Crab Cavity Cryomodules: Thermal Budget and Heat Loads

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with inputs from O. Capatina, K. Brodzinski, T. Jones, R. Leuxe, Z. Li, H. Park, N. Templeton, S. Verdú Andrés, C. Zanoni, and many others

Crab Cavities: SPS Cryomodule Engineering Review
CERN, Geneva, Switzerland – 10.11.2015

Engineering Department

Outline

- Thermal balance for DQW and RFD
- Highlights of thermal analyses
- Summary

Back to 2013 CC Workshop

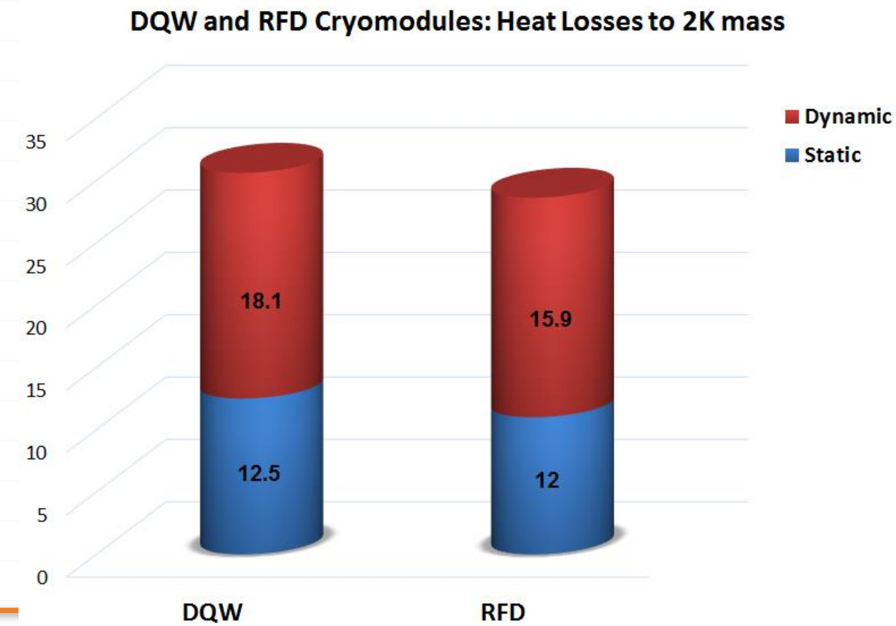
HL per cryomodule		HL @2K [W]	HL @80K [W]	Comments
Static	Radiation (Cavity + Phase Sep. Cold surface + Thermal shield)	**0.2**	**6.8**	Rescaling from LHC: $0.1W/m^2$@cold mass $1.7W/m^2$@thermal shield
	CWT	**3.0**	**12.6**	1 heat interceptor not optimized
	Supporting system	**0.2**	**3.3**	HL@2K estimated from SPL
	RF couplers	2 x 2 = **4.0**	2 x 50 = **100**	For a tube thickness t = 3mm
	Cables & Instrumentation	**1.0**	**0**	Tentative
	Tuner	**0.2**	**0**	Not thermalized
	Other order modes	4x0.2 + 2x2 ~ **5.0**	**100**	Max losses found in ODU cryostat: 4 small HOMs (4x0.2W @2K estimated from SPL) + 2 "chimneys" HOM (2x2W @2K for a thickness of 3 mm and a length outside He bath of 340 mm); @80K: 4x? + 2x45W
Total Static		**13.6**	**222.7**	
Dynamic	Deflecting mode	**6.0**	**0**	Tentative
	Beam current	**0.5**	**0**	Tentative
	RF couplers	2 x 2 = **4.0**	2 x 5 = **10**	For a tube thickness t = 3mm ; P_{avg} = 100 kW
	Other order modes	**0.6**	**10**	for a P_{avg} = 100 kW; f = 1000 MHz; @2K chimneys: 2x0.1 + small HOM (estimated from SPL): 4x0.1@2K; @80K: 4x?+2x4
Total Dynamic		**11.1**	**20**	
Total losses		**24.7**	**242.7**	

Thermal Budget: November 2015

	DQW		RFD	
	2K	80K	2K	80K
Static				
Radiation	2	40	2	40
CWT	0.2	2	0.2	2
Supports	2	50	2	50
FPC	4	100	4	100
Instrumentation	1	0	1	0
HOM/Pickup	3	50	2.5	35
Tuner	0.3	10	0.3	10
Total static	**12.5**	**252**	**12**	**232**
Dynamic				
Cavity	6	0	6	0
FPC	5.6	10	5.4	10
HOM/Pickup	6	20	4	20
Beam	0.5	0	0.5	0
Total Dynamic	**18.1**	**130**	**15.9**	**100**
TOTAL	30.6	282	27.9	262

Some considerations and changes wrt 2013:

- From active to **passive cooling**. He gas temperature >50K, 80K considered in the analyses.
- Heat interceptions via **Cu bands**, design under completion.
- Larger contribution by **radiation losses**: holes in the thermal screen to allow online instrumentation alignment
- **Coaxial lines** necessary for the HOM (standard cables too resistive for the RF @1kW, 1GHz)
- **Margin considered with respect to the ideal calculations**, to keep into account uncertainties (position and temperature of interceptors, machining tolerances, etc.)



Thermal Analyses

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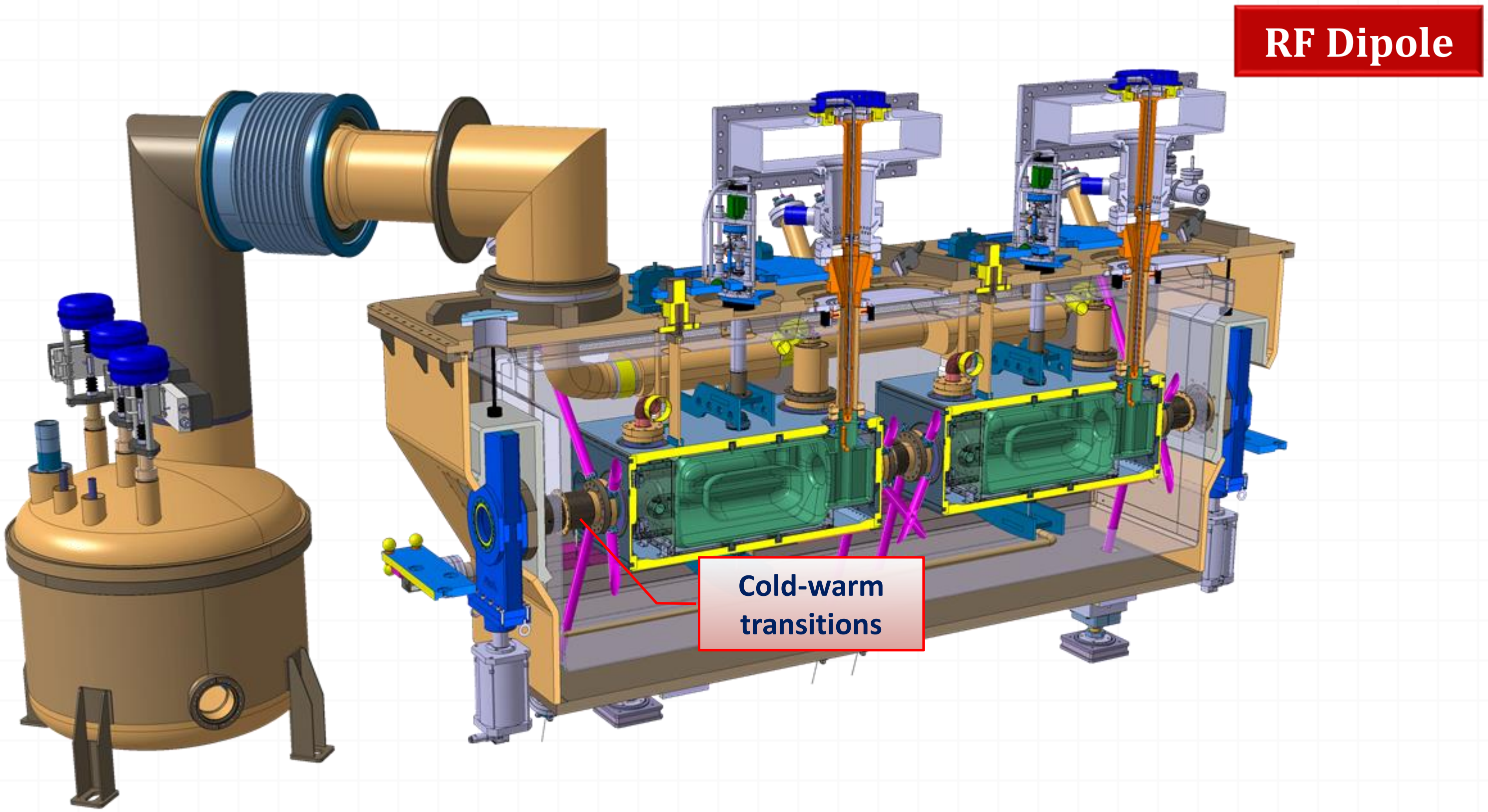
Highlights of calculations performed:

- Cold-warm transitions
- Supporting system → see T. Jones' presentation
- Fundamental power coupler
- High-order modes couplers
- He tank cool-down
- Radiation losses

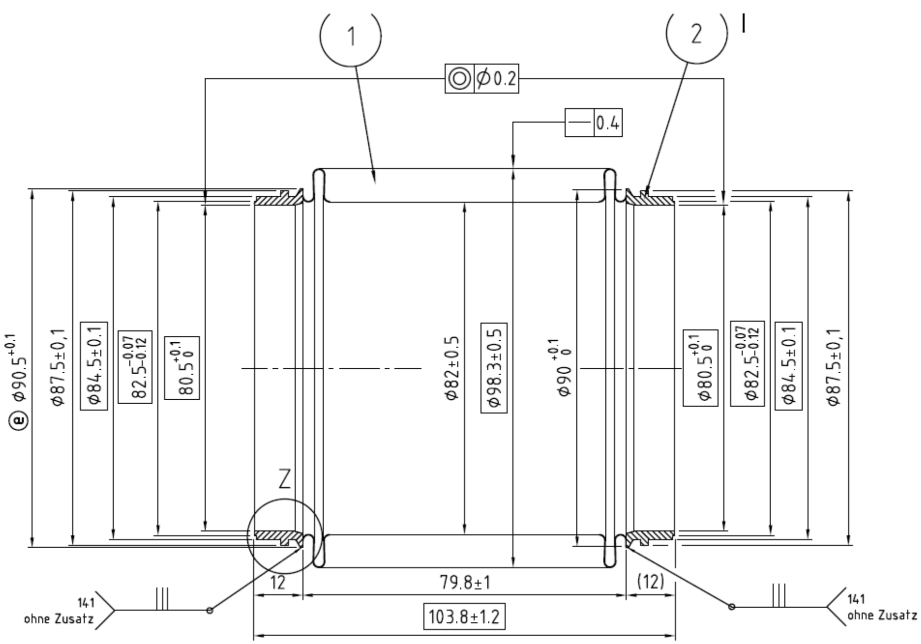
Cold-Warm Transitions

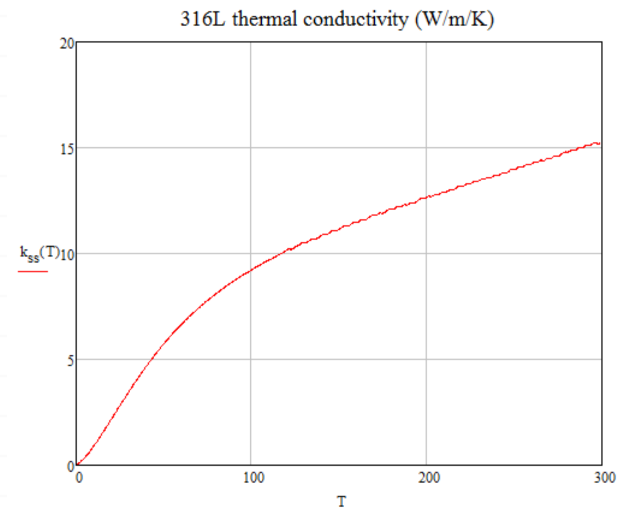
- Cold-Warm transitions (CWT) connect the cold mass to the warm beam pipe
- Losses are exchanged by **conduction** and by **radiation**



