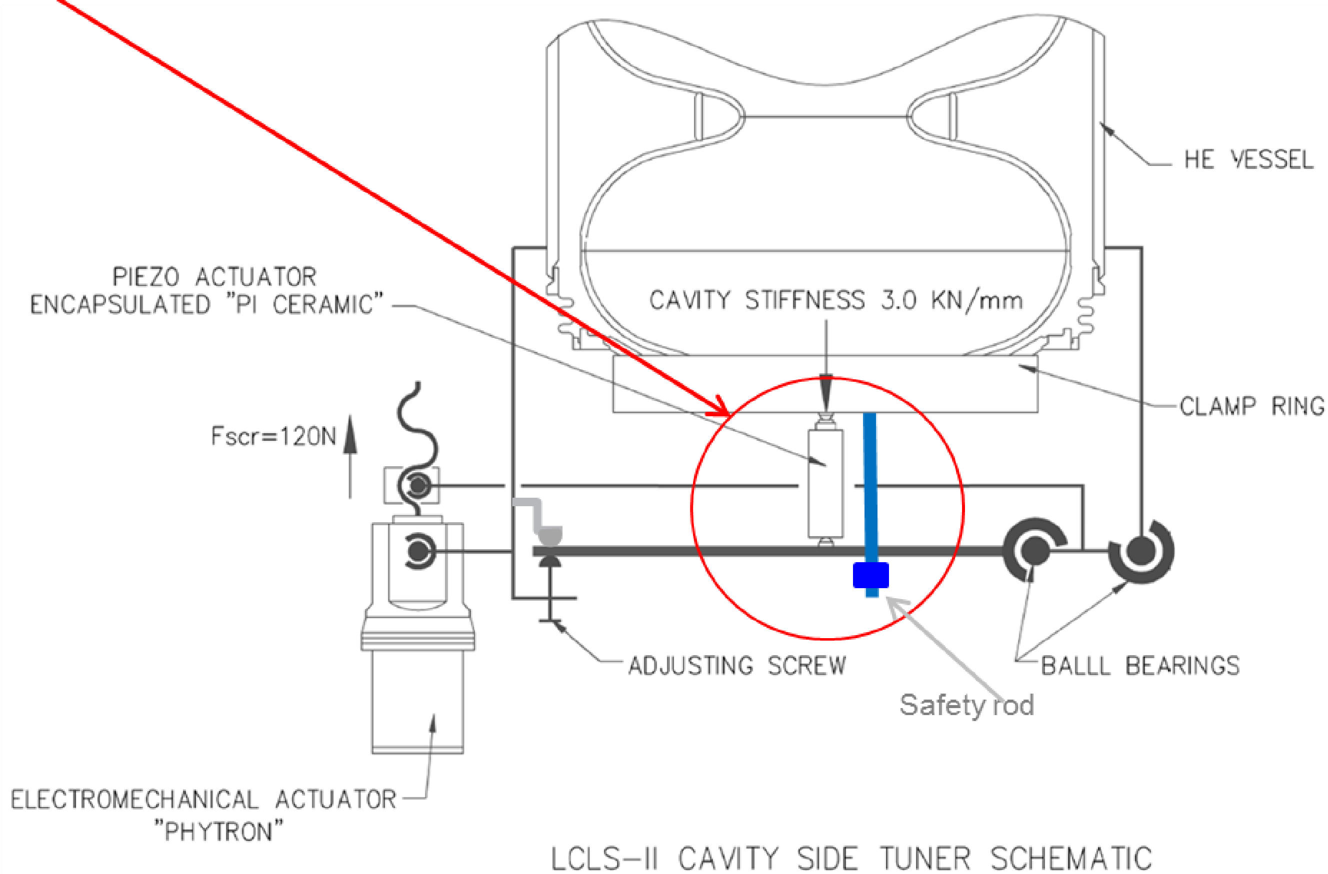
lifetime specs for Active Components

Slow Tuner/ electromechanical actuator lifetime (20 years)	**1,000 spindle rotations**
Fast Tuner/ electromechanical actuator lifetime (20 years)	**2.10^{10} pulses (V_{pp} = 2V@40 Hz) 6.10^{6} pulses (V_{pp}= 50V@10 mHz) 40 warm-cool down cycles**

Max Radiation exposure of the tuner components up 2-4*10^{8} Rad

LCLS II Tuner Schematics

- Slow/Coarse Tuner is double lever tuner (close to design of the SACLAY 1)
- Coarse Tuner ration 1/20 (Saclay 1 ~ 1/17)
- Fast Tuner - two piezo installed close to flange of cavity /translation of the **stroke from piezo directly** to the cavity *(tuner resolution reqs. 1Hz (or 3nm)*



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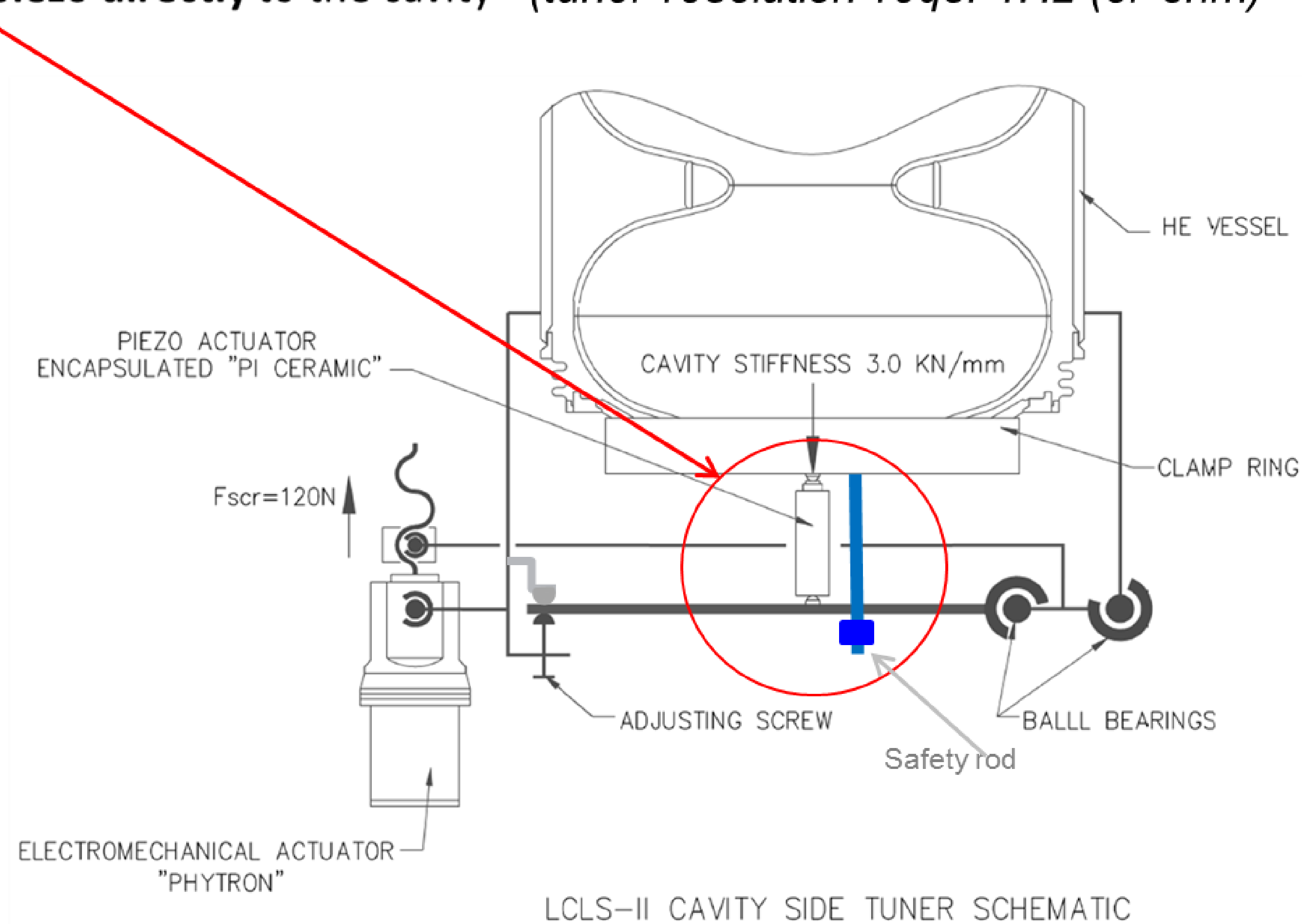
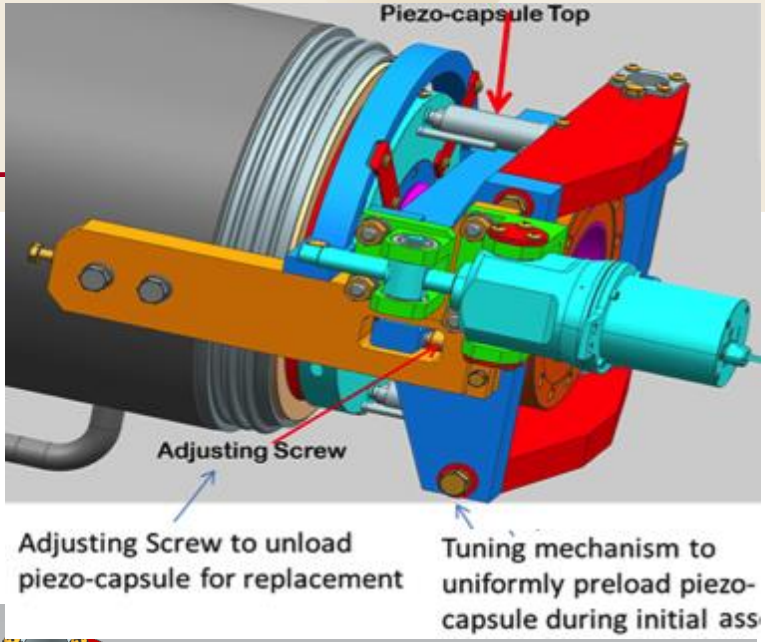
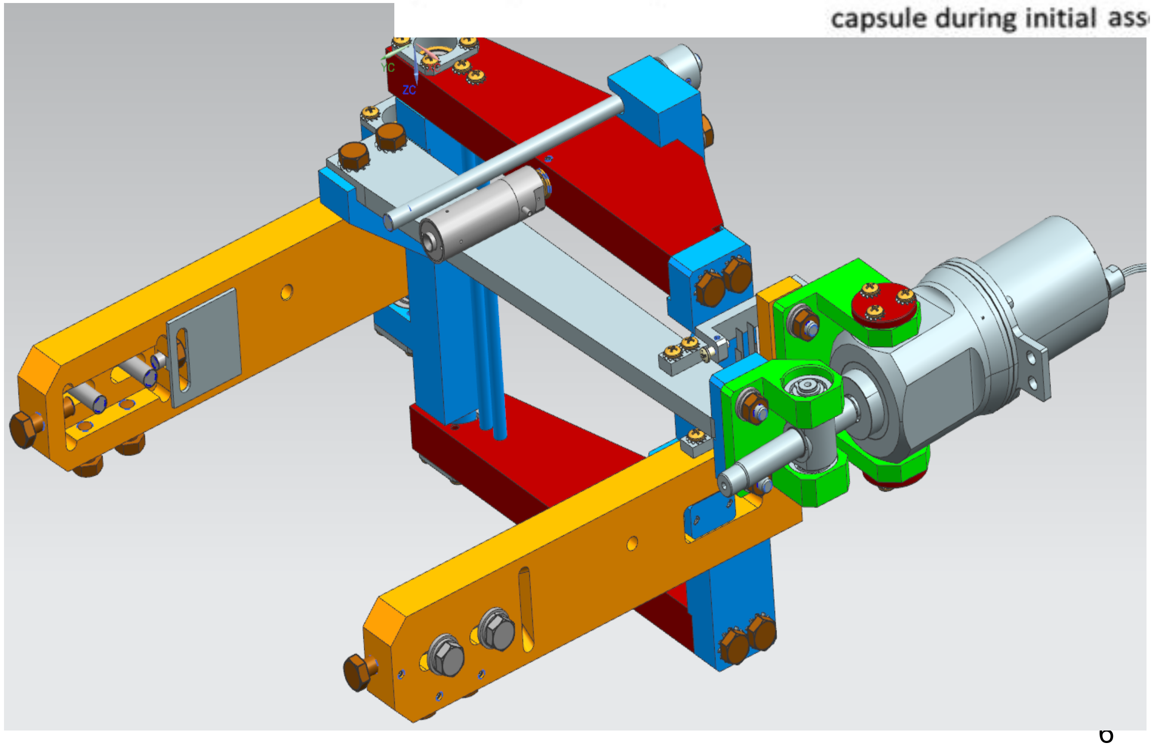


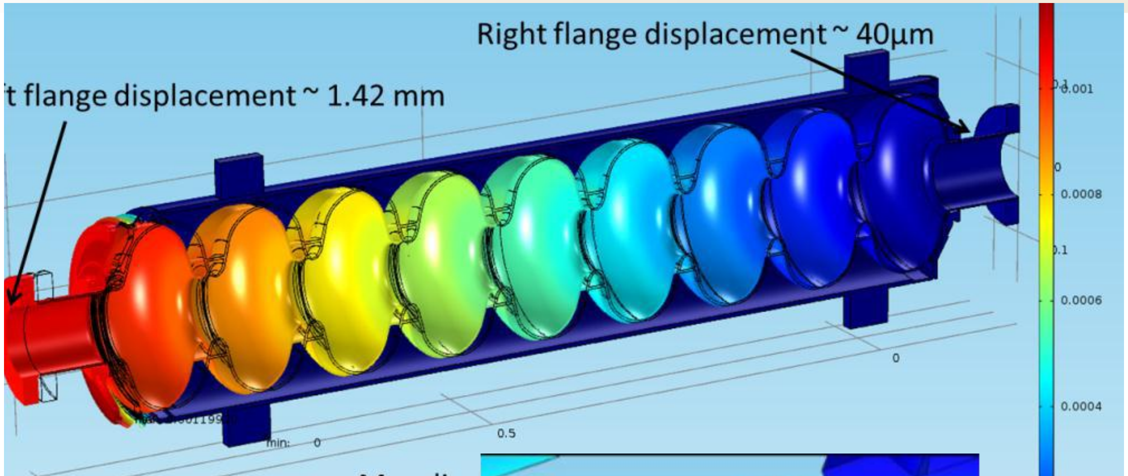
Tuner Design: 3D Model

- Similar to XFEL design
- Compressing cavity from non-coupler side (Push-action)
- Forces on the cavity applied through ring mounted on the cavity/beam pipe conical flange
- Designed to allow replacing active components (motor/gear box & piezo-stack) without disassembling whole fixture (through tuner port)





