HOM coupler heating in CW operation

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Outline

- Motivation
- High thermal conduction feedthrough design and HOM heating simulations
- HTS upgrade to CW operation and HTS test program
- Commissioning and first test results
  - *HOM heating at CW*
- Conclusion

Motivation

LCLS-II project is based on ILC/XFEL technology. Some modifications are required for cw operations (gradient 16 MV/m; beam: 300pC, 1MHz; σ_z=25µm in L3).

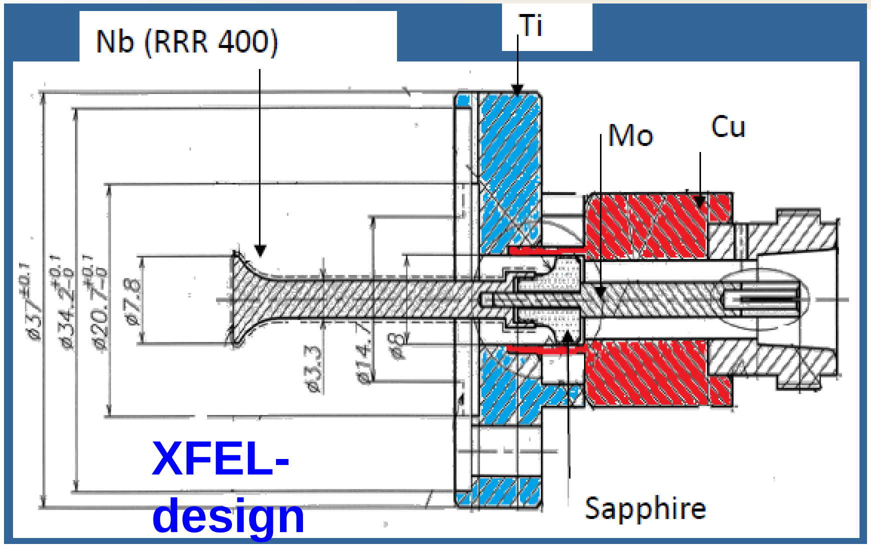
- High-Q technology (N2 doping) for tesla: Q0 > 2.7e10@16MV/m;
- HOM couplers should operate at 18 MV/m; maximum HOM power to HOM cable 2.5 W (*A.Sukhanov, K.Bane talk*)
- Fundamental coupler modifications for higher Q_{ext} and high average power
- HV and tuner modifications
  - Larger chimney
- CM modification (150W heat load)

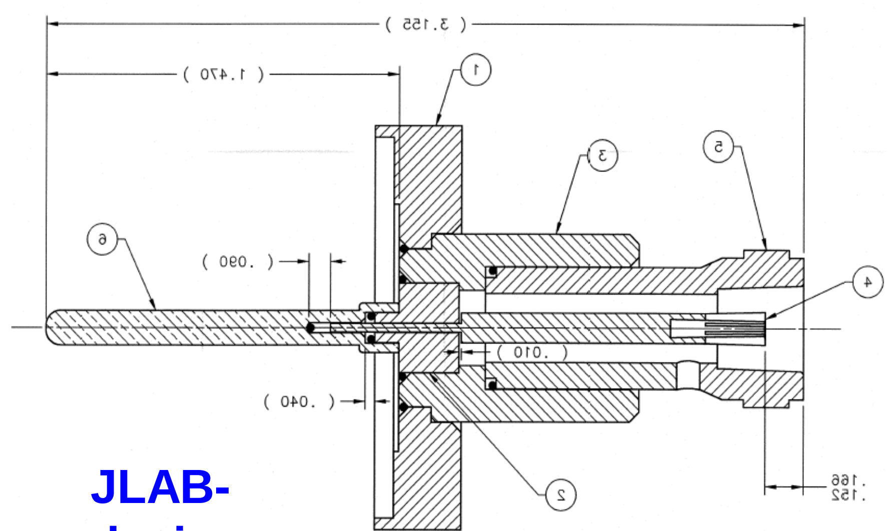
* One of the constraints: first two cryomodules will use existing at Fermilab ILC cavities (16+2 spares) with short-short beam pipe configuration; → no modification of HOM coupler design (except feedthrough) is possible

TESLA HOM coupler status

- >100 TESLA HOM couplers operate many years in TTF and around of world with beams up to 9 mA in short pulse regime(designed for 1% DF)
  - In acceptance tests was found that no Q change with HOM feedthru, no MP, gradient is not limited up to > 35MV/m if properly cleaned.
- At longer pulses in cavities with attached HOM feedthroughs DESY observed often heating in the HOM couplers (no heating at the nominal short pulse conditions)- limitations for CW operation
- New design of feedthrough (JLAB/DESY) was done to reduce heating
  - Pulse acceptance tests of TESLA cavities proved that HOM couplers, as designed, can operate at 24MV/m at least with DF ~ 10% , and 7.5MV/m in cw mode. The DF limit is not known yet.
- Modification of HOM design allows to reduce HOM heating further
  - The modified HOM TESLA couplers have been tested cw at 33+ MV/m, 20 MV/m and 21.5 MV/m for the JLab, DESY/JLab and DESY version respectively.

High thermal conduction feedthrough

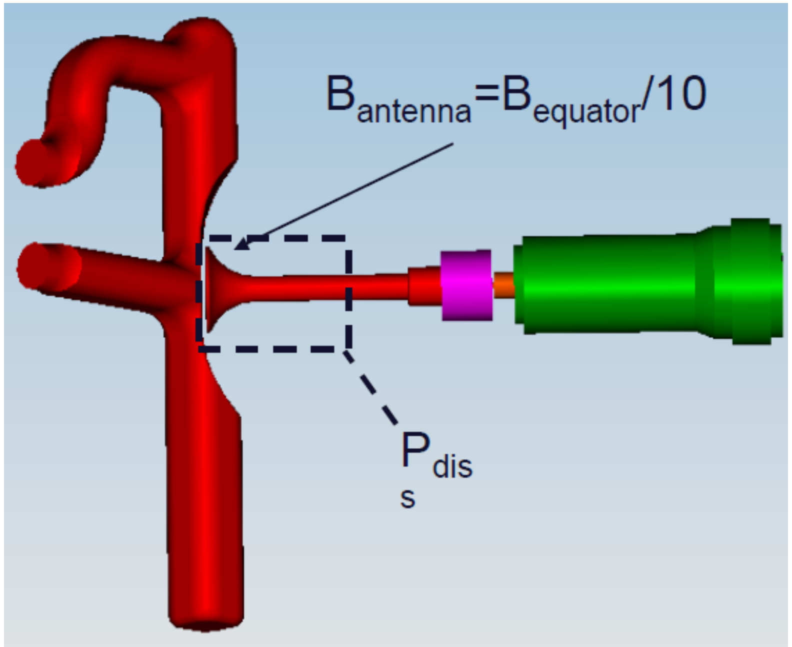




JLAB-design

- To reduce antennae heating HOM coupler will be equipped with high thermal conduction feedthroughs connected with copper braids directly to the 2-phase tube.
- Three designs are available : JLAB; DESY; FNAL (modified for 3.9 GHz cavity with frequency range ~10 GHz)
- General features:
  - *Sapphire instead of Alumina (x10 higher thermal conductivity)*
  - *Molybdenum instead of SS for the connector pin (x200 higher thermal conductivity)*
  - *Use Copper socket for better cooling*

Losses in antenna vs. Temperature

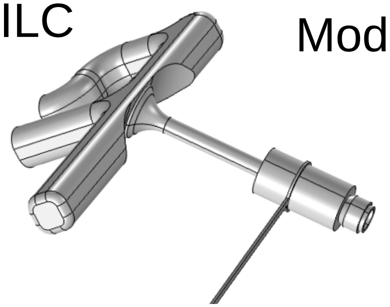


T_{ant} [K]	R_s+R_{bcs} [nΩ]	P_{diss} @16MV/m [mW]
7	4+3117	29.7
6	4+1873	17.9
5	4+1067	10.2
4	4+500	4.8
3	4+152	1.5
2	4+8	0.13