Cold-Warm Transitions

- Losses on the CWT are minimized by the presence of the stainless steel **bellows**
- Very **high thermal resistance** introduced



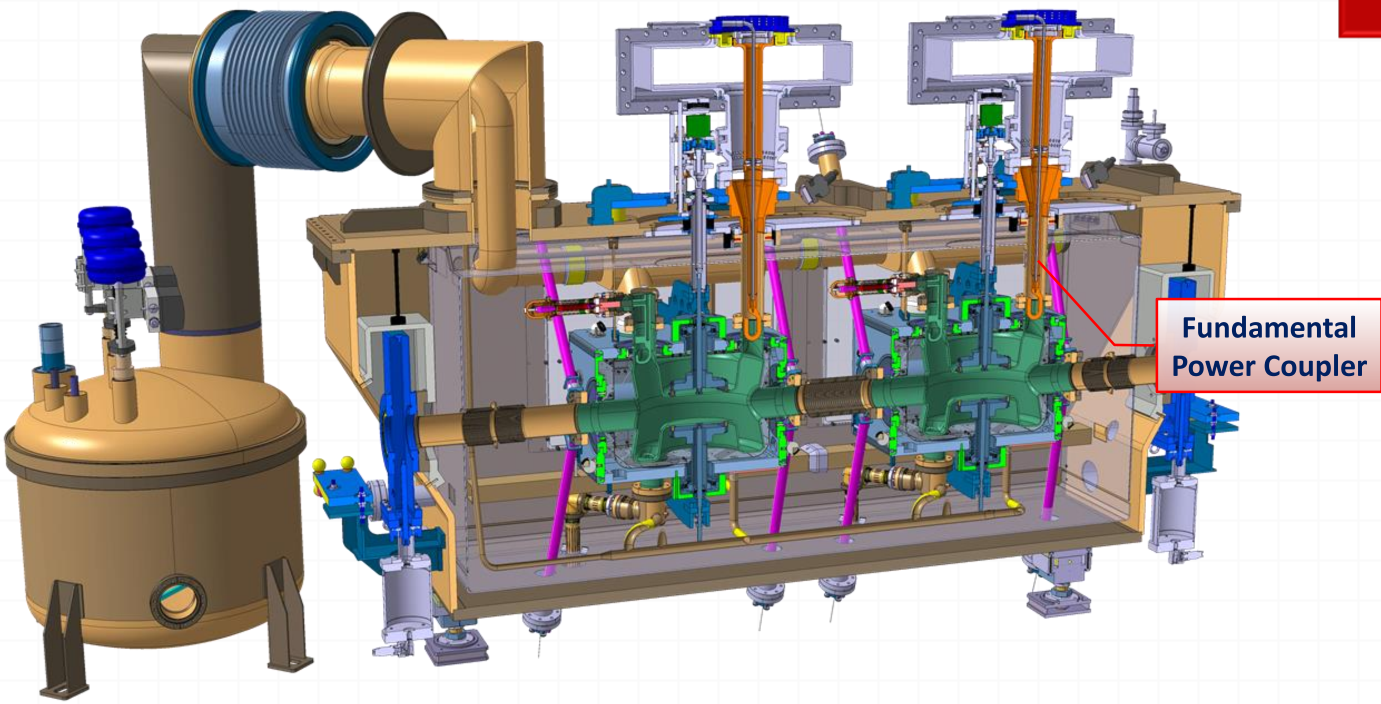


- No resistance of all the other components considered – bellows only
- Thickness: **0.15 mm**, length: 360 mm (15 convolutions)
- Simple analytical calculation: **0.35W/CWT** to 2K **without heat interceptors**, **0.05W/CWT intercepting**

Fundamental Power Coupler

- It brings the RF power to the cavity
- Exchanges heat with the cold mass by **radiation** (antenna) and by **conduction** (can)
- More details on FPC and RF lines in E. Montesinos' presentation

Double Quarter Wave



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Fundamental Power Coupler

FPC can – 316LN, copper coated

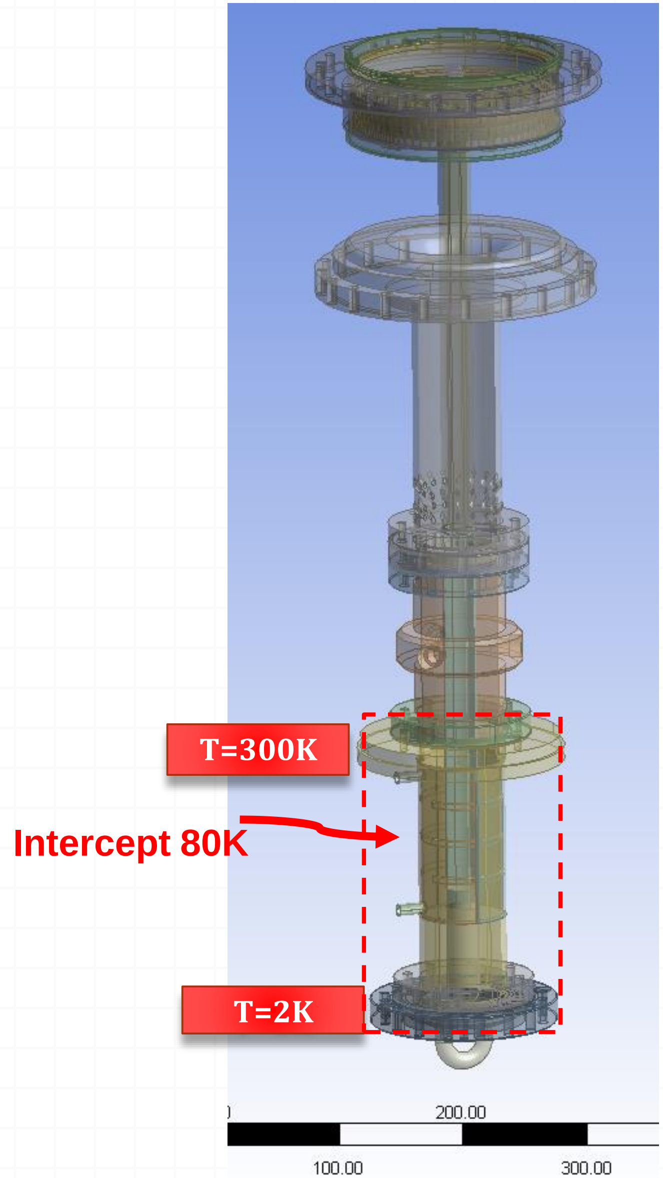
- Wall thickness: 3 mm – single wall
- Flange to flange length: 230 mm
- Optimized heat intercept @80K
- f = 400 MHz, P = 40 kW, 100% duty cycle
- Semi-analytical calculation
- Radiation from antenna kept into account

$$\mathrm{QcondI}(Ta,Tb) := -\int_{Ta}^{Tb} \frac{k(T)\cdot A}{dx}\, dT$$

$$\mathrm{Prf}(\mathrm{TwallI},i) := \frac{1}{2}\cdot\int_{x_i-\frac{dx}{2}}^{x_i+\frac{dx}{2}} \mathrm{I\_eq}(X)^2\cdot \mathrm{R\_wall}(\mathrm{TwallI})\, dX$$

$$I(x) := \mathrm{I\_0}\cdot 2\cdot \sin\left(\frac{omega}{c}\cdot x\right)$$

- x_i = coordinate of i-node
- dx = element length; A = conducting section
- k = equivalent thermal conductivity of the section
- R_wall = electrical resistivity of the inner face (copper)



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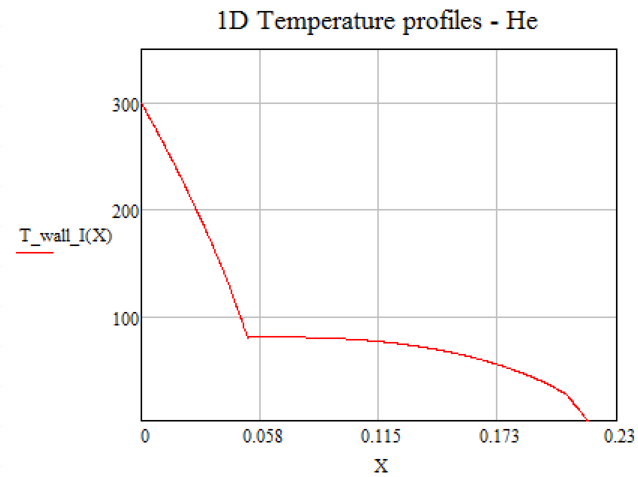
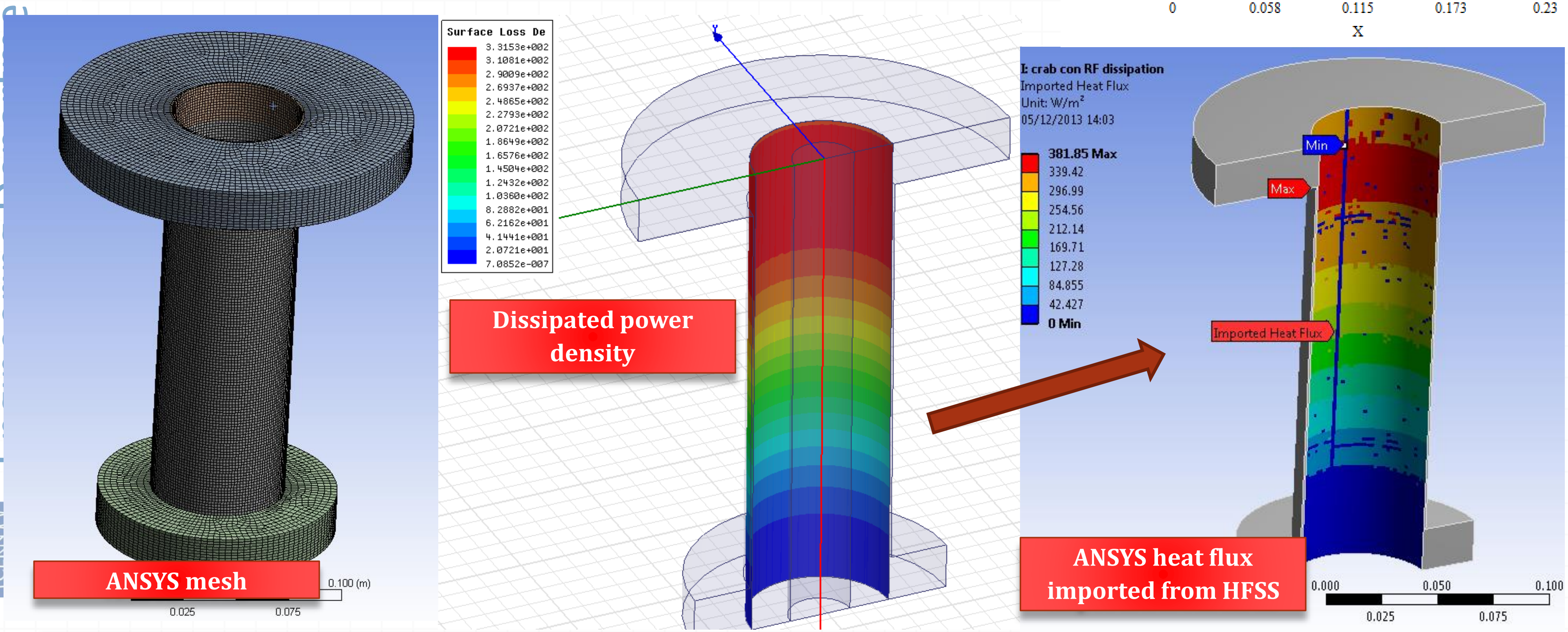
Fundamental Power Coupler



FPC can – 316LN, copper coated

- In the past, the analysis was performed with ANSYS/HFSS
- Further iterations were done with the semi-analytical method, which provided very similar results → much faster!



