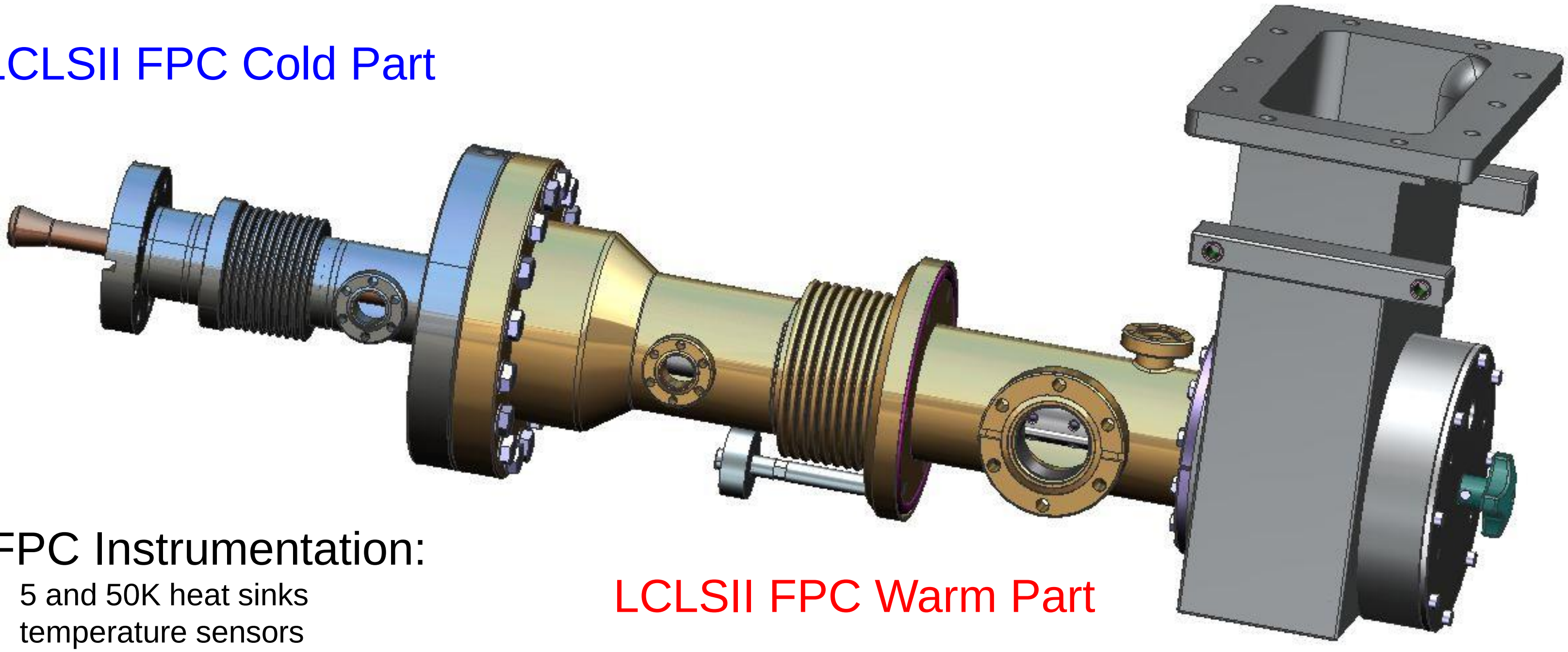
Experience with FPCs for LCLS II project at JLAB

Mircea Stirbet

LCLS II Fundamental Power Coupler

LCLSII FPC Cold Part

LCLSII FPC Waveguide



LCLSII FPC Warm Part

LCLSII FPC manual antenna actuator

FPC Instrumentation:

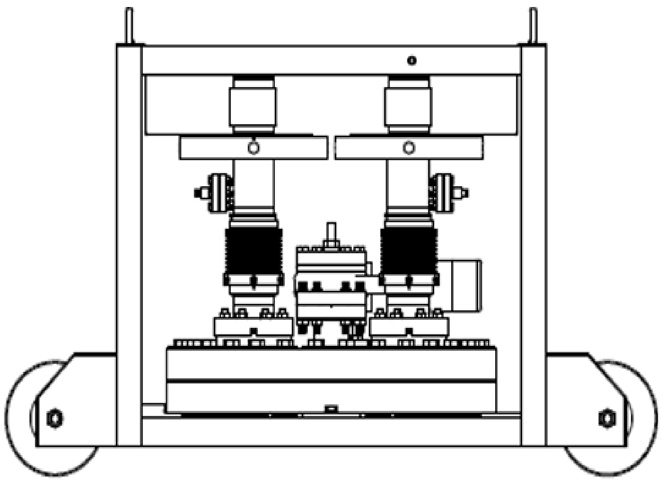
- 5 and 50K heat sinks
- temperature sensors
- Electron probes
- Arc detectors in the warm part
- Arc detector on FPC waveguide
- One ionic pump for 8 warm couplers
- One vacuum gauge for 8 warm couplers

JLAB's support to LCLS II project – deliver 21 cryo-modules

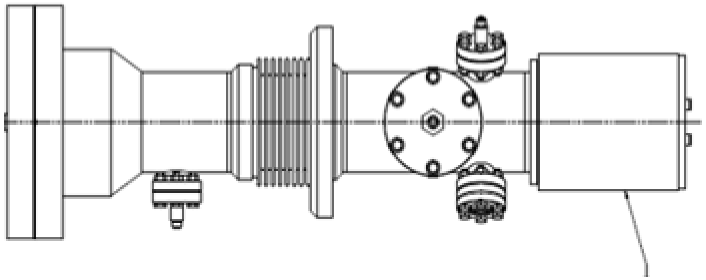
1. Fundamental Power Coupler procurement for LCLS II project was done by SLAC, JLAB receiving 168 Fundamental Power Couplers TTF3 style manufactured by two vendors: CPI (US) and RITH (France – Germany).
2. Both vendors had a well established experience with this type of couplers: several tens have been manufactured for ILC R&D US. Finally XFEL had several hundreds of couplers manufactured by these two vendors.
3. The LCLS II coupler production went in immediately after coupler production for XFEL.
4. **Major differences form XFEL couplers:**
   - **4.1. Thicker copper plating of the warm inner conductor**
   - **4.2. Shorter cold antenna**
   - **4.3 CW operation (max FWD power 7 kW, 2K Qext 4e7)**
5. Some of the ILC R&D couplers have been modified to fulfill the LCLS II requirements then used on preliminary tests done at JLAB on a single cavity cryo-module (HTB) and on JLAB's prototype cryo-module (pCM).
6. Two couplers from each vendors, after incoming inspection at JLAB and FNAL have been RF power tested on a room temperature test stand at TRIUMF – Canada.