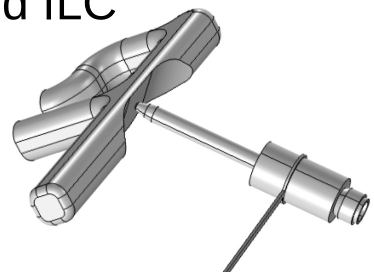
Courtesy of J.Sekutowicz

Modifying HOM Antenna Shape to Reduce Heating

ILC

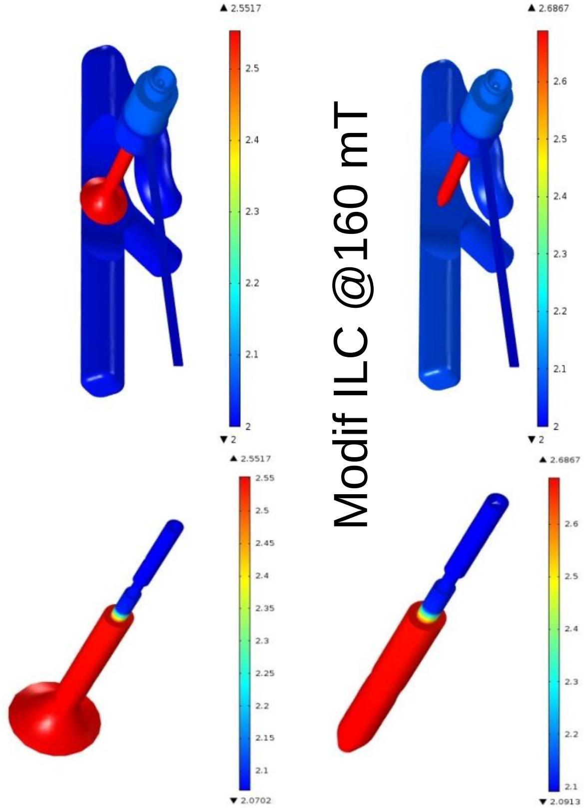


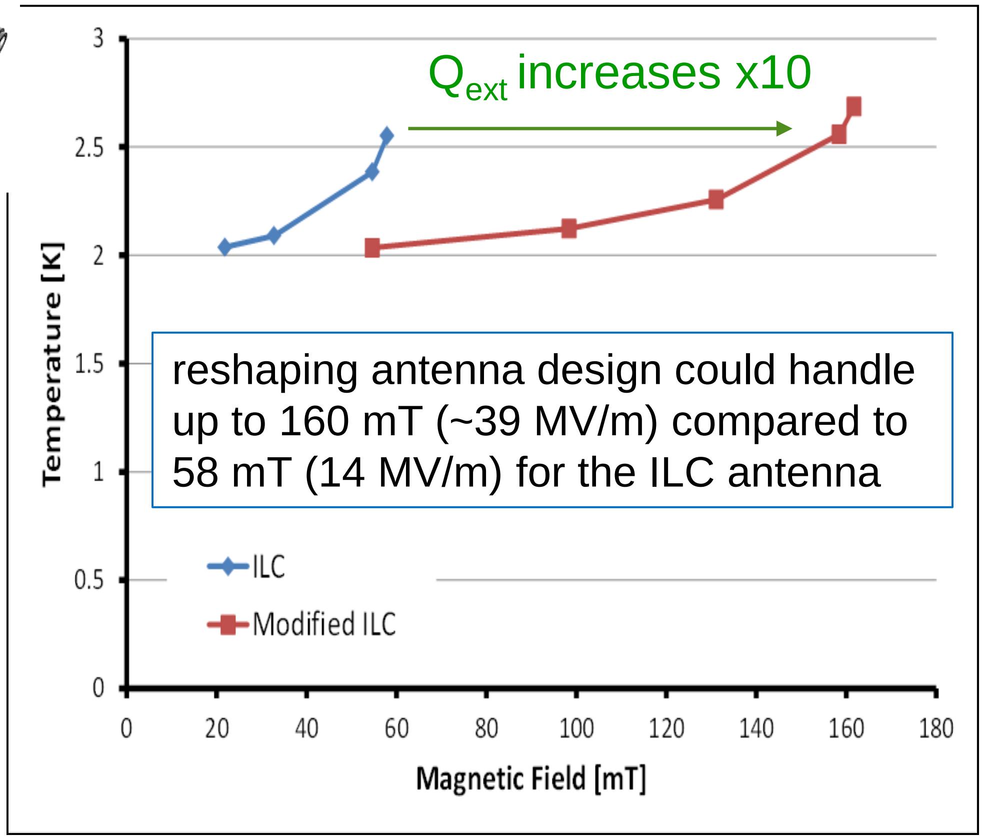
Modified ILC



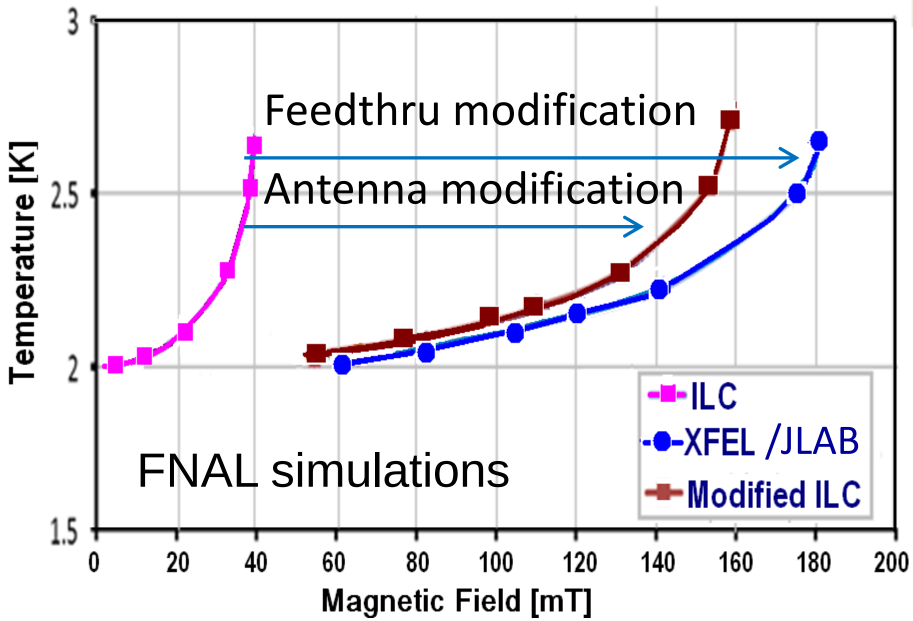
ILC @ 58 mT

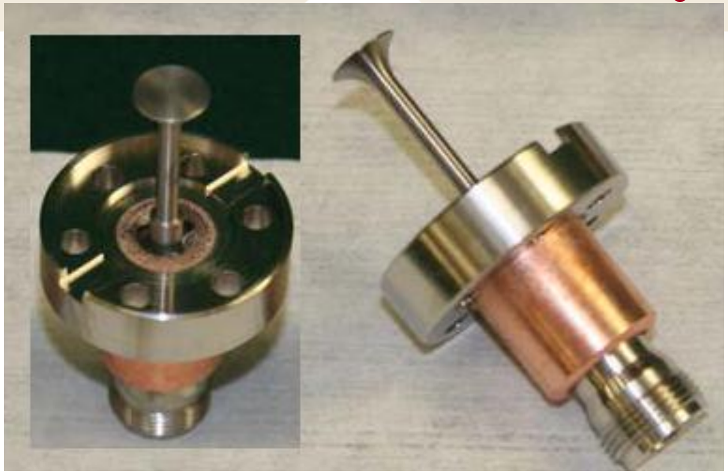
Modif ILC @160 mT





Effect of HOM feed-through for LCLS-II





XFEL HOM feedthroughs with sapphire windows

- ILC type feedtru limits cw gradient ~ 9.4 MV/m
- Modification (change antenna shape) will increase limit up to ~38 MV/m, but Q_{HOM} will be ~10 times higher
- XFEL (JLAB and FNAL) will be good ~40 MV/m. Need HTS test to prove at 24MV/m in cw mode
- Further improvement is possible (pre-product. CM delay; Q_{ext} increase)

Cable thermal connection and load

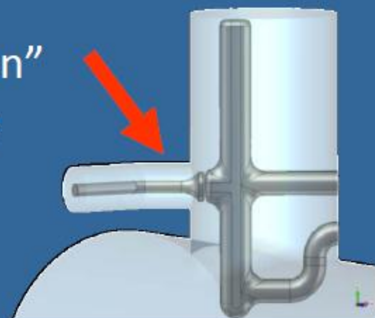
Further heating improvements

R&D program at DESY for cw-operating TESLA like cavity.