Fundamental Power Coupler

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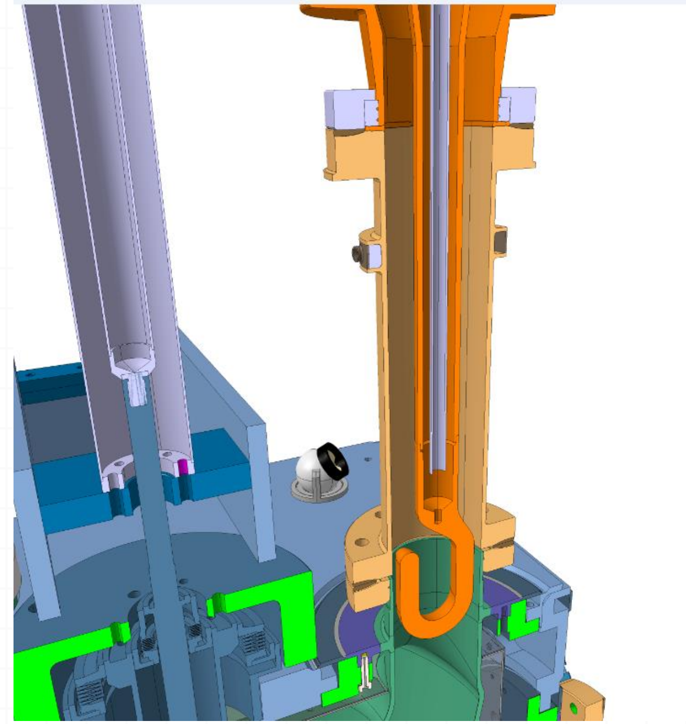
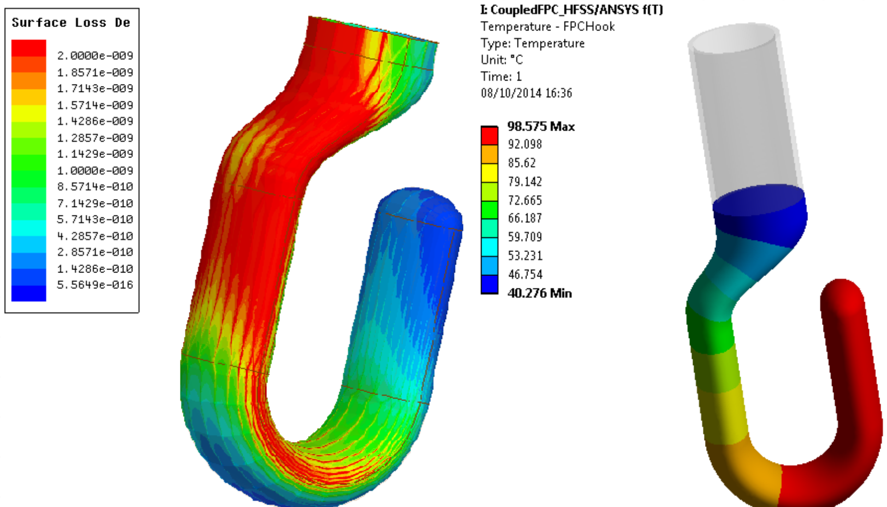
FPC antenna – Copper OFE

- Heating on the antenna generated when RF on
- Can lead to **high temperatures** of Cu (creep, outgassing, high radiation to cold mass)
- Water cooling necessary, water speed: **1.5 m/s**
- Thermal loss on the antenna:
  - DQW ~ 100 W
  - RF ~ 60 W



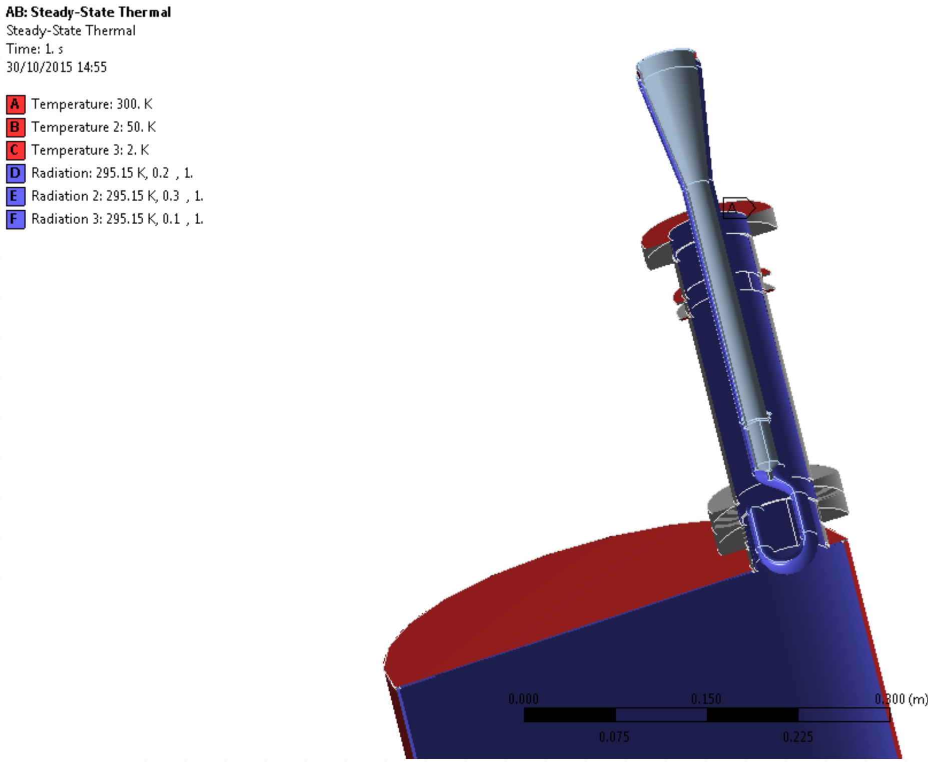


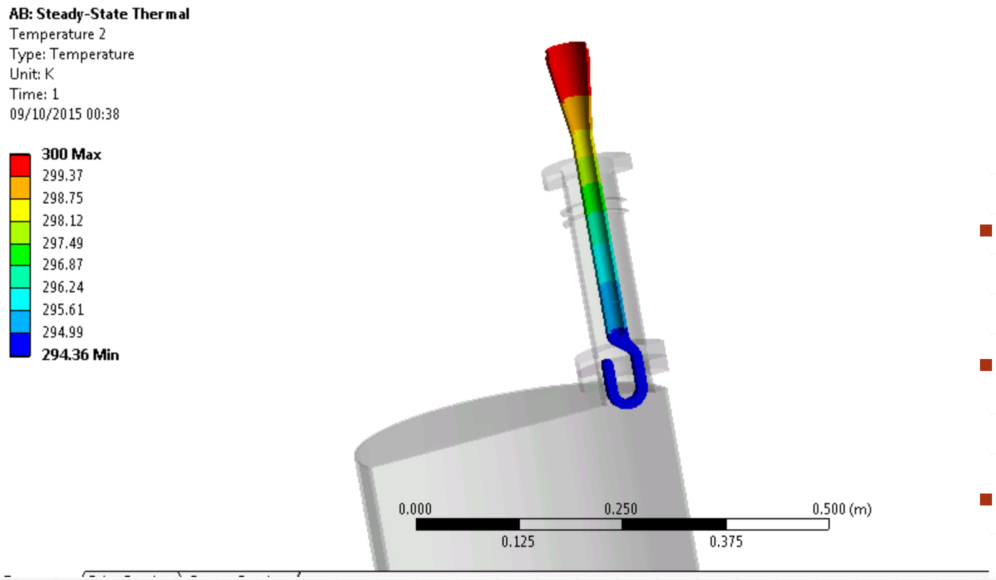
FPC surface loss density distribution & temperature increase

- **Iterative HFSS/ANSYS analysis** to evaluate T field on hook and radiation to cold mass
- With the final solution: **0.7 (RFD)-0.9 (DQW) W/FPC to 2K by radiation**
- **T_{max} hook < 100 ºC**

Fundamental Power Coupler

- If RF is off and water is not circulating, the antenna **could freeze** at the upper extremity
- Calculations show that **this is not the case**, given the low power exchanged by radiation with the cold mass



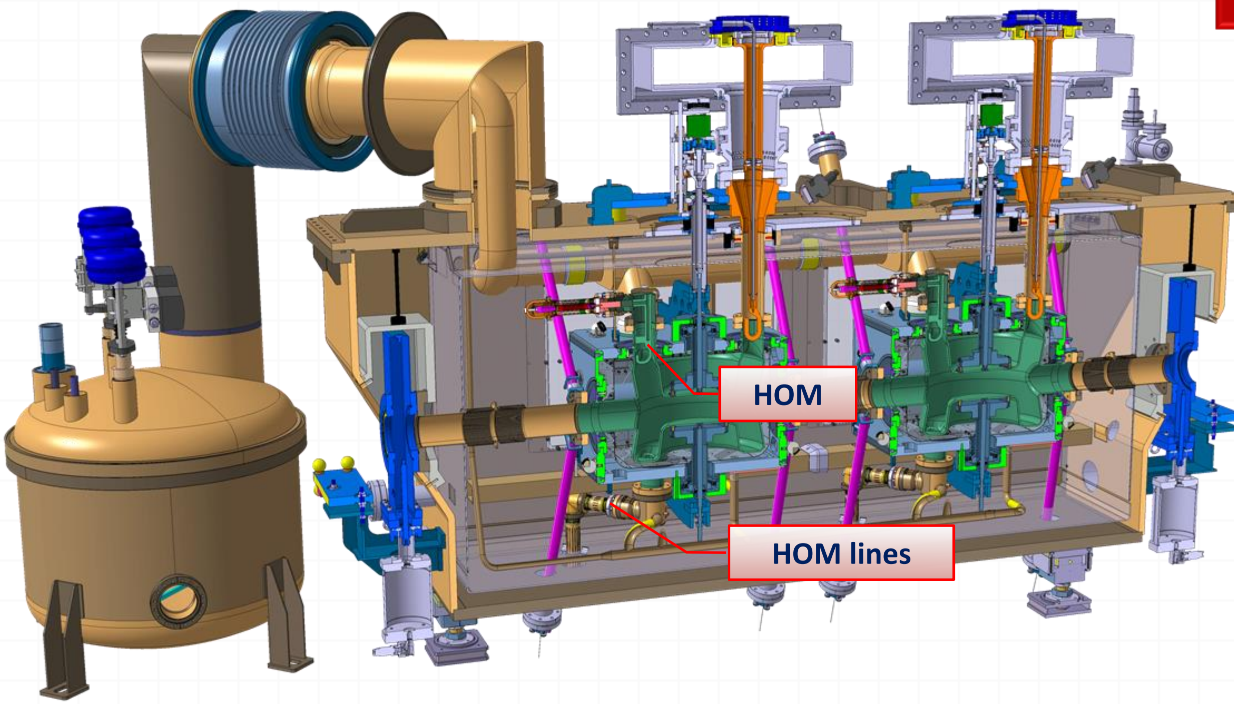


- The risk is higher on the can: flux to the 80K circuit is **40 W**
- Natural convection from air on tank plates: 4 $W/(m^2K)$
- **Heater will be installed to avoid freezing of the warm extremity of the can**

