From QPR to 1.3 GHz cavities

Lorena VEGA CID *on behalf of all the CERN colleagues from BE-RF, TE-VSC and TE-CRG contributing to these studies.*

Special thanks to A. Bianchi, G. Rosaz, G. Vandoni, P. Vidal and W. Venturini

CERN R&D on thin films

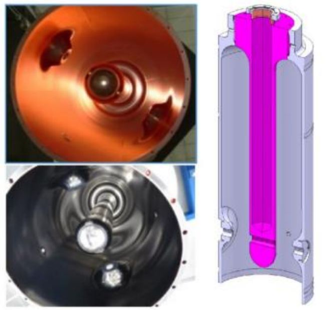
Niobium on copper

Technology used historically at CERN.

Interest in developing the RF performance

A15 on copper

Investigate new materials with potential SRF applications.

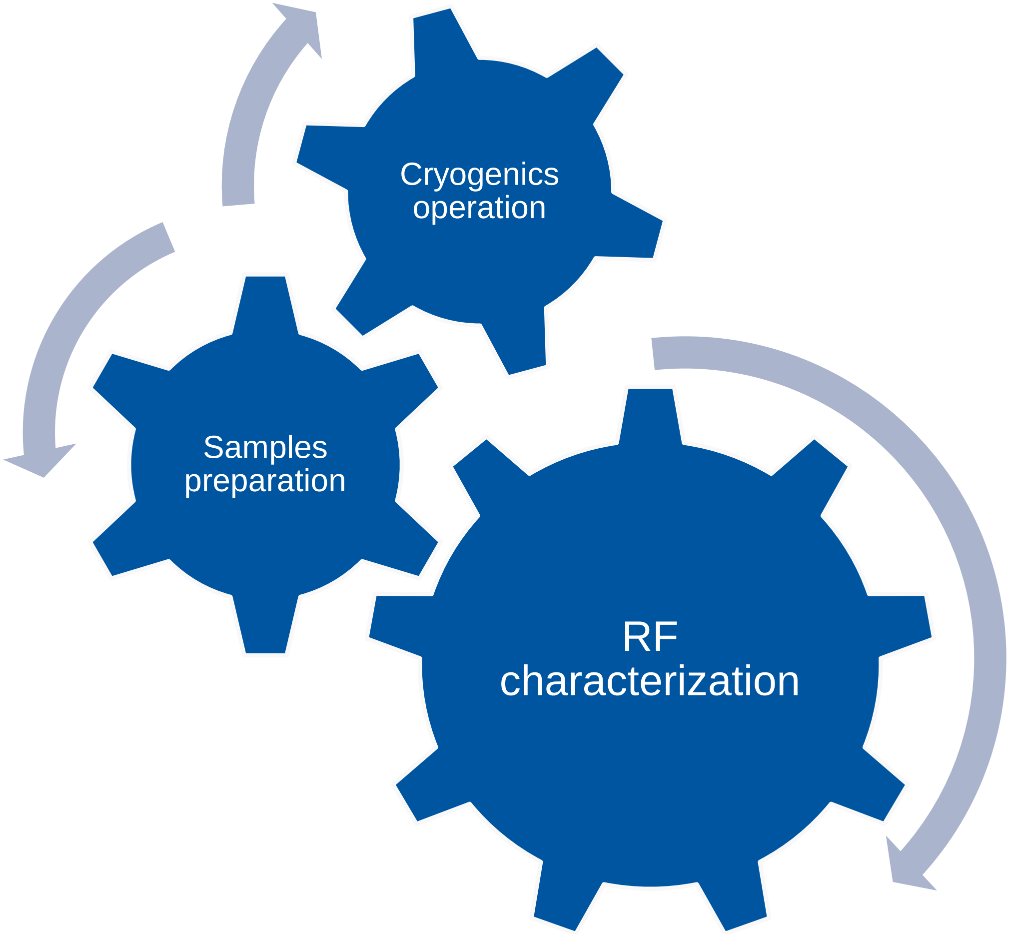


HIE-ISOLDE

LHC

RF characterization of thin films

Colleagues from different groups and fields are involved in the R&D activities



Cryogenics operation

Samples preparation

RF characterization

Path from QPR to coated cavities

QPR sample

Ingredients:

- Bias
- Temperature
- Pressure
- Pulse parameters
- Peak power

Directions:

Measure RF performance

Identify parameters that influence the RF performance

1.3 GHz cavity

Ingredients:

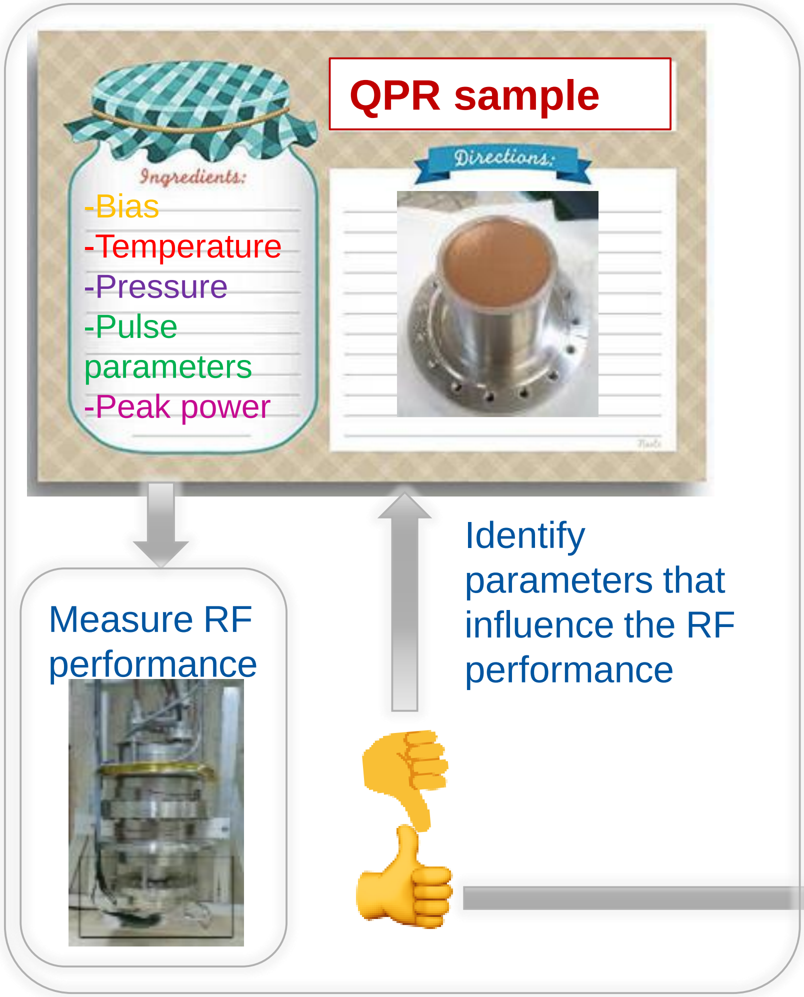
- Bias
- Temperature
- Pressure
- Pulse parameters
- Peak power

Directions:

Measure RF performance

?