Modeling of HOM-coupler with hidden antenna

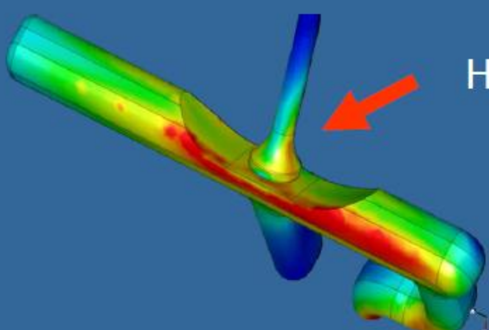
JLAB/Kneisel

Antenna is "hidden"
in the output tube

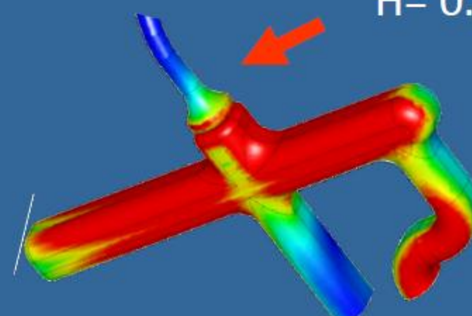


Courtesy D. Kostin, DESY

Peak H field on the antenna for the same stored energy



H= 0.045 A/m

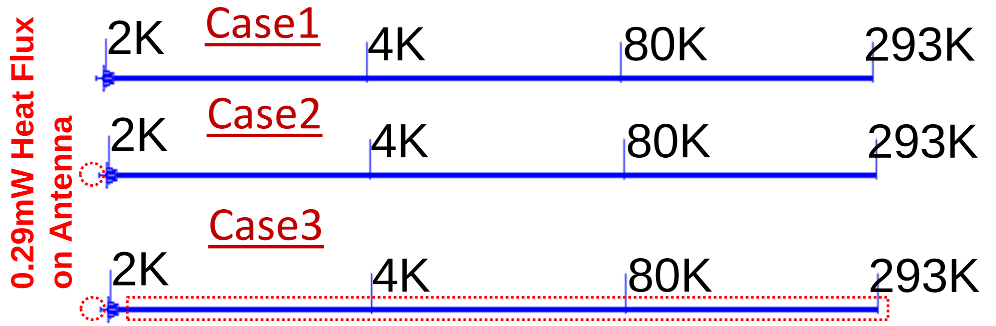


H= 0.022 A/m

For the modified HOM coupler, H is lower by 50%, antenna is shorter, F-part has better shape for cooling.

Effect of losses in cable (3m) connected to 4K(1m) and 80K (2m)

Preliminary: need re-evaluate taking into account T-dependence!!!

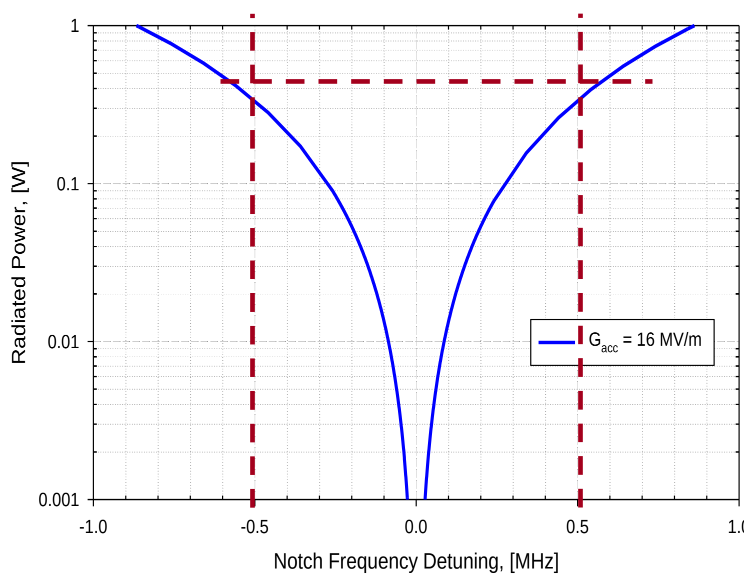


0.2dB/m loss for cable P_{HOM} = 5 W:
→ 0.52W on outer+ 0.13W on inner

Additional heating from RF losses:
RF power to cable (estimation):

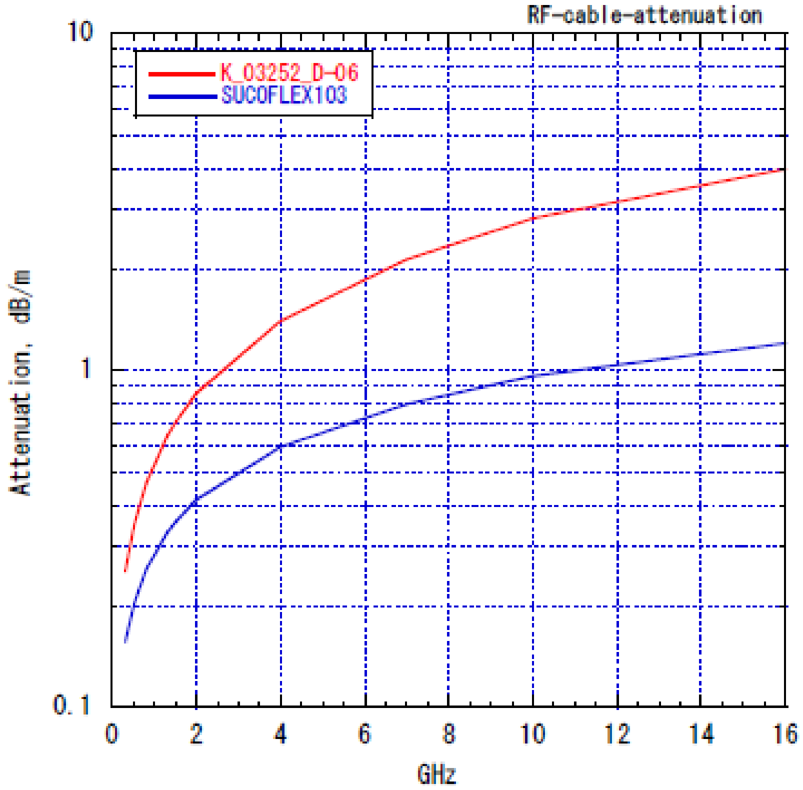
- *0.3 W leak of fundamental mode*
- *2.5 W HOM mid-freq range*
- *0.3 W HOM high-freq. range*

	Case 1	Case 2	Case 3
Tip Temp [K]	2.395	2.455	5.97
2K intercept [W]	0.007	0.008	0.116
4K intercept [W]	0.538	0.538	0.786
80K intercept [W]	0.577	0.577	0.740
293K intercept [W]	1.124	1.124	1.002