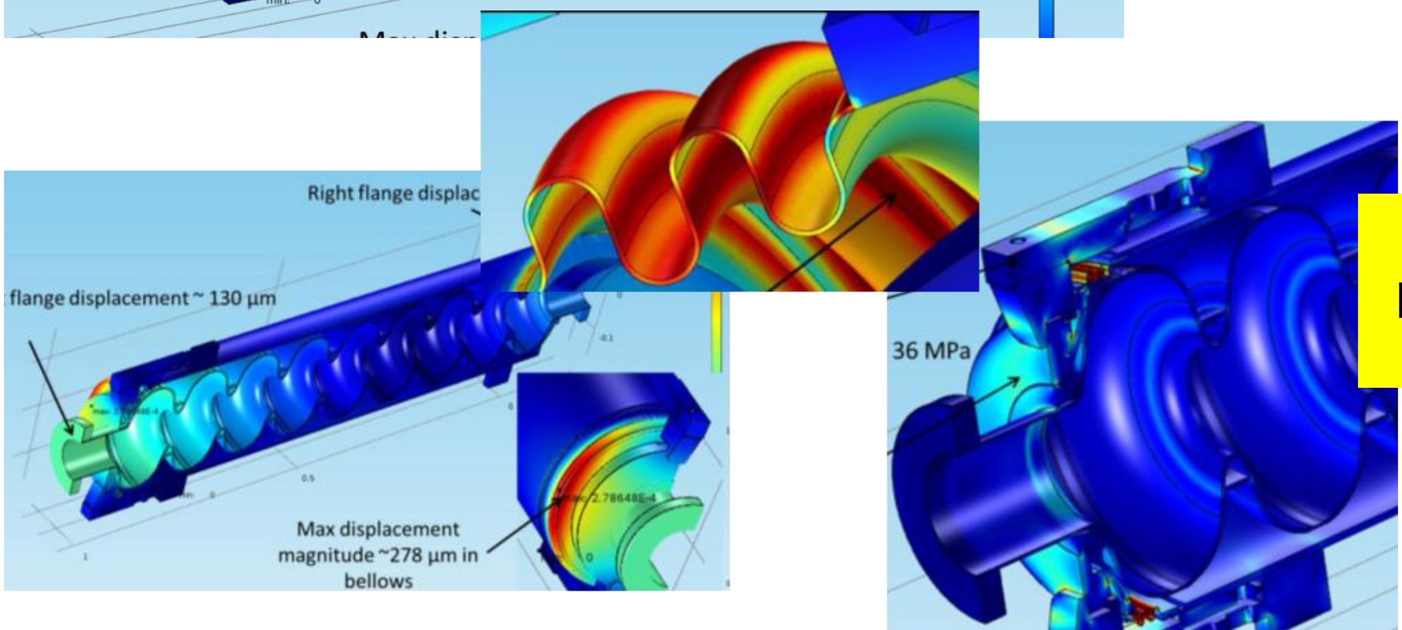
FEA Analysis of the Full Scale Assembly: Cav./He Vessel/Tuner



2.3 bar differential pressure without brace in RT conditions.

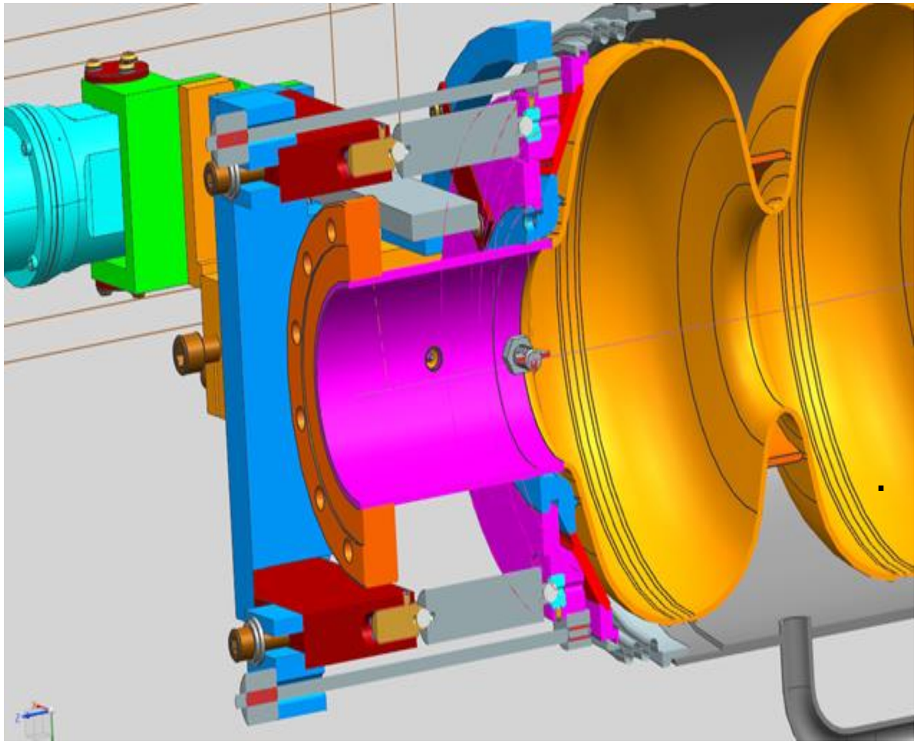
Total Cavity Deformation ~1.4 mm

Reqs: < 0.6mm, Nb in elastic regime @RT

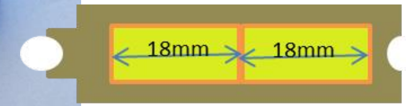


4 bar differential pressure with brace in 5K conditions.

Tuner Design: Piezo-stack

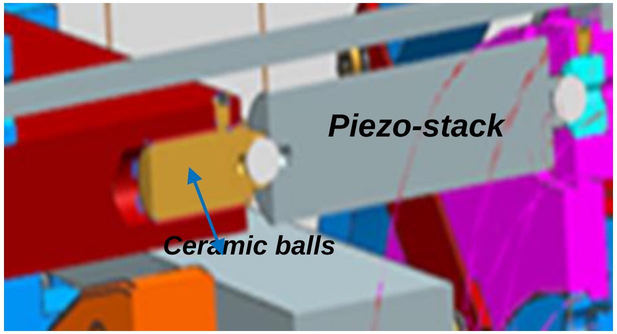


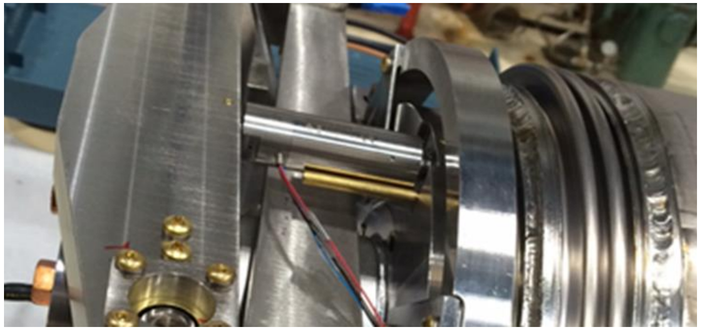
18*10*10mm



- Encapsulated piezo designed and manufactured by Physik Instrumente (PI) per FNAL specifications.
- Piezo preloaded with 800N.
- Each tuner equipped has 4 piezo-stacks, each piezo can be run independently

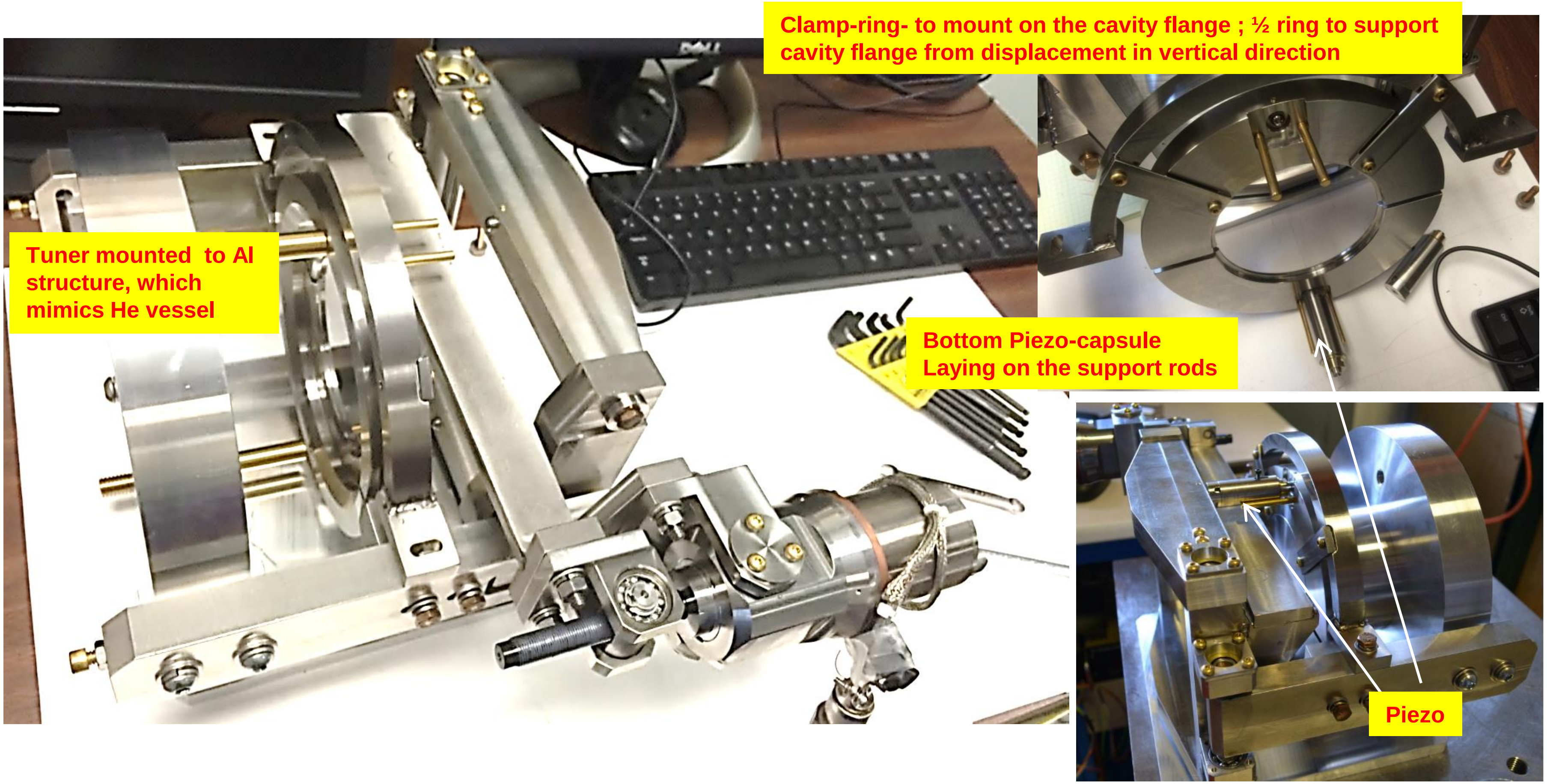
Piezo preload adjustment screw



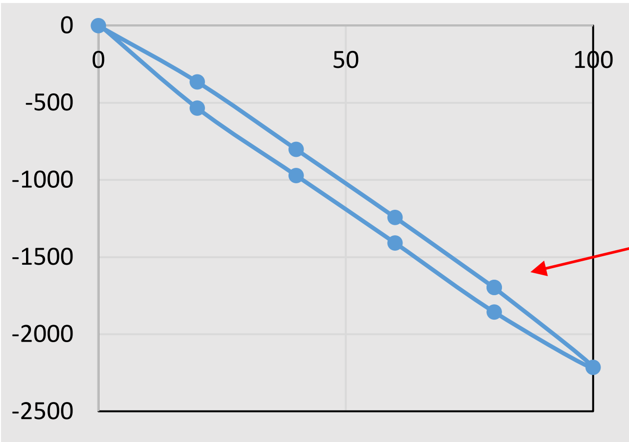


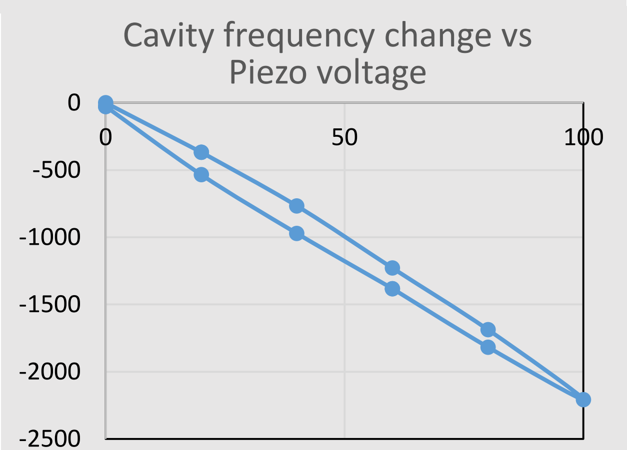
FNAL Tuner assembly (design details)