High-Order Modes

- Coaxial lines instead of commercial cables (high heat losses, high T otherwise)
- Nb antenna, LHe-cooled. Iterative ANSYS/HFSS calculations, similarly to FPC. See M. Garlasche's talk

Double Quarter Wave



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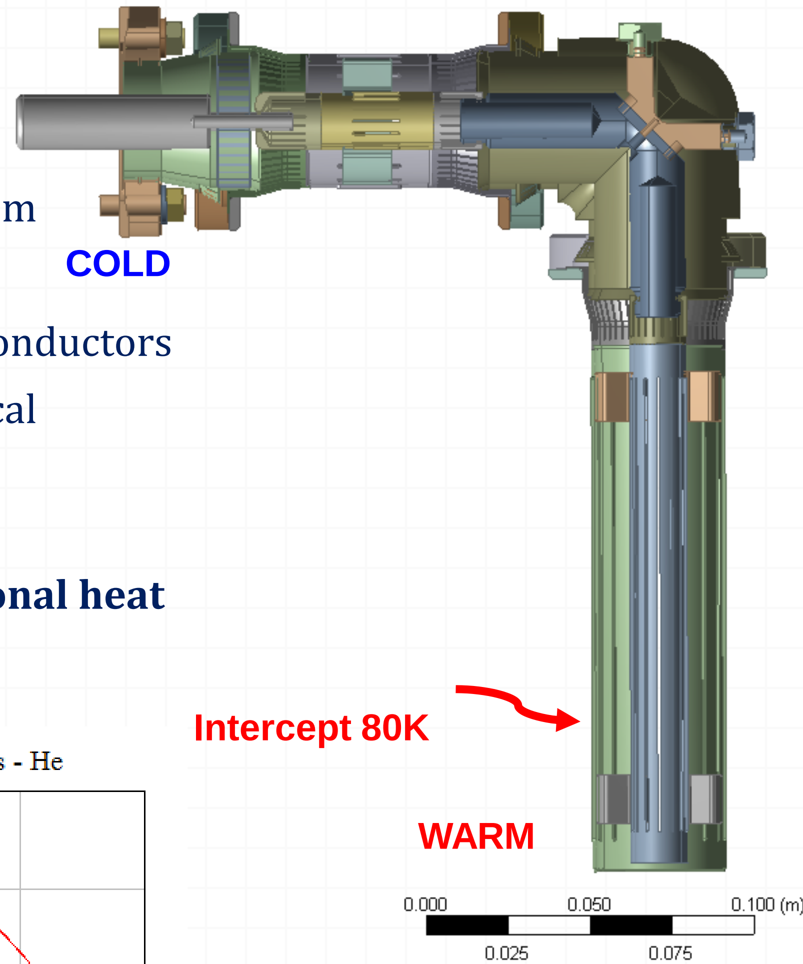
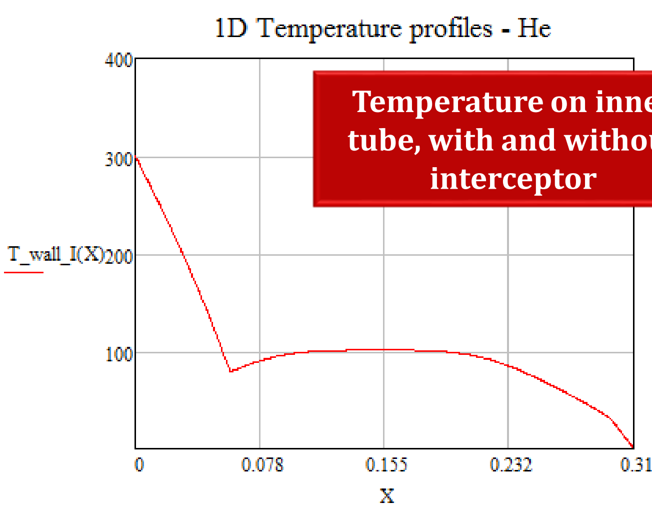
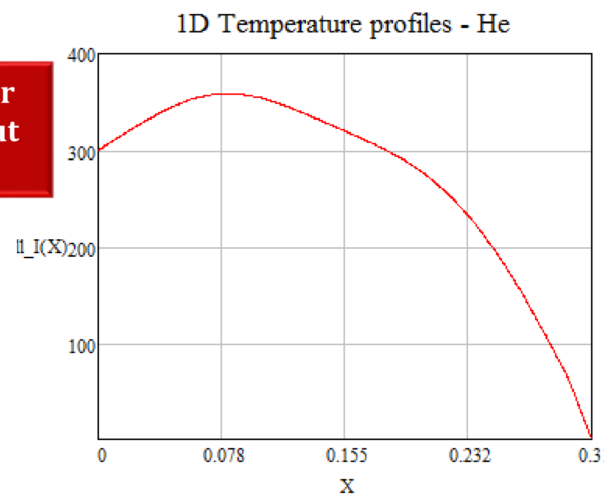
High-Order Modes

- **Coaxial lines**
  - 1 kW, 1 GHz
  - Stainless steel tubes, Cu coating: 5 microns
  - D_{ext} = 40.8 mm, D_{int} = 17.4 mm, thickness 0.5 mm
  - Length: 4x350 mm, 2x550 mm
  - Interception needed both on inner and outer conductors
  - Inner tube: interception with a ceramic electrical insulator, thermal conductor
  - Calculation performed semi-analytically
  - Thermal balance keeps into account an **additional heat loss of 0.4W/HOM** because of a 50 micron manufacturing error





Temperature on inner tube, with and without interceptor



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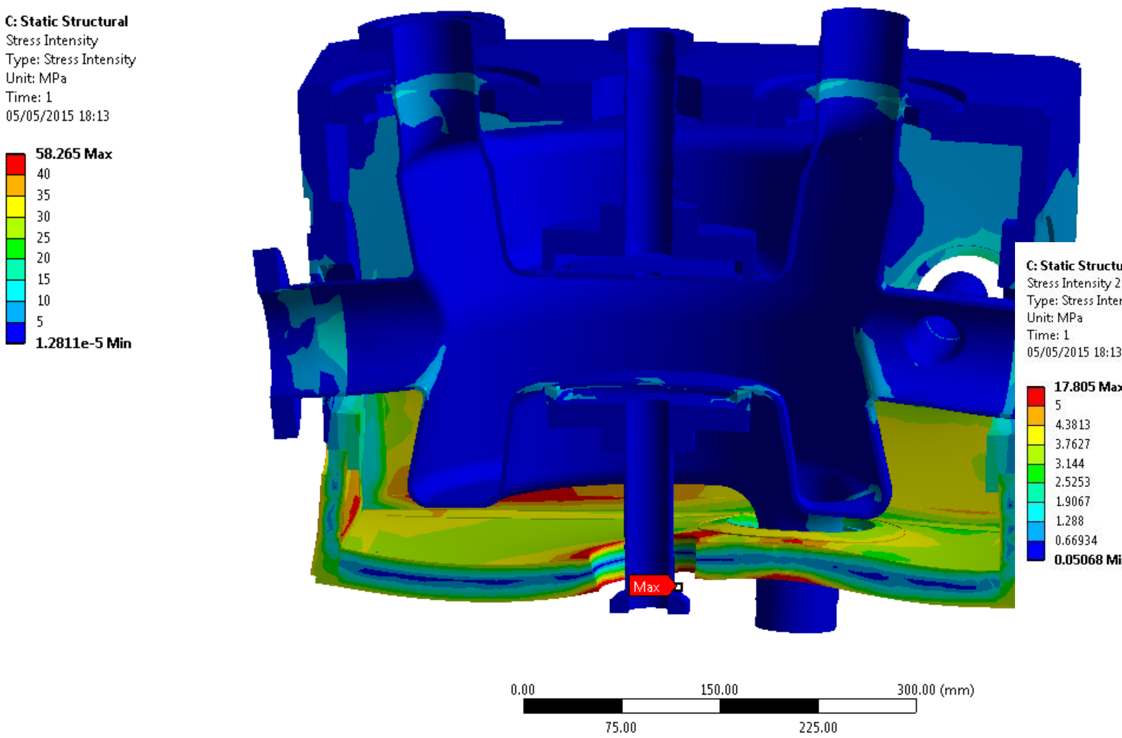
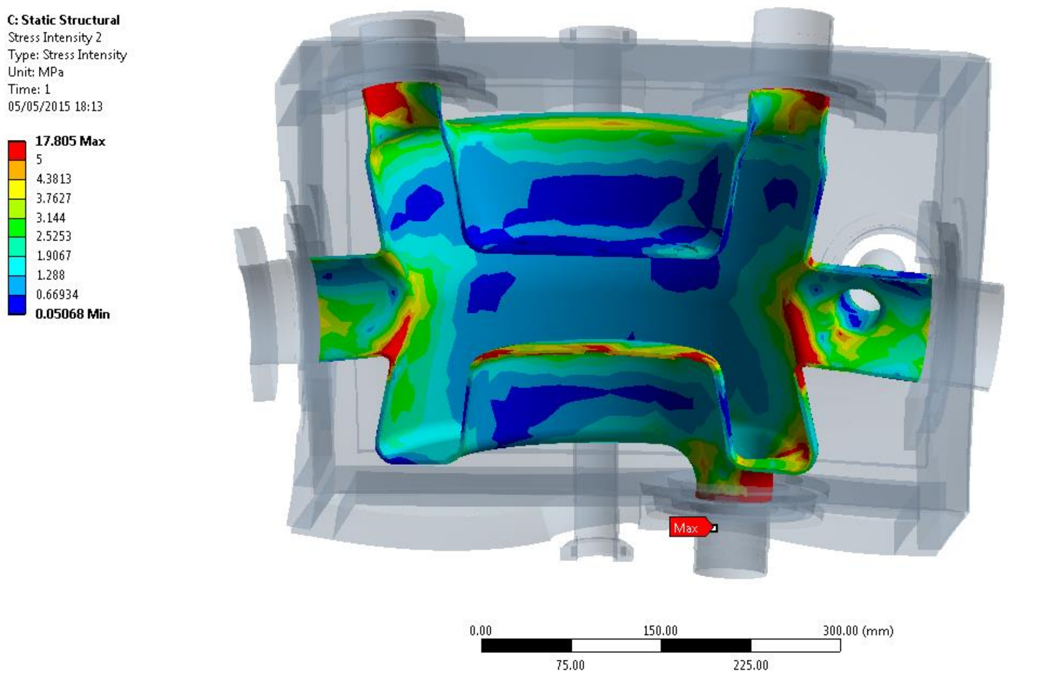
Tank and Cavity cool-down: FEA