Finding a recipe for a good QPR sample

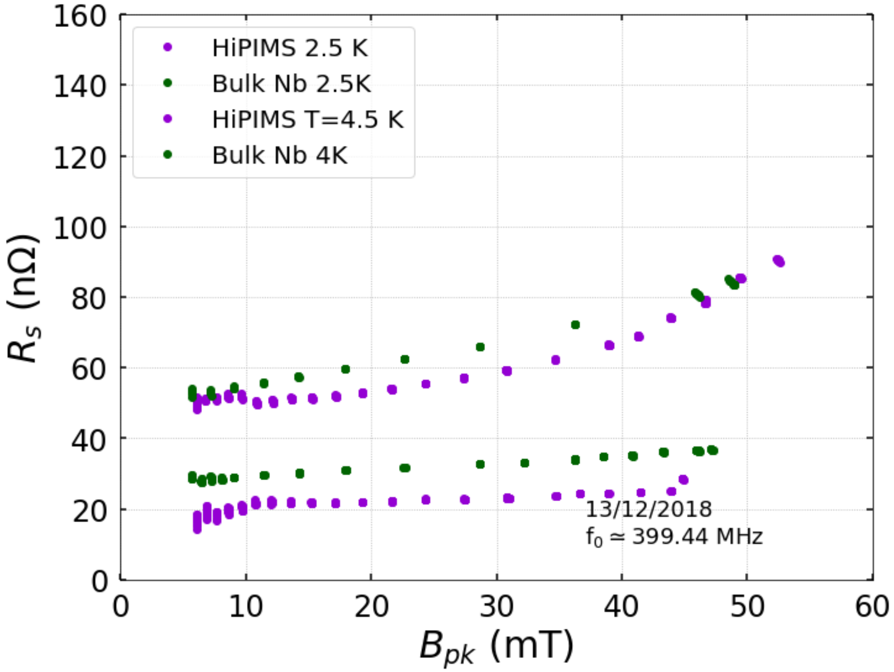


QPR sample

-Bias
-Temperature
-Pressure
-Pulse parameters
-Peak power

Measure RF performance

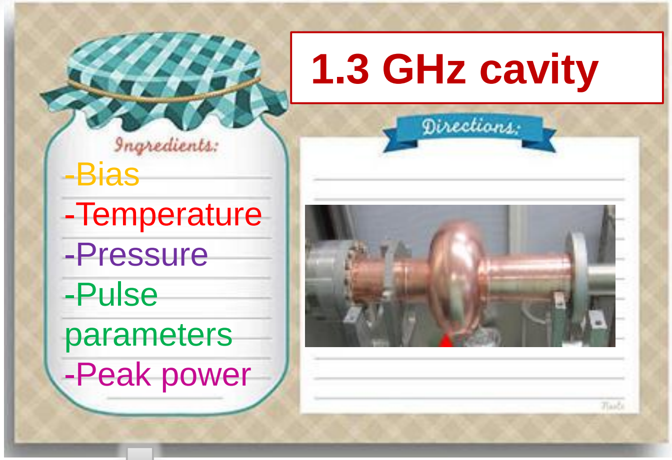
Identify parameters that influence the RF performance



13/12/2018
$f_0 \simeq 399.44$ MHz

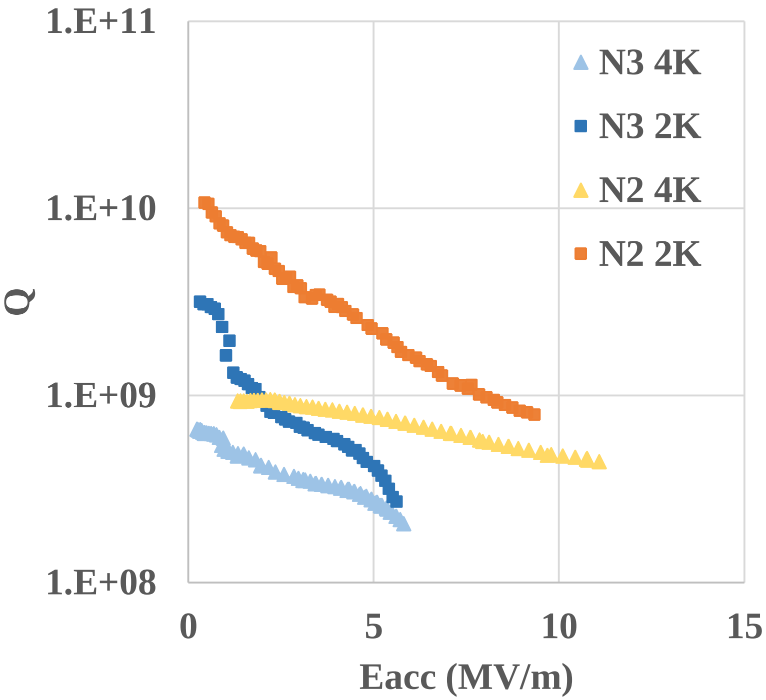
HiPIMS sample showing comparable performance to bulk niobium in terms of Q-slope