FPC shipping configuration from vendors to JLAB

The intention was to have the delivered couplers fully qualified at vendors: extensive mechanical check ups, visual inspections, cleaning, clean room assemble, bake, preps for shipment.
JLAB was supposed just to extract the couplers from the plastic bags and proceed with installation. **It was just a dream.**



Two cold coupler parts a on test stand under static vacuum, inserted in plastic bags, back filled with filtered Nitrogen.



Each warm coupler with restrained inner conductor placed in double plastic bags. Internal volume under filtered Nitrogen.

FPC work flow at JLAB during CM production for LCLS II project

Receiving FPCs

1. Large volume for 12 – 18 months.
2. Parts In Circulation (PICs) hardware had to be sent back to vendors.
3. Collect FPC vendor data from SLAC's dropbox.
4. Visual inspect shipping crates and contents.
5. Download shock recorders data.
6. Fill up receiving travelers.

FPC Incoming inspections

1. Cleanroom admission of the cFPCs on test stands
2. Collect vacuum leak check and RGA data.
3. Perform visual inspection on individual cFPCs
4. Recover cold bellows restrains
5. Check particulate counts
6. Store accepted parts under dry, filtered N2 in cleanroom cabinet.
7. Visually inspect the wFPC part (including the push-rod).
8. Remove shipping hardware (PICs)
9. Store the accepted parts under N2 in dedicated cabinet.
10. Fill up incoming inspection travelers.

FPC real estate

a. In dedicated cabinets store FPC components exposed to UHV and RF (cold and warm FPC parts)

b. Outside clean room - FPC waveguides, FPC waveguide brackets, auxiliary components for FPC assemble on cryomodule: spindles, frisbee flanges, Viton gaskets, vacuum pipes, and vacuum related hardware, ionic pumps, vacuum valves, hardware, tools for warm part assembly.

c. Transport boxes

FPC cold part preparation for string assembly

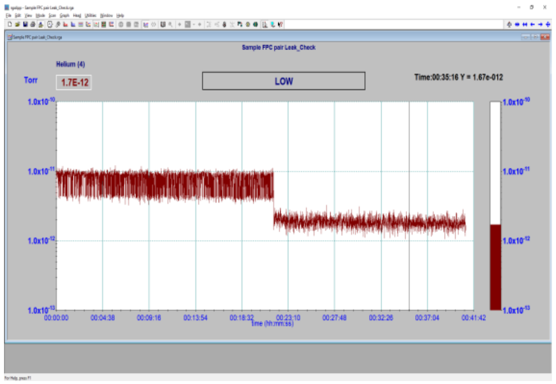
a. Recover the cFPC part form N2 storage cabinet.
b. Visual inspection
c. Assemble cold bellows restrains
d. Internal and external particulate counts.
e. Install cFPC on test stand
f. Protect the cold ceramic with metallic protection cup and bleed up with dry filtered N2.
g. Move cold part to string assemble area
h. Assemble the cold FPC part on cavity.

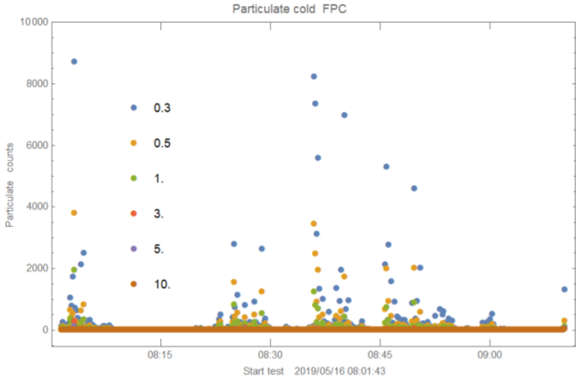
FPC warm part preparation for cryomodule assembly

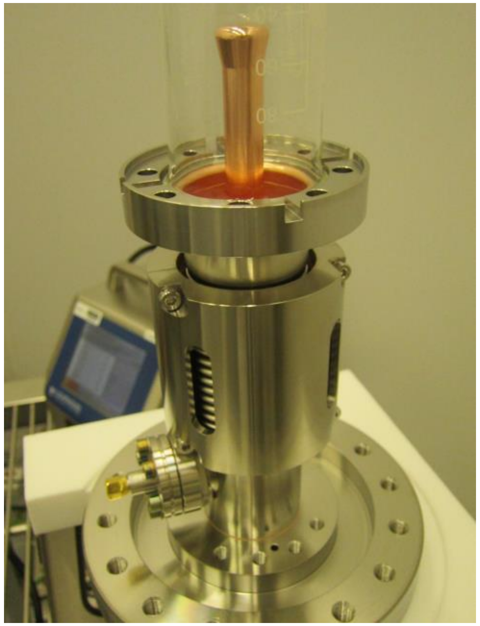
a. Recover the wFPC part from the N2 storage cabinet
b. Visual inspection
c. Protect warm ceramic with Kapton foil
d. Install warm bellows support
e. Install N2 admission valve and maintain N2 flow during wFPC assembly
f. Assemble the wFPC on cryo-module.
g. Fill up wFPC assembly travelers.,

Cold FPC incoming inspection and storage at JLAB

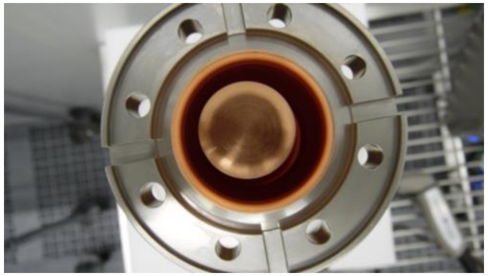
- Clean room vacuum leak checks
- Particulate counts
- Visual inspections
- Long term storage in N2 cabinet: **efficient solution, based on DESY published suggestion**.
- Preps for string assembly







Particulate specifications: less than 100 external surfaces, less than 10 internal. **Never happen, except on some couplers delivered by SLAC...**

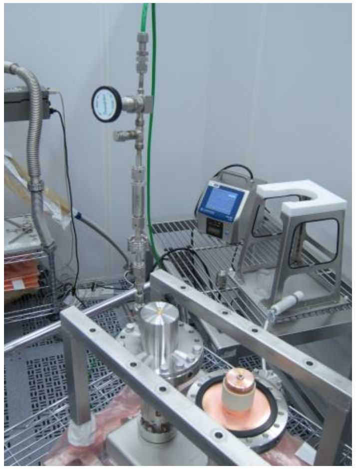


AlMg sealing surface

String cold FPC part installation

- Cold FPC preps for string assembly
- Visual inspection
- Particulate counts
- Install cold bellows restrains, PONGY bolt and cold ceramic protection cup
- Particulate counts just before assembly on cavity
- Clean room vacuum leak check on assembled string
- Once string is outside clean room:
- Remove cold bellows restrains, install 5 and 50 K heat sinks
- Install Berry bolts

