3.9 GHz CW challenges and recent horizontal test results at Fermilab

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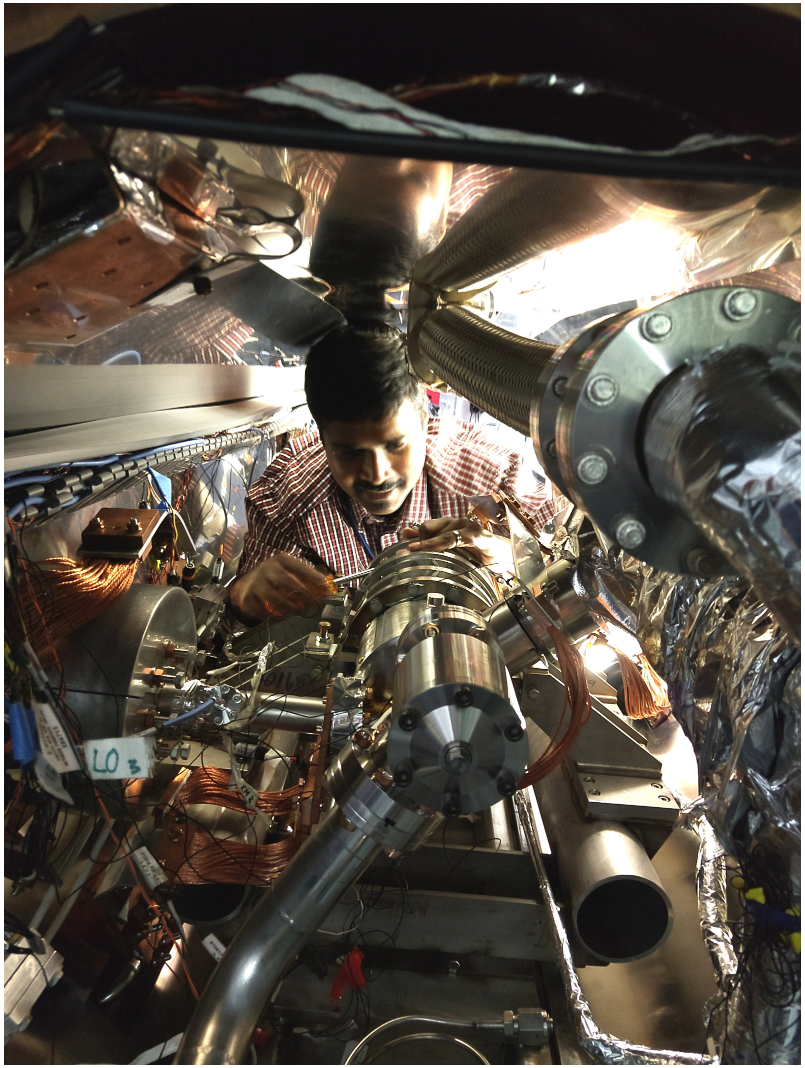
Acknowledgements

- LCLS-II 3.9GHz work at Fermilab is true team work
  - Many thanks to everyone working on the design verification and the horizontal testing in particular
- Special thanks for contributing material to this talk to:
  - Saravan Chandrasekaran, Yuriy Pischalnikov, Nikolay Solyak, Genfa Wu

Outline: Challenges

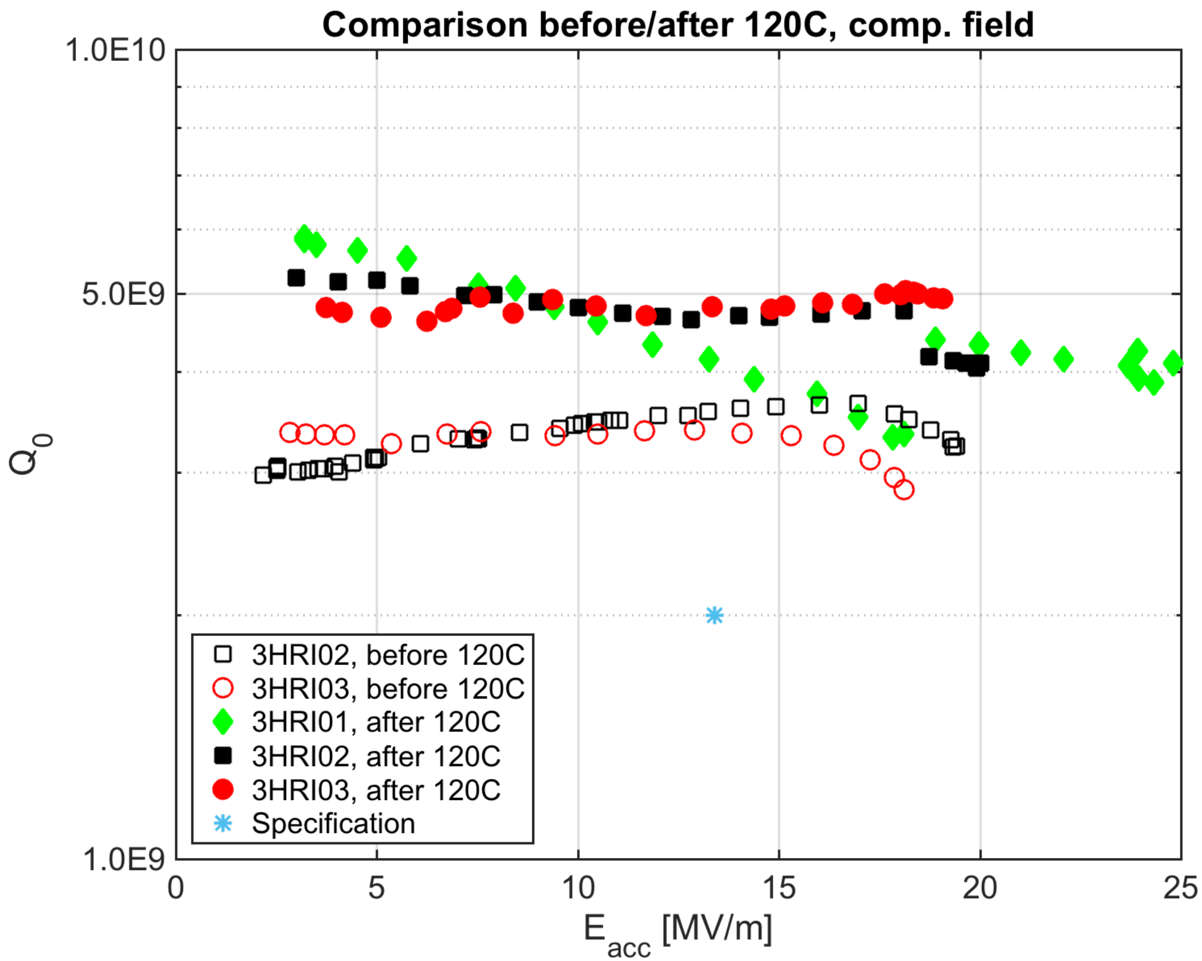
- LCLS-II specs
  - Q_0 = 2E9 @ E_{acc} = 13.4 MV/m (nominal operation)
- Heatload/Q0
  - He vessel/chimney must handle generated heatload
- Magnetic shielding
  - 15mG in cryomodule
- Tuner
  - Microphonics specification: 30Hz peak detuning
- Power coupler
  - Engineering specification: 2kW CW, travelling wave
- Integrated test of all components in horizontal cryostat