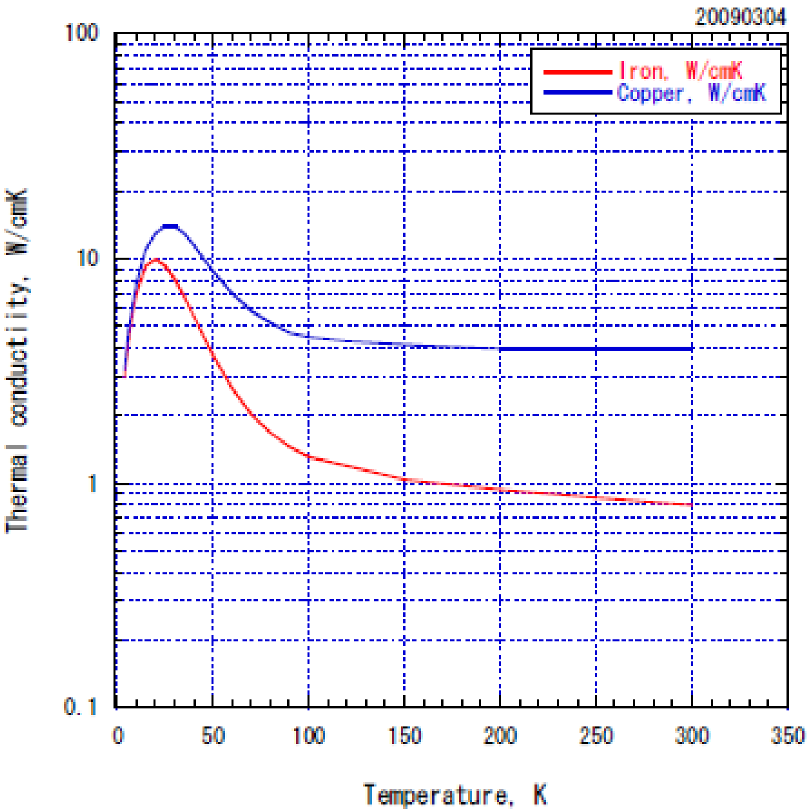


Need optimization of cable thermal connection points to reduce antenna heating

Cables



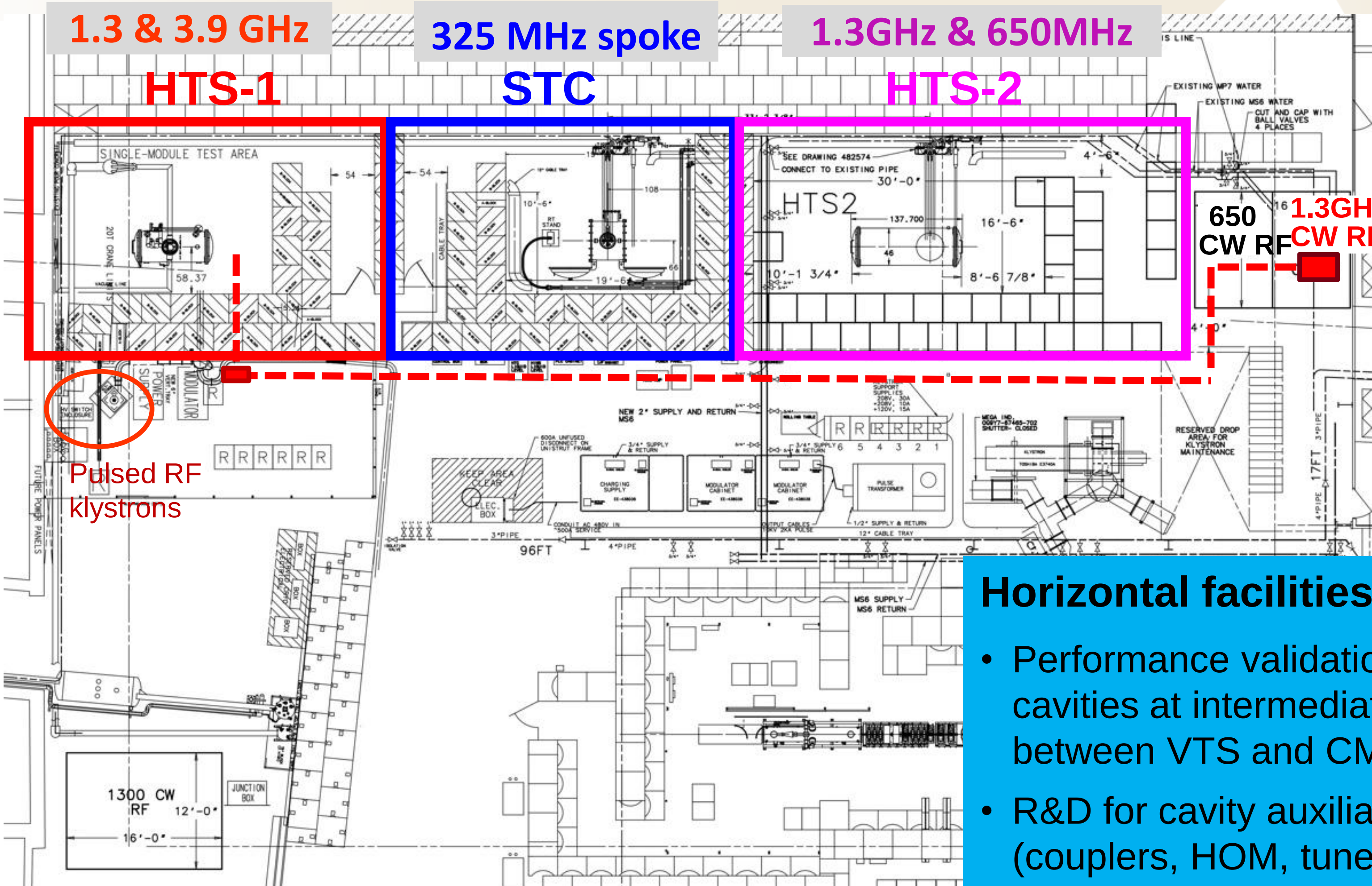
RF-cable-attenuation
K_03252_D-06
SUCOFLEX103
Attenuation, dB/m
GHz
10
1
0.1
0
2
4
6
8
10
12
14
16



20090304
Iron, W/cmK
Copper, W/cmK
Thermal conductivity, W/cmK
Temperature, K
100
10
1
0.1
0
50
100
150
200
250
300
350

HTS-1 upgrade for LCLS-II program and Testing Plans

Horizontal test stands facilities in MDB

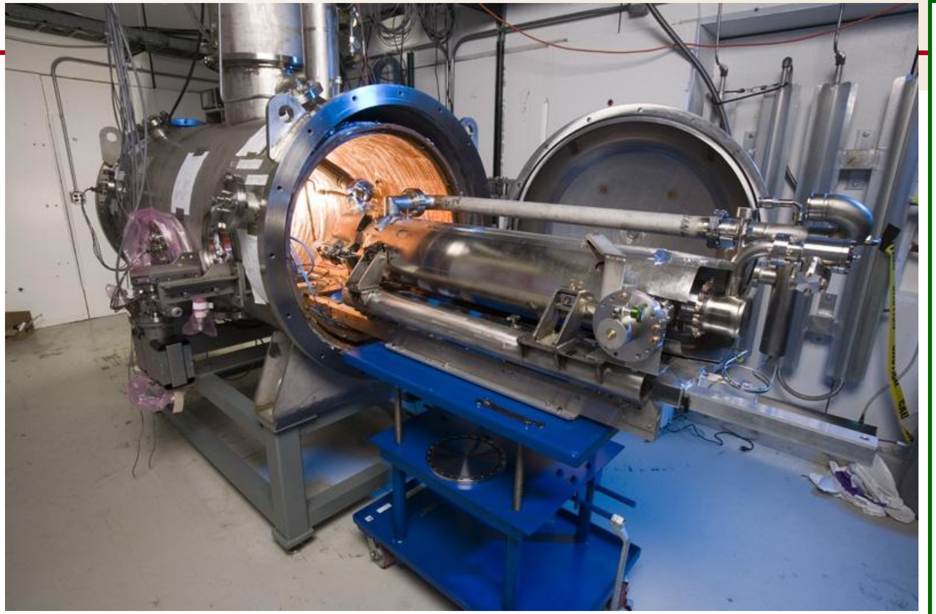


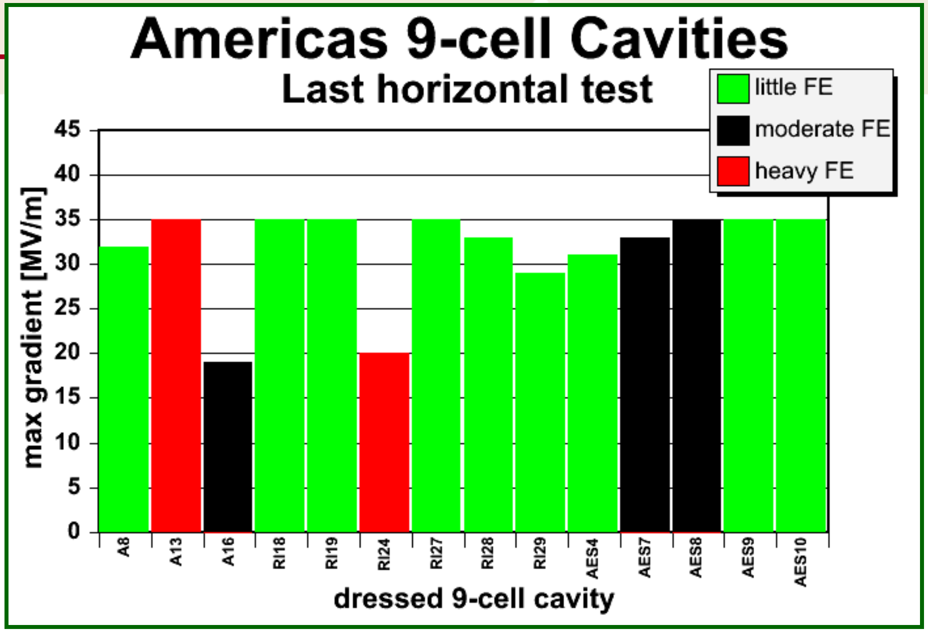
60-80 W @ 2 K refrigeration available

Horizontal facilities serve:

- Performance validation of dressed cavities at intermediate point between VTS and CM
- R&D for cavity auxiliary components (couplers, HOM, tuners, etc.)
- Microphonics and frequency control studies, algorithm verification

HTS -1





Operational since 2007, ~2 cavities/month throughput

- 1.3 GHz and 3.9 GHz cavities, ~1.5 ms RF pulses
- 1.3 GHz tests with long (8-9 ms) RF pulses;
  - Adopt long-pulse test as part of standard cavity run plan
  - Switch between long and short pulse operations
- **Recently modified for CW operation**

HTS program for LCLS-II CM design verification

Goals:

- **Validate critical technical decision needed for CM design complete.**
  - **(high-Q0 cavity, FPC, HOM feed-through, HV, Tuner, magnetic shielding, etc…)**
- **Provide test stand for cavity qualification before installation in CM.**
  - First Article, 1.3 GHz Prototype CM : complete Dec 2015.