Coating two 1.3 GHz cavities with the QPR recipe

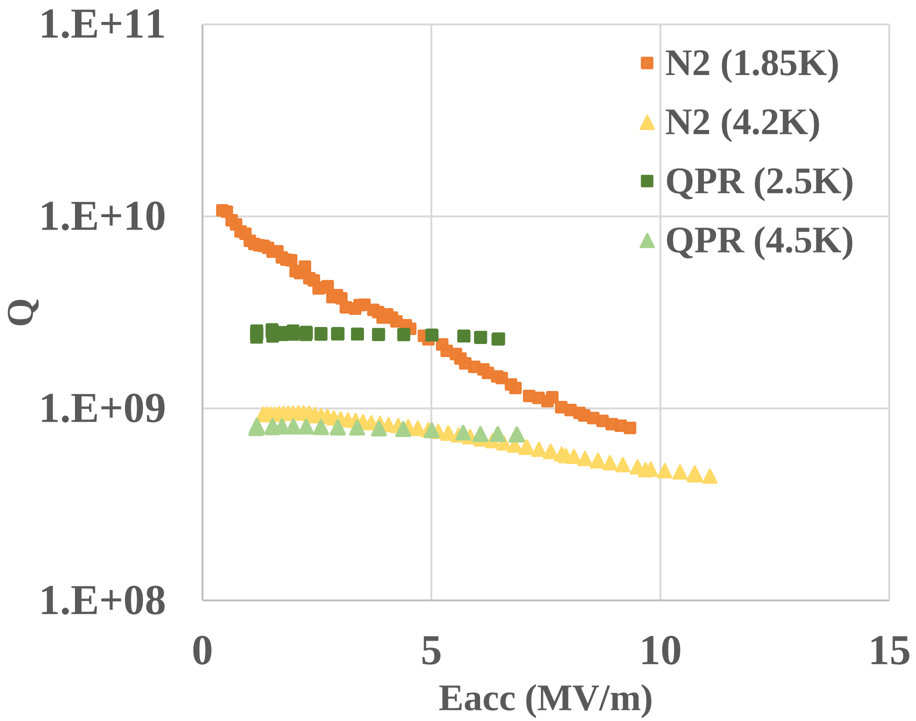


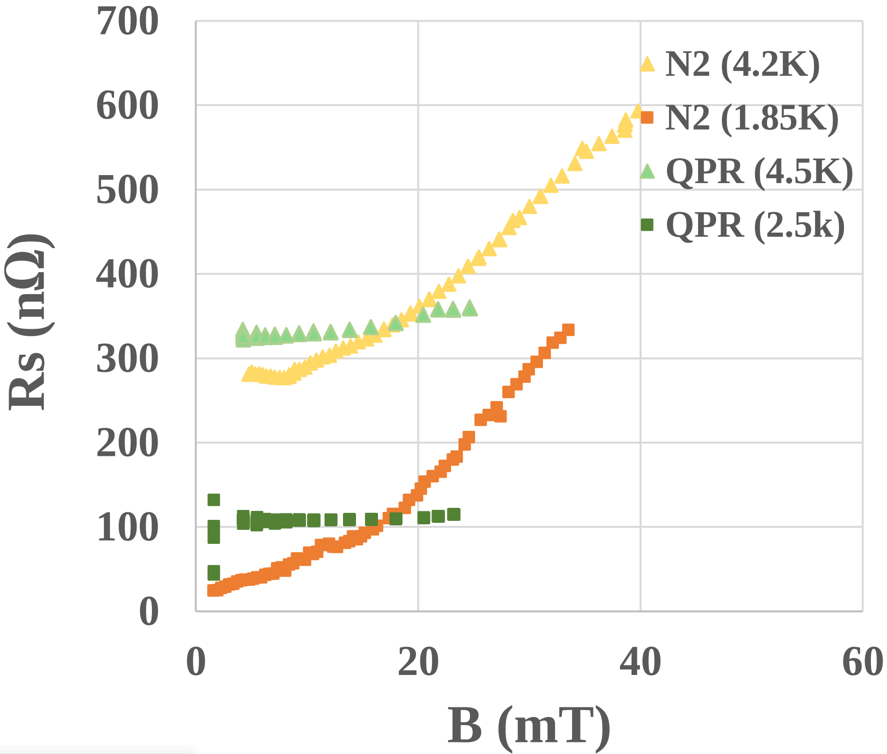
Measure RF performance

N2: Fully coated with the same QPR recipe (HiPIMS)
N3: Cut-off tubes coated with positive bias HiPIMS. The same QPR recipe for the cell.



Comparing QPR and cavity results





$$Rs = \frac{G}{Q} = \frac{268}{Q}$$

$$\frac{Bpk}{Eacc} = 3.59$$

Can we predict a cavity performance from QPR measurements?

QPR sample

Ingredients:

- -Bias
- -Temperature
- -Pressure
- -Pulse parameters
- -Peak power

Directions:

Measure RF performance

Identify parameters that influence the RF performance

1.3 GHz cavity

Ingredients:

- -Bias
- -Temperature
- -Pressure
- -Pulse parameters
- -Peak power

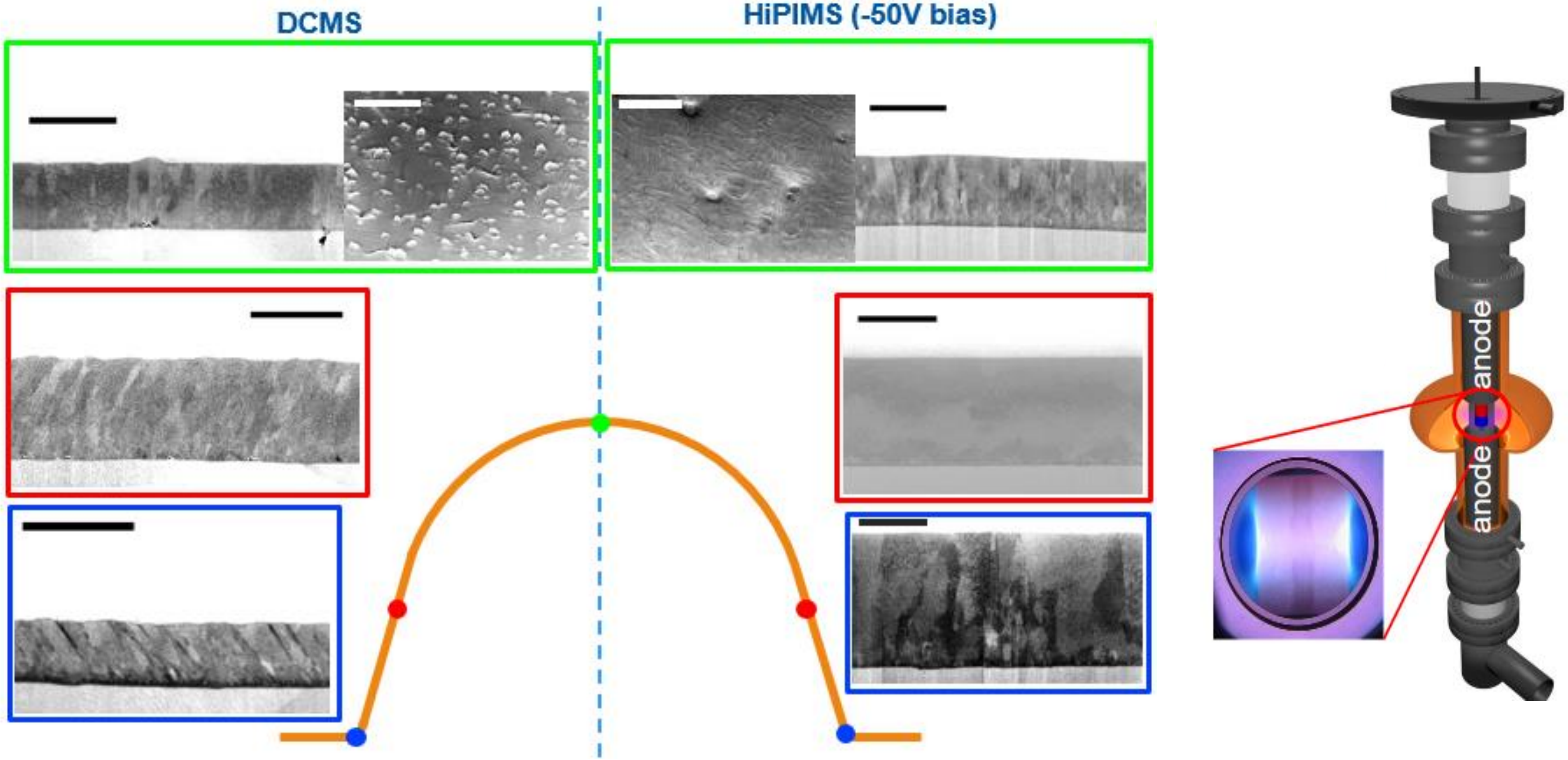
Directions:

Measure RF performance

Is the coating fully reproducible in a cavity by scaling the parameters?