Horizontal testing



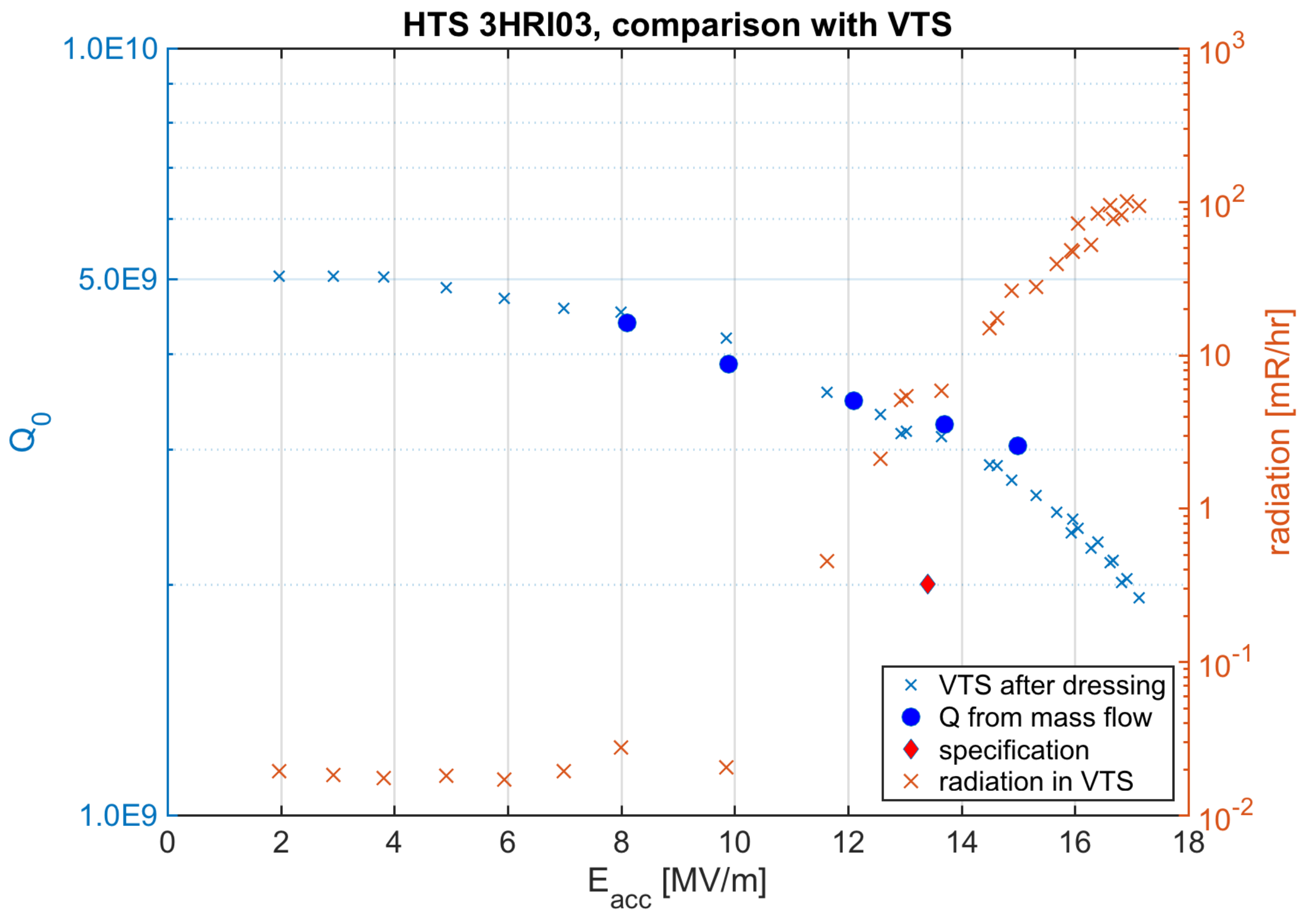
- Conditions similar to cryomodule operation
- Integrated testing of all components
- Resolve possible interference

VTS cavity performance



- BCP and 120 bake surpasses specification with big margin

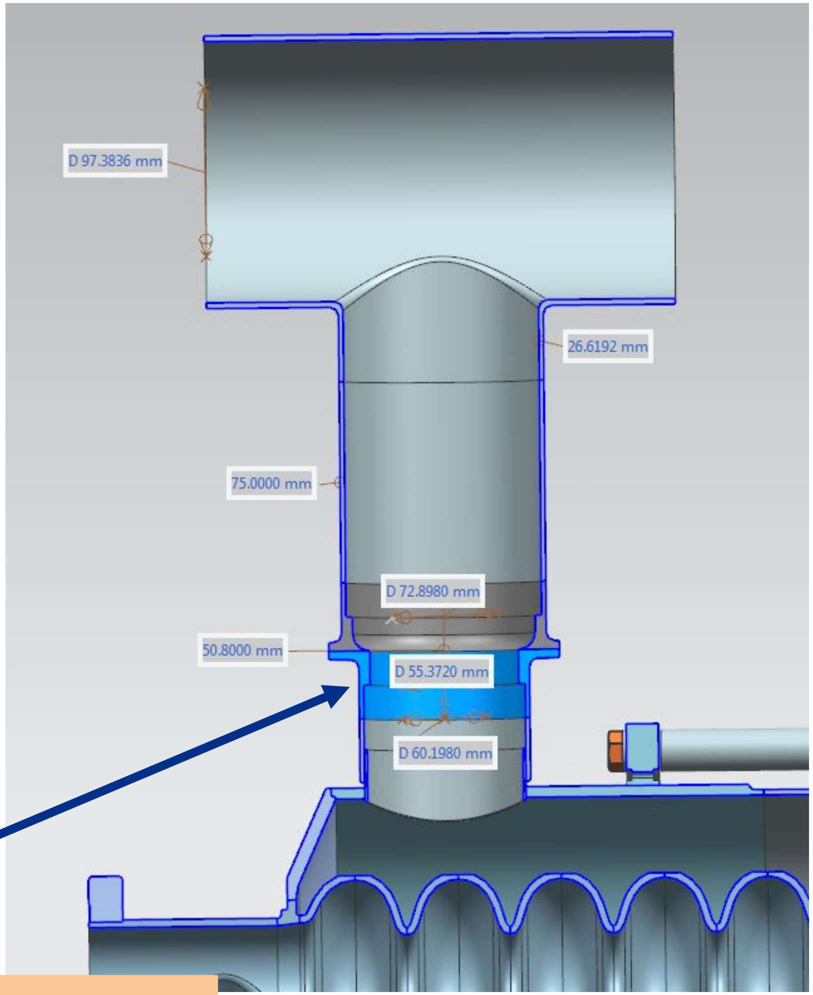
HTS performance 3HRI03



- Q in HTS matches VTS performance
- Ultimate quench in HTS at 20.4 MV/m (FE present)