All this work done under cavity string beam vacuum



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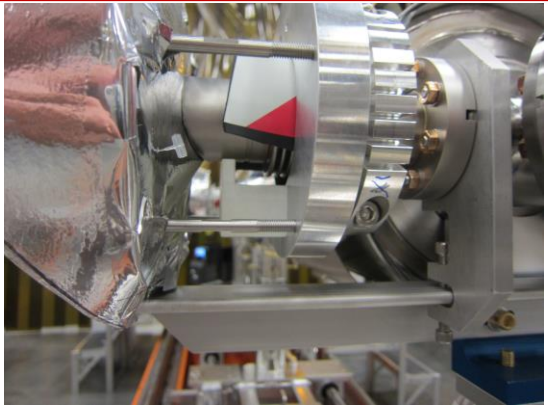
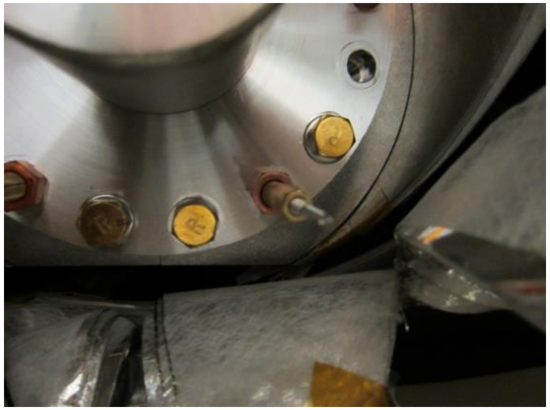
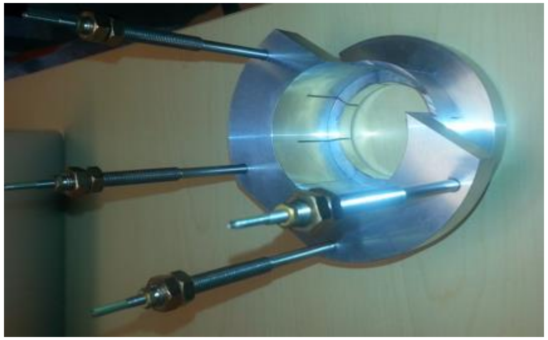
Cavity string out of the clean room: Berry bolts installation





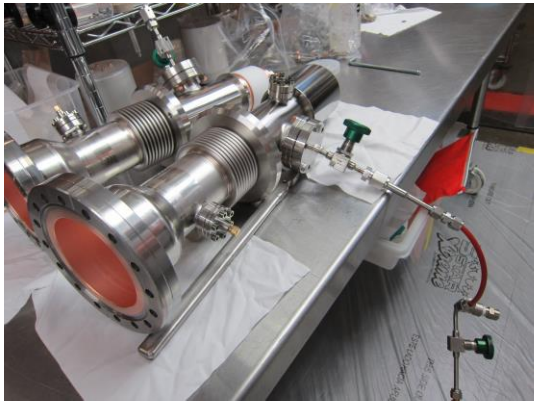
Beam line vacuum 5.3e-8 mbar.

Outside the clean room, on each cold coupler, 5 and 50 K heat sinks are installed, followed by **BERRY bolts** which will keep the CF100 flange at the same distance related with cavity FPC flange.



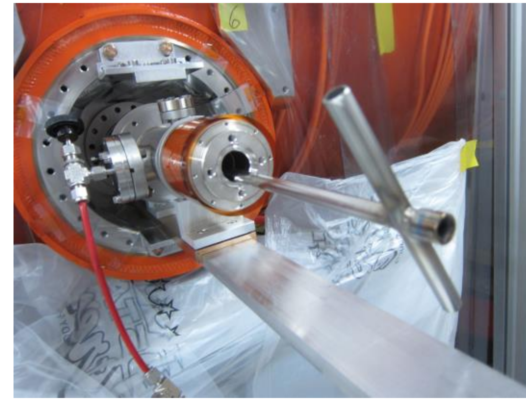
Warm FPC incoming inspection and storage at JLAB

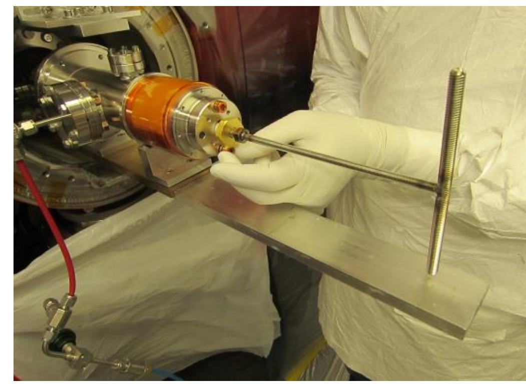
- Visual inspection
- Recover and ship the FPC PICs to vendor for production support
- Long term storage under N2 in dedicated cabinet
- Transfer stored wFPC to WS5 for cryo-module assembly using a plastic bin.
- wFPC checkups and preps for CM assembly



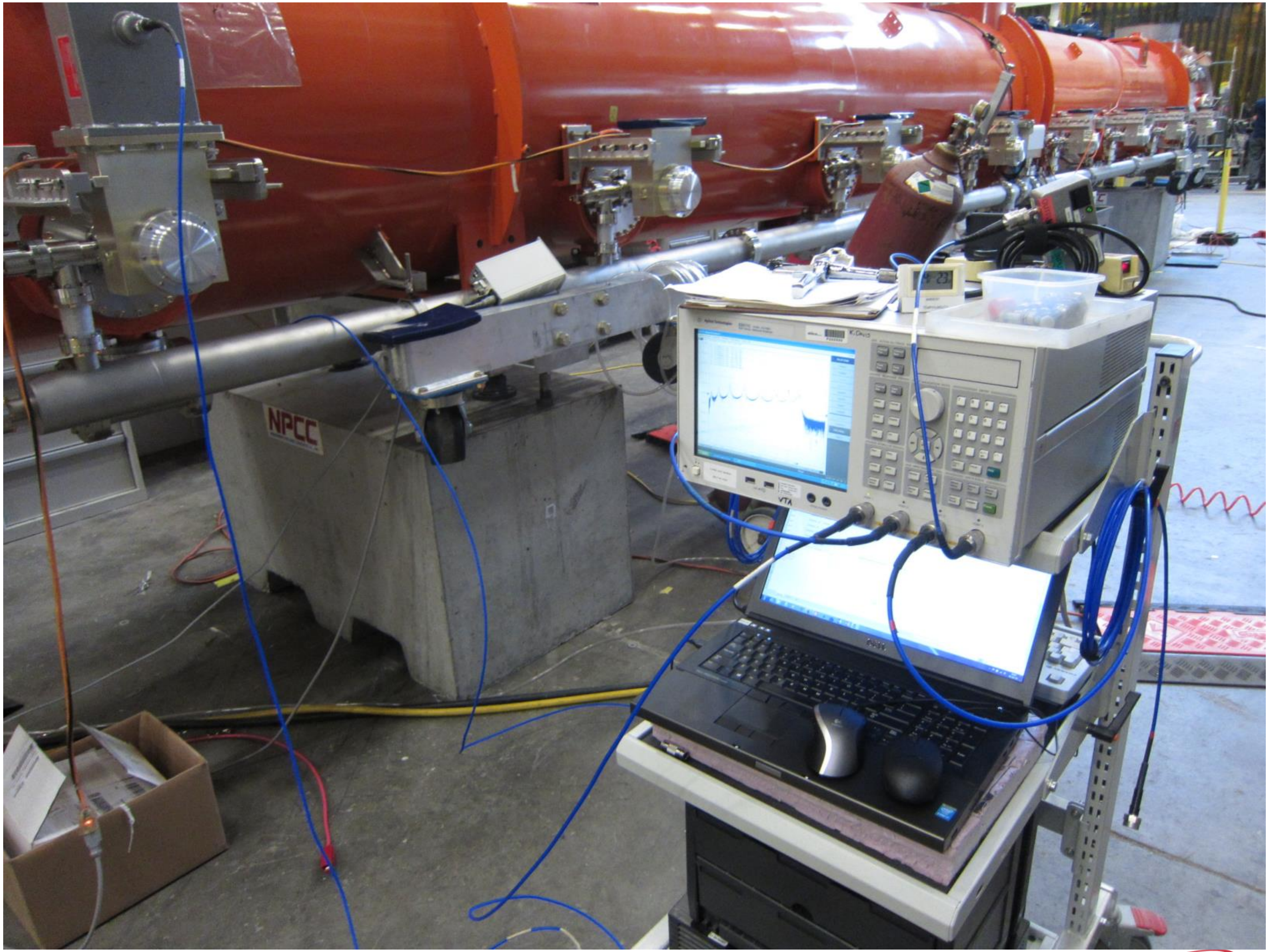
Cryomodule warm FPC part installation: TOOLS