    (All cavities should be tested at VTS and ¼ in HTS before installation ➔ 2 cavities)

Critical tests needed to prove technical decisions (CM design verification)

- ***Performance of dressed high-Q cavity in cryomodule: Q > 2.7e10 @16 MV/m***
- ***Verify HOM coupler and feedthru designs @ 16 MV/m CW (18 MV/m adm. limit)***
- ***Main coupler design: Q_L=4.e7; RF cw power = 7 kW with full reflection***
- ***Test LCLSII-type Helium Vessel, magnetic shielding, end-lever Tuner (+piezo)***
- ***Resonance frequency control and microphonics studies (hardware, algorithm)***
- ***Tuner components reliability tests***

HTS upgrade for CW operation

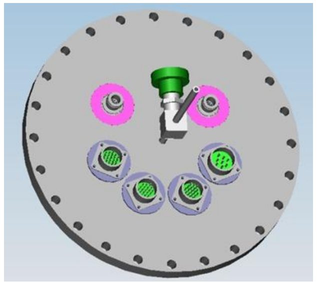
In support of the LCLS-II project, the Horizontal Test Stand (HTS) was recently upgraded to allow for low-power and high-power CW testing of dressed SRF cavities.

Major Modifications:

- ***New CW LLRF system with phase-locked loop control (like 325 MHz system)***
- ***Blanking off the cryostat input coupler port with a flange (RF & diagnostic)***
- ***RF cw power systems:***

  Low-power: 200 W SSA as the RF source

  High-power: 30 kW CW IOT transmitter (in progress)



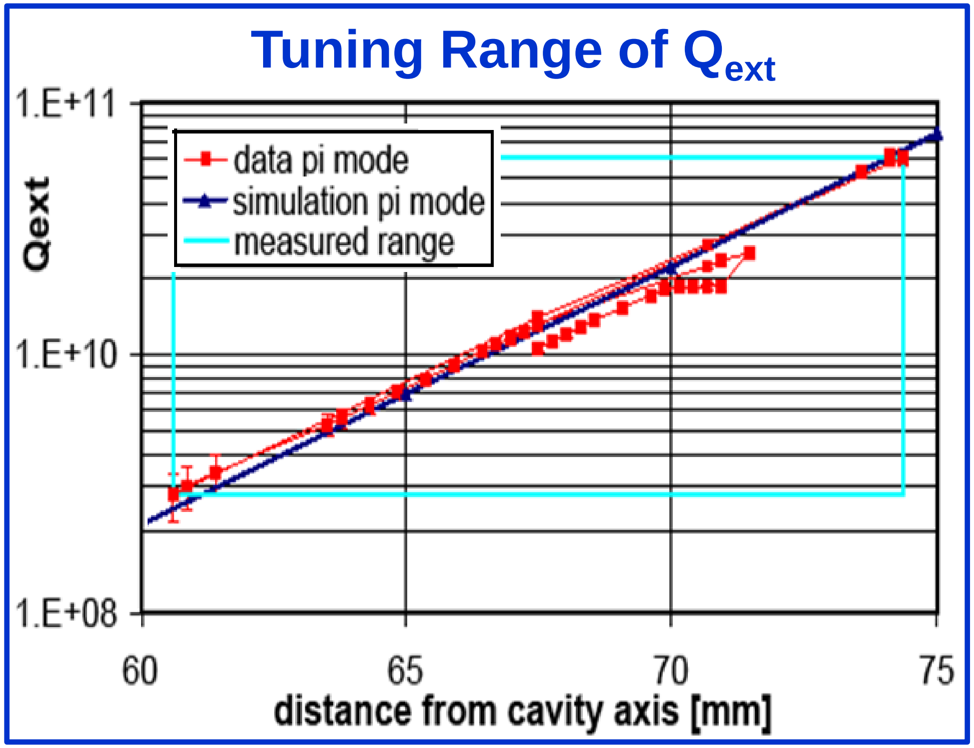
- ***Set of Helmholtz coils for 3D cancellation of the Earth's magnetic field inside the cryostat.***
- ***Interlocks and Safety documentation***

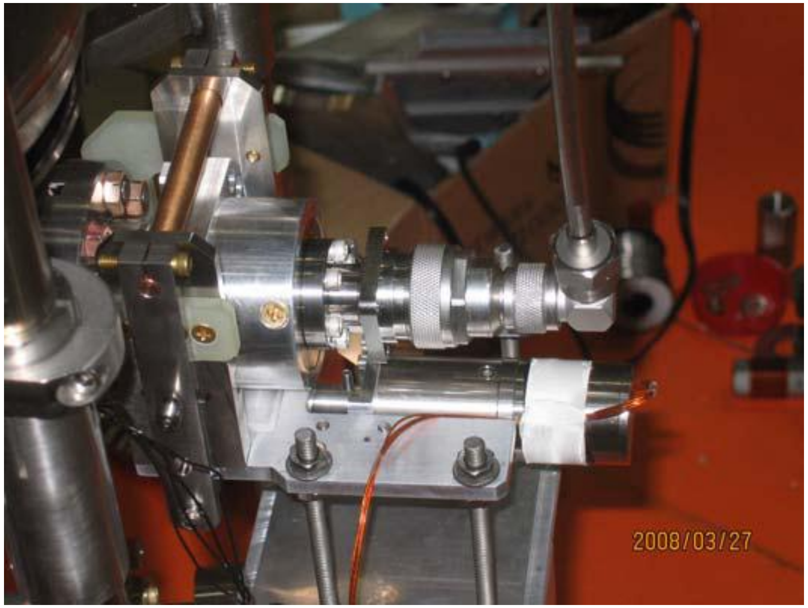
This upgrade was commissioned in June 2014 with a cold test of cavity TB9RI026 (not high-Q)- ILC-style dressed cavity with the following modifications:

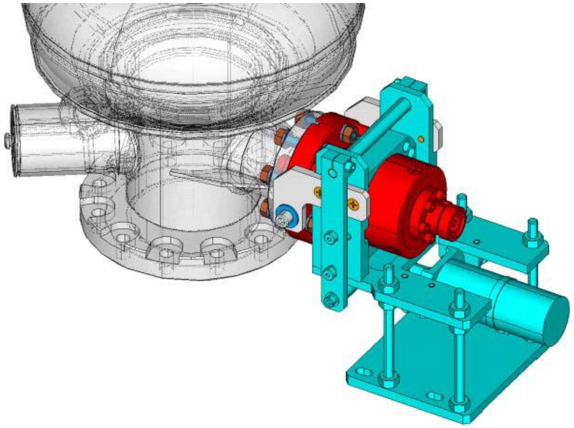
- ***The TTF3 coupler was replaced with a variable coupler (unity coupling)***
- ***ILC-style HOM feedthroughs were replaced with XFEL-style feedthroughs (DESY).***
- ***New thermal intercepts anchored to the cavity's 2-phase pipe***
- ***RF cable from flange to coupler (200 W SSA)***

Low power variable coupler (unity coupling)

- Used in VTS for high-Q0 program.
- Spare built for HTS.
- Fixed coupler also available (back up)