Heatload

- Heat load capacity limited by chimney size
- Limited area on helium vessel
- -> stepwise diameter increase



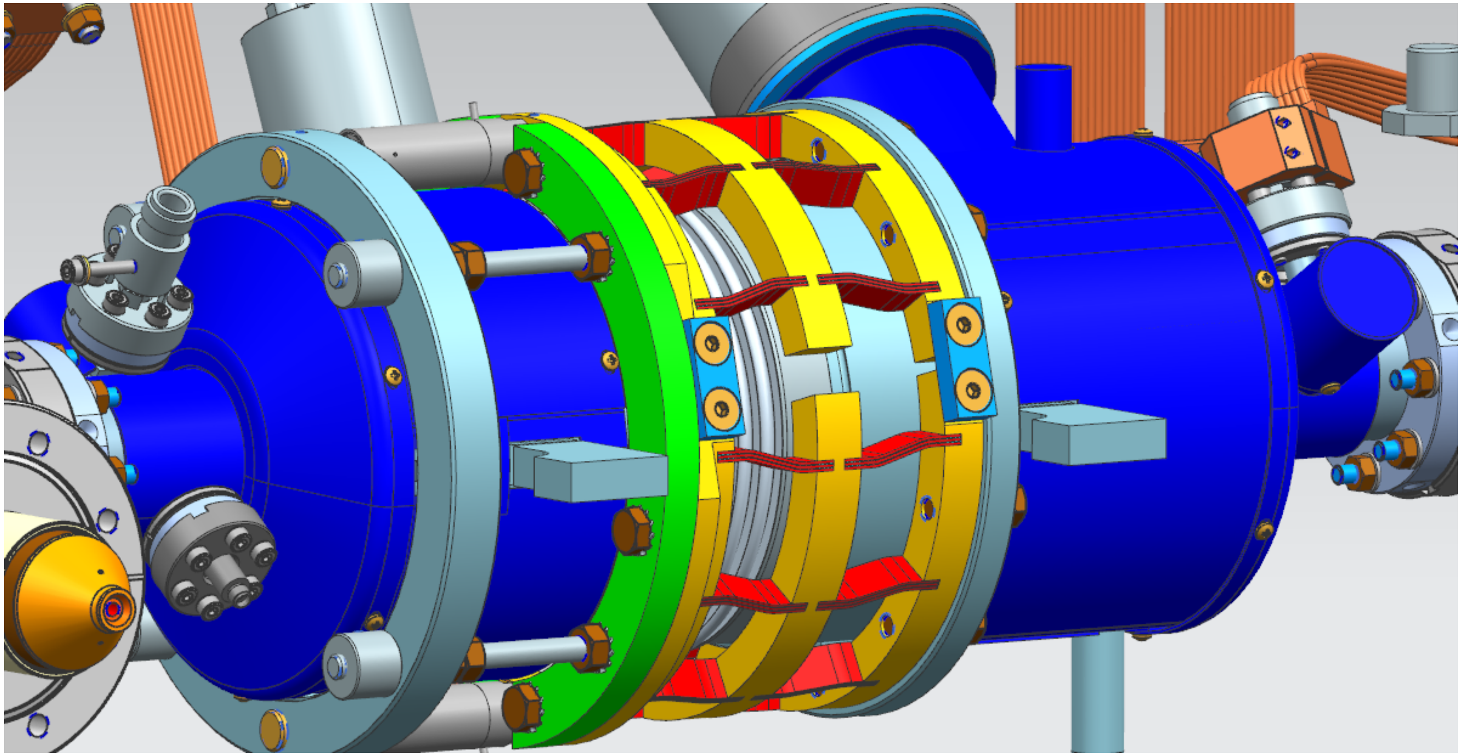
Gradient [MV/m]	Q0	Dynamic Heat Load [W]
13.4	2.0e9	14.3
14.9	1.5e9	23.6
14.9	4.0e9	8.9