RT BL vacuum on different CMs during wFPC installation

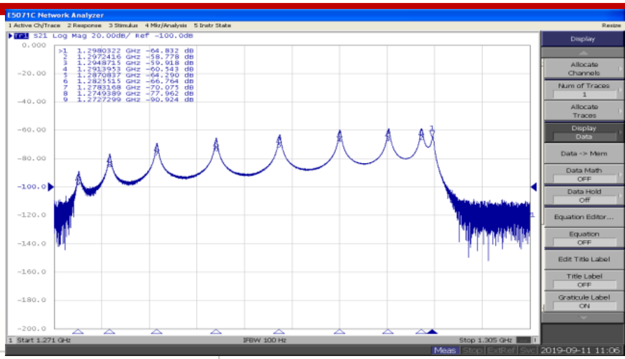




RT FPC checkups, passbands and Qext measurements



RT and 2K LPRF measurements



With Cryo-module at RT:

- Check antenna movement: 5 turns in and out.
- Collect RT passbands data
- Measure Qext FPC for each coupler

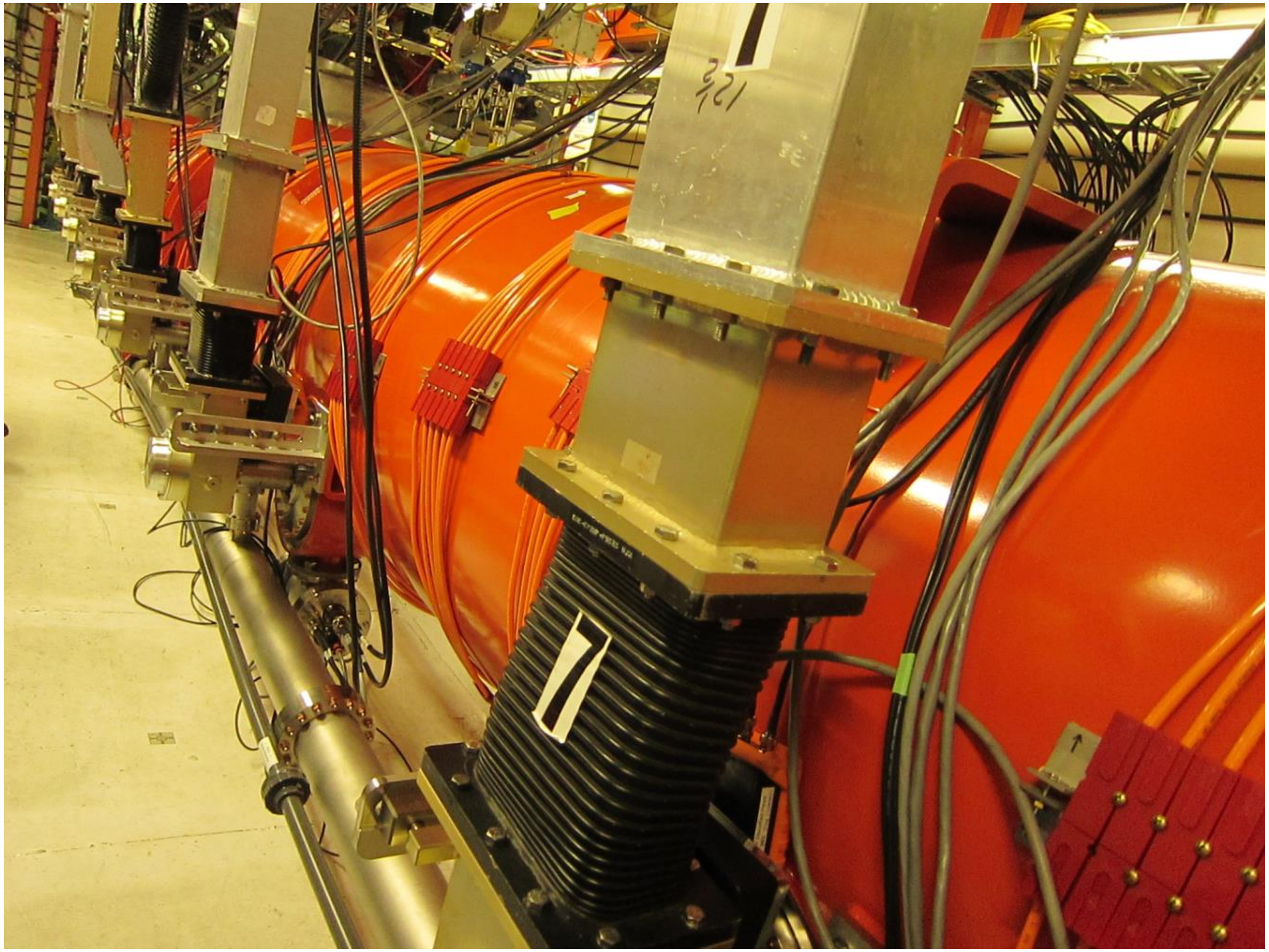
CM19 RT passbands

	Cav1	Cav2	Cav3	Cav4
Pi mode	Measured Frequency (MHz)	Measured Frequency (MHz)	Measured Frequency (MHz)	Measured Frequency (MHz)
π/9	1272.786314	1274.188018	1274.211623	1274.017994
2π/9	1274.97852	1276.276776	1276.334529	1276.127543
3π/9	1278.352572	1279.524639	1279.591994	1279.397744
4π/9	1282.590796	1283.539593	1283.599699	1283.448759
5π/9	1287.126252	1287.838058	1287.795101	1287.737785
6π/9	1291.428533	1291.859805	1291.818052	1291.842815
7π/9	1294.911919	1295.181673	1295.162589	1295.176851
8π/9	1297.260256	1297.357159	1297.328955	1297.371019
π	**1298.07066**	**1298.124517**	**1298.107381**	**1298.163329**