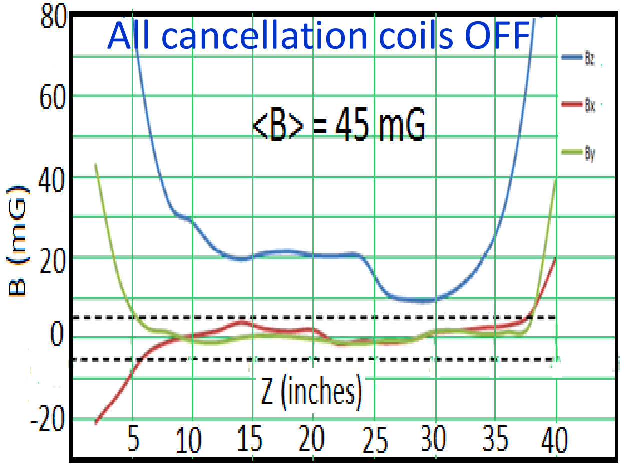


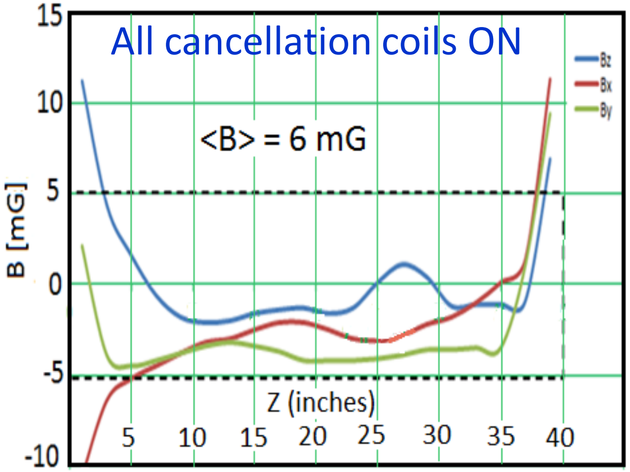




Helmholtz coils cancellation of magnetic field inside cryostat

One ILC shield, measurement on cavity centerline



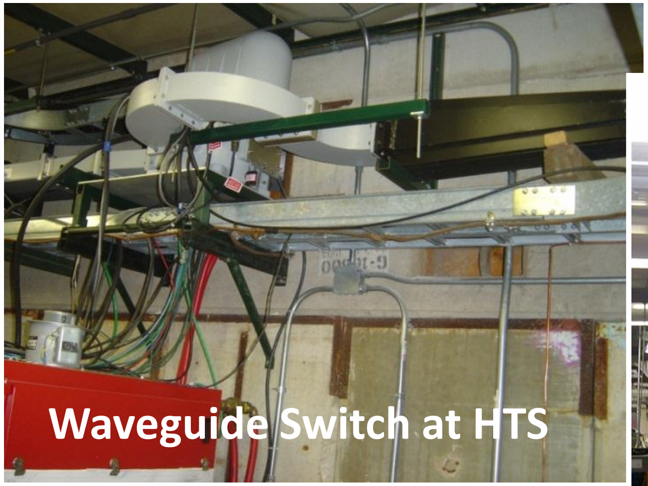


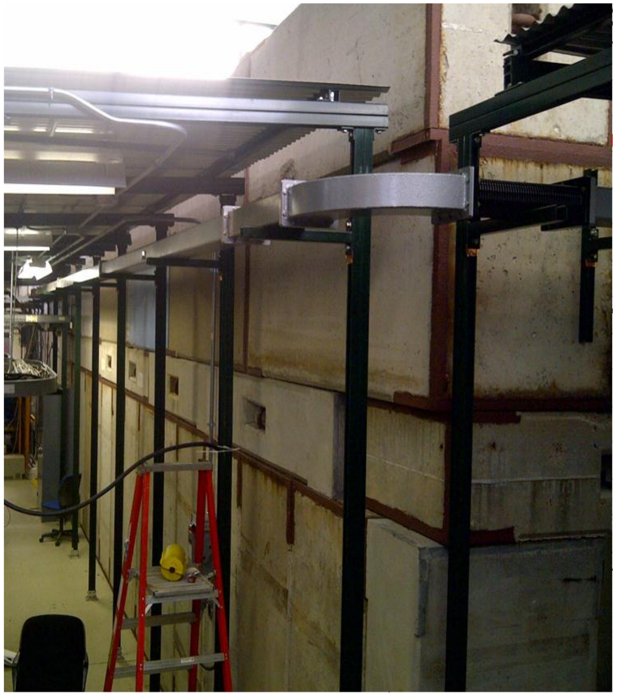
High-power RF: IOT Transmitter, 30 kW CW

Connect existing IOT to current HTS-1 switch.

- *Run about 42 meters of WG-650 waveguide.*
- *Install new calorimetric W/G load to switch*

Run signal cables between IOT and HTS control room.





- Modify slow and fast interlock system to accommodate two RF power sources: pulsed (300 kW) and CW (30 kW).
- Commissioning (Calibration of RF couplers, Checkout of all interlocks and ACNET parameters)

HTS tests schedule

#	Test, goal	Start 2014	Cav. type	Helium Vessel	HOM antenna	Coupler (cold)	Coupler (warm)	Magn shield	Tuner	RF
1	HTS commissioning XFEL feedthru test μ-phonics study start	June	ILC RI26	ILC	XFEL	variable	None	1-layer +coil	None	SSA 200W
2	High-Q0 cavity (AES011) verification	July	high-Q#1	ILC	None	variable	None	1L+coil	None	SSA 200W
3	FPC cold modified JLAB feedthru test μ-phonics study	July Aug	high-Q#1	ILC	JLAB	FPC modif	FPC He cooled	1L+coil	blade	IOT 15kW
4	FPC#1 modified; μ-phonics study	Aug	high-Q#1	ILC	JLAB	FPC modif	FPC#1 modif	1L+coil	blade	IOT 15kW
5	High-Q cav. #2 FPC#2 modified; HV	Sept	High-Q#2	LCLS-II	XFEL	FPC modif	FPC#2 modif	1L+coil	None	IOT 15kW
6	High-Q#3 integrated test Tuner; magn.shield	Oct	High-Q#3	LCLS-II	JLAB	FPC modif	FPC#1 modif	2-layer	Lever tuner1	IOT 15kW
7	high-Q#2 integrated test Tuner reliability	Oct	High-Q#2	LCLS-II	XFEL	FPC modif	FPC#2 modif	2-layer	lever tuner2	IOT 15kW

Test schedule is tentative and based on assumed delivery of elements;

Assumption: cavity test and next cavity preparation in parallel

*High-Q0 cavities #2 and #3 will be qualified for installation to pre-production CM

HTS commissioning and first results

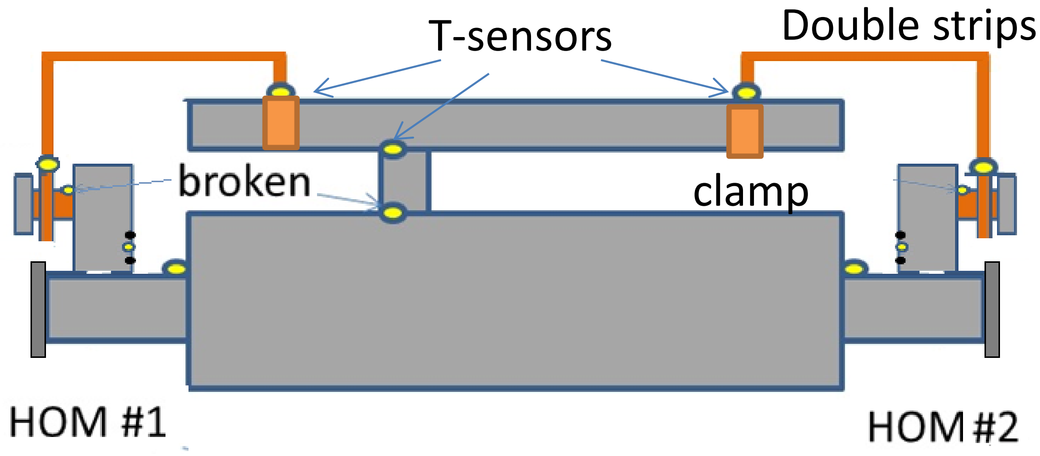
- System identification, tuning and commissioning
- E vs. E and Temp, Effect of magnetic field
- Cryogenic loading calibration (heater vs. RF loses)
- Cool-down rate (slow 0.2K/min and fast 2K/min)
- Resonance frequency control and microphinics