Maximum heat load capacity is calculated ~ 36.2 W

Heat load margin ~ 50%

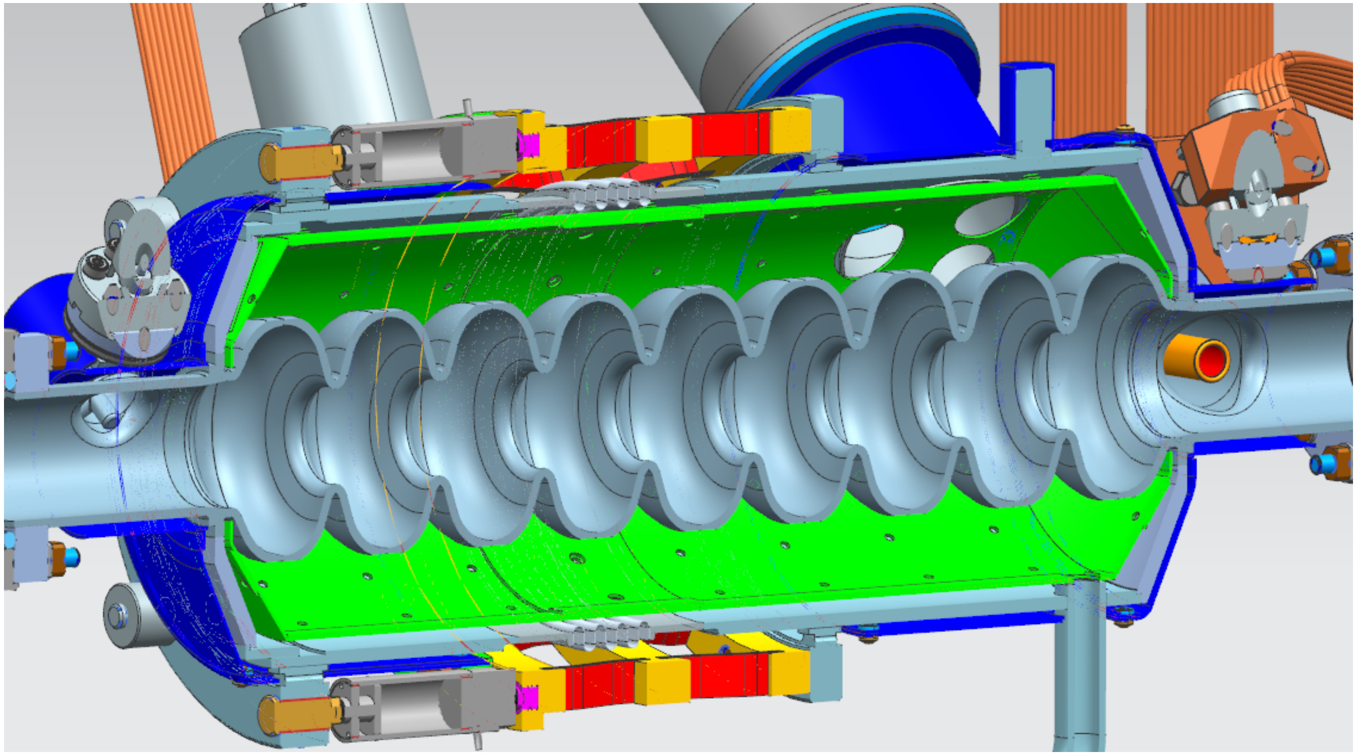
Magnetic shielding

- Hard/impossible to fully cover outside of helium vessel
  - Hybrid shield approach
- External magnetic shield – primarily “end caps” to shield beam tube and chimney openings

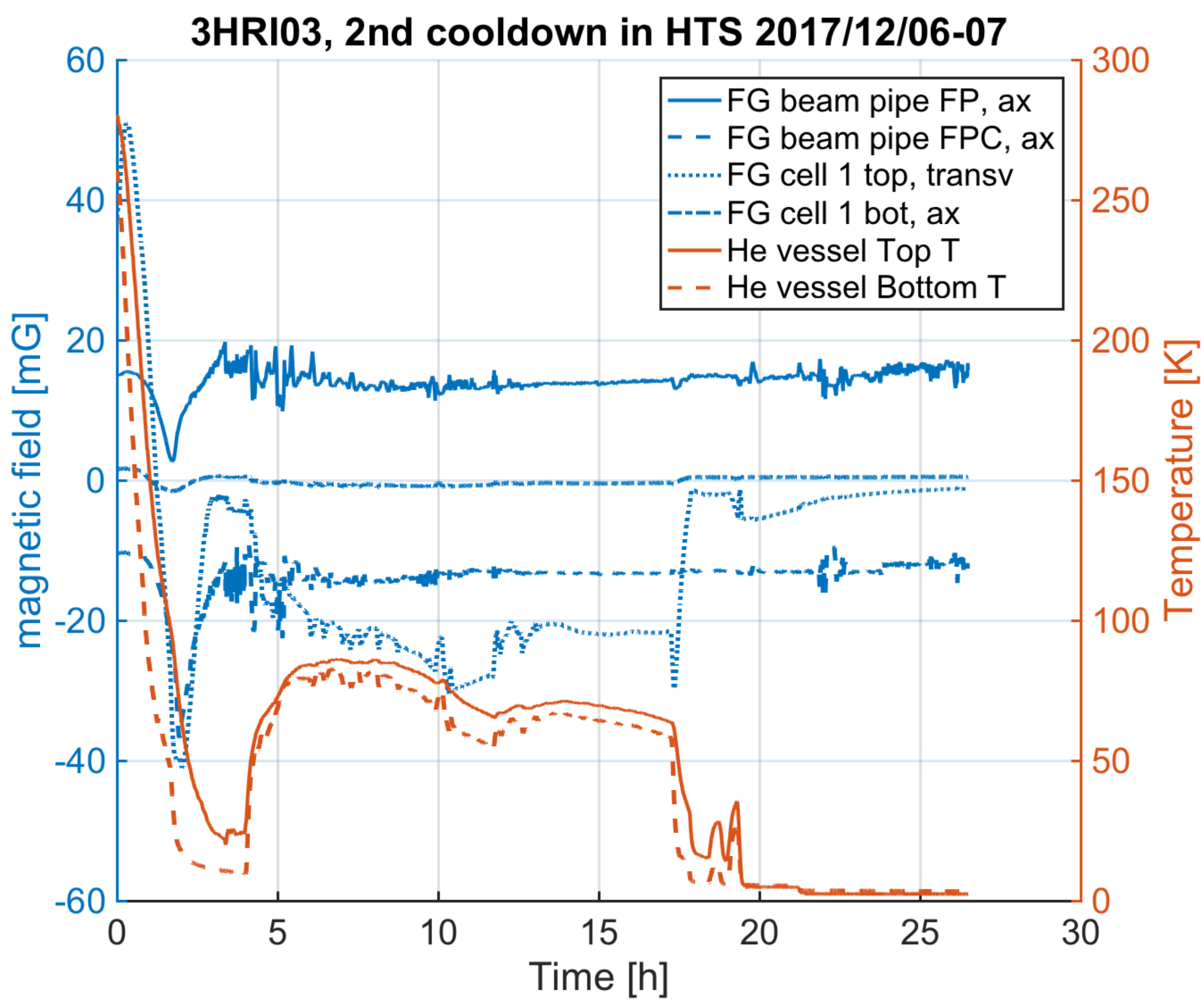


Magnetic shielding

- Internal magnetic shielding covering cavity
- small holes to allow liquid helium/heat transfer
- 3 big holes next to chimney



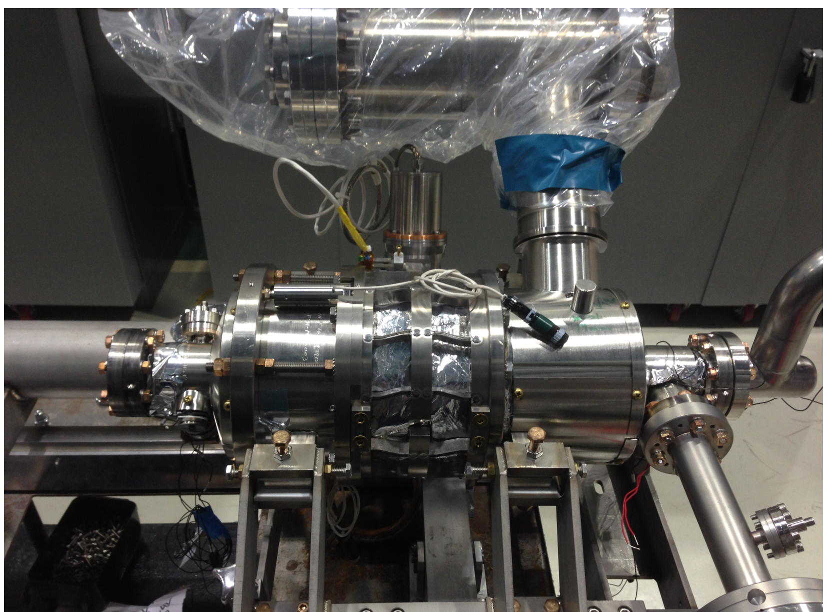
Magnetic shielding (cooldown data)