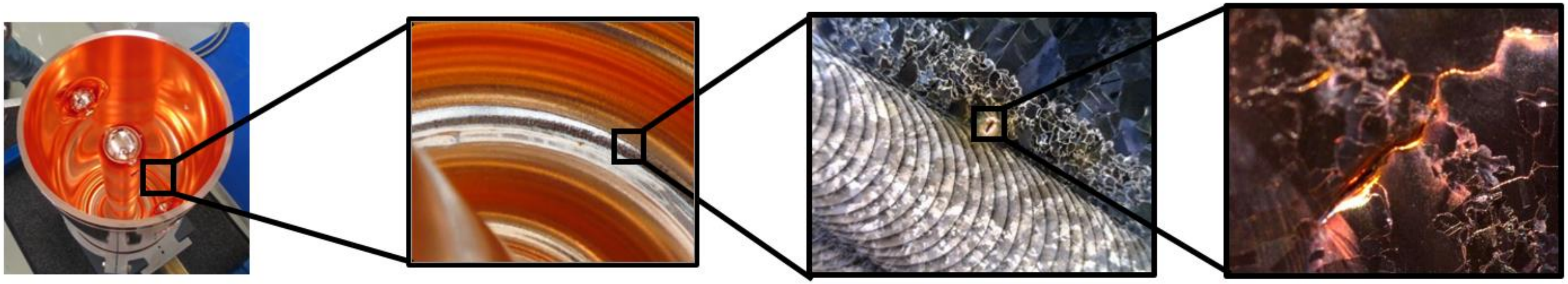
Influence of impinging angles on coating morphology

- ✓ HiPIMS technique allows to achieve denser layer in all the orientations.
- ➢ This technique may still need specific optimization for the cavity geometry.



Influence of the quality of the substrate

- ✓ Welds are potential sources of defects, holes may trap chemicals and contaminate the SC layer.
- ✓ Use seamless substrates: this solved the problem for HIE ISOLDE cavities (100 MHz and 4.5 K)→ not a Nb/Cu thin film specific issue

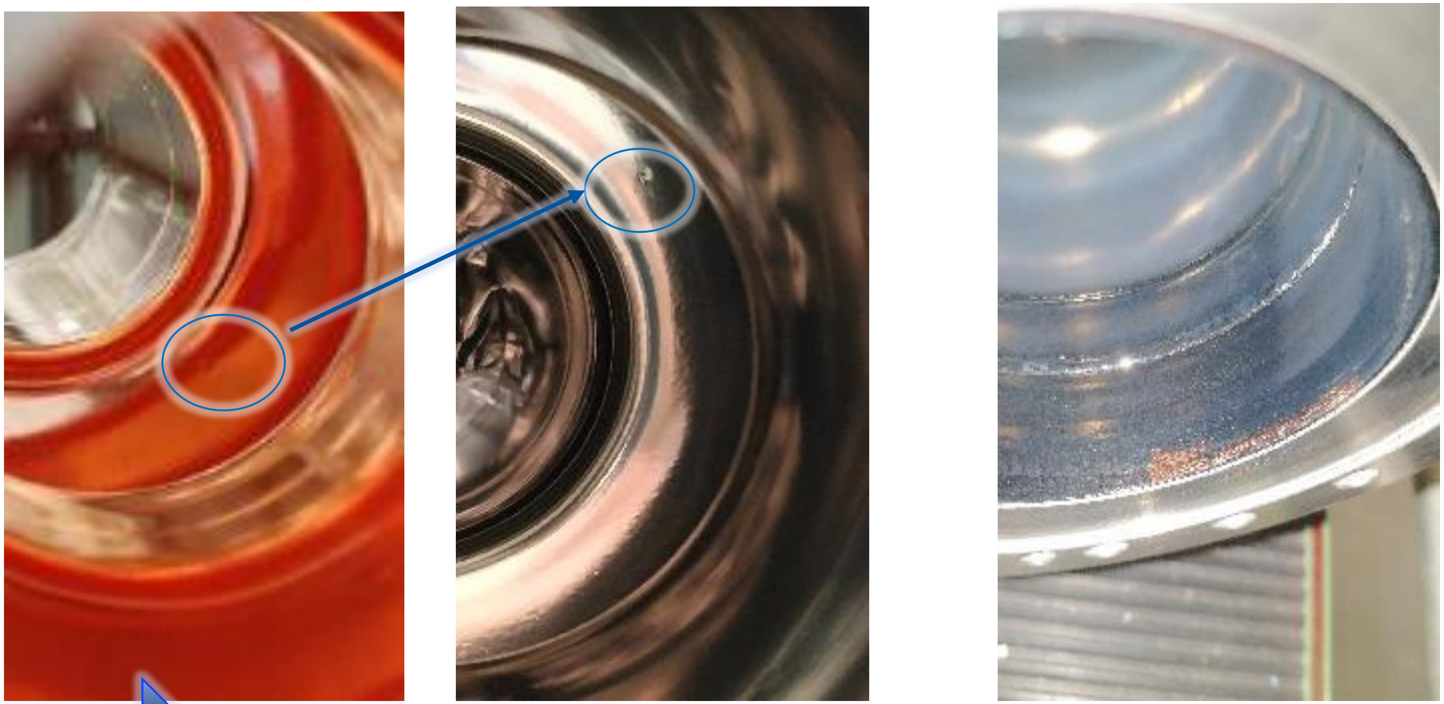


To be done

- Use electroformed substrate
- Machine from bulk a 1.3 GHz cell to get a high quality substrate

Influence of the quality of the substrate

- ✓ Defects in substrate are propagated to the coating.
- Last 2 cavities were spun and then treated at JLab (tumbled), nonetheless some defects were still present

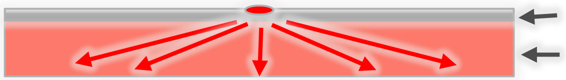


To be done

- Install thermal mapping system to localize defects.

Understanding Q drop with simulations

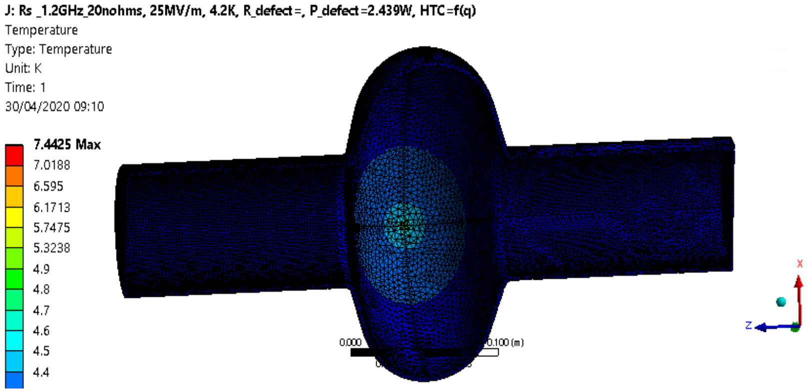
- Thermal quenches are not observed in niobium on copper cavities.
- The temperature increases locally in presence of defects, but thanks to the high thermal diffusivity of copper, heat quickly spreads and the temperature of Nb film is maintained below Tc in steady-state conditions.
- As a result, an area of increased temperature (thus, increased Rs) surrounds the defect: This contributes to the global surface resistance, leading to Q drop.