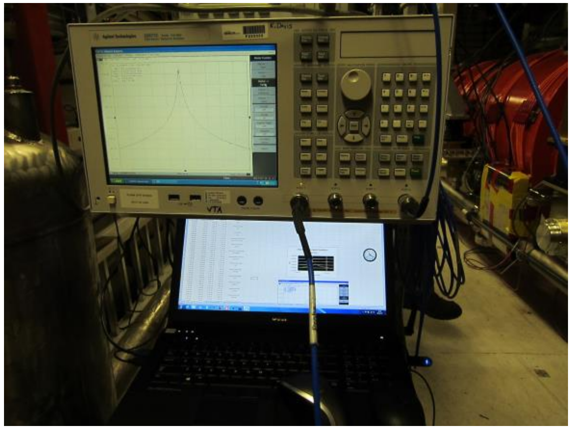
	Cav5	Cav6	Cav7	Cav8
Pi mode	Measured Frequency (MHz)	Measured Frequency (MHz)	Measured Frequency (MHz)	Measured Frequency (MHz)
π/9	1274.133157	1273.799169	1272.823052	1274.252461
2π/9	1276.307012	1276.027297	1275.049481	1276.354038
3π/9	1279.554968	1279.335506	1278.482704	1279.628098
4π/9	1283.591874	1283.365744	1282.713277	1283.60234
5π/9	1287.825432	1287.631145	1287.226078	1287.826305
6π/9	1291.838555	1291.745007	1291.543732	1291.853253
7π/9	1295.168847	1295.143601	1295.08138	1295.171705
8π/9	1297.347092	1297.356444	1297.387032	1297.362079
π	**1298.125145**	**1298.138352**	**1298.189883**	**1298.137145**

CM19	RT Qext FPC
Cav1	1.17E+07
Cav2	7.79E+06
Cav3	1.17E+07
Cav4	1.75E+07
Cav5	1.47E+07
Cav6	1.08E+07
Cav7	9.13E+06
Cav8	6.19E+06

2K FPC tuning to Q 4e7, cold passbands measurements

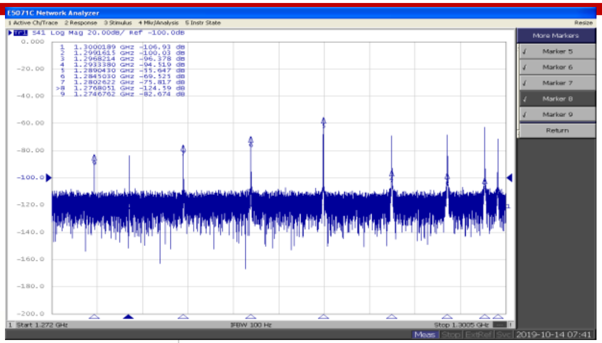


Typical BL and FPC vacuum at JLAB



LCLS II cryo-module in JLAB's CMTF (Cryo-Module Test Facility)

RT and 2K LPRF measurements



With Cryo-module at 2K, after each cavity is tuned to Pi mode:

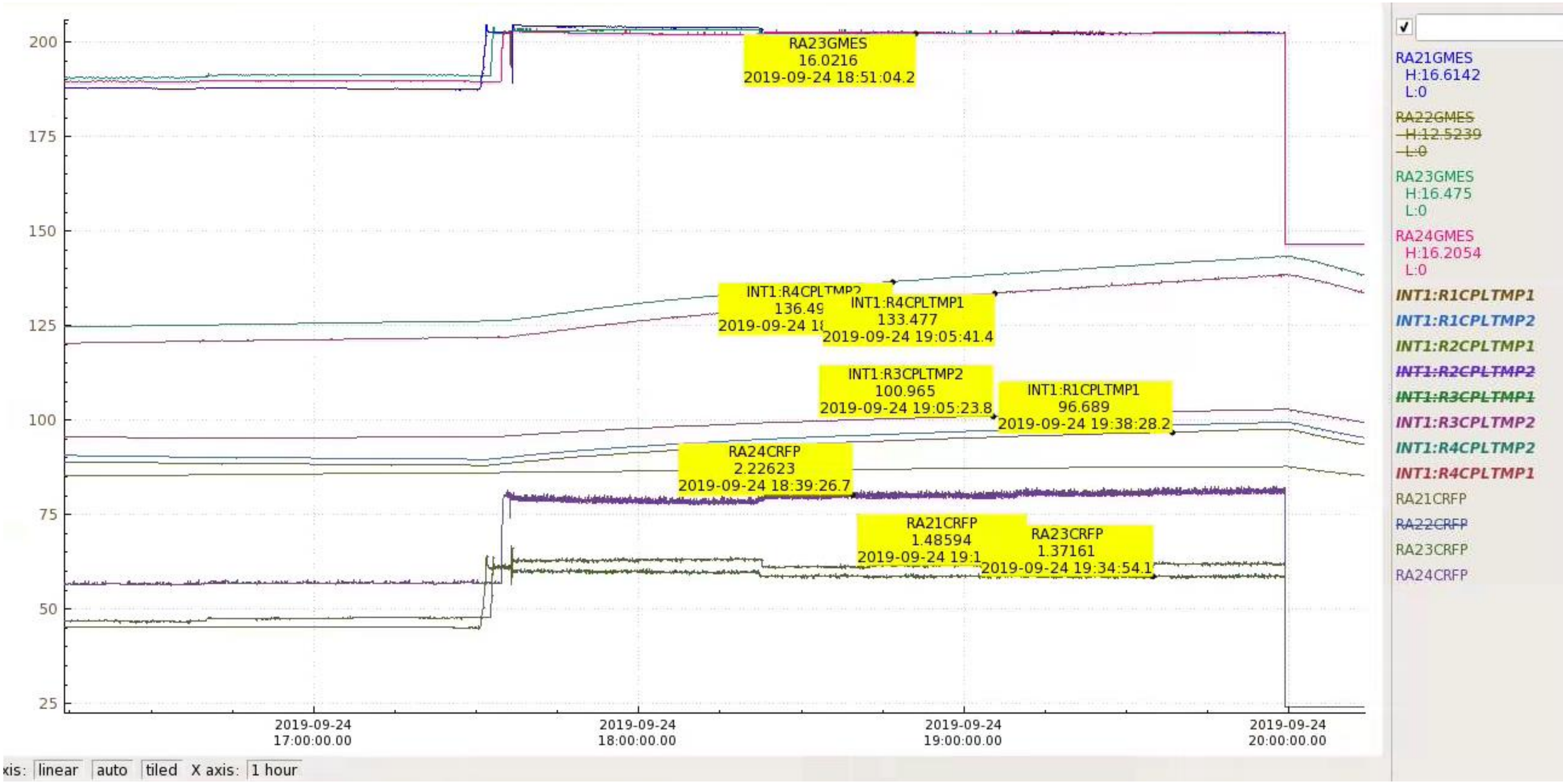
- Adjust each coupler to a Q of about 4e7.
- Collect 2K passbands data