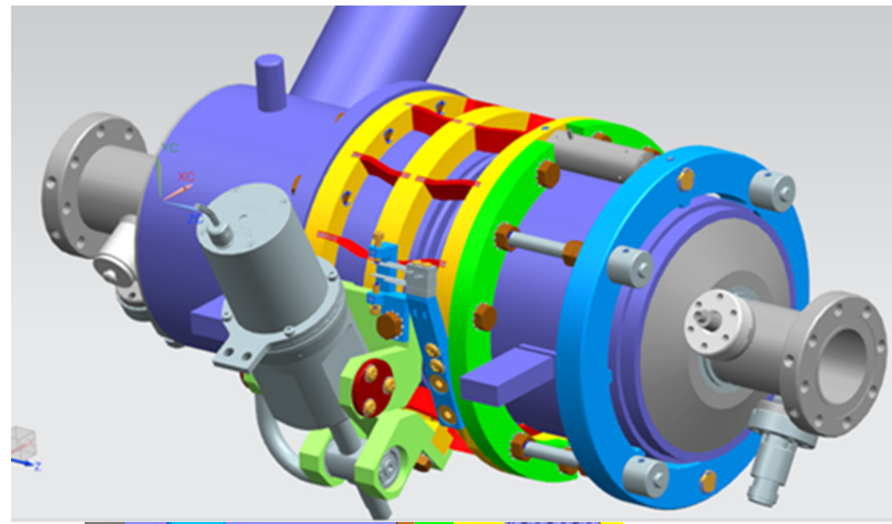


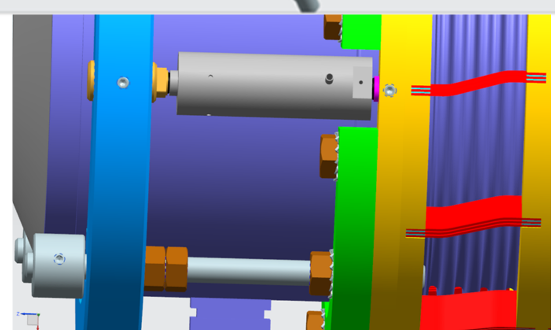
- 2 FGs on beam pipe
- 2 FGs inside He vessel on cell 1
  - Reading < 0.5 and < 1.5mG

Tuner

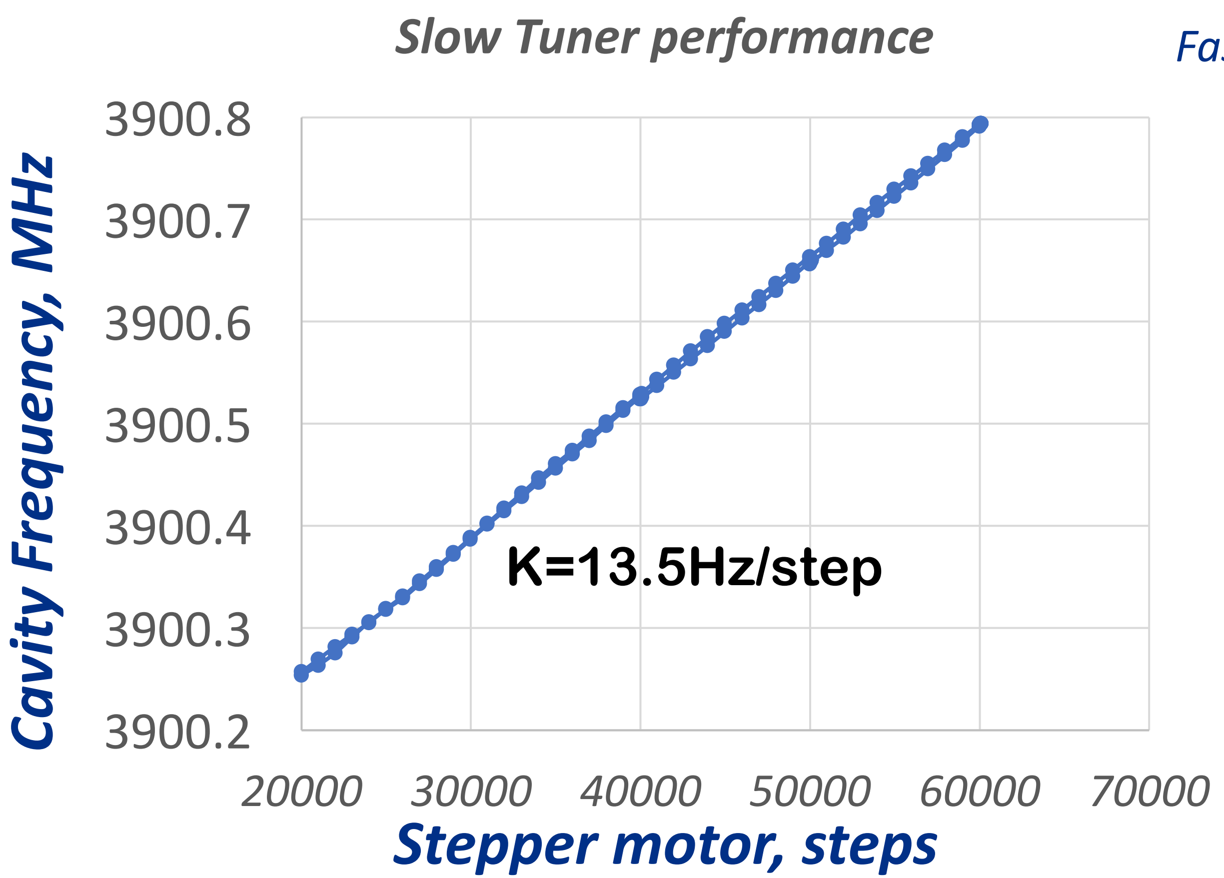
- LCLS-II adopted a modified INFN slim blade tuner design
- Added 2 piezo-capsules for fast tuning
- Active elements are the same as used for 1.3 GHz LCLS-II tuner:
  - Phytron electromechanical actuator (and limit switches)
  - Two PI piezo-capsules







Tuner performance at 2K



Fast/Piezo Tuner performance

Cavity Frequency change by fast tuner:
ΔF=45Hz/V
or
ΔF =5kHz for V_{max}=120V

Specification for fast tuner:
ΔF_{specs}=1kHz

More results in Y. Pischalnikov's talk (Thu, 14:15-14:45)