Niobium thin film

Copper

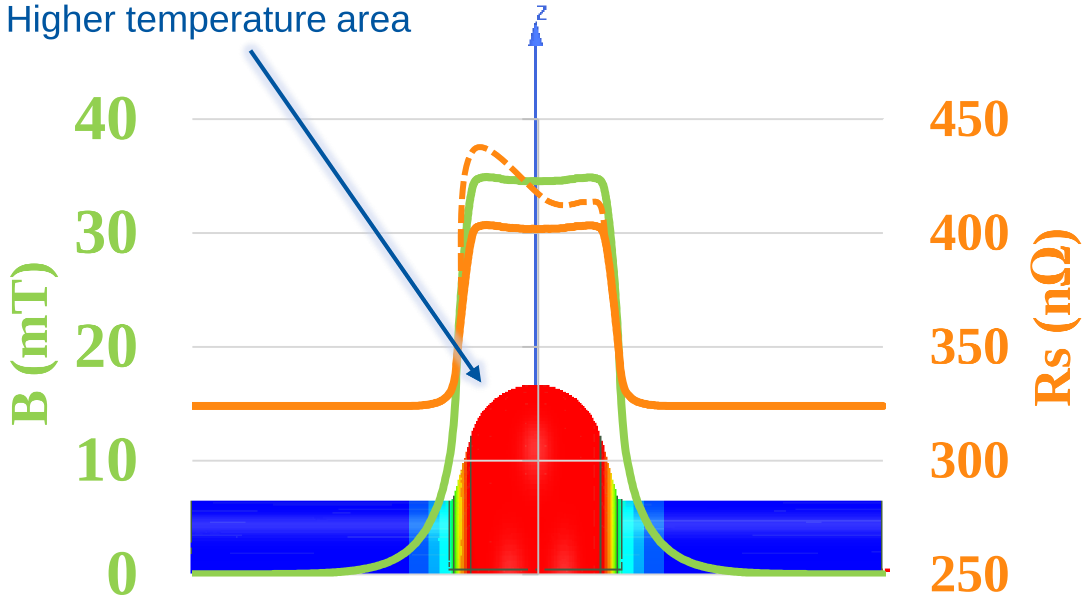
High thermal diffusivity in copper: High spread of temperature!



Q drop in presence of defects

$$\downarrow Q = \frac{\omega U}{\frac{1}{2\mu}\int_S R_S(B,T)\|B\|^2 dS} = \frac{G}{R_S(B,T)}\uparrow$$

Higher temperature area

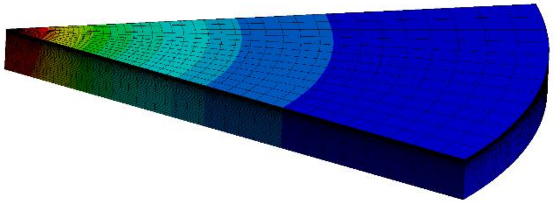


Data calculated for 16 MV/m

Building the model

Dimension of defect causing hot spot ?

Nb/Cu interface:
Thermal resistance?



Cu/He interface:
Heat transfer regime?

Definition of material properties

Definition of RF loads

Definition of boundary conditions

Definition of material properties

Definition of RF loads

Definition of boundary conditions:

- ✓ Correct definition of thermal properties are key to obtain realistic results.

- ✓ Parametrize the properties in function of RRR and temperature!

Definition of material properties

Definition of boundary conditions

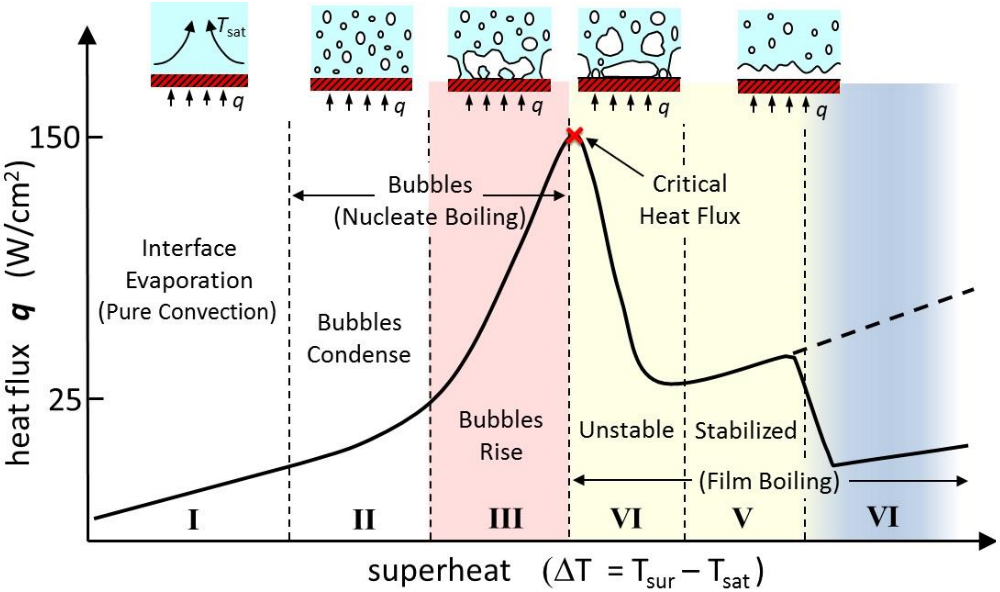
Definition of RF loads

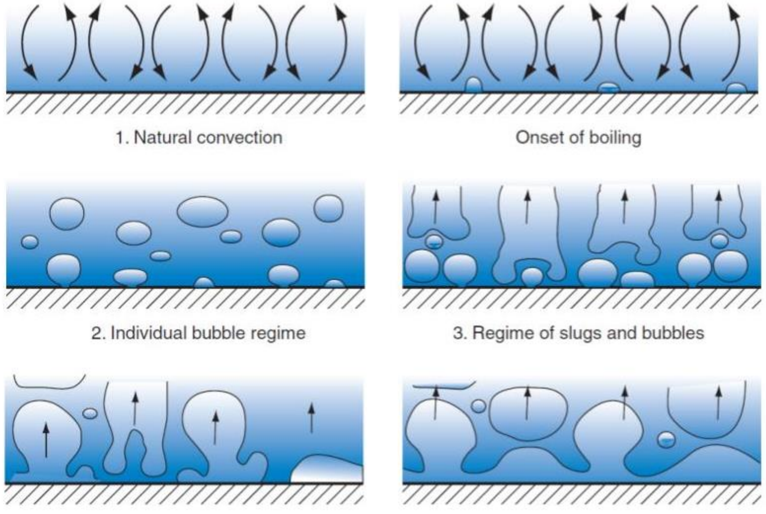
Interface between helium and copper

Natural convection

Nucleate boiling

Film boiling





1. Natural convection

Onset of boiling

2. Individual bubble regime

3. Regime of slugs and bubbles

4. Transition film boiling

5. Stable film boiling

He I has a rather small thermal conductivity and large specific heat:

- Conduction heat transport is of little significance to the overall heat transfer
- Heat transport is dominated by convection mechanisms.