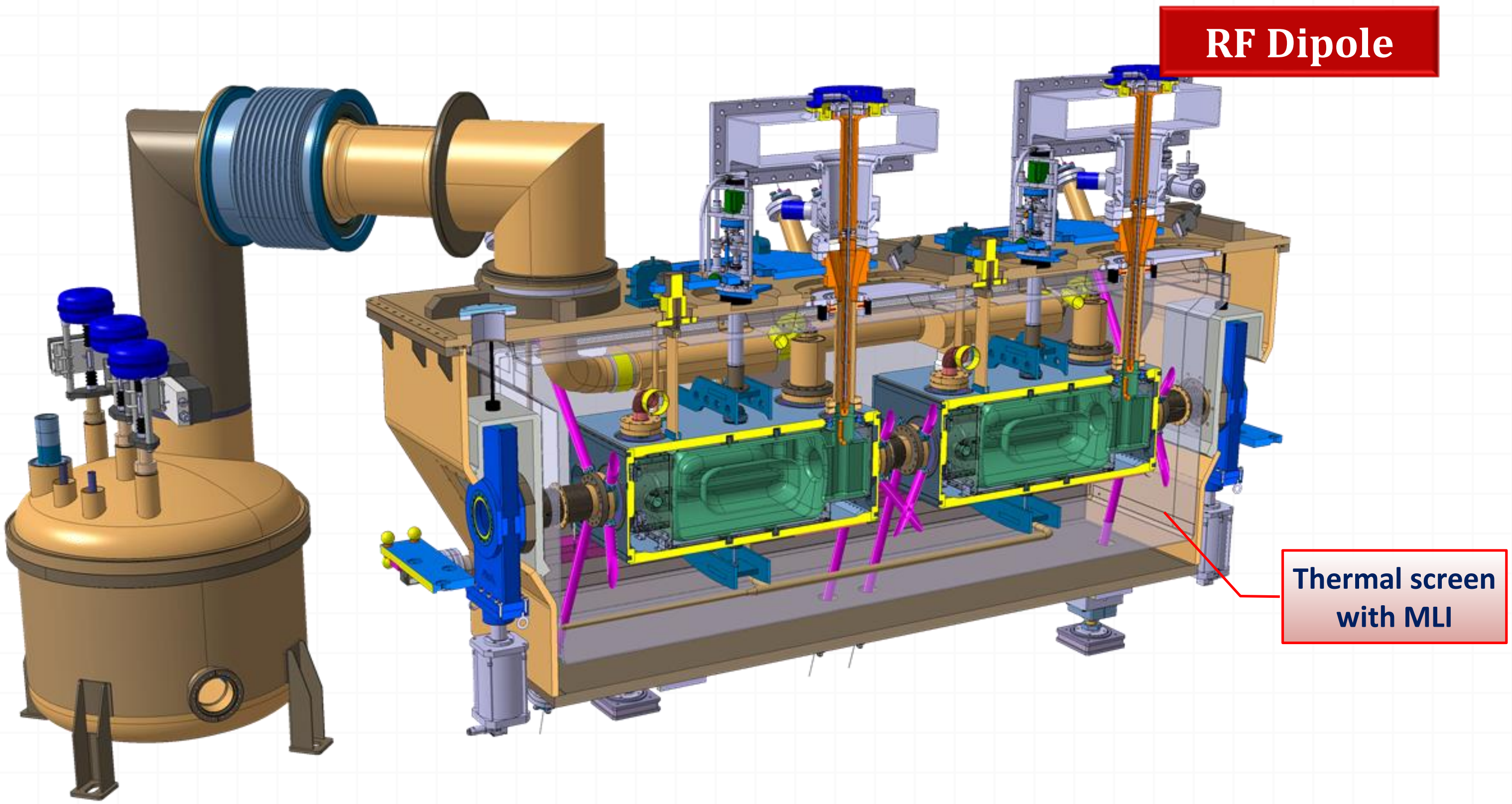
- We checked what happens in terms of stresses when a maximum gradient of 50K is generated during cool-down on cavity and He tank → **everything ok**





Radiation Losses

- Radiation losses: minimized by the introduction of a **thermal screen**, with **MLI** on the inner and outer surfaces of the screen and the cold mass



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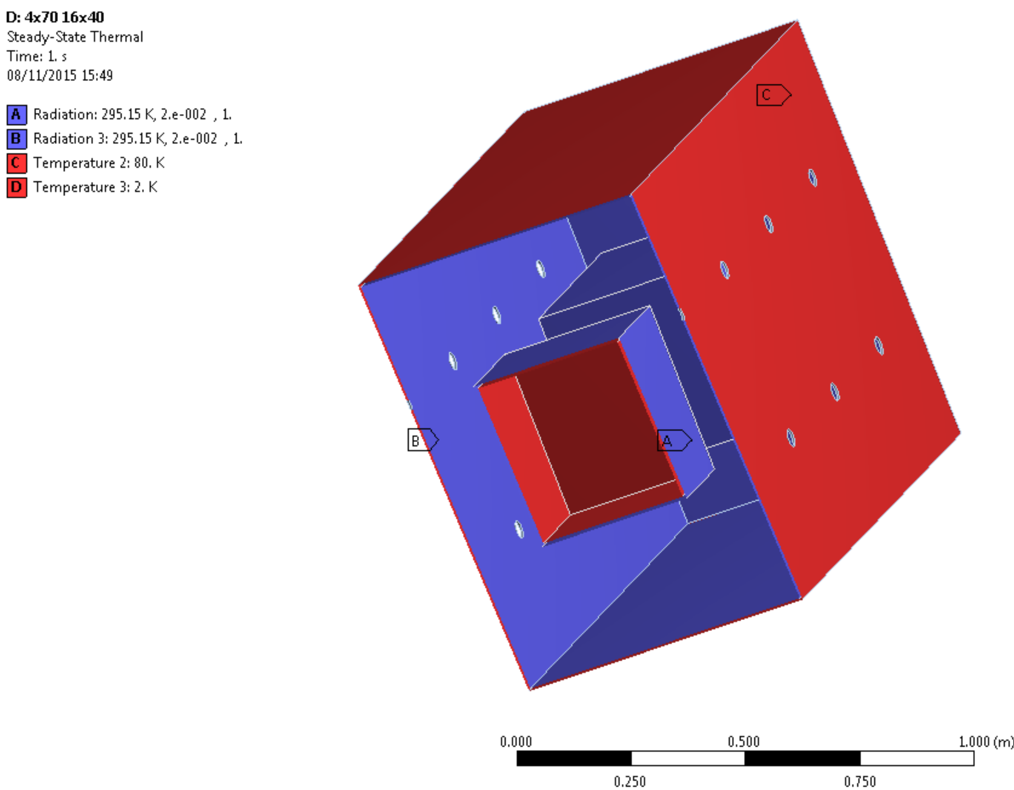
Radiation Losses

- Holes are present in the thermal screen, to allow measurements for the aligning system → see M. Sosin's presentation
- Holes act almost as black bodies in the exchange by radiation. Calculation with ANSYS of the additional losses with holes



$$q_1 = -q_2 = q_{12} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}}$$

- Thermal load (LHC measurements, V. Parma and R. Bonomi) ~ $0.1 W/m^2$
- Additional heat losses because of holes ~2W

Summary

- The thermal balance of the cryomodule, estimated at first in 2013, has been continuously updated and reviewed with the design advancement
- One of the main differences is the change from **liquid N** to **gas He cooling** for the heat interceptors
- The calculations done for evaluating the total heat losses encompass **analytical**, **semi-analytical** and **numerical methods**
- Advanced iterative simulations where performed with HFSS and ANSYS to take into account the **intrinsic coupling between thermal and electrical resistance of components of complex shape**
- **Additional safety margins** (~10%) on the heat losses are contained in the table, to consider tolerances in the machining, temperature and position of the interceptors and other minor uncertainties
- **No showstoppers highlighted during all this exercise!**

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Thank you for your attention!

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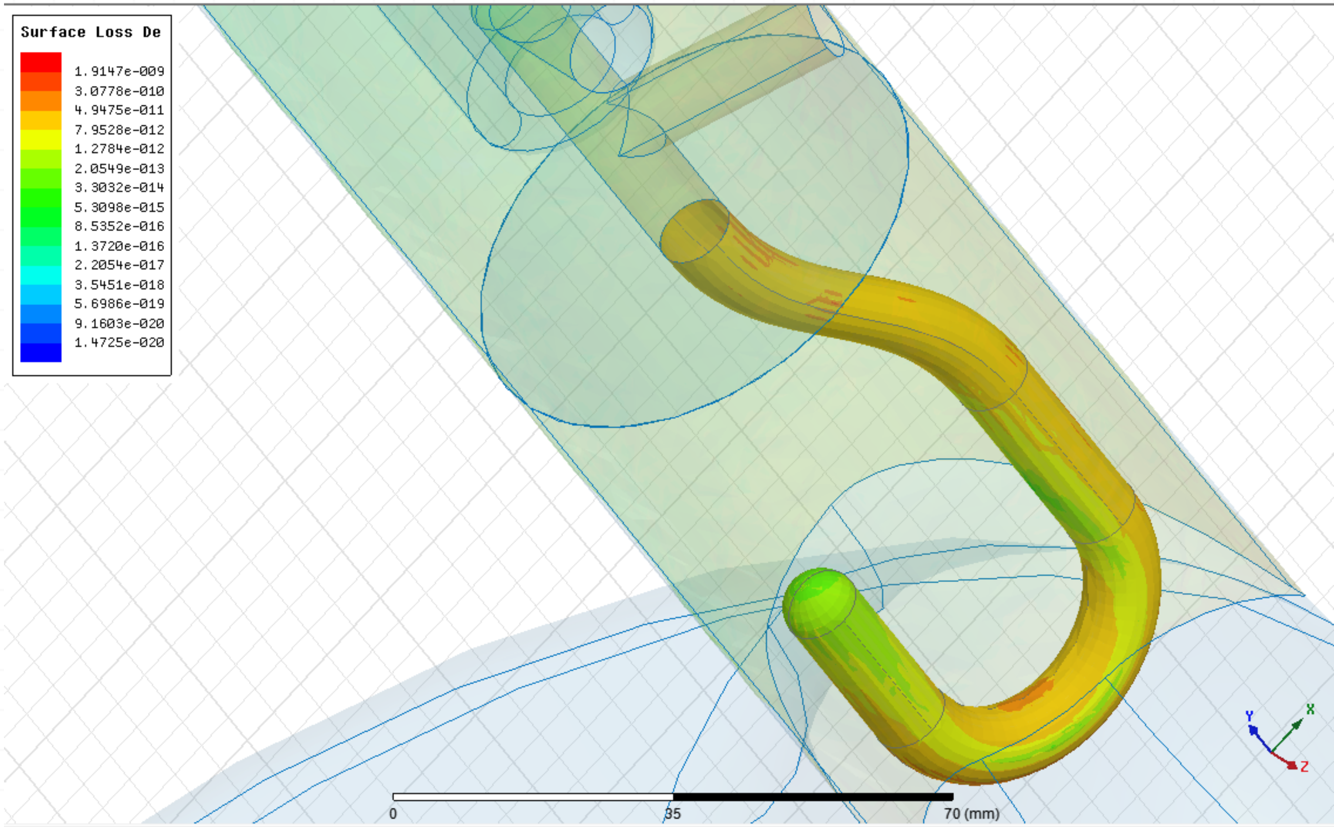
Backup slides