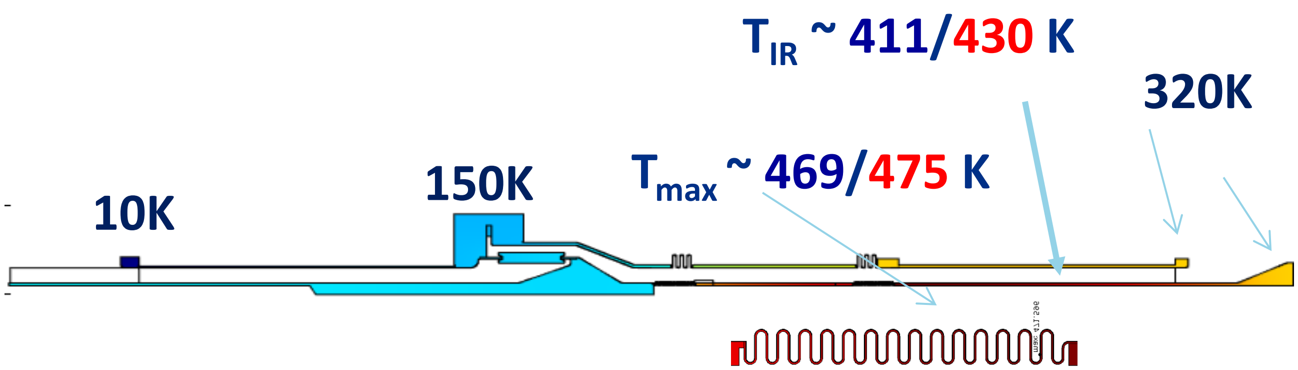
Power coupler

- LCLS-II 3.9GHz power coupler is modified from old FNAL/XFEL style coupler
  - Increased copper plating thickness on inner conductor in warm part (30um -> 120um)
  - Reduced number of convolutions for two bellows on inner conductor part of warm section (20 -> 15)
  - Antenna material is changed from copper plated stainless steel to pure copper
- Note: HTS testing was done with a partially modified coupler with un-modified antenna tip made of SS with 50um copper plating
- Observation in HTS:
  - Significant change in Q_{ext} with coupler heating (1.5E7 -> 1.05E7)

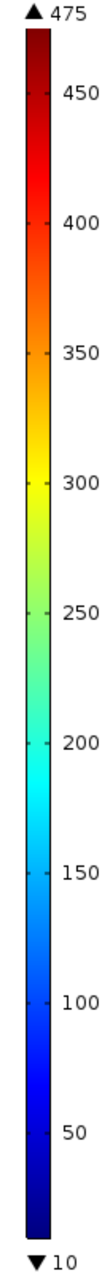
Power coupler (on resonance)

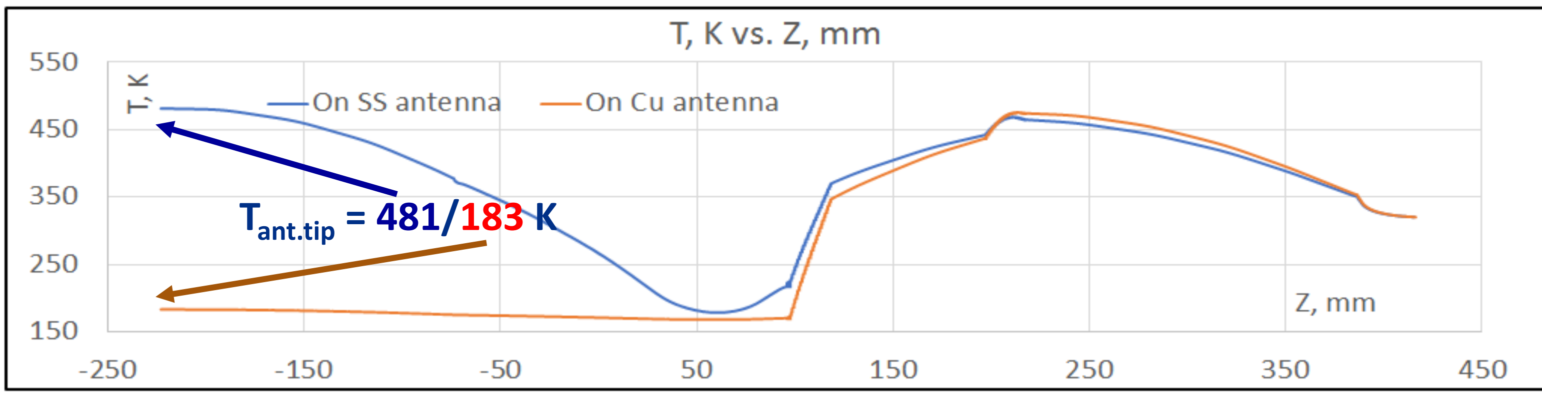
Parameters: P_{in}= **1 kW SW**, 10µm outer plating, ε=9.8, tan=3e-4, roughness 10%

Antenna: SS+50 µm Cu covered / solid copper



Port : 1kW



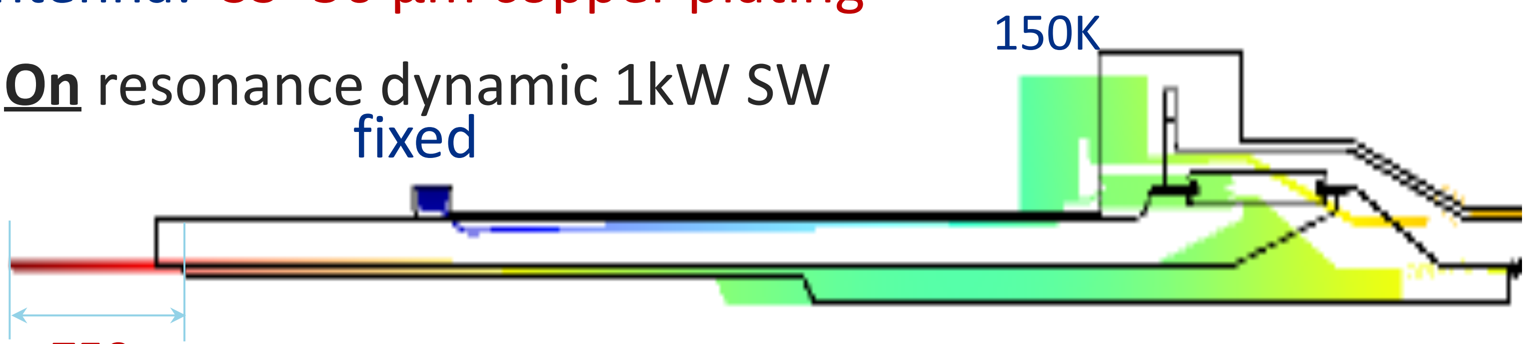


Temperature distribution vs. Z of inner conductor

Antenna deformation due to thermal stress (HTS)