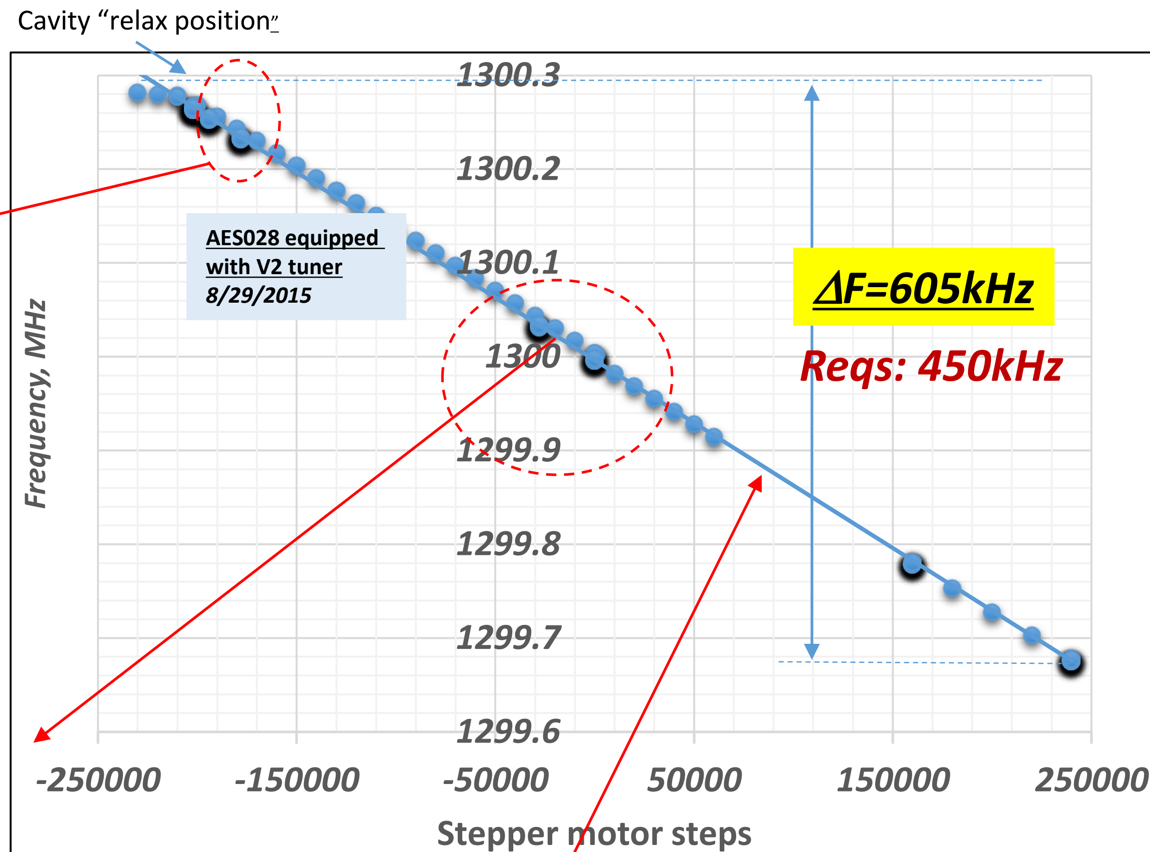
- FNAL developed Tuner for “short-short” cavity, available fro pre-production CM
  Active tuner components replaceable from special port (reliability)



Tuner performance at HTS test at 2K (prototyping)





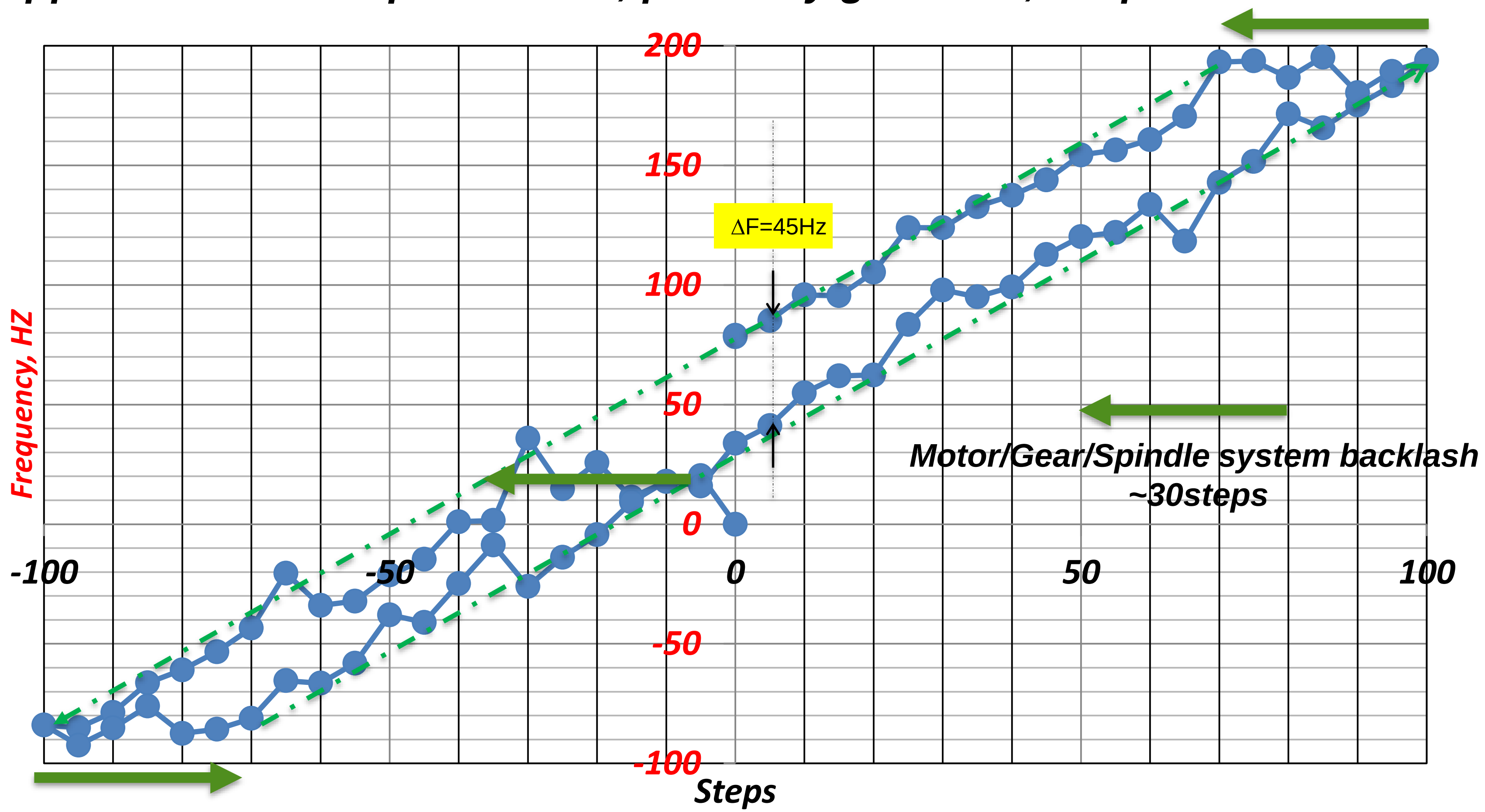


- Piezo sensitivity -2.4Hz/V,
- Range 2.4kHz per 4 piezo Resolution <0.5 Hz

Slow Tuner sensitivity (slope) ~1.3Hz / step

Slow/Coarse Tuner short range hysteresis *(backlash)*

Stepper motor 200steps/one turn; planetary gear 1:50; Ti spindle M12X1mm



Piezo-stack Lifetime tests

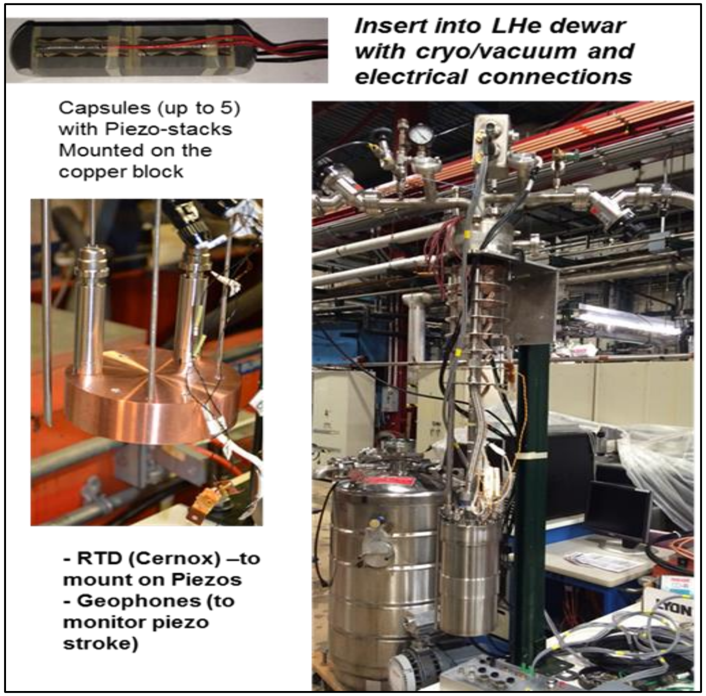
SRF2015, Whistler, BC, Canada THPB065

Lifetime: cycles and heating

Accelerated piezo-stack lifetime test

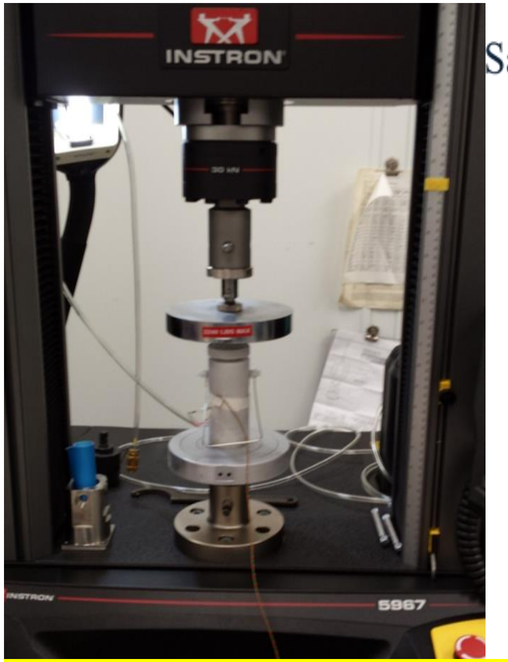
$2*10^{10}$ *pulses* ($V_{pp} = 2V$ & $F = 40Hz$)

20years → 2 month (40Hz→5kHz)



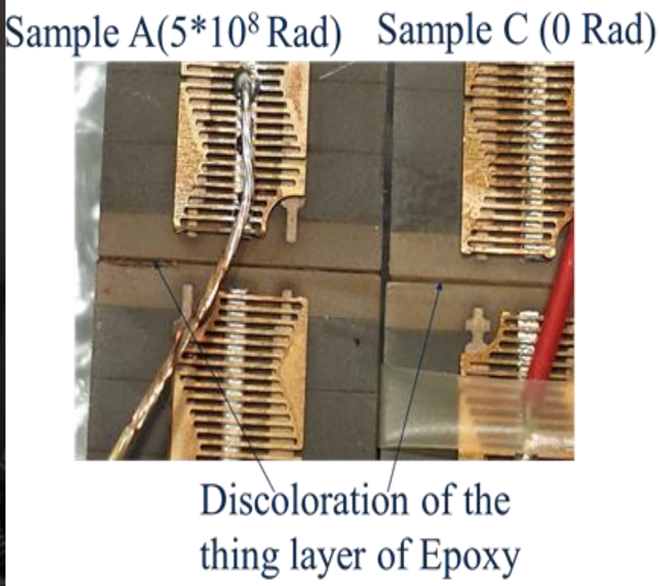
LCLS II Tuner piezo-stacks run for <u>2.5*10^10 pulses (or 125% of LCLS II expected lifetime</u>) without any degradation or overheating

Force/stress



Fixture with piezo-capsule was cool-down inside LN2,
Piezo survived 25kN,
2Piezo-stacks = 50kN
(10kN requirements)
Ceramic crashed at 28kN

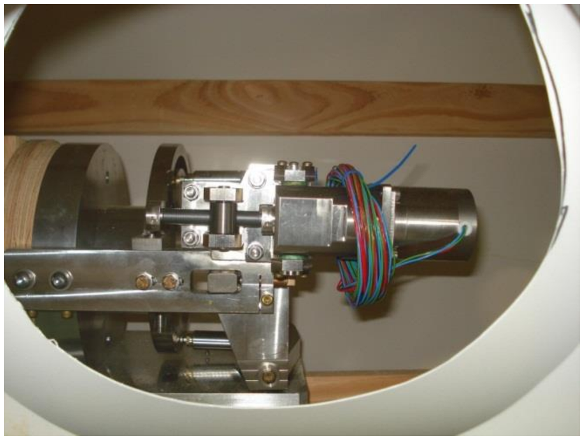
Irradiation 10^9Rad (gamma)

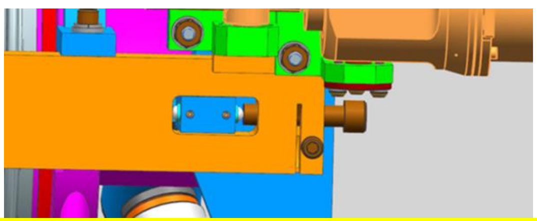


Stroke of the piezo-stack decreased only on 10% after irradiation up to 10^9 Rad

Active tuner components (electromechanical actuator& piezo-stack) need to be replaceable through special port

Tuner installed on the CM mock-up at FNAL





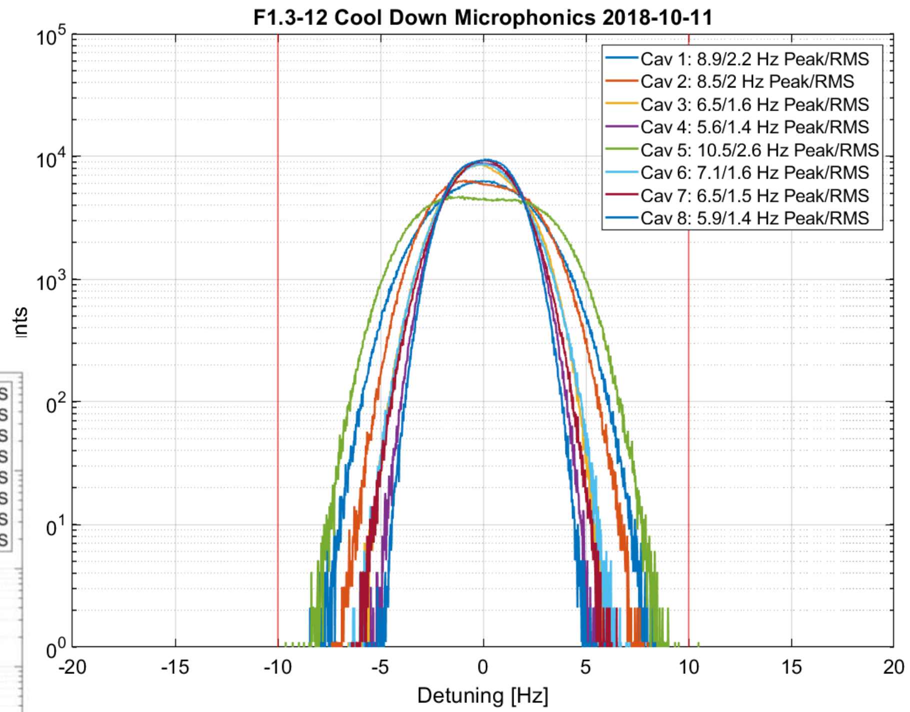
Function of this screw to unload tuner to replace piezo/motor