CM19 2K passbands

	Cav1	Cav2	Cav3	Cav4
Pi mode	Measured Frequency (MHz)	Measured Frequency (MHz)	Measured Frequency (MHz)	Measured Frequency (MHz)
π/9	1274.676719	1275.997185	1276.06667	1275.811651
2π/9	1276.885077	1278.116968	1278.18802	1277.92358
3π/9	1280.261707	1281.366221	1281.450161	1281.202768
4π/9	1284.503199	1285.388795	1285.464513	1285.257739
5π/9	1289.043044	1289.693374	1289.667342	1289.557707
6π/9	1293.34885	1293.72326	1293.696813	1293.666706
7π/9	1296.835491	1297.0501	1297.046027	1297.009466
8π/9	1299.184589	1299.228982	1299.216554	1299.206469
π	1299.9994	1300.021452	1299.999585	1300.01863
	Cav5	Cav6	Cav7	Cav8
Pi mode	Measured Frequency (MHz)	Measured Frequency (MHz)	Measured Frequency (MHz)	Measured Frequency (MHz)
π/9	1275.9659	1275.619599	1274.603189	1276.071031
2π/9	1278.139867	1277.849529	1276.822601	1278.17744
3π/9	1281.39441	1281.162665	1280.255757	1281.459177
4π/9	1285.438192	1285.200481	1284.494217	1285.43957
5π/9	1289.677864	1289.472373	1289.013963	1289.670762
6π/9	1293.698009	1293.594099	1293.339658	1293.70409
7π/9	1297.034723	1296.997656	1296.880689	1297.029275
8π/9	1299.217815	1299.214199	1299.188826	1299.221286
π	1300.016841	1299.999166	1300.017864	1299.999003

CM19	QL at 2K
Cav1	4.33E+07
Cav2	4.42E+07
Cav3	4.41E+07
Cav4	4.18E+07
Cav5	4.48E+07
Cav6	4.37E+07
Cav7	4.21E+07
Cav8	4.22E+07

CM18 Cav4 – heating issues during run at constant gradient



CF100 flange Coupler temps for CM18 Cavity 4 ~30% was higher than other cavities operating at the same gradient. **Why?**

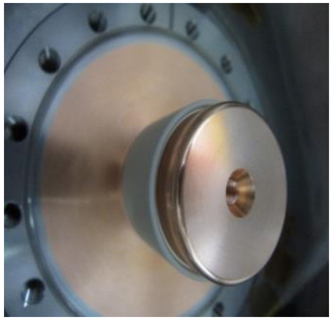
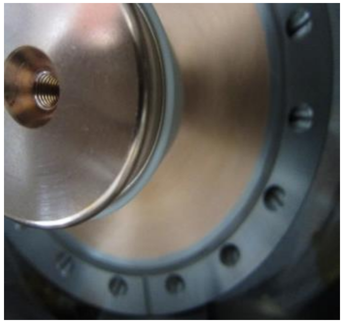
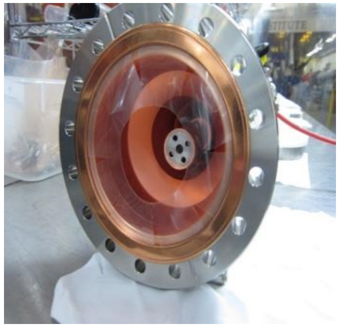
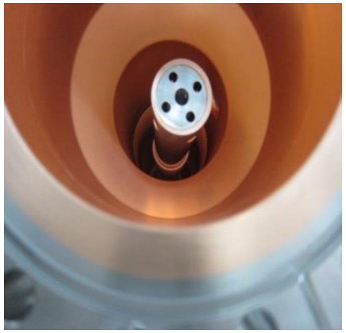
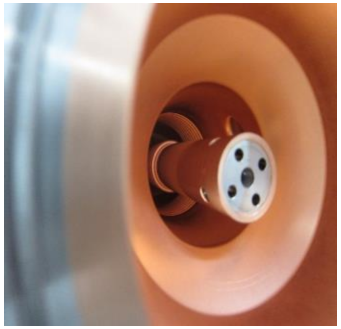
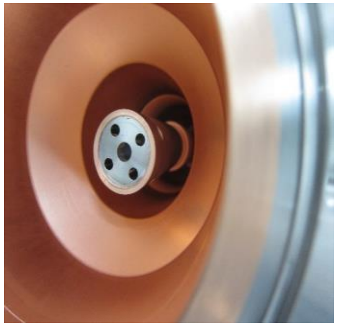
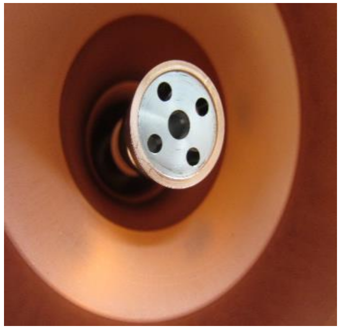
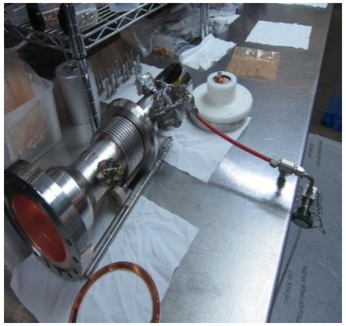
CM18 Cav8 wFPC removal done on 14 Nov 2019





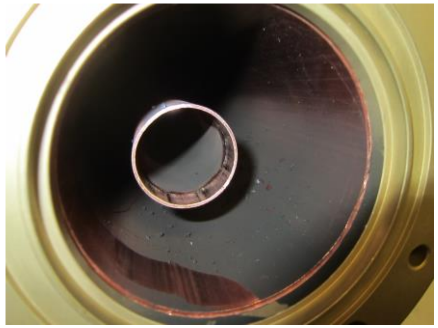
Warm coupler bellows, super insulation, cold and warm copper plating, cold Ceramic and RF contact in perfect condition post CMTF 2K qualification tests: no traces of arcing or heating marks.