Definition of material properties

Definition of boundary conditions

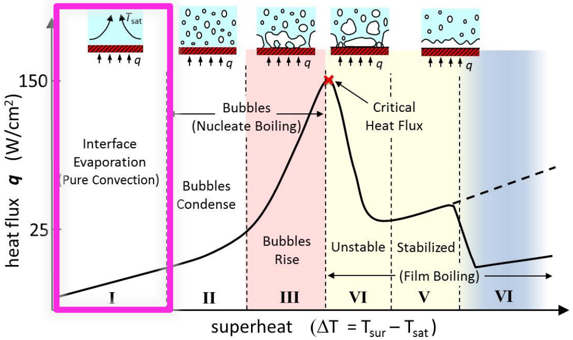
Definition of RF loads

Natural convection

Nucleate boiling

Film boiling

At low fluxes, up to a few W/m2, heat is transfer via density-driven convection currents near the heated surface



	Q (W/m²)	Regime	h	Equation
He I	<10	Natural convection	500 W/m²K	$Q=h(T_s - T_{He})$

The convection coefficient is obtained from empirical correlations based on dimensionless parameters dependent on the properties of the system. There is sufficient quantity of experimental data for normal liquid helium (He I).

$$h = \frac{Nu\, k_f}{L}$$

k_f: Thermal conductivity of the fluid

L: Characteristic length

Nu: Nusselt number

$$Nu = C\, Ra^n$$

*Assuming free convection

C, n: Empirical parameters depending on orientation and regime (laminar/turbulent)

Ra: Rayleigh number

$$Ra = Gr\, Pr$$

Pr: Prandlt number

$$Pr = \frac{\mu c_p}{k}$$

Gr: Grashof number

$$Gr = \frac{g\beta(T_s - T_b)L^3}{k}$$

Definition of material properties

Definition of boundary conditions

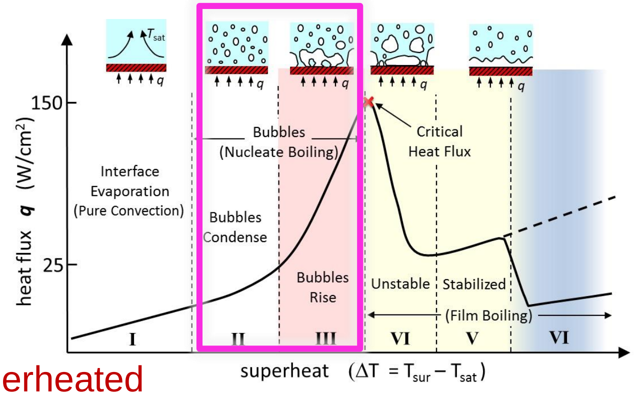
Definition of RF loads

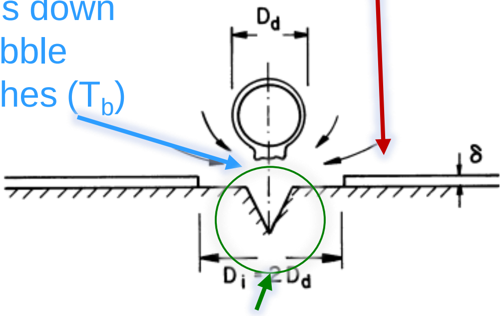
Natural convection

Nucleate boiling

Film boiling

As heat flux increases, bubbles start forming at preferred sites: activation of nucleation sites.





Layer of superheated liquid (T_s)

Cold liquid rushes down as bubble detaches (T_b)

Nucleation site

Improved cooling of the surface:

- A layer of superheated liquid is formed near the heated surface (Ts>Tbath)
- As a bubble is detached from the surface, cold liquid from above rushes down and cool down the surface.

Definition of material properties

Definition of boundary conditions

Definition of RF loads

Natural convection

Nucleate boiling

Film boiling

	Q (W/m^2)	Regime	h	Equation
He I		Nucleate boiling		

- Calculate separately contribution from natural convection of bulk and bubble hydrodynamics:

- $q_{NB}=q_b+q_{NC}$
  - q_{NC}=>Adimensional numbers (Nu, Ra)
  - q_b=> Hsu and Graham correlation

Highly experimental: very difficult to estimate!

$$q_b = \boxed{\frac{4\pi}{3} h_{fg}\rho v \int_A n f r_b^3 \, dA} + \boxed{2\pi \Delta T_s C_l \rho_l \delta \int_A n f r_b^2 \, dA}$$

f-frequency rate of detachment
n-number of nucleation sites per area
rc-critical size of a departing bubble.
…

Latent heat of He in the bubble

Heat needed to superheat the part of the layer of liquid that has been detached with the bubble

Van Sciver, Steven W

Helium cryogenics

Definition of material properties

Definition of boundary conditions

Definition of RF loads

Natural convection

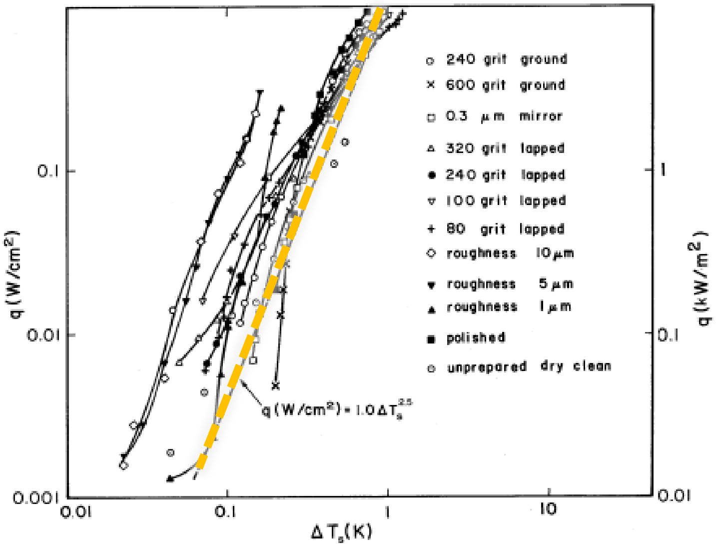
Nucleate boiling

Film boiling

	q (W/m²)	Regime	h	Equation
He I	10<q<?	Nucleate boiling	10000 W/m²K$^{2.5}$	$Q=h(T_s-T_{He})^{2.5}$

- ❑ Use empirical fit (*C. Schmidt, “Review of steady state and transient heat transfer in pool boiling He–I”, Proceedings of the SaclayWorkshop on Stability of Superconductors in He-I and He-II, International Institute of Refrigeration, Paris, 1982, pp. 17-31*) :

$$q\left(\frac{W}{m^2}\right) = 10000(T_S - T_b)^{2.5}$$



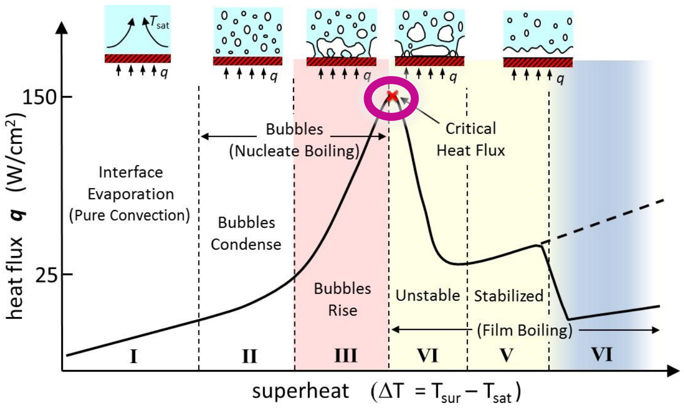
Graph for flat Cu samples facing upward, different roughness: The rougher, the more efficient the cooling. In yellow, *Van Sciver, S. W. (2012). Helium cryogenics. Springer Science & Business Media.*

Definition of material properties → **Definition of boundary conditions** → Definition of RF loads