Antenna: SS+50 µm copper plating

On resonance dynamic 1kW SW



ΔL1 = 750 µm

ΔL2 = - 456 µm

ΔL1 = - 28 / - 123 µm

ΔL2 = -508 / -608 µm

ΔL total (dynamic-static) = (750+123) um = 873 um

ΔL shift (warm-to-cold static) = -123 um

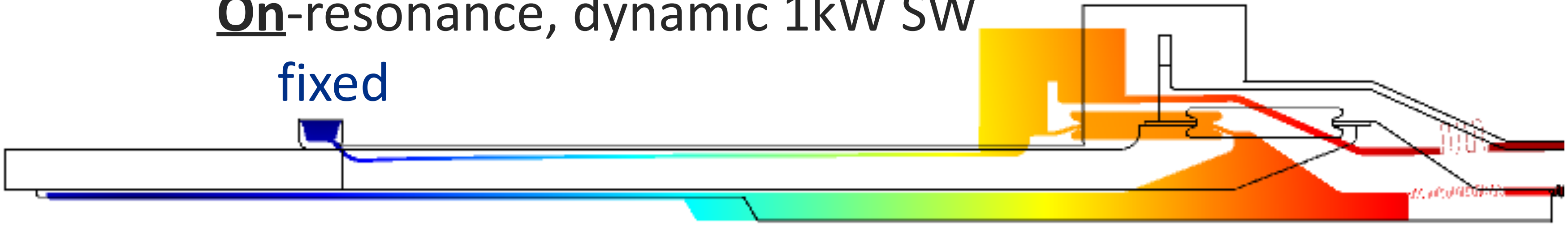
Antenna deformation due to thermal stress

Antenna: solid copper

On-resonance, dynamic 1kW SW

150 K

fixed



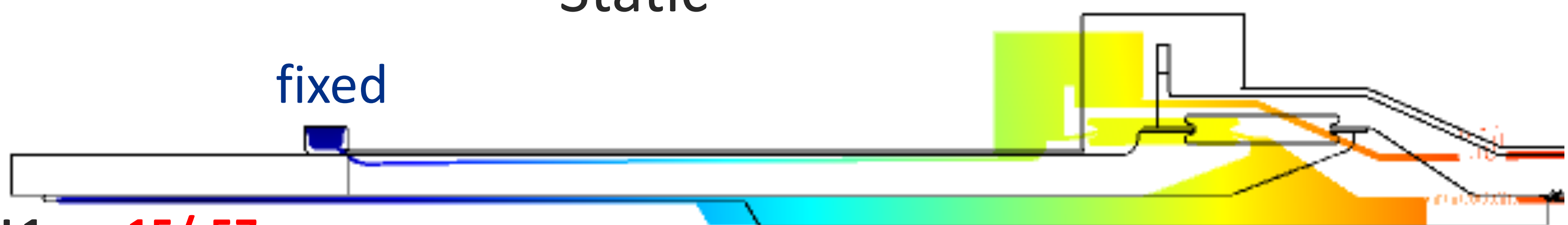
ΔL1 = - 35 µm

ΔL2 = - 486 µm

Static

150 K / 85 K

fixed



ΔL1 = - 15/-57 µm

ΔL2 = - 516 / -593 µm

ΔL total (dynamic-static) = (-35+57) um = 22 um

ΔL shift (warm-to-cold static) = - 57 um

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Influence of coupler heating on Qext

	Q_{nom}	Depth, mm
Modified coupler	**2.5E7**	**11**

Sensitivity of loaded Q_L to the antenna length:

$$(\Delta \boldsymbol{Q_L}/\boldsymbol{Q_L})/\Delta \boldsymbol{z} = \mathbf{0.275};$$

$$then: for\ Q_L = 2.5e7 \Rightarrow (\Delta Q_L/\Delta z) = 0.68e7/mm$$
$$for\ Q_L = 1.5e7 \Rightarrow (\Delta Q_L/\Delta z) = 0.41e7/mm$$

ON-resonance case:

$\Delta z_{dynamic}$ = 750 / -35 µm

Δz_{static} = - 123 / -57 µm

Antenna: SS / Cu

Δz_{total} = + 873 / 22 µm

Deviation	Δz, µm	CM: Q_L x10^7	HTS: Q_L x10^7
Warm	0	2.50 / 2.5*	1.50
Cold static	-123 / -57	2.58 / 2.54*	1.56 / 1.55**
Cold dynamic, 1kW	750 / -35	1.99 / 2.48*	1.12 / 1.05**

** Measurements

Power coupler heating summary

antenna		T max, K coupler	T probe K	T antenna K	ΔL (ant.), µm dynamic	ΔL (ant.), µm static (85K)	ΔL (ant.), µm total
Copper	ON-resonance	475	430	183	-35	-57	-92
	OFF-resonance	428	411	174	-42	-57	-97
SS+50µm Cu plating	ON-resonance	469	411	481	750	-123	-873
	OFF-resonance	447	422	386	468	-123	-591

- Simulations match T and Q_{ext} behavior of existing coupler
- Modified (full Cu) coupler will mitigate existing problems

Summary

- Integrated test in HTS reproduces cavity VTS performance with Q = 3.2E9 @13.7 MV/m, quench at 20.4 MV/m

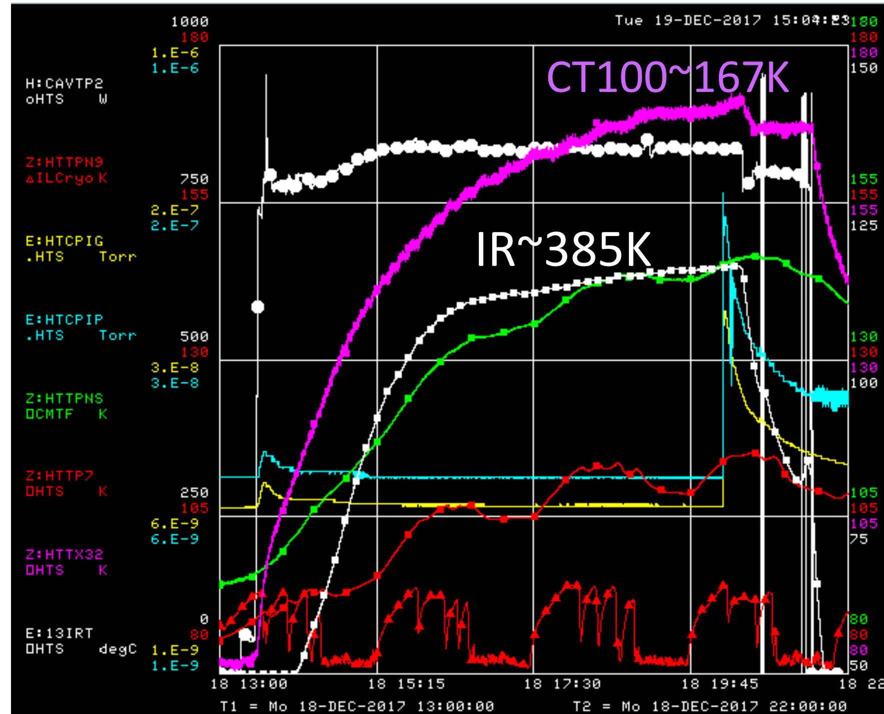
- Hybrid magnetic shield works
  – Average field <15mG achieved