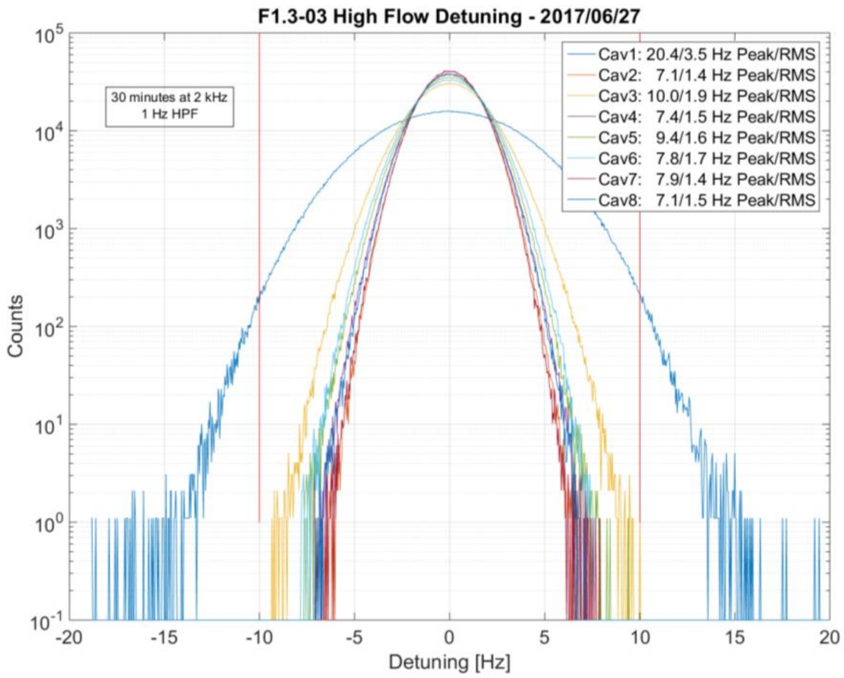
Cavity Tuner Performance:

LCLS-II Data

Showing real-time resonator tune

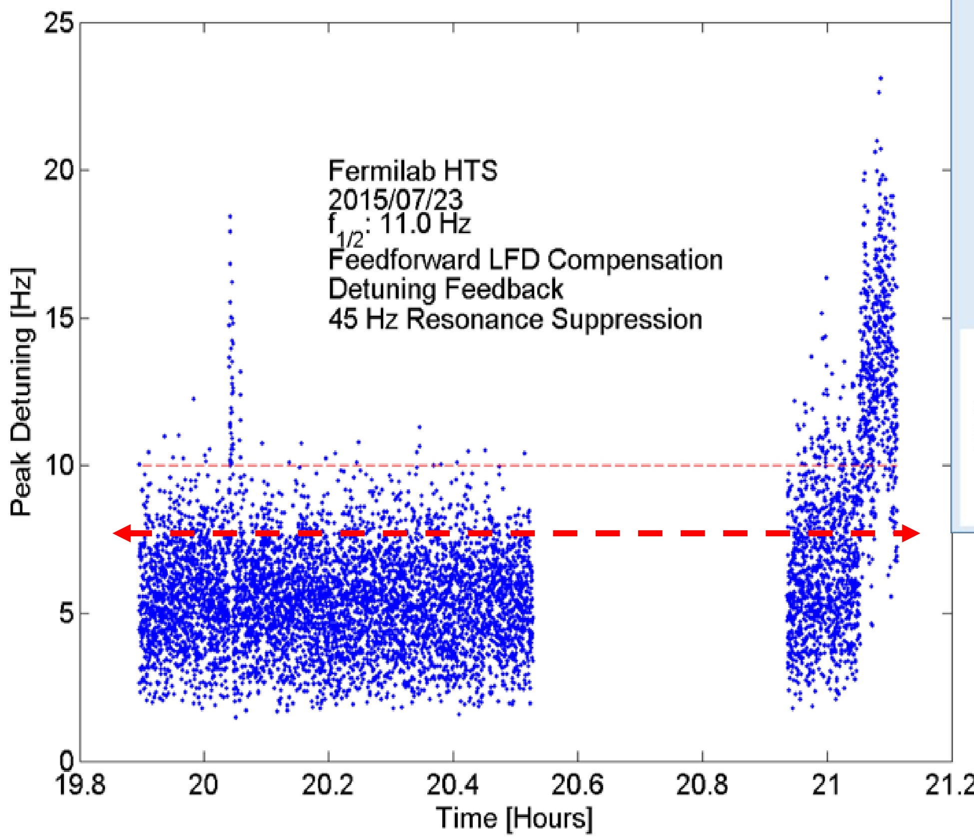
Spec: +/- 10 Hz deviation must not happen more than once ~ hours



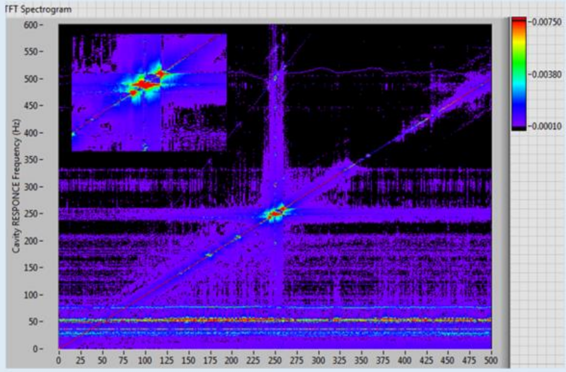


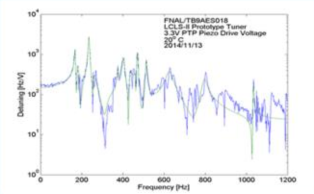
LCWS18 M. Ross (SLAC)

LCLS II Tuner – demonstration of active resonance control at HTS with piezo



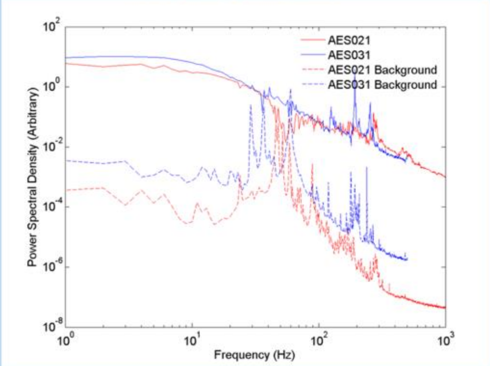
Drive piezo actuator with stepped frequency sine wave





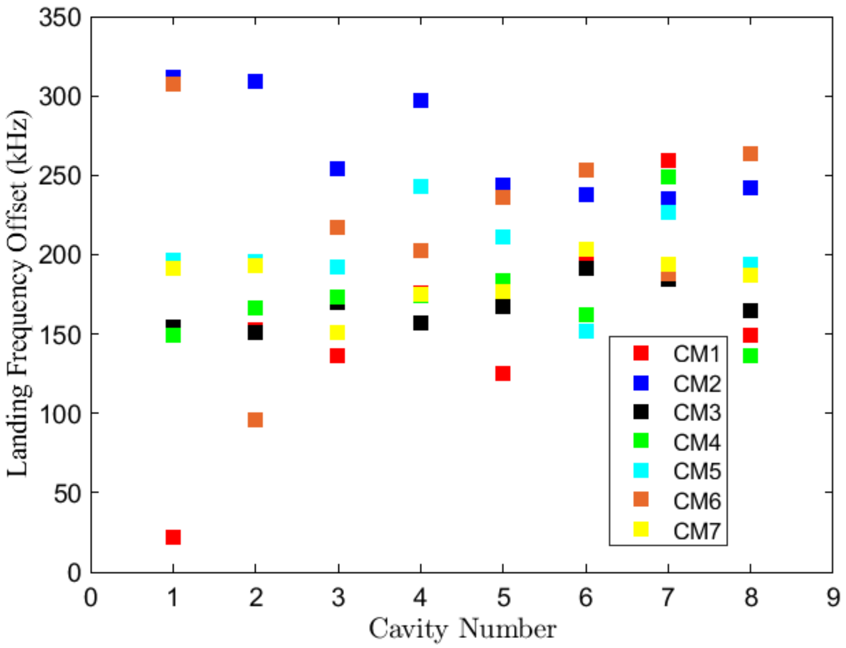
#	f(Hz)	tau(ms)	kappa(Hz/V)	Strength
1	**235**	49	14.5	***0.65***
2	**168.1**	41	6.86	***0.1***
3	**471.2**	46	5.79	***0.09***
4	**402.2**	17	1.29	***0.04***
5	**232.6**	126.4	1.29	***0.03***

Modulate cavity drive with stepped frequency sine wave

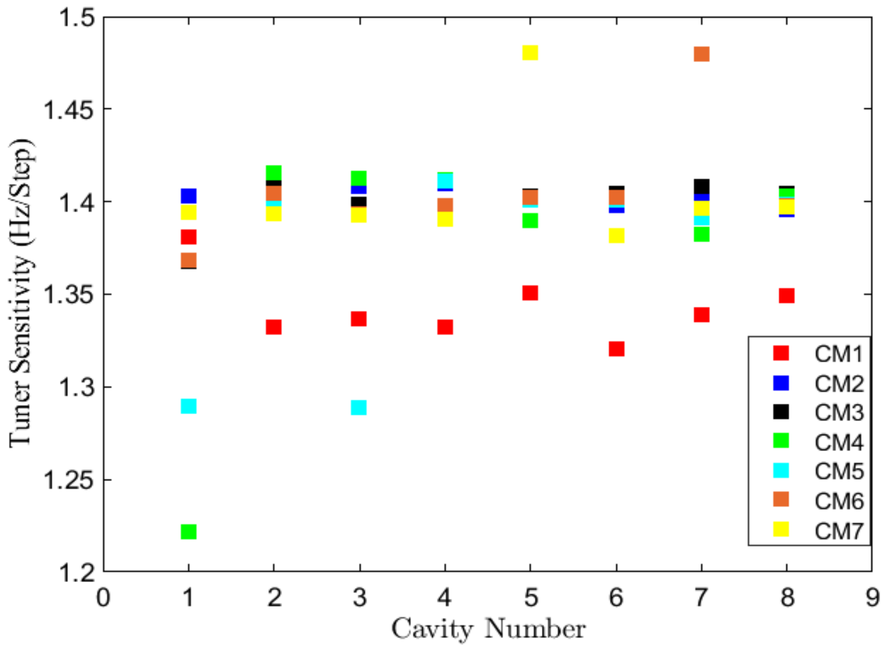


Two LCLS II Cavity measured at horizontal test stands at FNAL& Cornell
Notable differences between the two cavities

Slow Tuner performance in CM



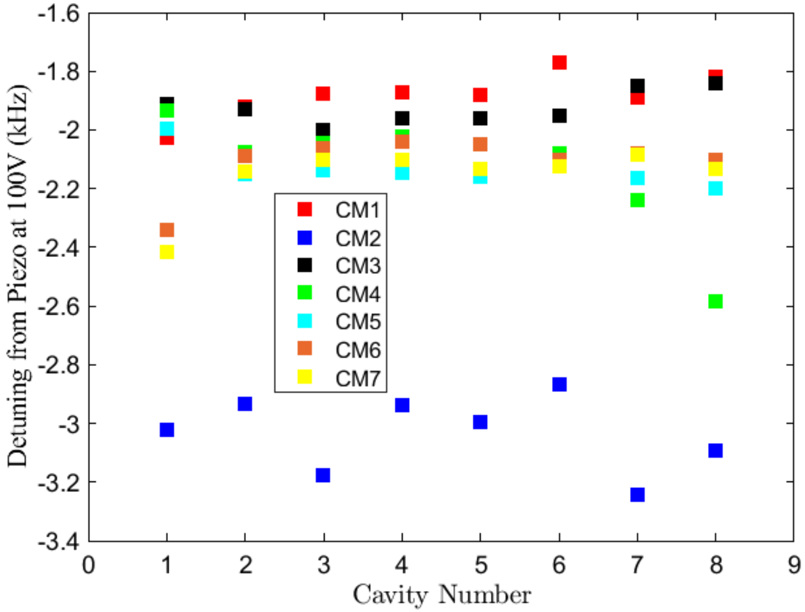
Cavities frequency offset from 1.3GHz after CM cool-down to T=2K. Measurements for 7 CM tested at CMTS.

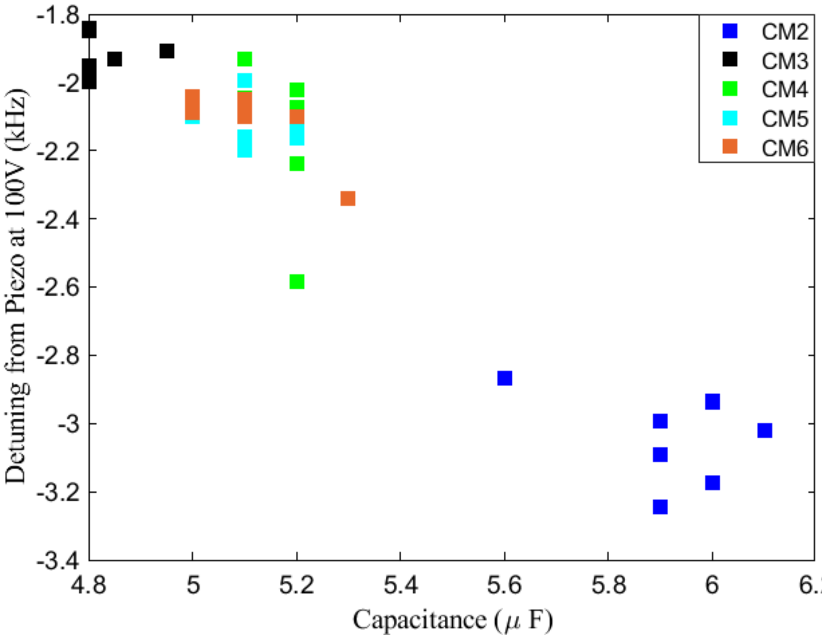


Slow tuner sensitivity for 56 tuner/cavity system installed on 7 CMs.