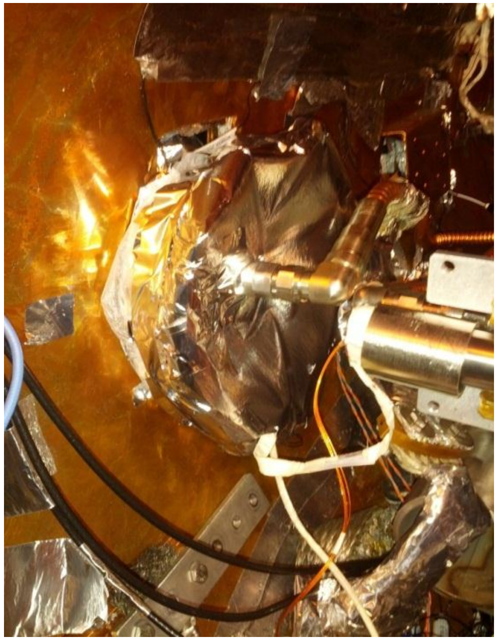
The objectives of the 1st HTS test

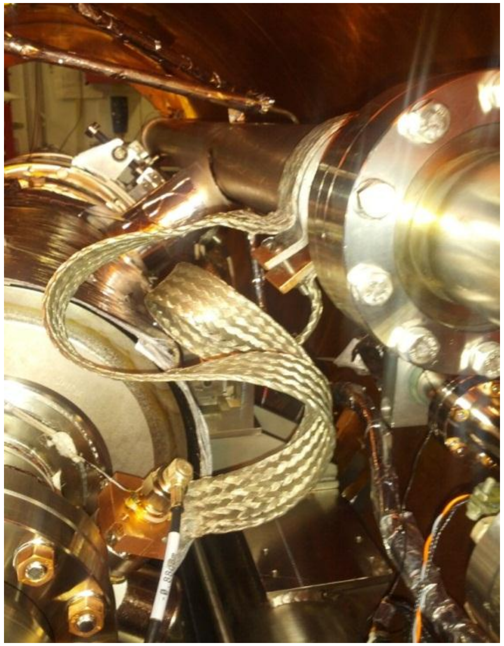
TB9RI026 cavity dressed in ILC type HV with blade-tuner, equipped with two XFEL HOM feedtroughs. Cavity was excited by tunable antenna able to provide critical coupling. The main goals of this test are:

- *Commission the CW upgrades (via the accomplishment of the subsequent objectives).*
- *Validate the thermal performance of the XFEL HOM feedthroughs*
- *Measure the cavity Q vs. E curve from the RF signals*
- *Calibrate Q0 measurements by cryogenic loads (compare with direct Q measurement)*
- *Evaluate performance of active magnetic field compensation provide by Helmoltz coils*
- *Develop a method of controlling cool-down rate, so that fast vs. slow cooldown effects can be studied.*
- *Begin commissioning of piezo-based microphonics compensation system*

TB9RI026 in HTS







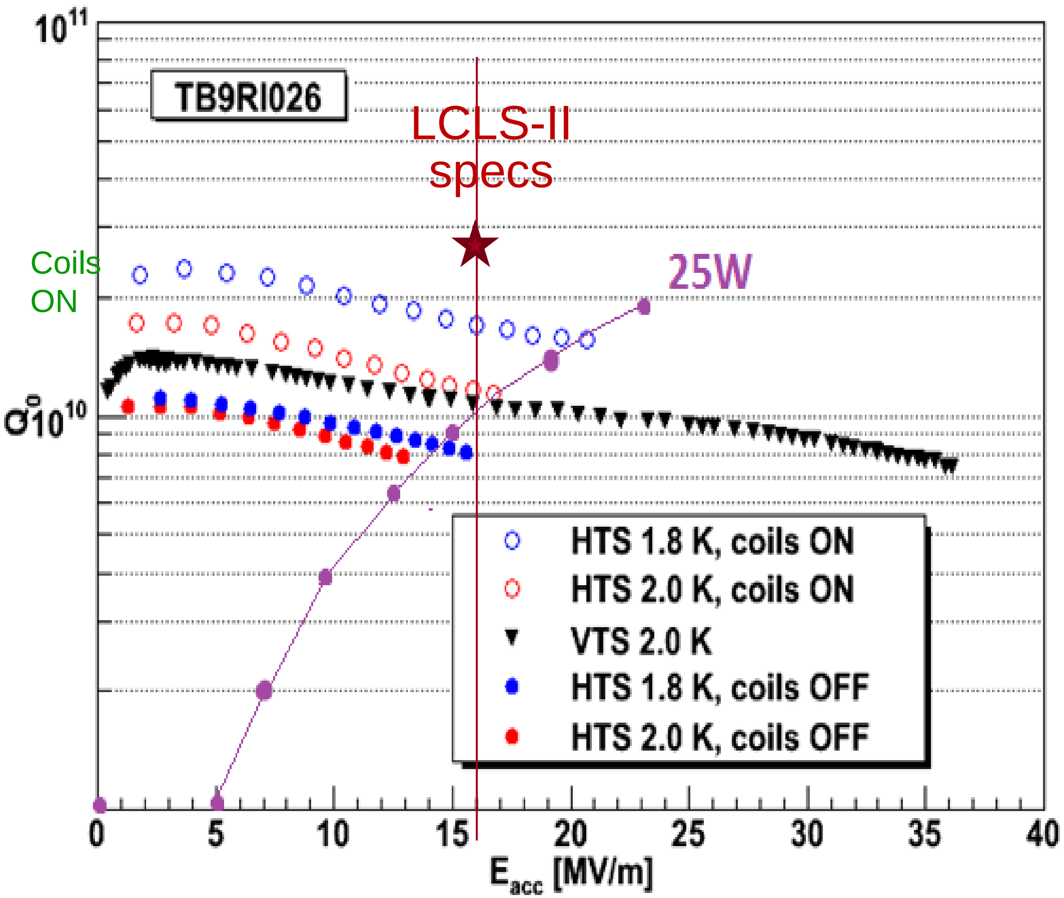
Standard ILC dressed cavity, except:

- *High-Q_{ext} variable coupler*
- *XFEL-style HOM feedthrough (sapphire window)*

Good thermal connections !!!

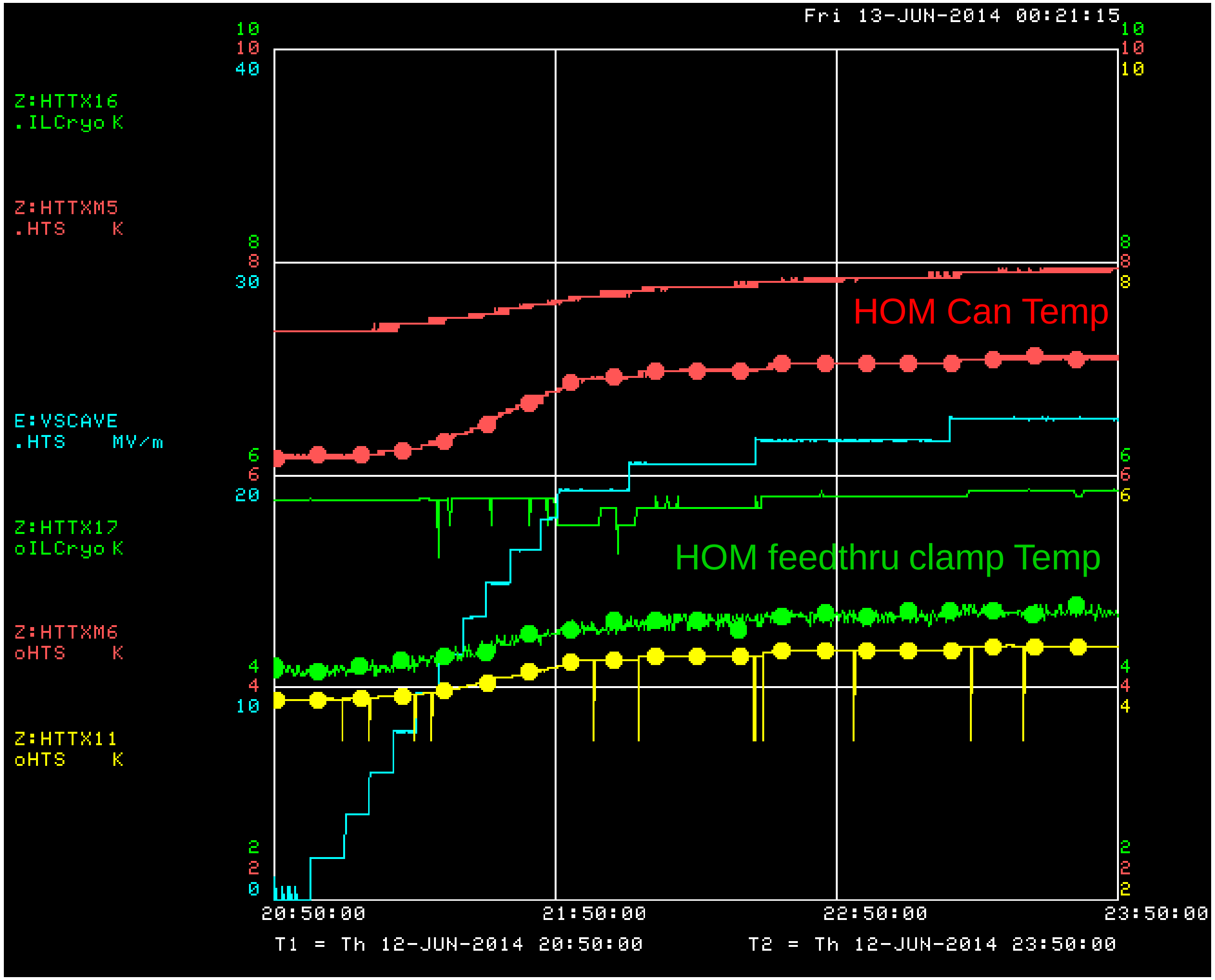
- *double strips soldered to clamp*
- *Solid copper clamps,*
- *glued T-sensors*