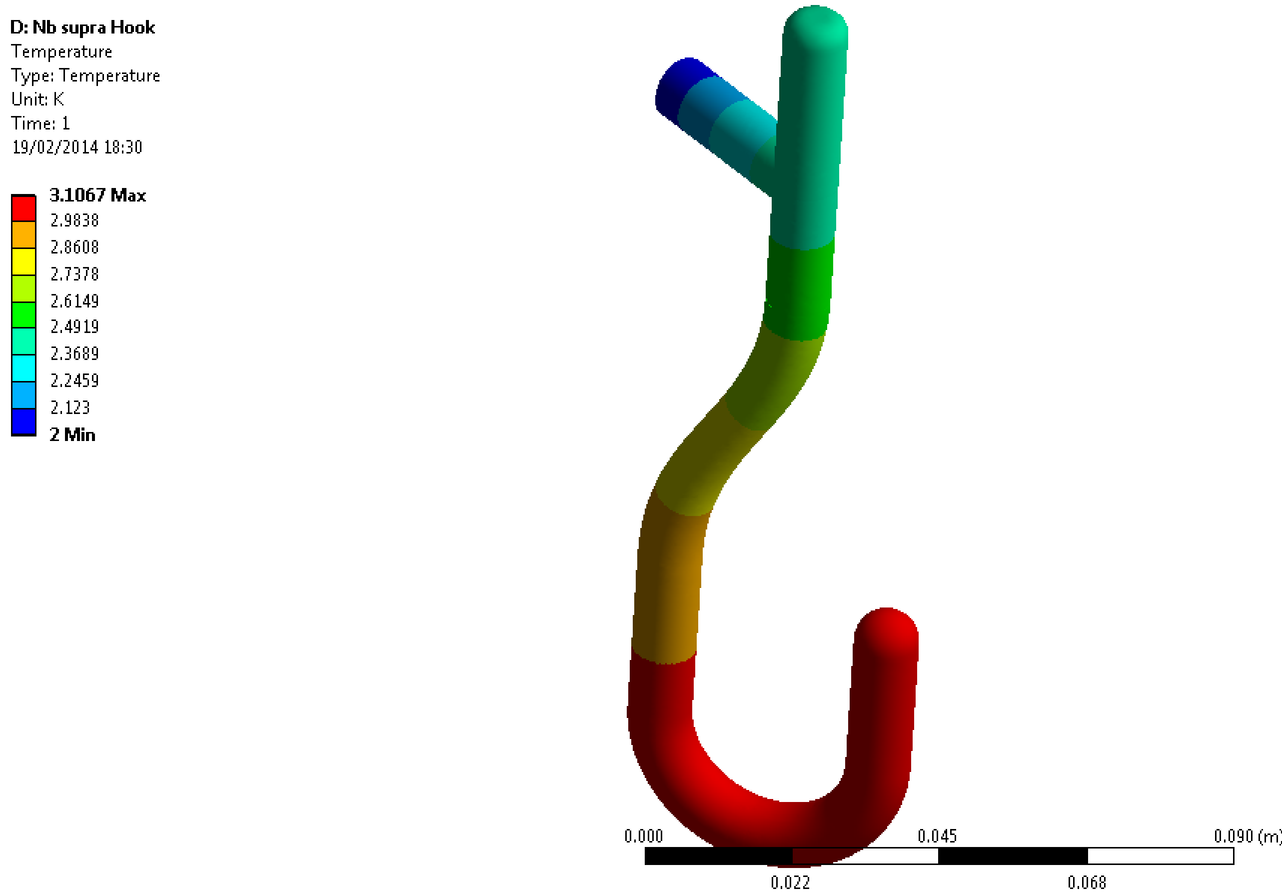
HOM hook

- Power losses evaluated on the old hook geometry, HFSS calculation performed by M. Navarro and S. Verdú
- Scaling factor HFSS/ANSYS for Nb supra: 3.996E10
- Scaling factor HFSS/ANSYS for Cu: 2.056E16
- Total RF losses on the hook:
  - Nb supra ~ **5 mW**
  - Cu ~ **2.5 kW!!!**



HOM hook – Nb supra

- HFSS→ANSYS to evaluate temperature distribution on the hook
- Objective: $T_{max} < T_{supra}$ (to avoid losing Nb superconductivity)
- Conduction only considered (2K boundary on the contact hook/HOM wall)
- Results:
  - **T_{max} = 3.1K OK!**
  - **Low heat flux to He bath (5 mW) OK!**
  - **The solution is acceptable from the thermal point of view**



HOM hook – Copper

- Thermal load too high → the ANSYS calculation is not even converging due to the too high temperature gradient on the hook!
- Rough calculation by hand: T_{max} on copper > **10.000K!!!**
- One can think about studying a cooling circuit for that (very difficult), but anyway the **thermal losses to the He bath are huge!**

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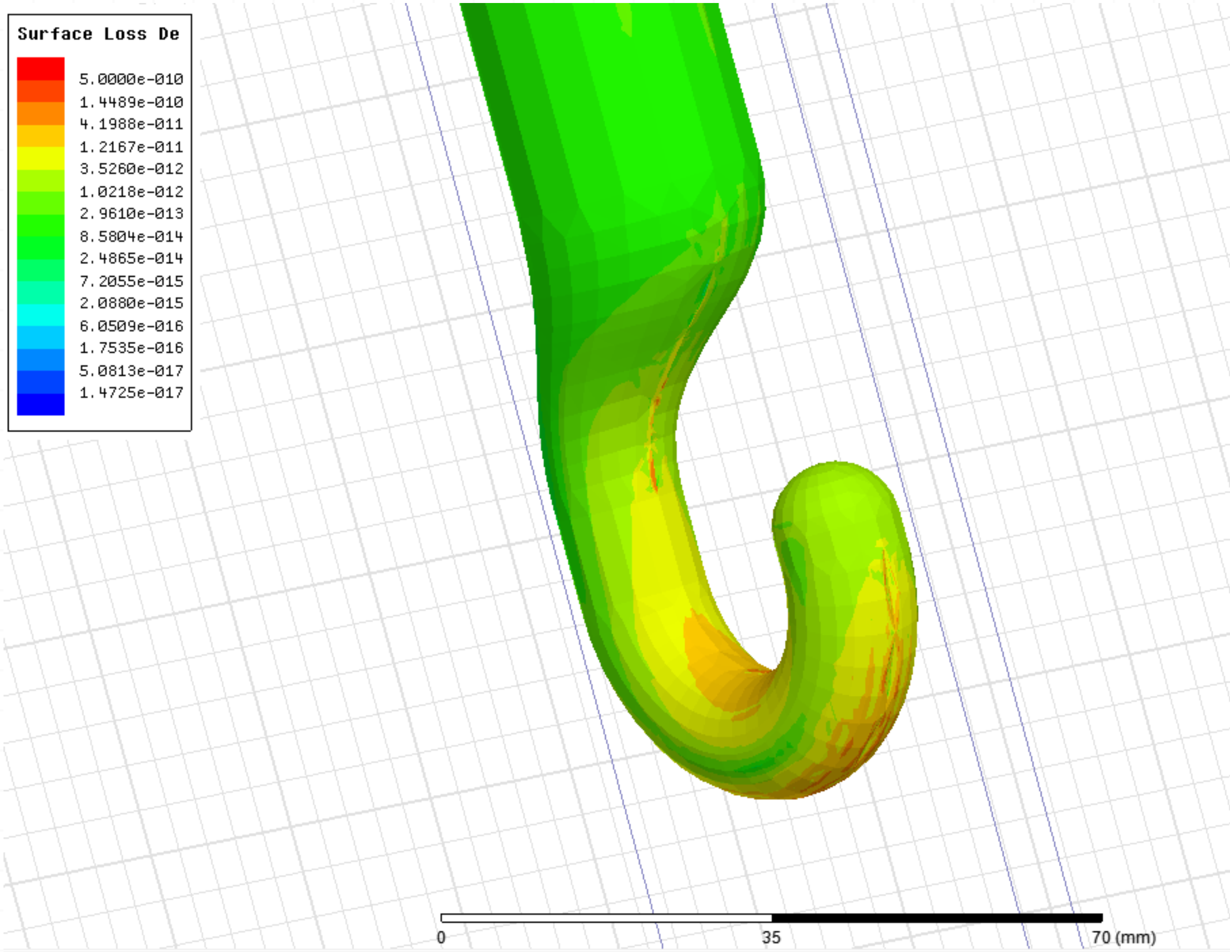
FPC hook – Copper

- Total RF losses on the Cu hook ~ **500 W**
- Lower than the HOM hook (Cu version), but still quite huge
- Active cooling needed (most likely water: heat load very high!)



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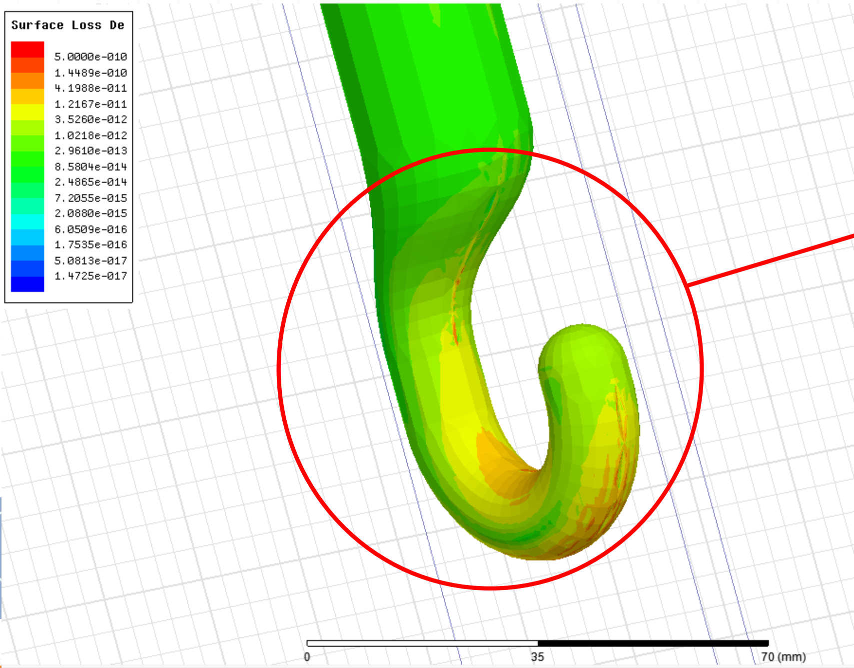
FPC hook – Copper