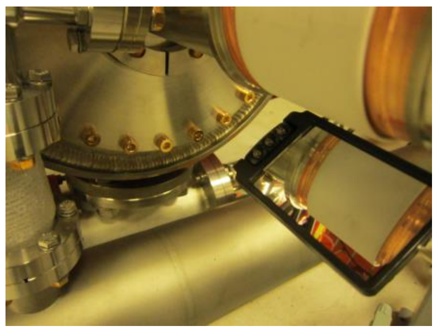


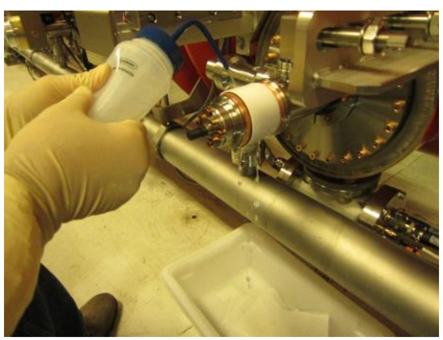









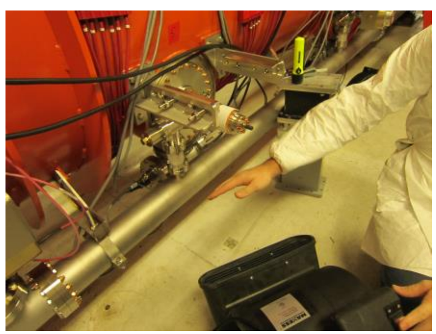
Untypical FPC response during 2K qualification tests

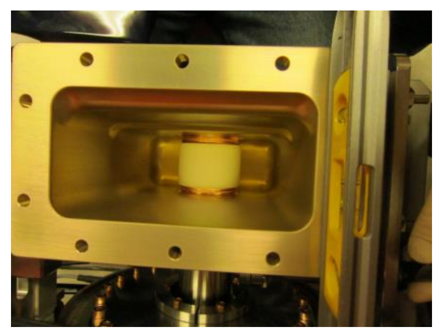
Safety: cold coupler recover work done on **cold cryo-module**, **but without liquid helium**. Gas barriers on FPCs waveguide would have help : **A LOT!!!**







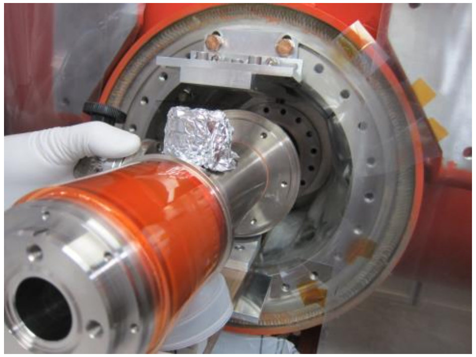




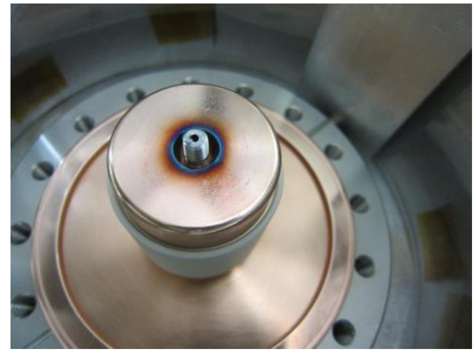
CM04 Cav5 was cooled back to 2K and the RF power qualification tests successfully finalized.

Untypical FPC response during 2K qualification tests

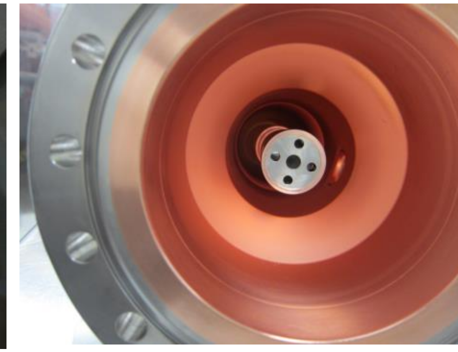
CM03 Cav4 had high temperature readings on CF100 flange during CMTF qualification tests: **had to check the warm coupler, maintain the cavity string under vacuum**.



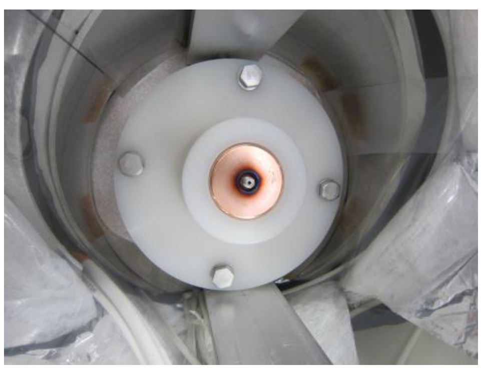

Vented bolt cannot be removed, even after soaking with alcohol



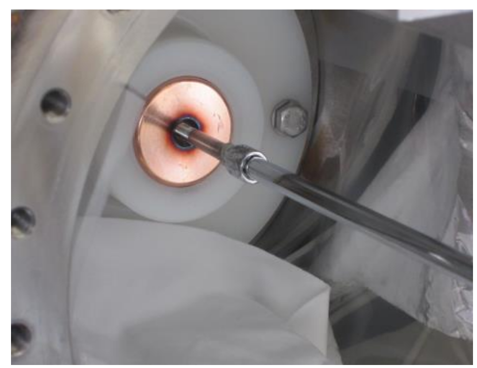
Vented bolt gave up in the cold ceramic…



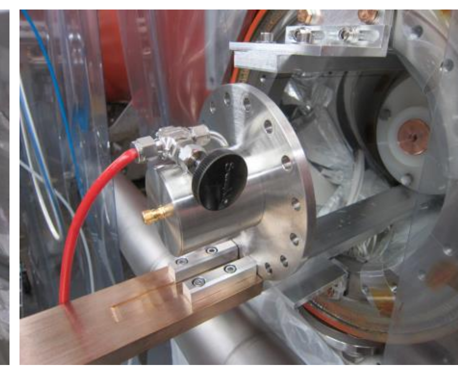
Perfect warm coupler part and WIC contact