J.Holzbauer et.al., , IPA2018

Piezo Tuner performance

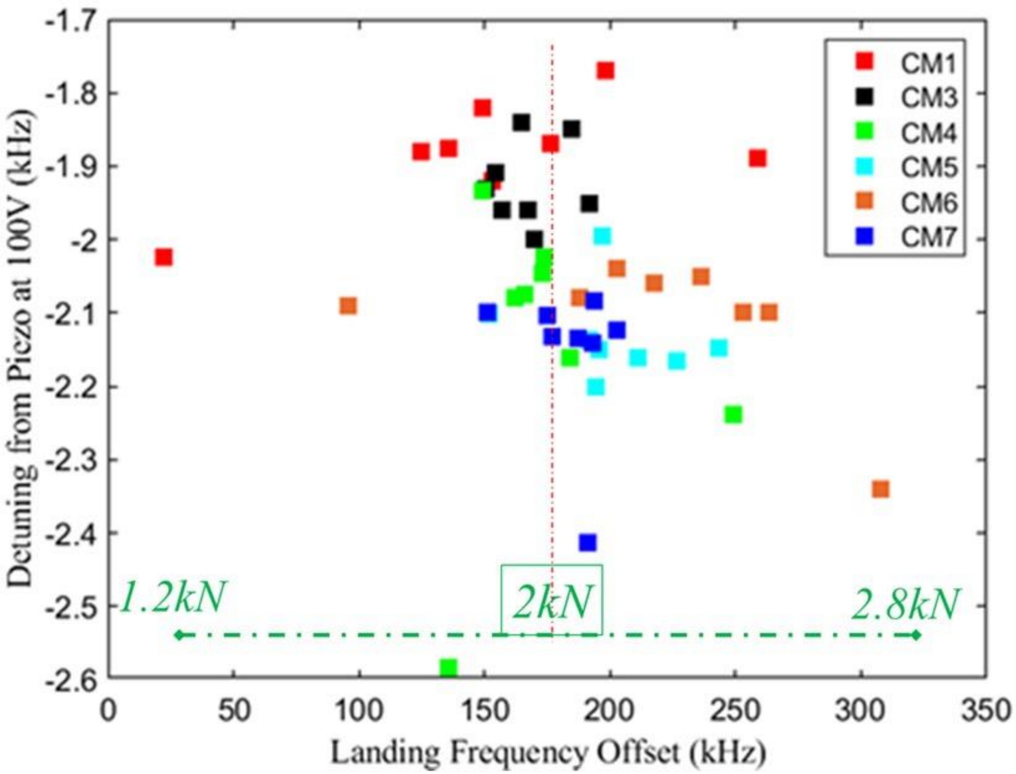




Piezo tuner sensitivity. Cavity detuning when DC voltage 100V applied to both piezo-actuators.

Piezo tuner sensitivity vs. capacitance of the piezo-actuators.

Piezo tuner



Detuning the cavity with fast/piezo tuner.

Developed and implemented procedure of the tuner testing as a part of assembly tuners on the CMs. Also procedure of the testing tuners as a part of the CM cold test at CMTF developed and implemented.
All 64 tuners (installed inside 8 CMs) tested cold. Parameters of all 64 tuners met requirements specifications.

Summary (Tuner)

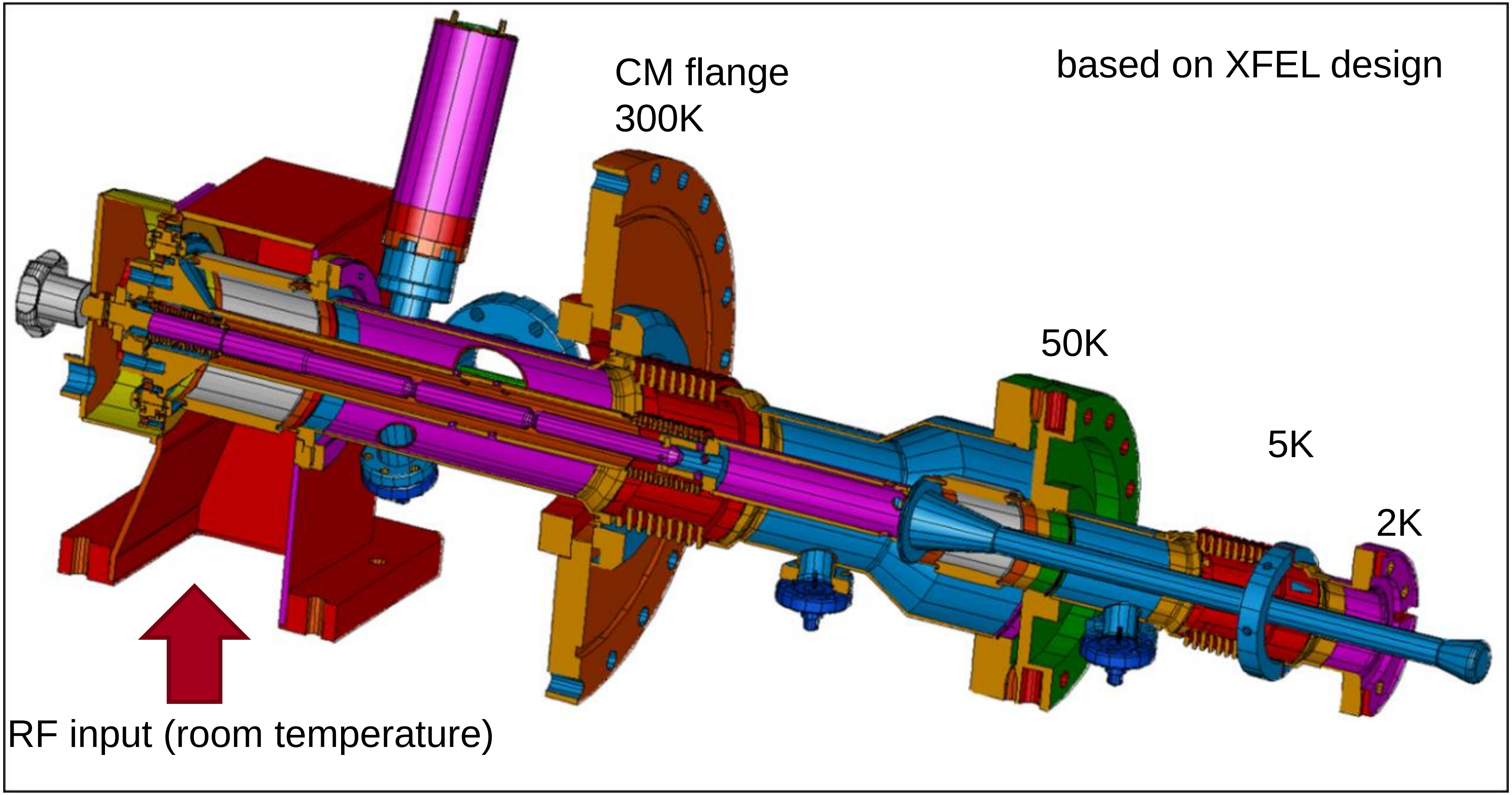
- Tuner parameters, measured during cold-tuner test at HTS and in all tested cryomodules meet/exceed technical requirements specifications.

- Reliability of the tuner is addressed by two measures:
  - tuner is accessible through designated port
  - the active component (electromechanical actuator& piezo-actuator) illustrated required longevity (ALT tests and Gamma Irradiation tests)

- Remnant magnetic field from tuner parts (made from 316L SS) did not compromised SRF cavity Q0.

- FNAL Resonance Control Team illustrated that using piezo we control resonance of the cold cavity (at HTS and few tests in CM) with peak detuning below 10Hz

LCLS-II Power Coupler



Bellows is challenging parts: Cu plating and stresses (damaging)

System Description

- Coupler design is based on XFEL design
  - Mature design, technically sound with operational experience, “commercially” available
  - Two modifications to existing design
    - Shorten antenna 8.5 mm – increase cavity Qext
    - Increase Cu plating to 150µm on warm inner conductor – reduce temperature rise
- 280 Fundamental Power Couplers (CPI and RI)
  - Vendors deliver assemblies UHV & “particle-free” cleaned and vacuum baked directly to FNAL and JLAB
- Waveguide Box
  - New design-Aluminum box, copper flex ring
- High Power CW RF Processing
  - Completed processing of prototype pair from each vendor
  - No HP processing in CMs (MP threshold well above operation power)

LCLS-II Power requirements for main coupler

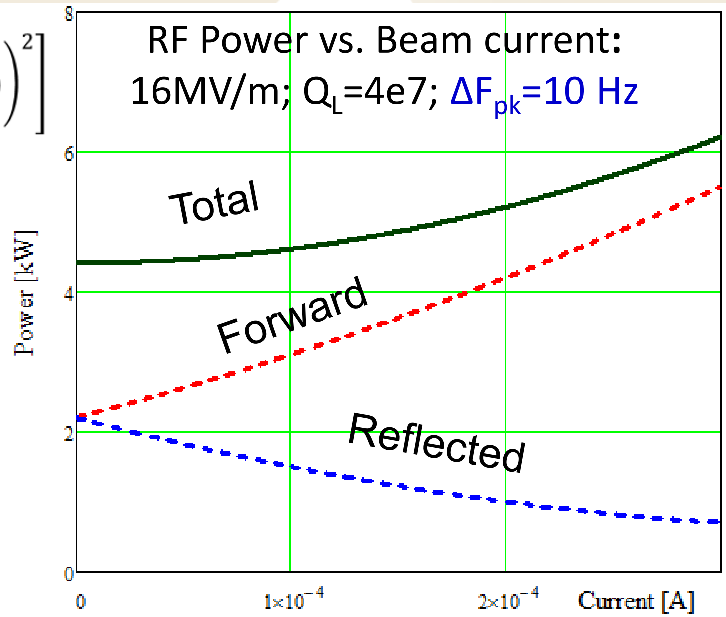
$$P_f = \frac{V^2}{4(R/Q)\cdot Q_L}\cdot\left[\left(1+\frac{I\cdot(R/Q)\cdot Q_L}{V}\cos(\emptyset)\right)^2+\left(2\cdot Q_L\frac{\Delta F}{F_0}+\frac{I\cdot(R/Q)\cdot Q_L}{V}\sin(\emptyset)\right)^2\right]$$

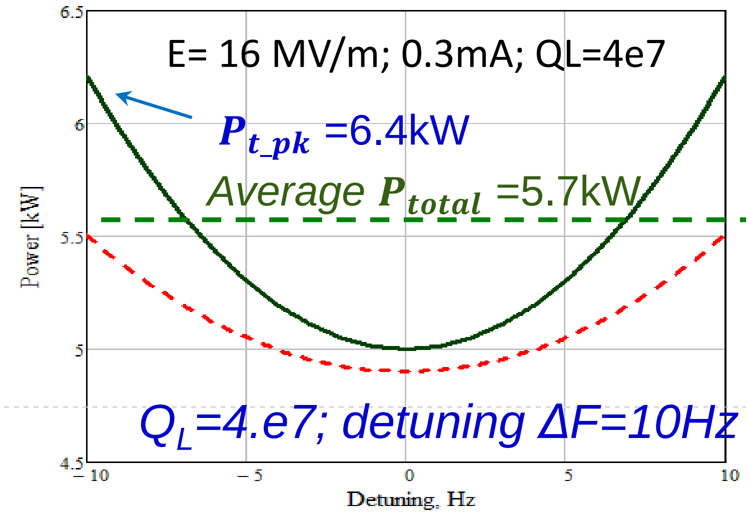
$$P_r = P_f - I\cdot V\cdot\cos(\emptyset) \quad \boldsymbol{P_t = P_f + P_r}$$

Table: Total Power in coupler (QL=4e7, ΔF_{pk}=10 Hz)

	P_{total}, *peak / average*	
	0.1 mA	0.3 mA
16MV/m	4.6/4.1	**6.4 / 5.7**

- Dissipation in coupler ~ $P_{tot.}$
- Maximum temp depends on reflection phase.
- In CM coupler tested at 3.2kW SW➔ P_t=6.4kW (QL ~1.e7)





System Status

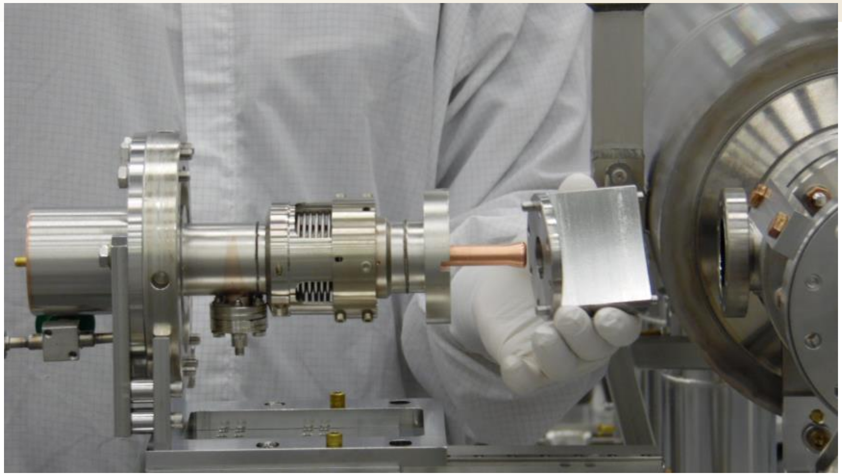
Pair of cold assemblies as received on test stand