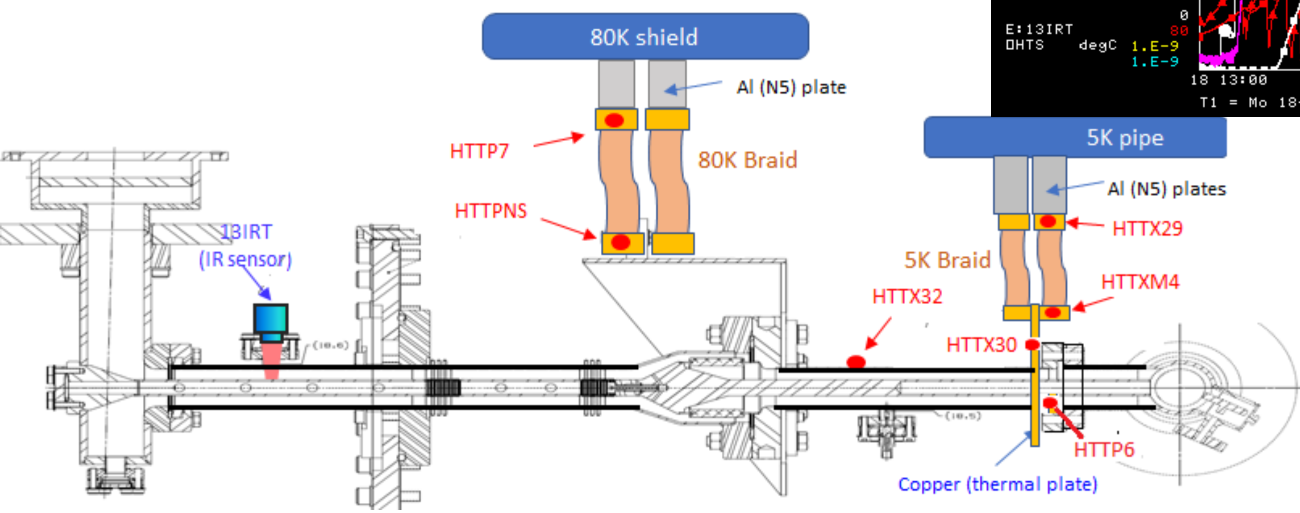
- Individual tuner components work, full integrated test and microphonics measurement to be done

- Simulation of heating and thermal expansion of power coupler matches behavior in HTS
  – Production power coupler with solid Cu antenna eliminates high temperatures on antenna tip and big change in Q_{ext}

Additional slides

Power coupler temperature measurement in HTS





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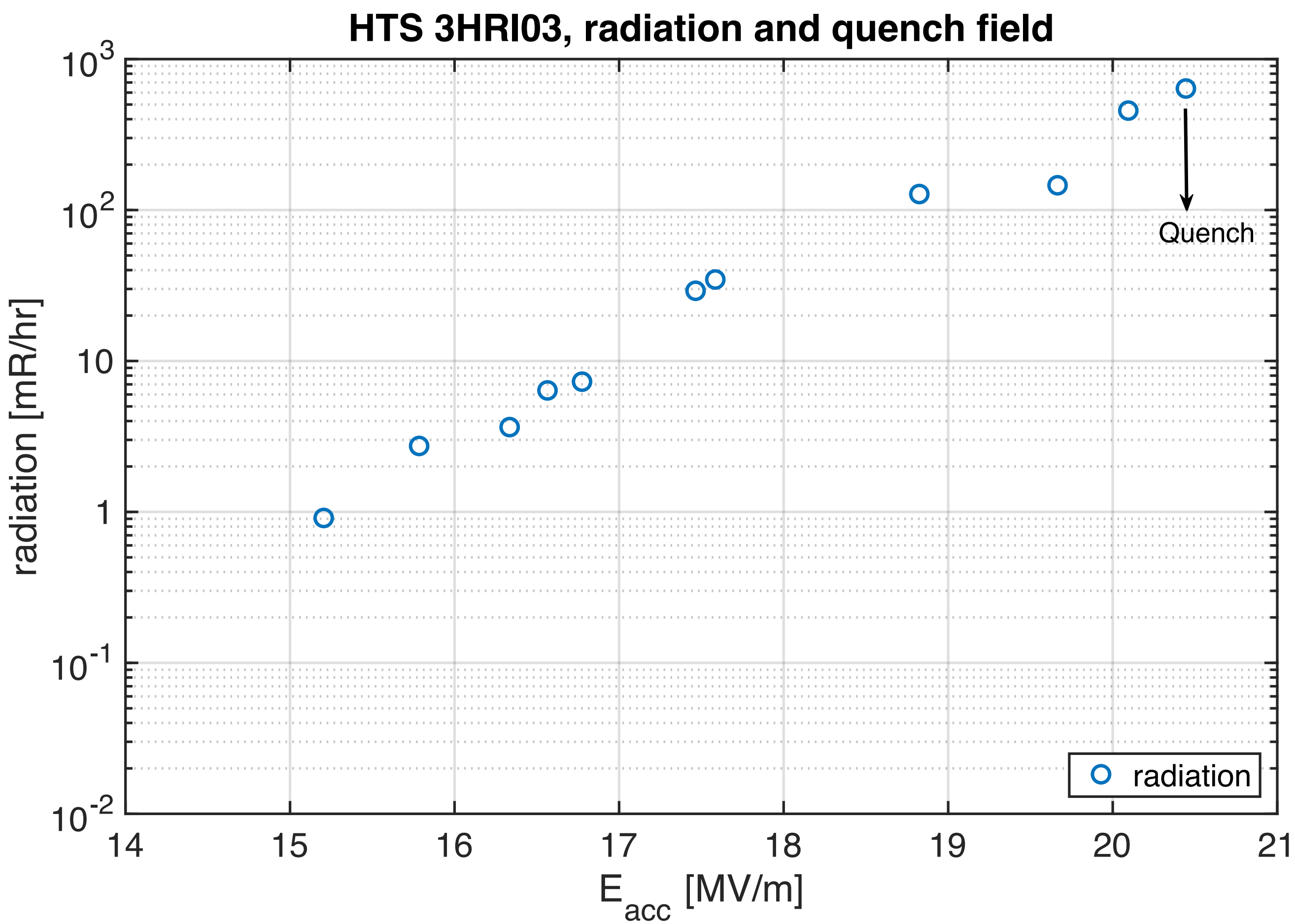
3HRI03 radiation



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3HRI03, with and without comp. field