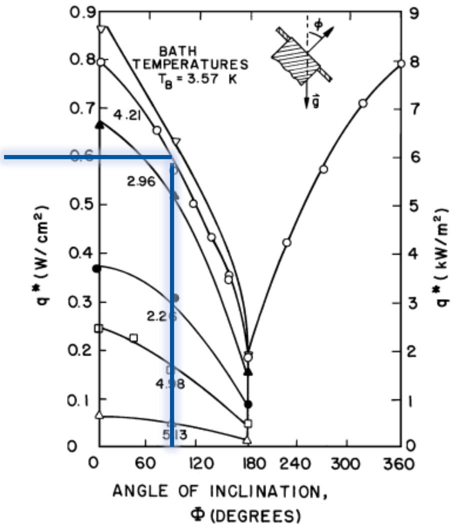
Natural convection → **Nucleate boiling** → Film boiling

	q (W/m^2)	Regime	h	Equation
He I	10<Q<10000	Nucleate boiling	10000 W/m^{2}K$^{2.5}$	$Q=h(T_s-T_{He})^{2.5}$

- According to experimental data: 5000-15000 W/m^2
- Orientation needs to be accounted! Note that having a defect in the cell below the equator can lead to a considerable decrease in the heat transfer efficiency.



At 90 (equator), q*~6000W/m^2



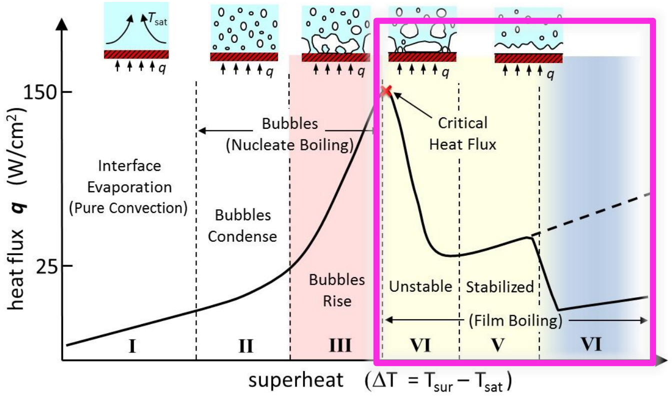
Lyon, D. N. (1965). Boiling heat transfer and peak nucleate boiling fluxes in saturated liquid helium between the lambda and critical temperatures. Adv. Cryog. Eng., 10, 371.

Definition of material properties → **Definition of boundary conditions** → Definition of RF loads

Natural convection → Nucleate boiling → **Film boiling**

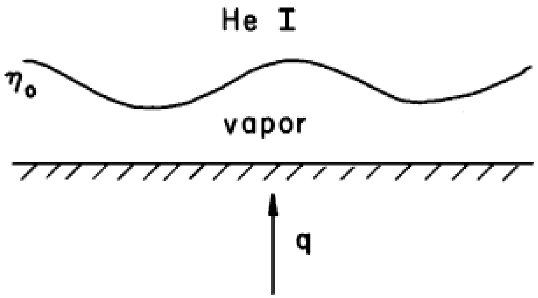
At higher heat flux rates, bubbles get larger and detachment rate increases, becoming unstable and forming a continuous

	Q (W/m^2)	Regime	h	Equation
He I	>10000	Film boiling	250 W/m^{2}K	$Q=h(T_s-T_{He})$



Film boiling stabilization:

- Liquid He is heavier than vapour so the tendency is to rewet the surface.
- The waves at the interface liquid-vapor oscillate with amplitude η: They must be damped for the interface to be stable, otherwise the amplitude would grow beyond the vapor film thickness and rewet the surface.
- Typical values of heat transfer coefficient are 100 to 2000 W/m^{2}K *(C. Schmidt, International Institute of Refrigeration, Paris, pp. 17-31, 1982)*
- A value of 250 W/m^{2}K is selected based on *Paudel, D, Quench Simulation of Superconducting Magnets with Commercial Multiphysics Software, CERN-THESIS-2015-090, 2015.*

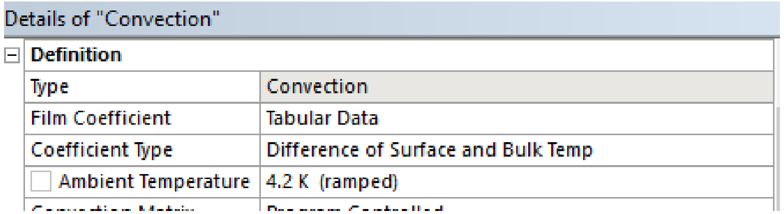


Definition of material properties

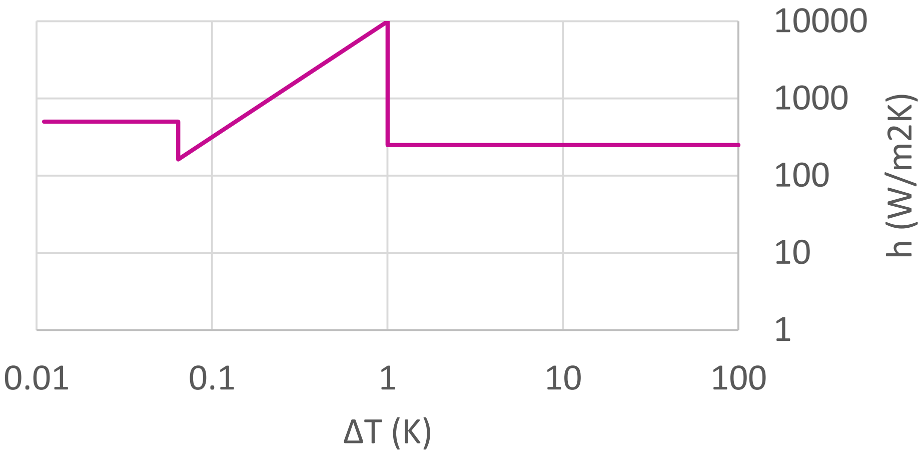
Definition of boundary conditions

Definition of RF loads

	Q (W/m^2)	Regime	h	Equation
He I	<10	Natural convection	500 W/m^2K	$Q=h(T_s-T_{He})$
	10<Q<10000	Nucleate boiling	10000 $W/m^2K^{1.5}$	$Q=h(T_s-T_{He})^{2.5}$
	>10000	Film boiling	250 W/m^2K	$Q=h(T_s-T_{He})$

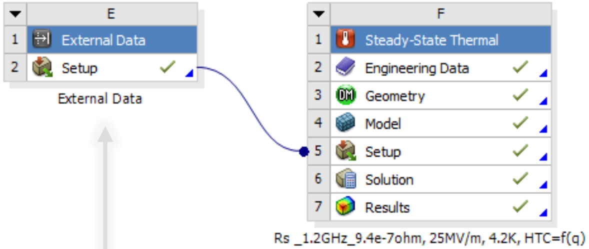

Details of "Convection"

Definition	
Type	Convection
Film Coefficient	Tabular Data
Coefficient Type	Difference of Surface and Bulk Temp
☐ Ambient Temperature	4.2 K (ramped)
Convection Matrix	Program Controlled



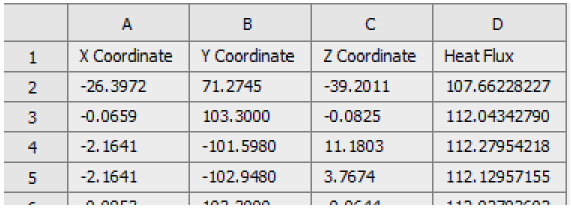
Definition of material properties → **Definition of boundary conditions** → **Definition of RF loads**

- Heat flux mapping: The RF loads are imported from CST to ANSYS Mechanical
- To do this across the dissimilar mesh interface used in each of these softwares, the nodes of the CST mesh are mapped to the local coordinates of a node/element in the ANSYS mesh.