Warm assembly during incoming inspection

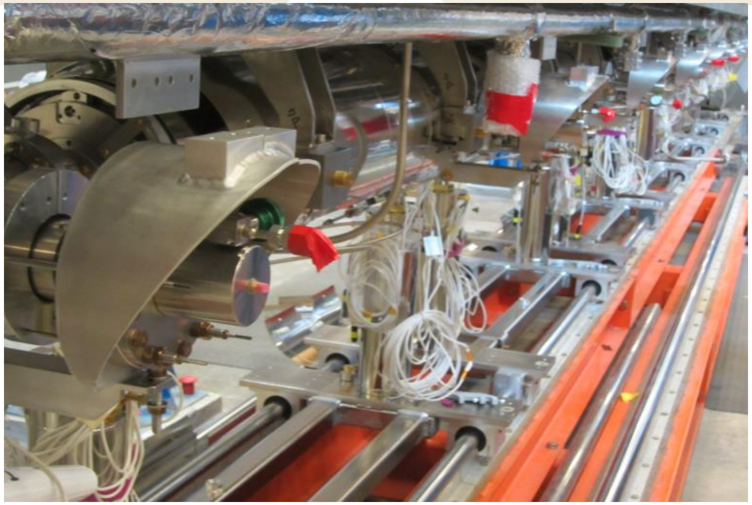
Assembling warm and cold pair for RF processing

Photos courtesy J. Tice

Assembly of Couplers on Cryomodule



Installation of cold section during string assemble

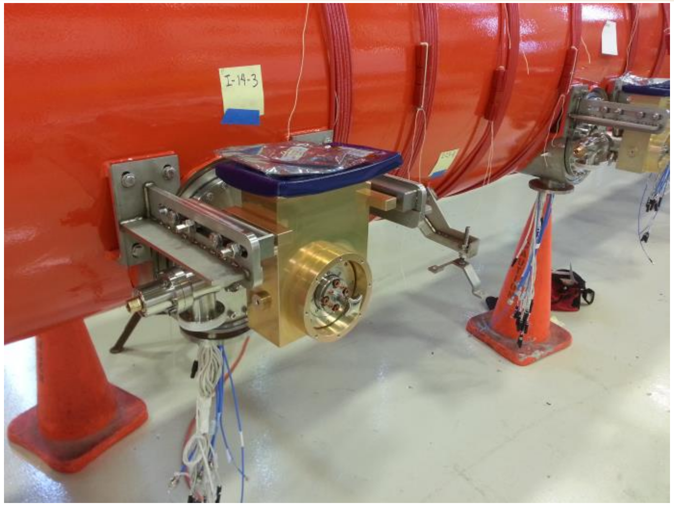


cold couplers outside clean room

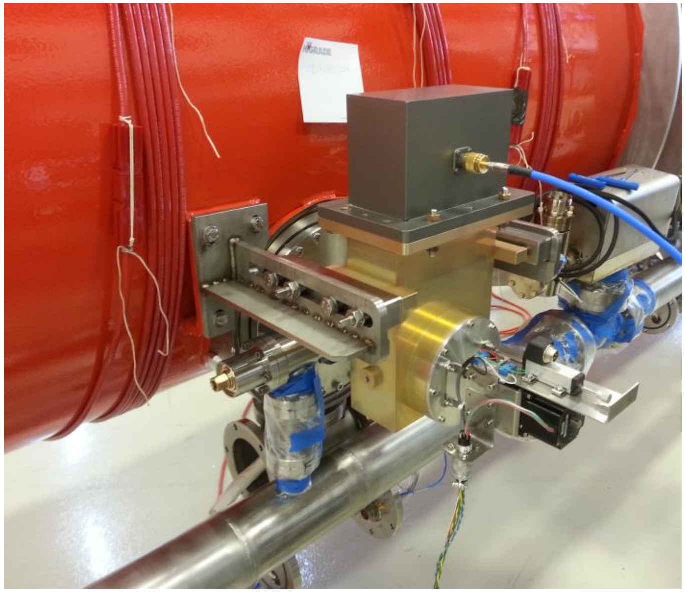
pCM string in clean room during vacuum leak check

Photos courtesy M. Stirbet

Assembly of Couplers on Cryomodule-FNAL



FPC installed with waveguide box
(manual adjustment knob)