Q vs. E, Gradient limit



- Gradient was limited by 25W power dissipated in HV (chimney limit).
  - 13/17 MV/m @2K,coils=Off/On
  - 14/20 MV/m @1.8K,coils=Off/On
  - 22.6 MV/m @1.8K, 8π/9 mode
- 2K, coils ON is comparable to VTS
  - 20% higher low-field Q at HTS, but not unreasonable to assume 10% systematic uncertainties
- Compensation coils work really well.
- Stronger mid-field Q-slope at HTS

HOM Temperature vs. E



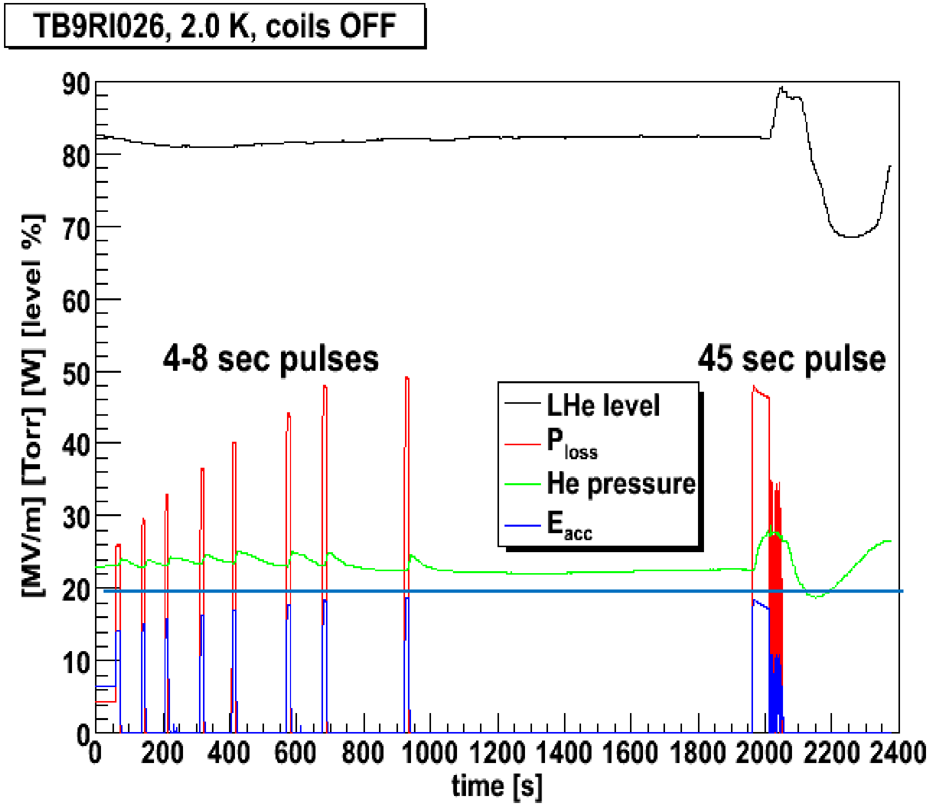
Blue = E_{acc}, Red = T_HOM can, Green = T_HOM feedthru clamps, Yellow = T_HOM feedthrough. Lines = HOM1, circles = HOM2

- 8pi/9 mode, 22.6 MV/m in end cells
- 1.8K, B-field compensation=ON
- ~1°on HOM body, ~0.5° on feedthru
  - OK for LCLS-II

Gradient Limit

First thing we did was rediscover the "chimney limit"

- *ILC HV chimney has A = 23 cm²; 1 W/cm² → will choke heat transport for heat loads > 25 W (HZB)*
- *…and in fact TB9RI026 quenched whenever P_{loss} approached 25 W (+ 5W static load)*
- *Could push cavity higher by using short pulses*



- 25 W limited us to 13 MV/m @2K, no B-field compensation. Running above limit is possible for ~45sec before quench developed,~20MV/m @2K see plot)
- HOM temperatures barely budged, but need to go to at least 20 MV/m in order to OK the feedthrough design for LCLS-II
- So, increase Q0 by running at 1.8 K instead of 2.0 and turning on B-field compensation (~20 MV/m), and increase field at HOMs by running in 8pi/9 mode (22.6MV/m)

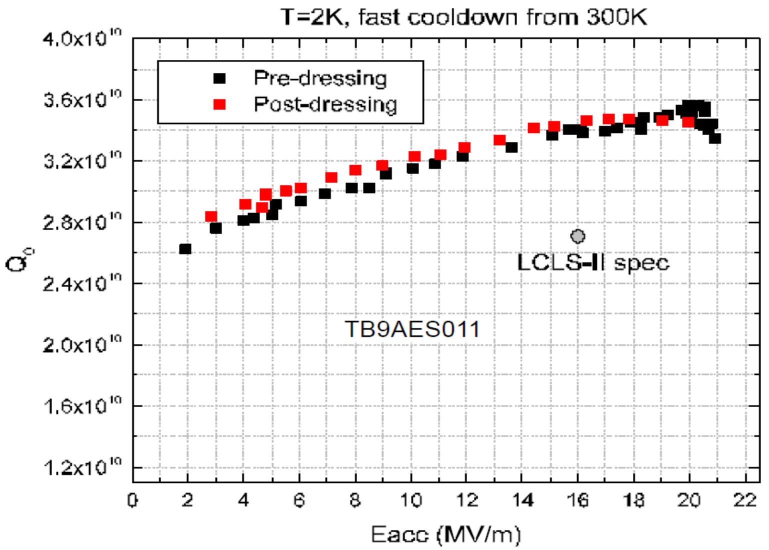
Summary of 1st cavity test

Very successful cavity test

- *Commissioned CW upgrades*
- *Validated XFEL-style HOM feedthroughs for LCLS-II (>22.6 MV/m, cw)*
- *Demonstrated reliable Q vs. E measurements from both RF and cryosystem*
- *Developed techniques for controlling cooldown rates*
- *First look on resonance control and microphonics to test hardware and software*

➔Next test is high-Q cavity (this week)

➔then cavity with LCLS-II style main Coupler and JLAB feedthrus



Conclusion

- Thermal simulations prove that existing TESLA HOM coupler design and XFEL/JLAB can be accepted for LCLS-II for cw operation.
- Two XFEL feedthroughs were assembled on ILC cavity and tested in HTS in CW mode. Temperature rise ~0.5K was measured at 22.6MV/m accelerating gradient. RF power from HOM ~0.5W was measured outside of cryostat. (Prove)
- HTS after upgrade for CW operation and commissioning is available for LCLS-II High-Q, FPC and CM design verification programs to prove baseline design
- Expected results of HTS tests:
  - Qualify 3 high-Q cavities. Two of them will be ready for CM installation
  - Prove HOM design and HOM feedthru (done for XFEL design, >22.6 MV/m)
  - Prove FPC design and test alternative cooling option
  - Prove Helium Vessel, Magnetic shield and Lever Tuner designs
  - Study frequency control and microphonics

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