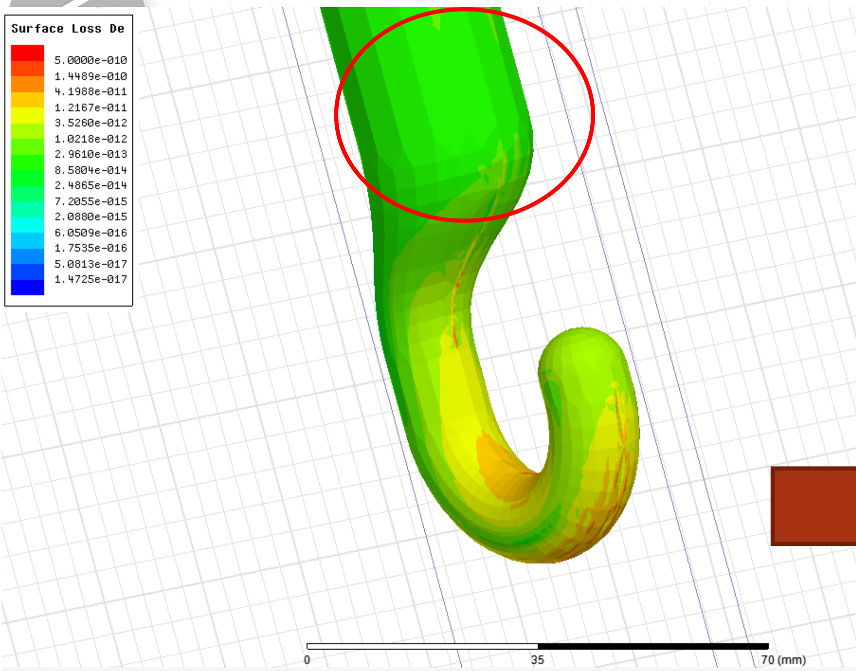
- **Example of cooling circuit calculation – WATER**
- Cooling channel diameter = 4 mm, water speed = 1.3 m/s (should be acceptable for copper) → **Q = 1 l/min**
- **h_c ~ 7 kW/m²/K** (to be checked if this is sufficient depending on the total surface of the cooling channels)
- $\Delta T_{water} = W/(\rho_{water} \cdot c_{p\_water} \cdot Q) =$ **7 °C** (should be ok)
- These characteristics would probably be acceptable, **but**:

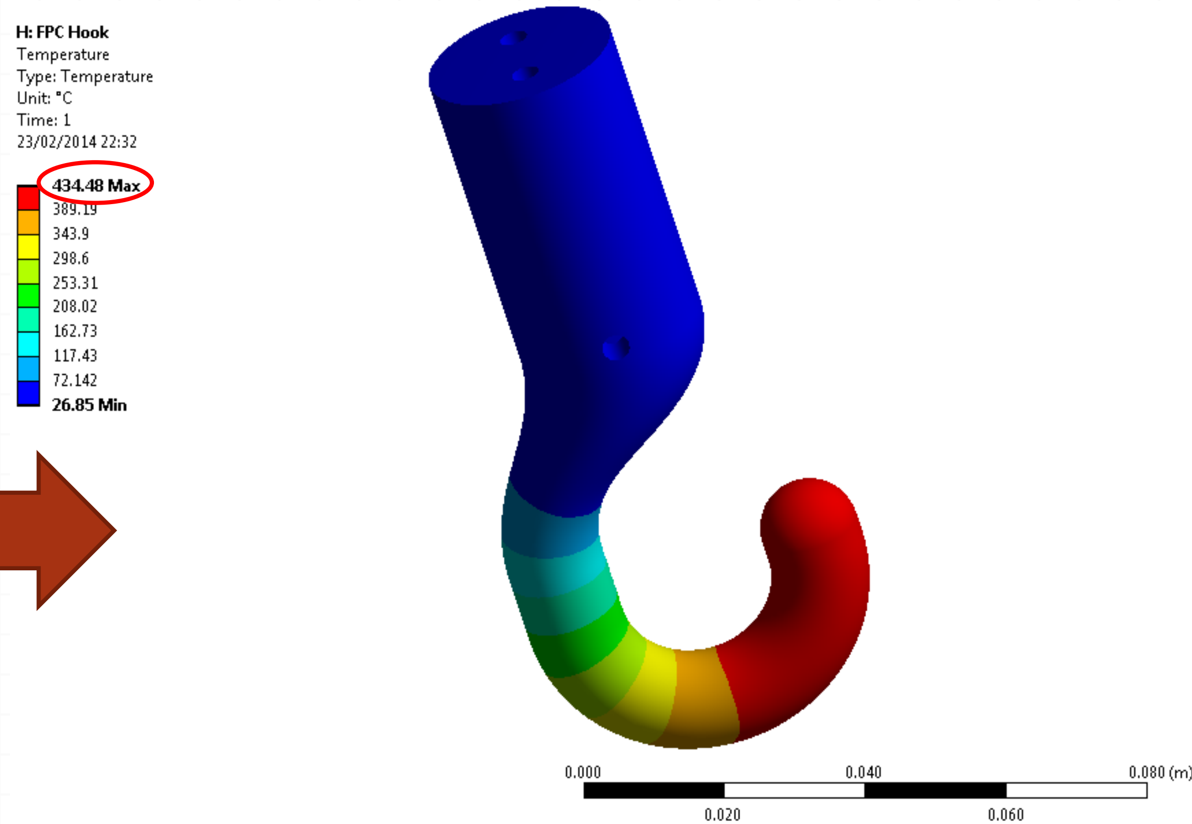


- **Probably difficult to design a circuit which cools down also the curve part of the hook!**

FPC hook – Copper

- In this case, imagine that we have a perfect cooling of the straight part (temperature = 26°C imposed to the zone circled in red)



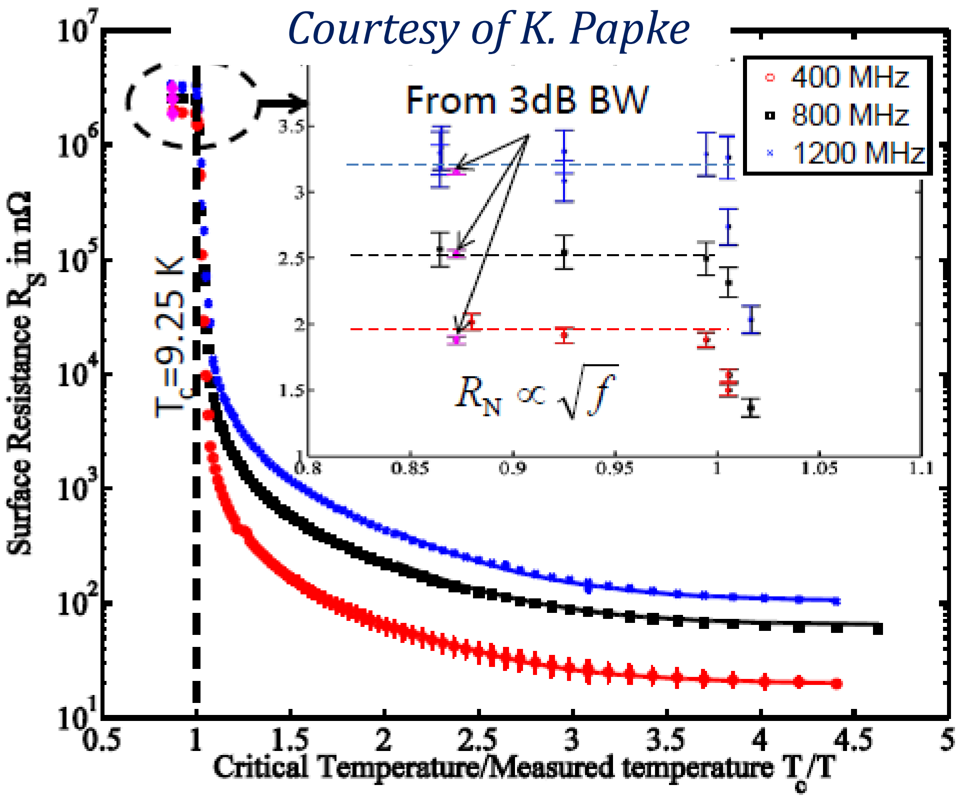


- **Huge temperature increase on the curve part! (it's the most loaded one & it's not actively cooled)**

HOM hook Nb

- Presentation 21/2: Nb ok for HOM hook, Cu not ok
- In that calculation, Rs of Nb was calculated at 2K
- Actually, thermal analysis shows that the hook reaches 3K of temperature for the evaluated RF losses (no active cooling of Nb hook)
- Iterative calculation HFSS/ANSYS is needed to calculate the real temperature distribution if Rs(Nb) is a function of T

Courtesy of K. Papke



- Rs (2K) ~ 10 nΩ
- Rs (3K) ~ 13 nΩ
- Rs (3.3K) ~ 20 nΩ
- Rs (3.5K) ~ 30 nΩ
- Rs (4K) ~ 50 nΩ
- Rs (5K) ~ 85 nΩ

HOM hook Nb

- The thermal conductivity is a function of temperature (this was already considered in 21/2 presentation) and RRR
- See “RF Superconductivity”, H. Padamsee, pag. 53 for the plots λ/T as a function of RRR
- Two calculations performed: RRR=380, RRR=40
- No active cooling of Nb hook considered! Massive hook

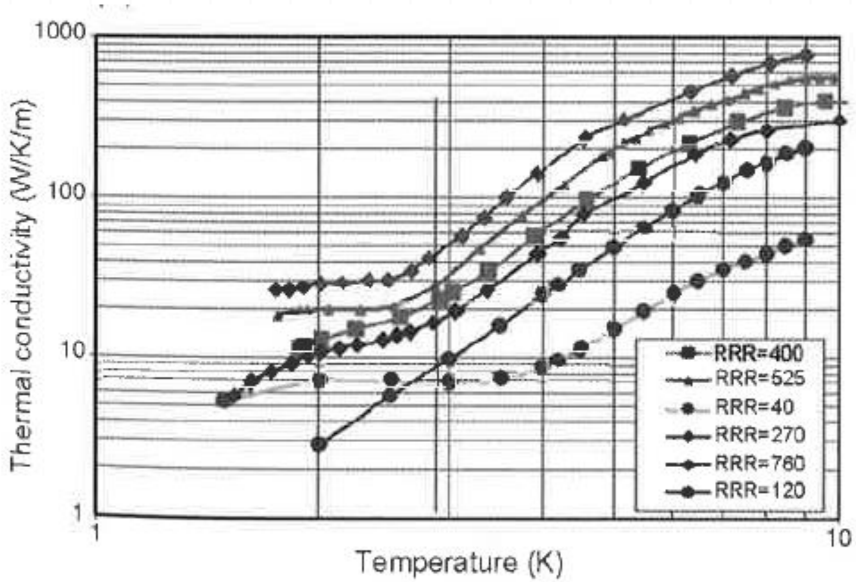
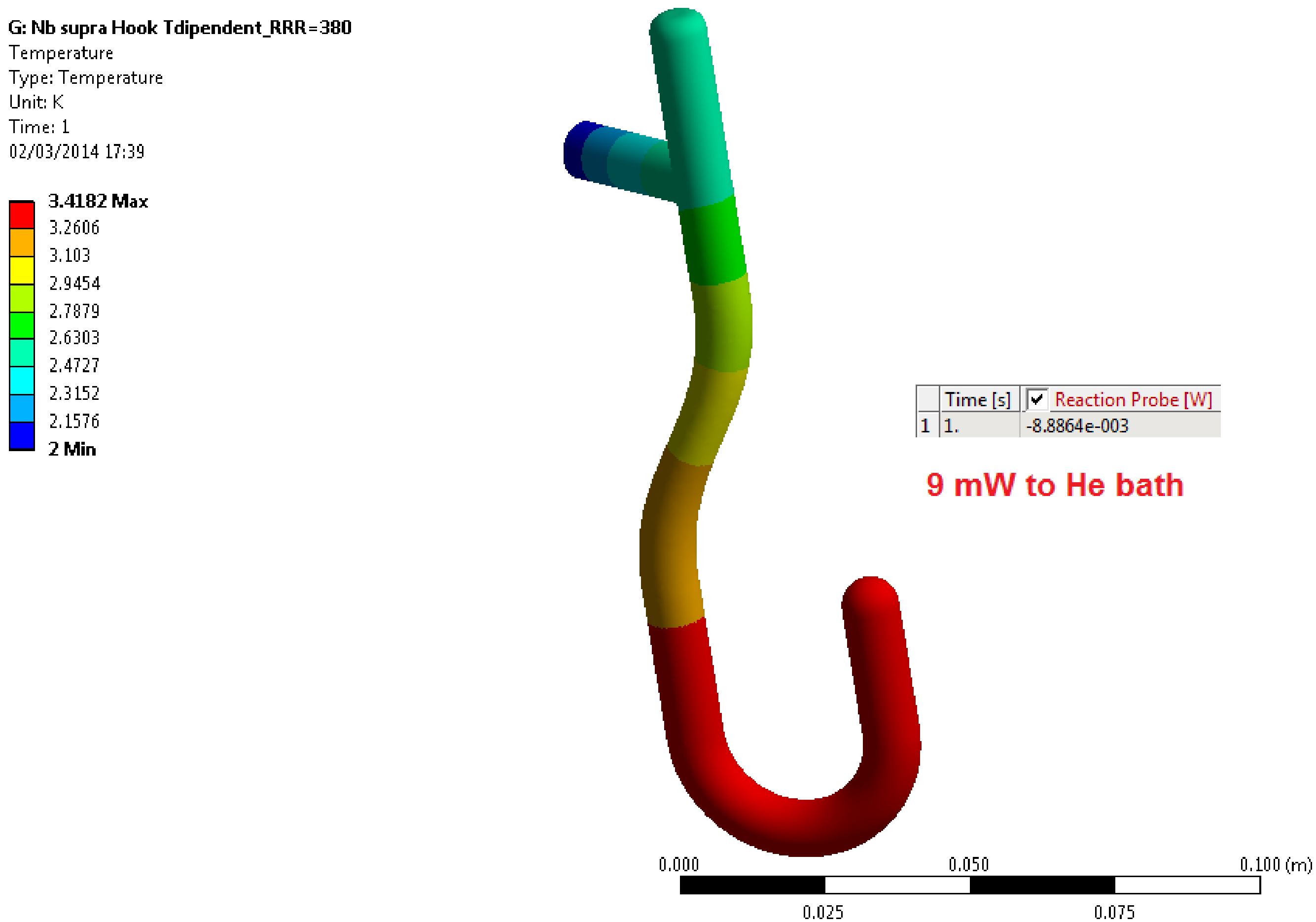