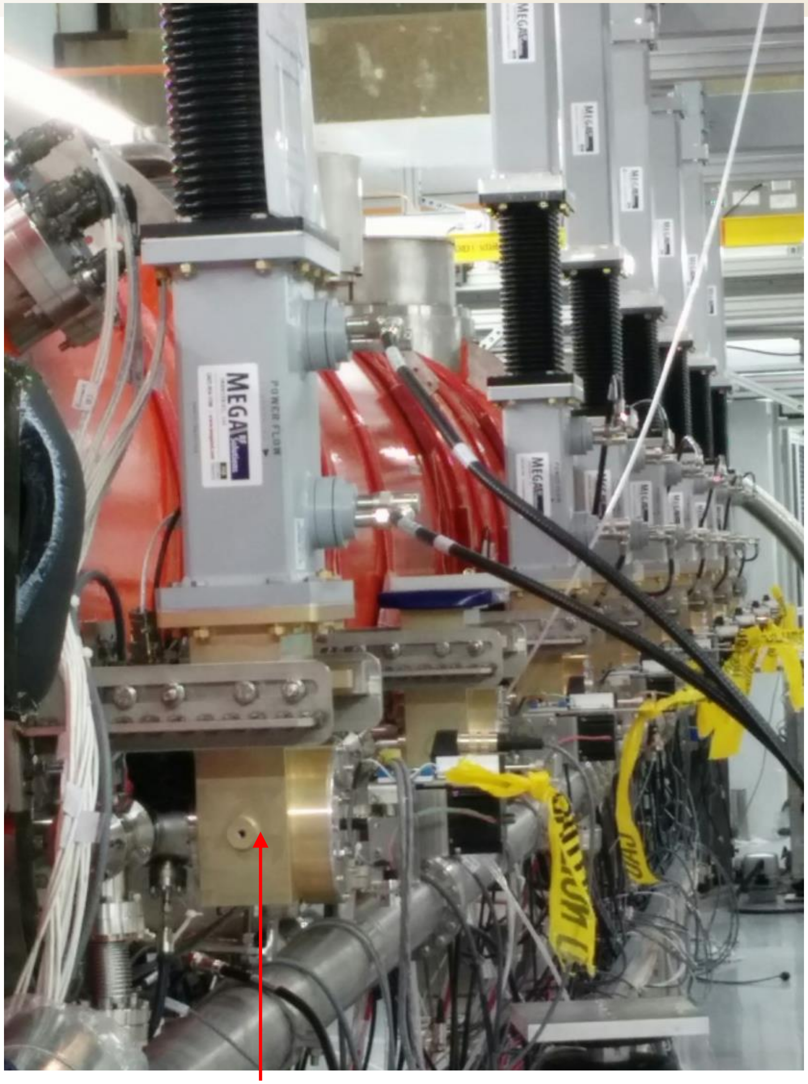


Motorized FPC tuning

pCM with all eight FPC’s installed

Photos courtesy K. Premo

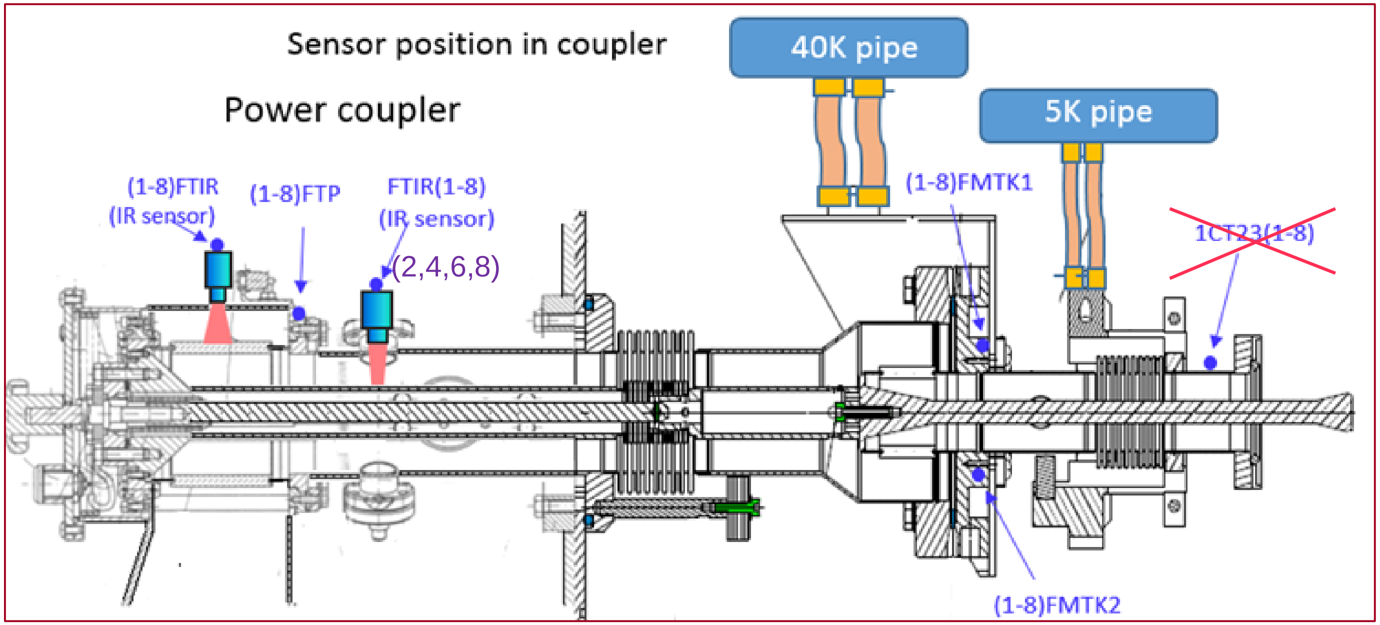
FNAL pCM on Test

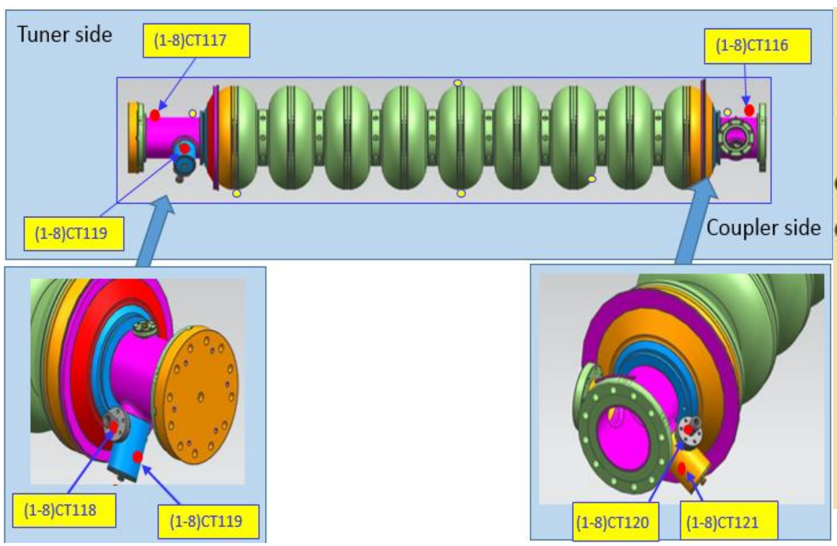


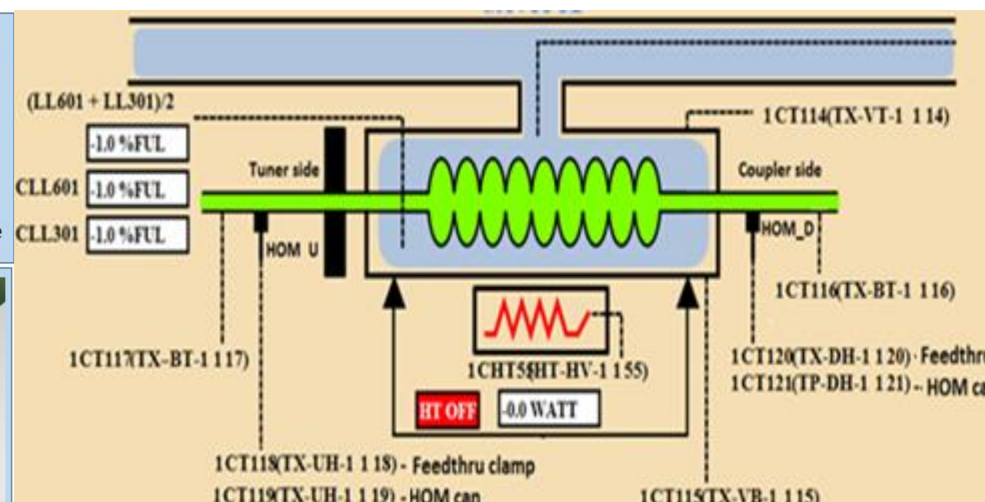
Fundamental Power Couplers

Photos courtesy J. Nelson

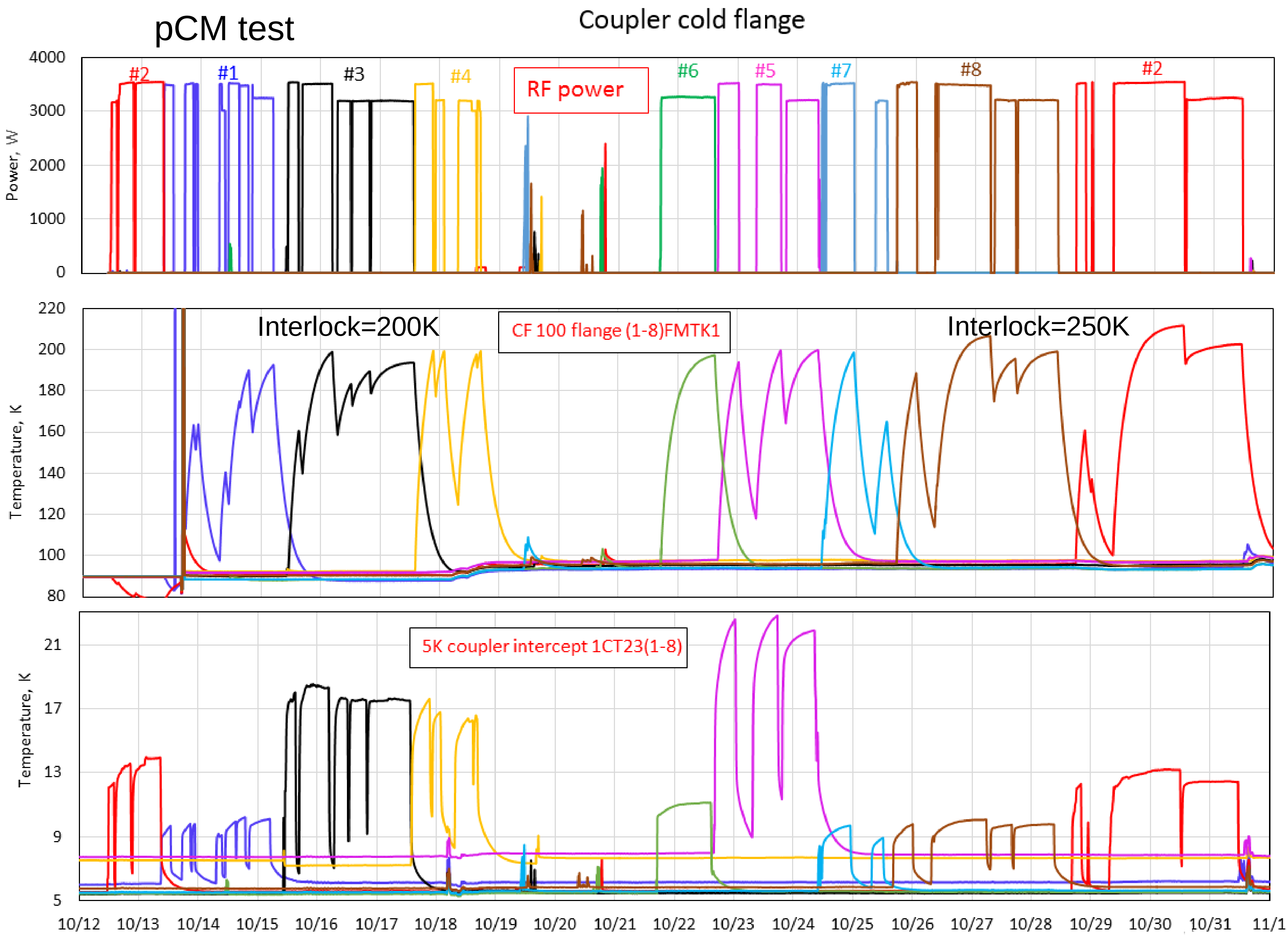
Coupler and cavity end-group diagnostics







pCM test

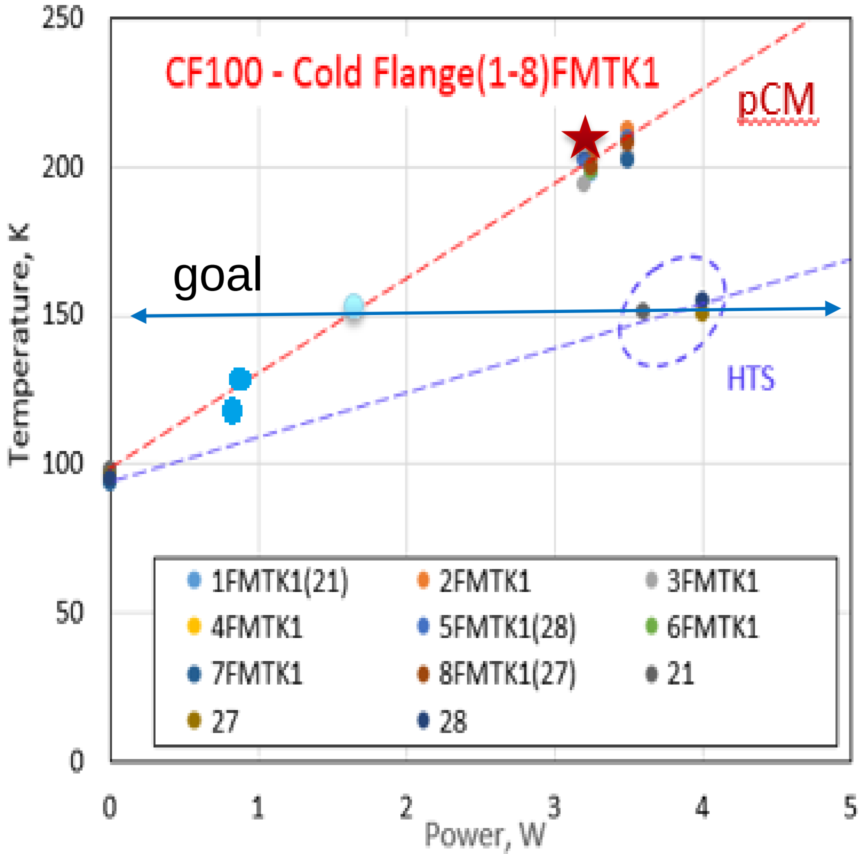


Coupler cold flange
Power, W
4000
3000
2000
1000
0
#2
#1
#3
#4
RF power
#6
#5
#7
#8
#2
Temperature, K
220
200
180
160
140
120
100
80
Interlock=200K
CF 100 flange (1-8)FMTK1
Interlock=250K
Temperature, K
21
17
13
9
5
5K coupler intercept 1CT23(1-8)
10/12
10/13
10/14
10/15
10/16
10/17
10/18
10/19
10/20
10/21
10/22
10/23
10/24
10/25
10/26
10/27
10/28
10/29
10/30
10/31
11/1