Protect cold ceramic and CF100 flange

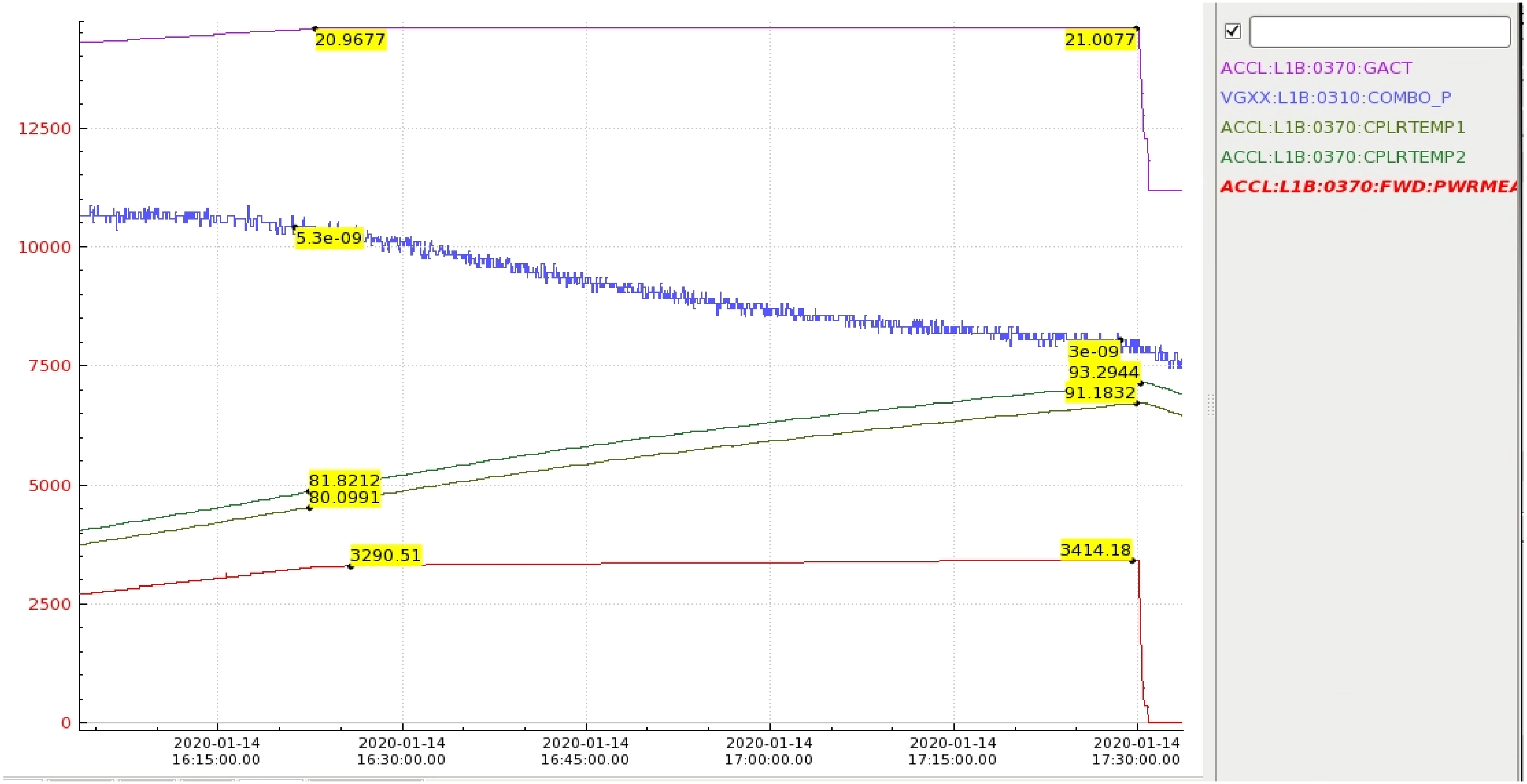



Expert mechanical work to remove the broken bolt and repair the threads



Clean and dry with N2 the repaired cold coupler

Typical FPC response during cryomodule qualification tests



LERF CM20 Cav7: Gradient 21 MV/m FPC vacuum about 5e-9 mbar, FPC CF100 temperature range 80 – 90 C during about 1 hour run at a FWD RF power of 3.3kW.

CMTF qualification tests done, the CM is prepared for shipment

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Cryo-module on shipping trailer

For shipment, the wFPC is kept under static vacuum (right angle valves closed) and the MC line is maintained under Nitrogen over pressure.

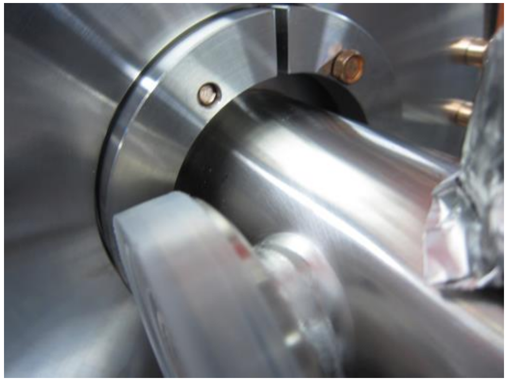
NO coupler failures during to SLAC

Dealing with LCLS II strings and cryo-modules re-work

Had to remove the cold couplers and sent them to the vendors for cleaning and re-qualification on three strings: 6 (beam line vented due to a mechanical incident, strings 9 and 11 due to bellows damage on cavity vacuum vessel). String 6R is ready for CMTF qualification tests, string 9R will follow in about one month from now, string 11R left the clean room this week.
During cold coupler removal, a dent was identified on one bellows. This dent was probably generated during 5K heat sink assembly or removal.

A number of cryo-modules had to be disassembled (pCM to CM10 !!!) after successful CMTF or LERF RF qualification tests, to address hardware issues related with BPM. This **work done with cavity string under UHV**, involved warm couplers removal and storage under N2, cold ceramic protection with metallic cups backfilled with N2, restraining the cold coupler with Berry bolts.

During this work, no arcing, heating events have bee identified. We had a broken SiBr bolt and… melted superinsulation on the warm bellows of pCM Cav7.



Extensive amount of work !!!!

Remarks

- The method of long term storage for couplers parts (in cabinet desiccator under dry, filtered nitrogen) have proven to be very useful and cost effective. No differences have been identified on cryo-modules equipped with couplers as delivered by vendors or long termed stored in the desiccator cabinets.
- Dedicated procedures and tools to **install** the warm couplers with cavity string with beam line under ultra high vacuum have been developed and successfully implemented at JLAB. This has direct and important implication in minimizing cavity field emission.
- **Procedures to repair LCLS II couplers with keeping the cryo-module under ultra-high vacuum have been developed and implemented at JLAB.**
- All 21 strings have the cold couplers installed.
- 18 Cryo-modules have been qualified in CMTF
- **17 cryo-modules have been shipped to SLAC, and none of the installed couplers failed during these shipments (or preliminary shipment tests done on pCM or CM07).**
- Next phase: upgrade project LCLS HE (High Energy) requesting 20 cryo-modules with FPC intended to operate at a Qext of 6e7.
- Preliminary data collected at JLAB LERF testing facility: most of the couplers tested can be adjusted at 6e7.

The LCLS II project had a very important advantage using almost the same FPC design (as XFEL project at DESY) and the same vendors with well established experience (by the way, during cryo-module qualification tests at JLAB, the couplers delivered by the two vendors, had similar, very good response.

Then, we've been doing our best dealing with this couplers and have been fully rewarded**: adequate response during JLAB's CMTF or LERF qualification tests and JLAB had no lost couplers during cryo-modules shipping tests or shipping to the final destination SLAC - California.**

But… this is a complex coupler, I wished it was simpler.

Will this coupler demonstrate similar performances as we had on power couplers installed on LEP, LHC or SNS machine?

I am eagerly looking for LCLS II beam operation.

Thank you for your attention!
Mircea

Backup slide: FPC proposed changes for LCLSII-HE project