E
1 External Data
2 Setup ✓
External Data

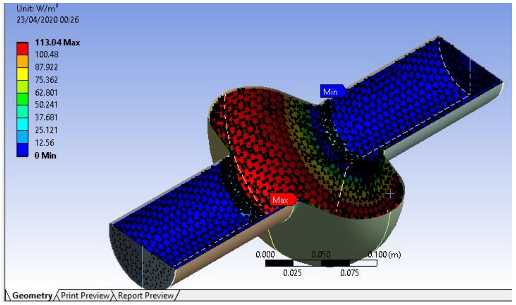
F
1 Steady-State Thermal
2 Engineering Data ✓
3 Geometry ✓
4 Model ✓
5 Setup ✓
6 Solution ✓
7 Results ✓
Rs _1.2GHz_9.4e-7ohm, 25MV/m, 4.2K, HTC=f(q)



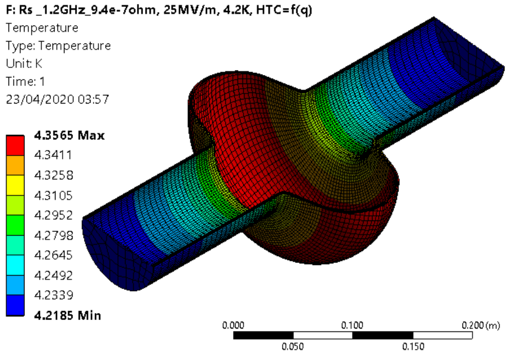
	A	B	C	D
1	X Coordinate	Y Coordinate	Z Coordinate	Heat Flux
2	-26.3972	71.2745	-39.2011	107.66228227
3	-0.0659	103.3000	-0.0825	112.04342790
4	-2.1641	-101.5980	11.1803	112.27954218
5	-2.1641	-102.9480	3.7674	112.12957155

From CST, a .txt file is generated with 4 columns: X, Y, Z and heat flux.

RF power density imported from CST to ANSYS

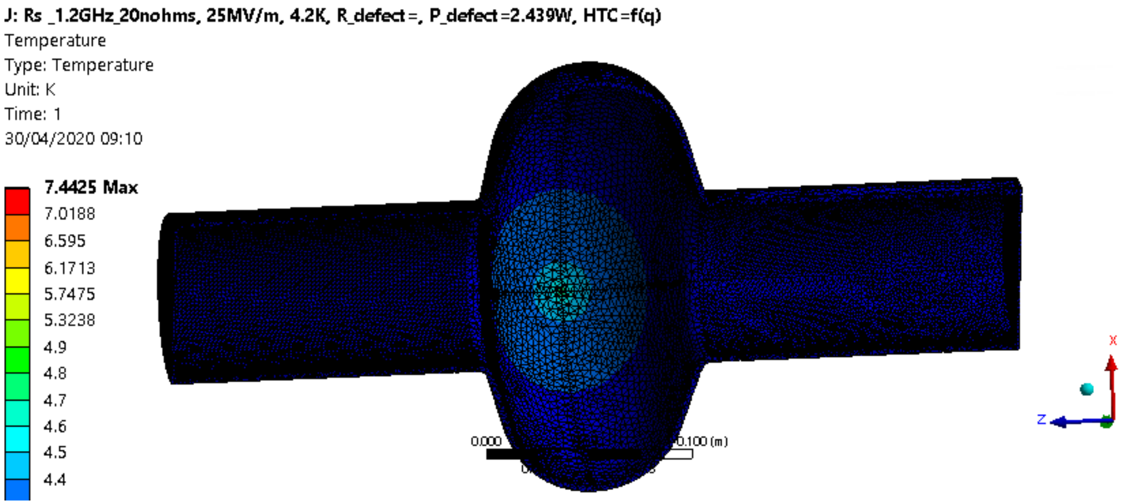


Temperature profile calculated for 25MV/m, 4.2 K bath



Example of temperature distribution in presence of a defect

Temperature profile calculated for 25MV/m, 4.2 K bath, with a defect of 0.01 cm, assuming a tool-steel particle



J: Rs _1.2GHz_20nohms, 25MV/m, 4.2K, R_defect =, P_defect =2.439W, HTC =f(q)

Temperature

Type: Temperature

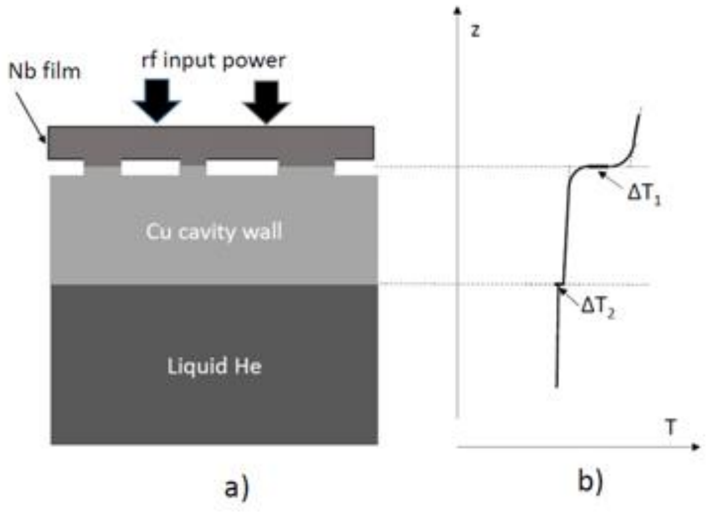
Unit: K

Time: 1

30/04/2020 09:10

Future studies: Including effect of blisters in the coating

- A bad adhesion of the film to the substrate can lead to thermal contact resistance of 110 cm^{2}K/W (Bonded contact would be 0.3 cm^{2}K/W)
- The interface Nb/Cu could be included in the simulations with the corresponding thermal resistance.



V Palmieri, and R Vaglio, Thermal contact resistance at the Nb/Cu interface as a limiting factor for sputtered thin film RF superconducting cavities, 2015, Superconductor Science and Technology, Volume 29, Number 1:

Wrap-up

- ✓ At CERN, RF characterization of thin films is carried out to find potential applications to SRF cavities.
- ✓ HiPIMS coatings applied to QPR samples have shown Q-slopes comparable to bulk Nb.
- ✓ When applying the same coating technique to 1.3 GHz cavities the RF performance is not as good as expected.
- ✓ Efforts should be put on:
  - **Specific optimization of the coating technique for the cavity geometry.**
  - **Have good substrates (seamless cavities with thermal mapping system)**.
- ✓ Simulations are powerful tools that can help us to keep investigating the mechanisms behind the Q drop .

Thanks for your attention.