Fig. 3.7 Thermal conductivity versus temperature for l=0.5 mm and RRR=100 (solid), 200 (short dashed line), 300 (medium dashed line), and 500 (long dashed line). (b) Measured thermal conductivity of Nb for various RRR [167] (courtesy of DESY).

HOM hook Nb

- **RRR=380**: T_{max} ~ 3.4K after iterative calculation, **flux to He bath ~ 9 mW**
- Acceptable results!



HOM hook Nb

- **RRR=40**: **$T>T_c$** not acceptable!
- Solutions if RRR=40 is chosen:
  1. Either active cooling (hollow hook He superfluid-cooled)
  2. Or copper hook with Nb coating
- **The minimum RRR acceptable without active cooling seems to be around 250** (qualitative estimation, pag. 53 Padamsee → to be refined if needed)

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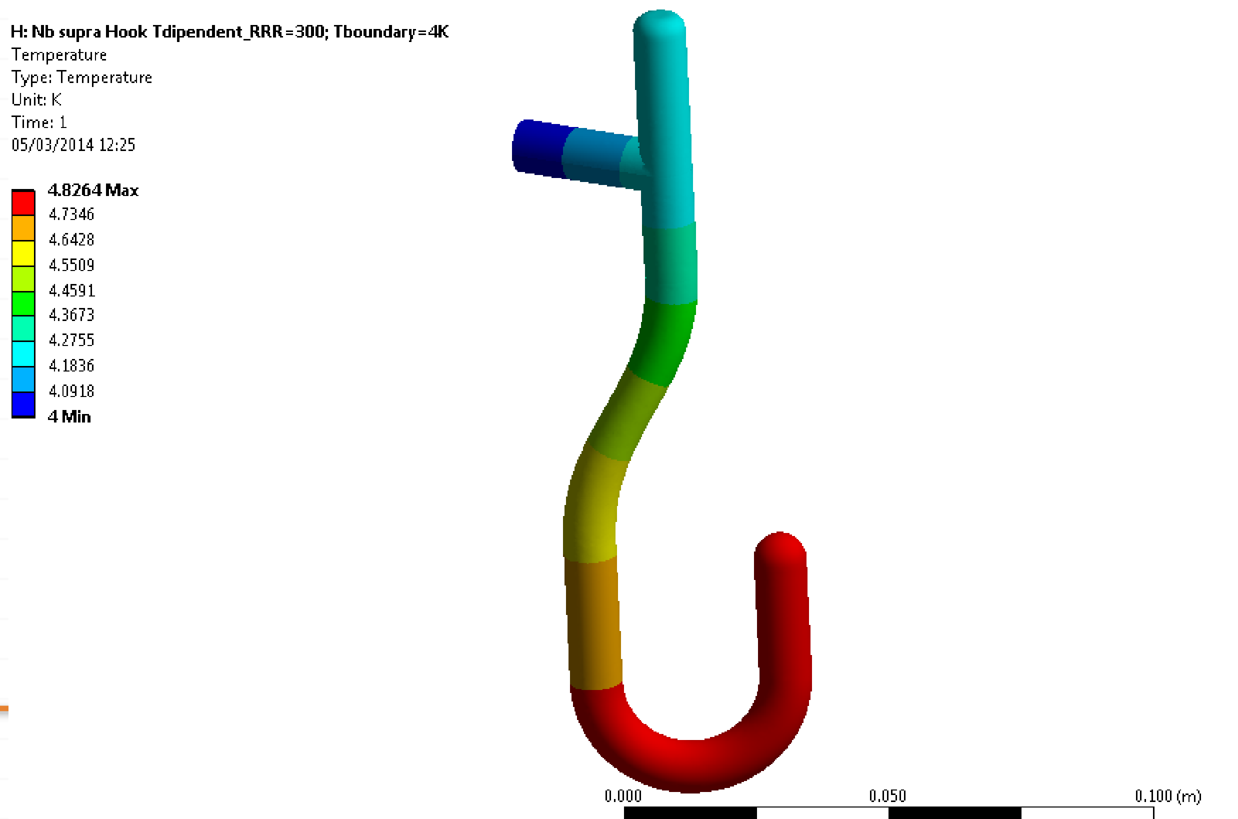
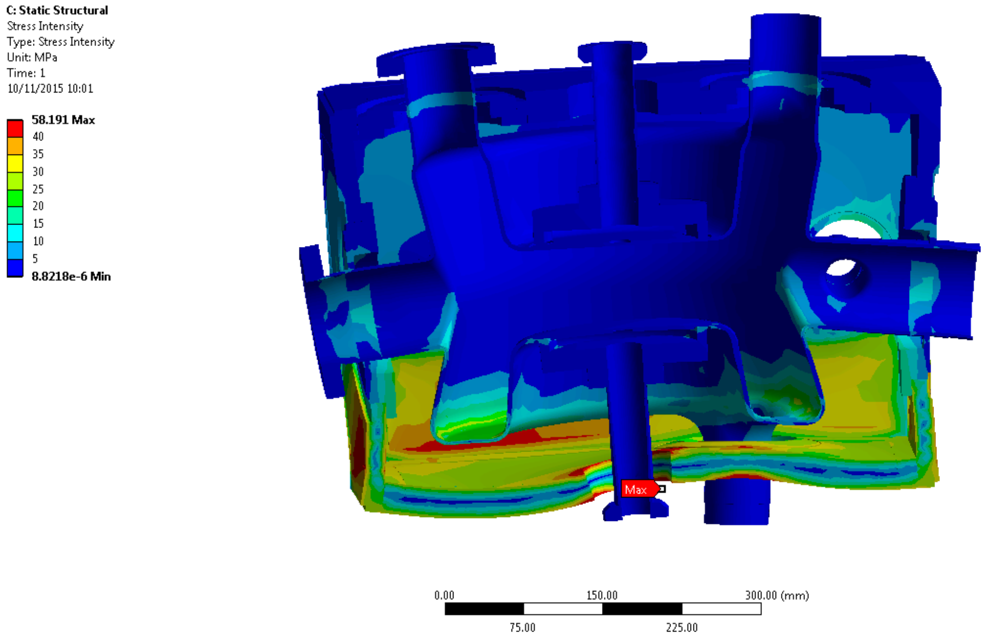
Backup slide: HOM hook with T=4K boundary condition

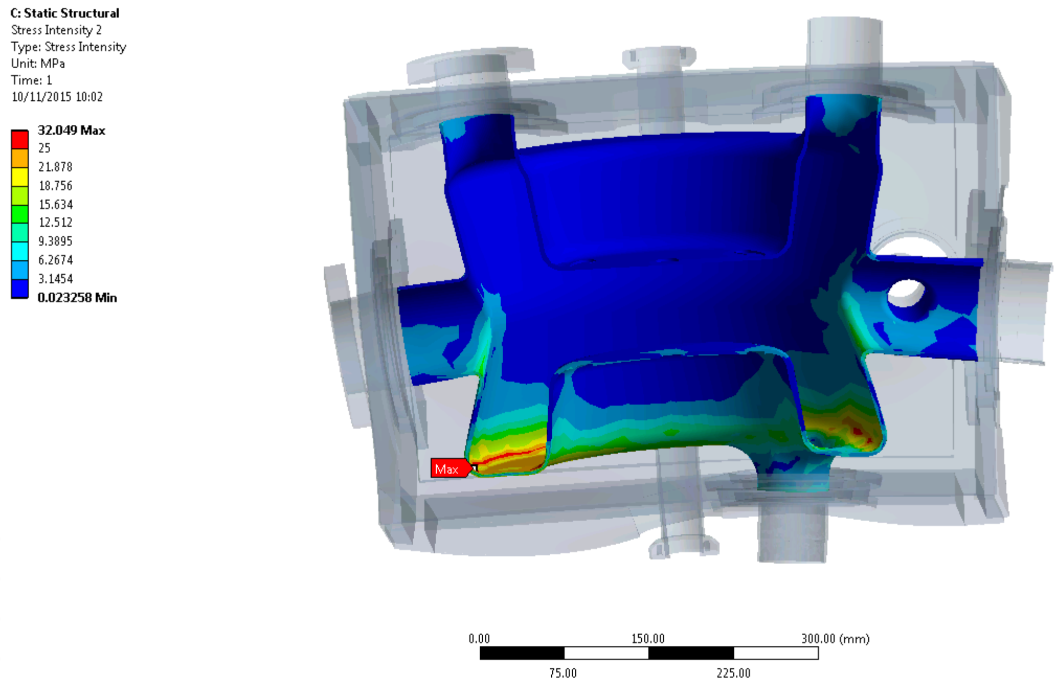
- A boundary condition of 2K is not realistic because there is a certain resistance between the 2K He bath and the hook fixed support
- A new calculation has been performed imposing to a RRR=300 Nb hook (massive) a boundary of 4K
- Results are acceptable: **T_{max} < 5K, Heat losses to He bath ~ 35 mW**



Tank and Cavity cool-down: FEA

- A difference of 50K in the temperature between the inner and outer cavity face generates thermal stresses and deformations on the component: picture for an even more conservative case





Tank and Cavity cool-down: FEA

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- Grey bodies sigma(T1^4-T2^4)/

$$\text{gray} := \frac{1 - \text{eps1}}{\text{eps1} \cdot \text{A1}} + \frac{1}{\text{A1} \cdot \text{F12}} + \frac{1 - \text{eps2}}{\text{eps2} \cdot \text{A2}} = 731.52 \frac{1}{\text{m}^2}$$