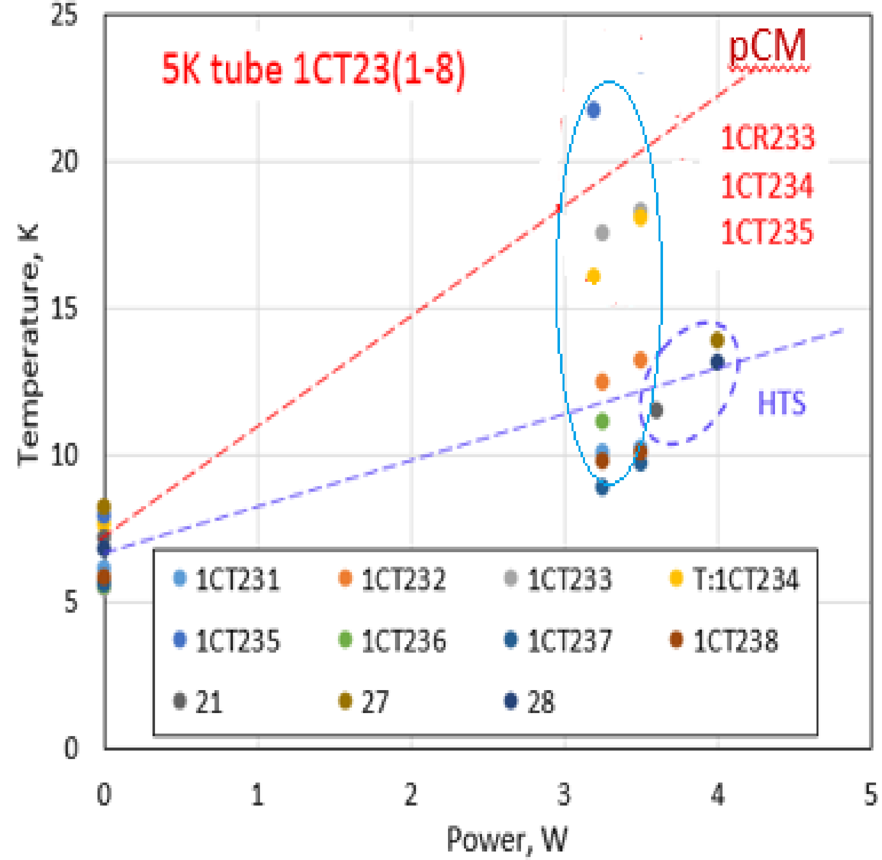
Summary of coupler heating in pCM

Coupler Cold Flanges

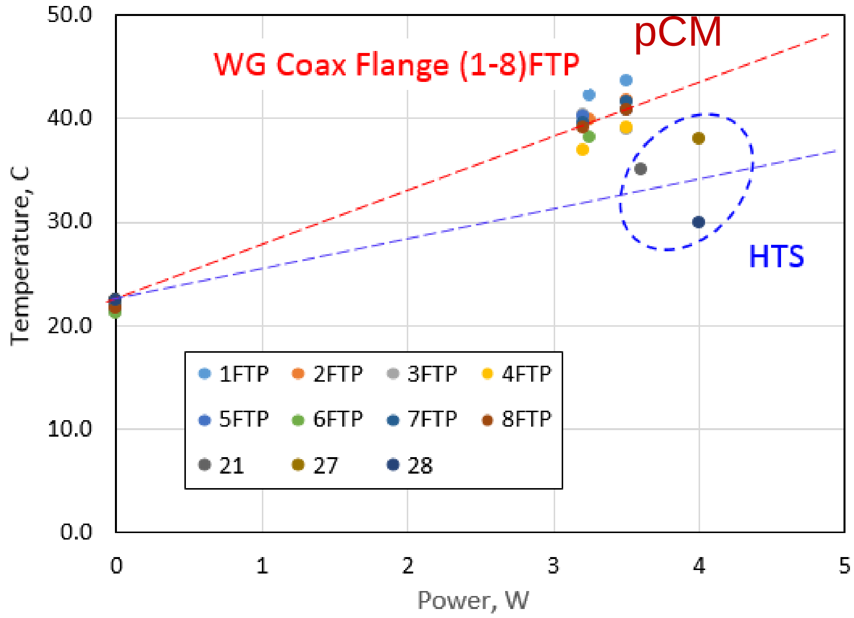
50K

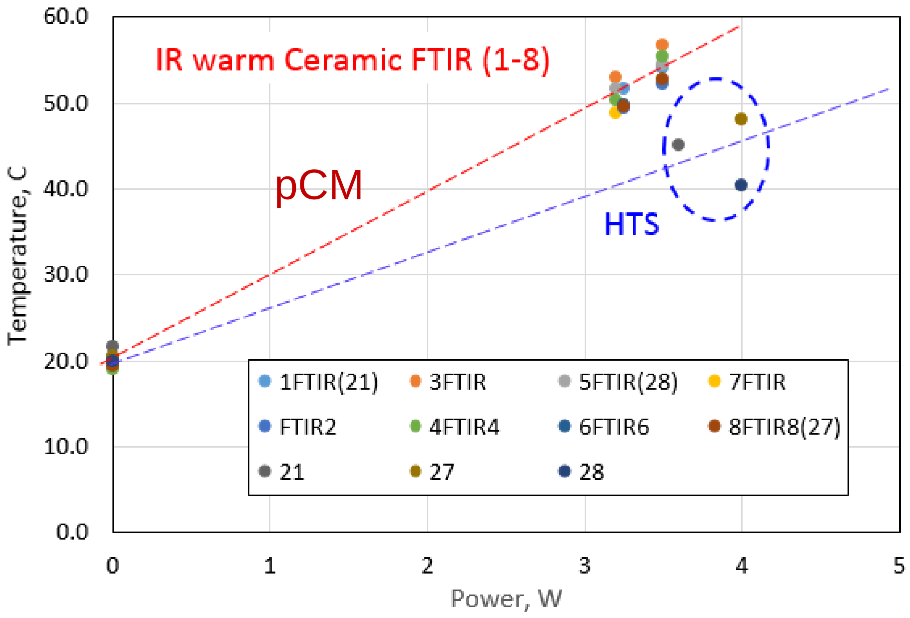


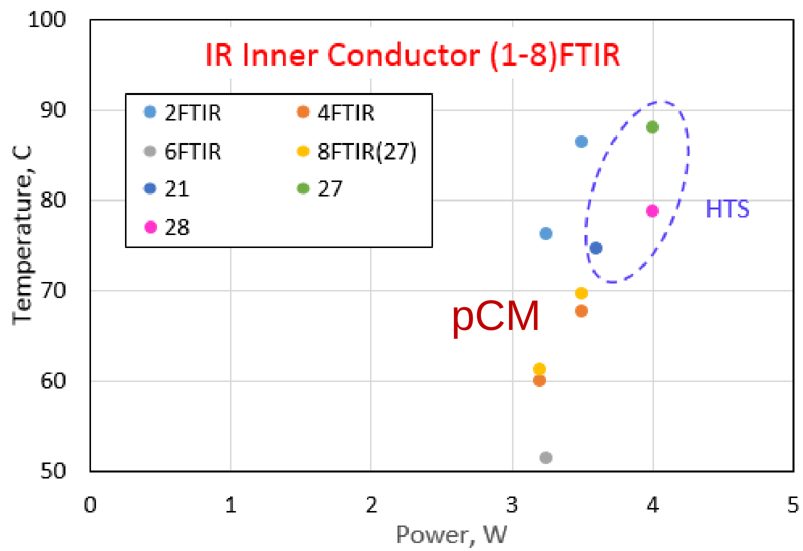
5K



Coupler warm end



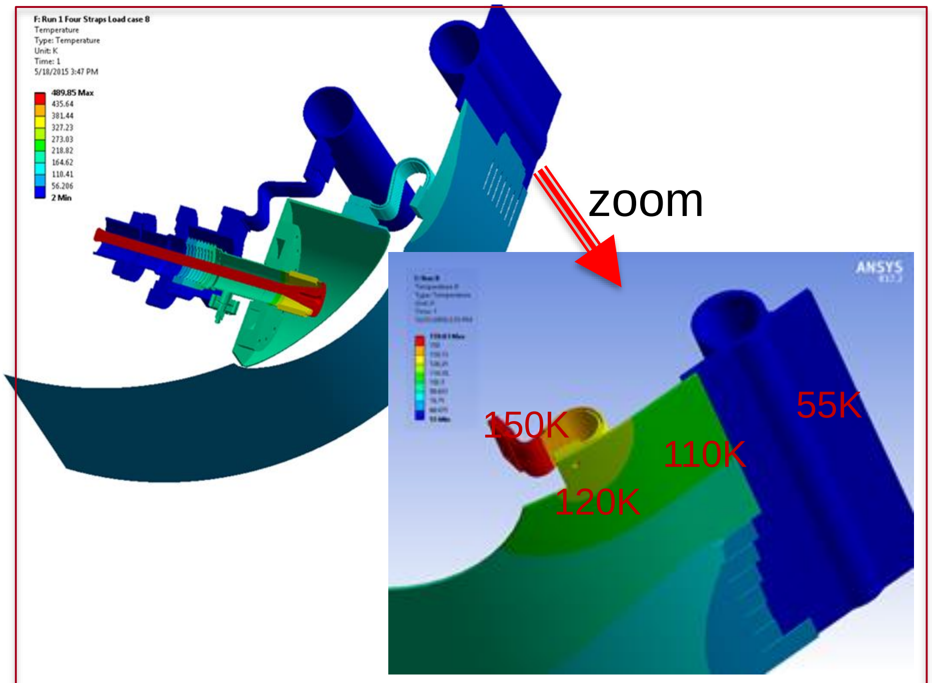




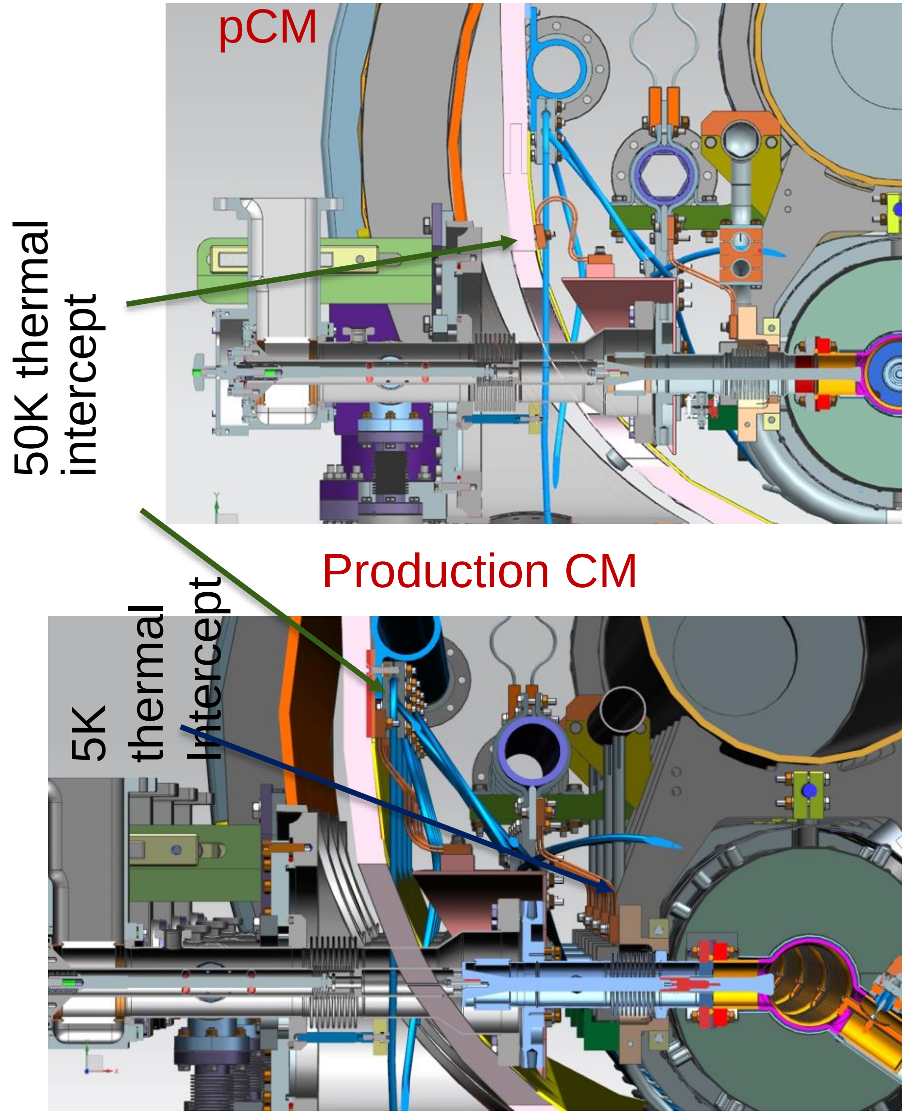
- No air cooling in CM

Thermal intercept improvements in production CM (vs. pCM)

- Reconnect thermal strap to 50K pipe (vs. 50K shield-see thermal analysis)
  - *Better thermal contact between braid and copper extension (flat surfaces)*



pCM: Thermal analysis – R.Fischer/ANL



Power Coupler performance in production CM

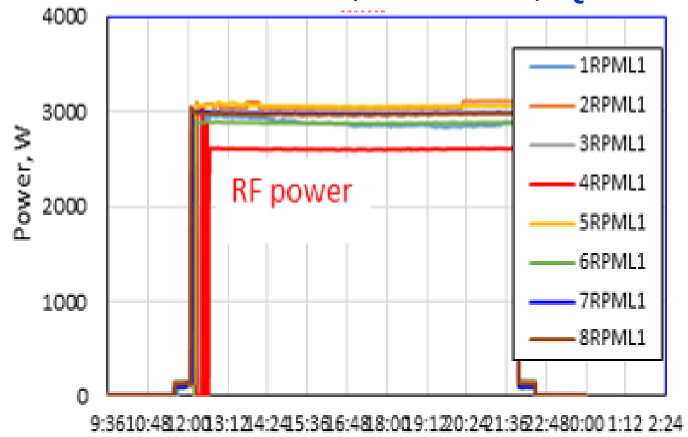
Two sets of data
- *FPC heating at max power ~3kW, ~10MV/m, QL=1.e7,12 hrs*
- *Unit test: ~ 1.6kW, 16MV/m, QL~4e7, 24 hrs*

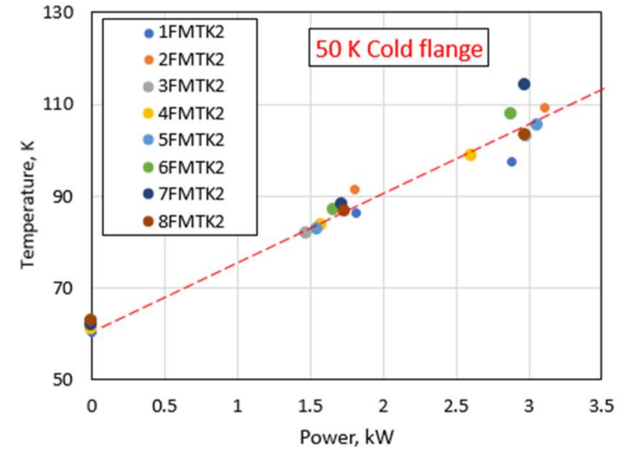
Specification for coupler Temp:
- <150K -CF100 flange
- <450K on inner conductor

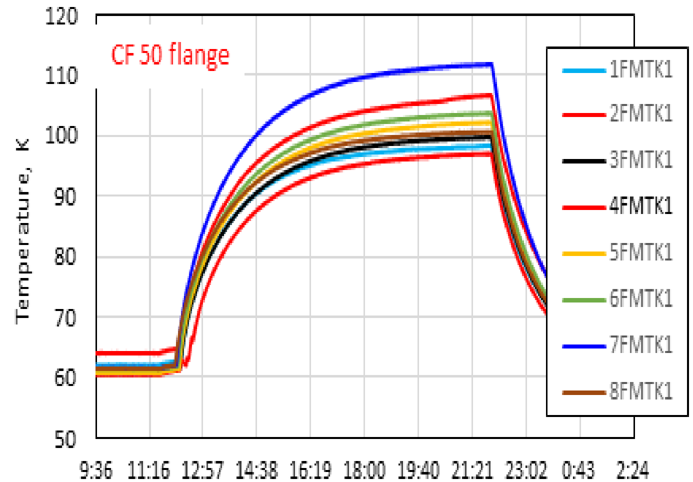
Coupler flange overheating at pCM ~200-220K (3.6kW)

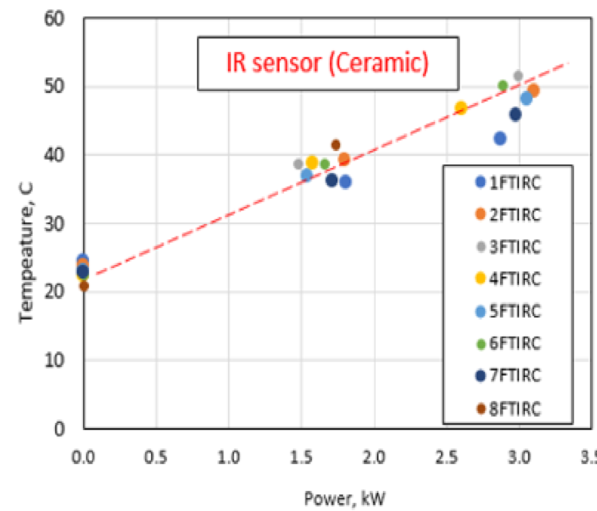
Modified thermal strap connection. Connected to 40K return pipe instead of low 40K thermal shield.

Example for F1.3-09. ➔

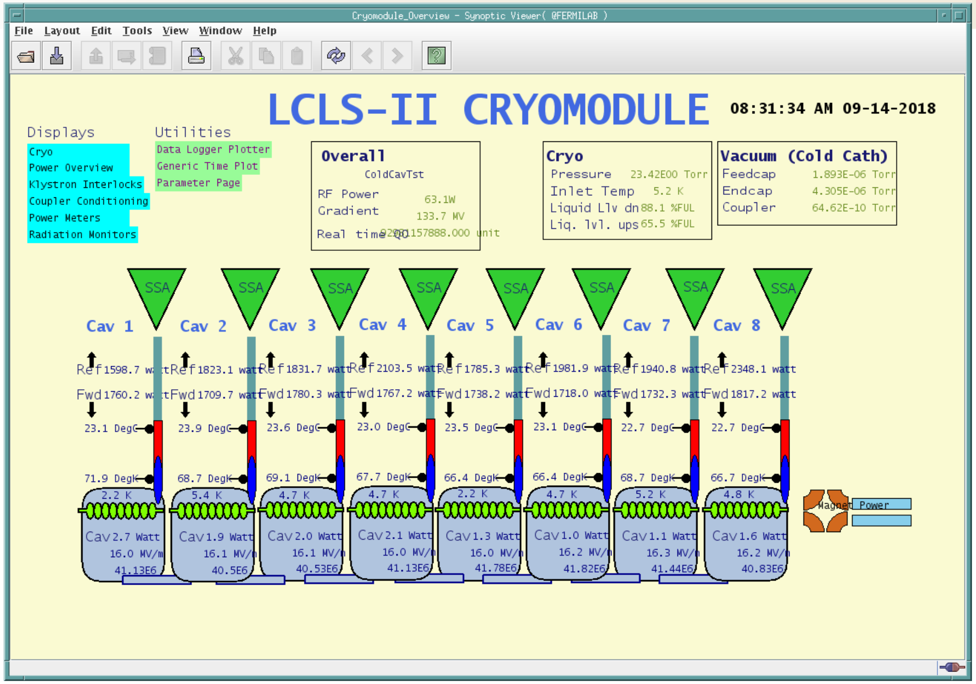


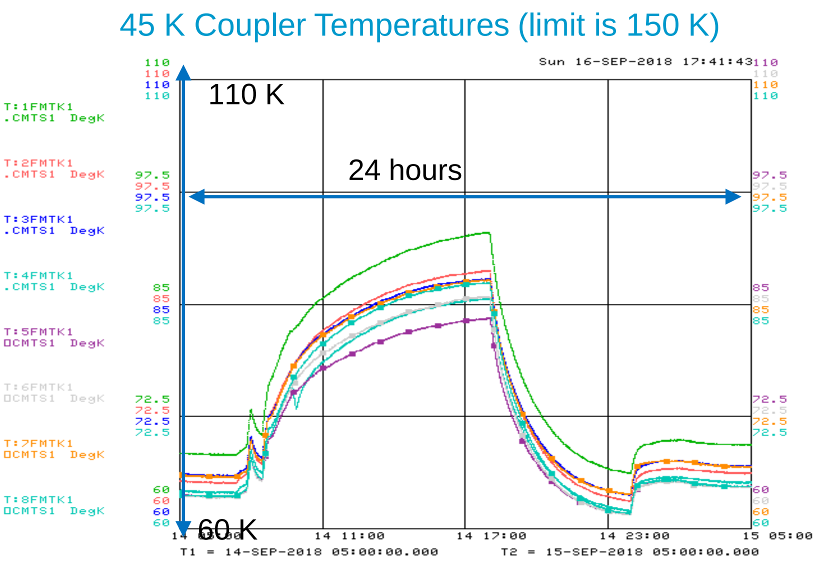


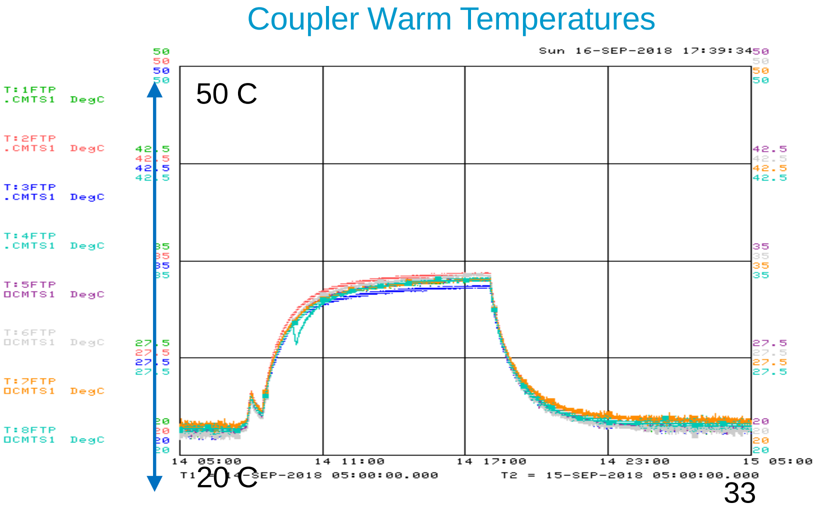




F1.3-11 Unit test







- 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

Summary of power coupler tests

- Power coupler is one of the critical component in a system.
- LCLS-II coupler design is based on XFEL design with minor modifications.
- Thermal properties of the coupler after modification done after pCM input is good. All production cryomodules test does not show coupler overheating or other problems.
- Mechanical design (restrain of bellows) require some modification/improvements/stabilization to prevent it from damages during transportation.