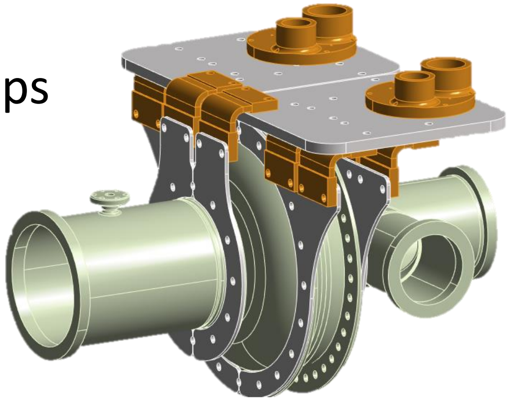
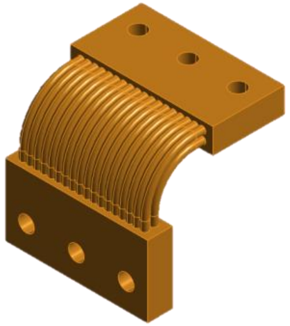
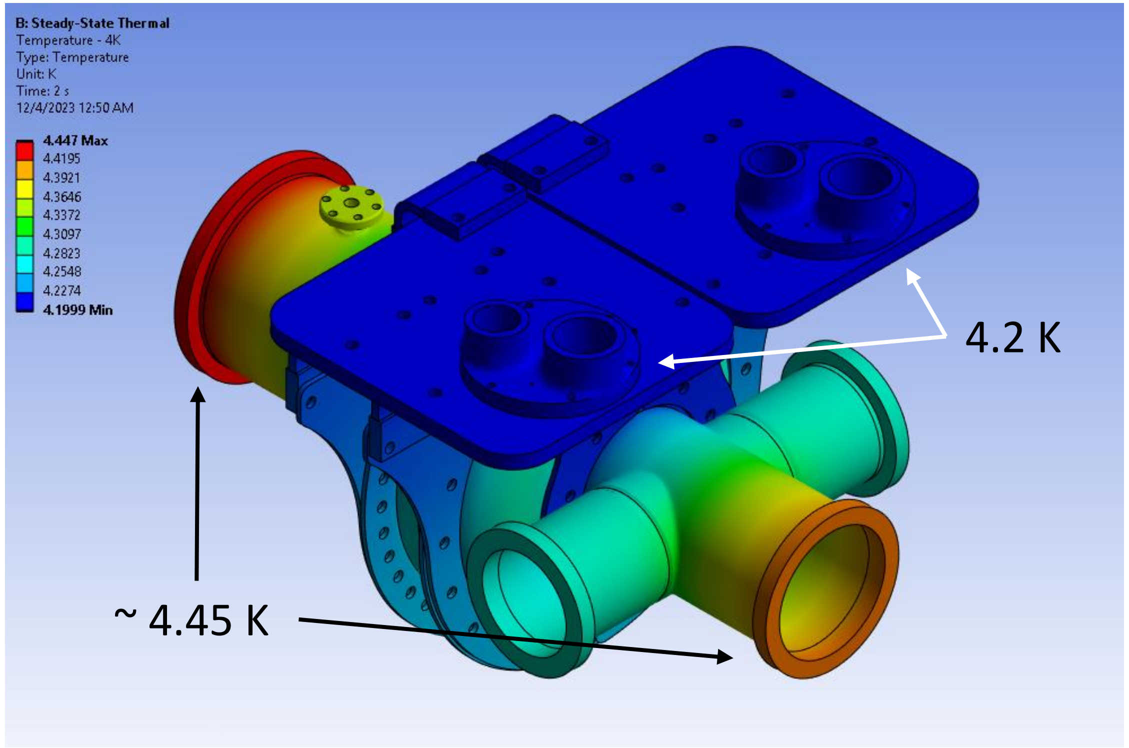
2a

Cornell Implementation

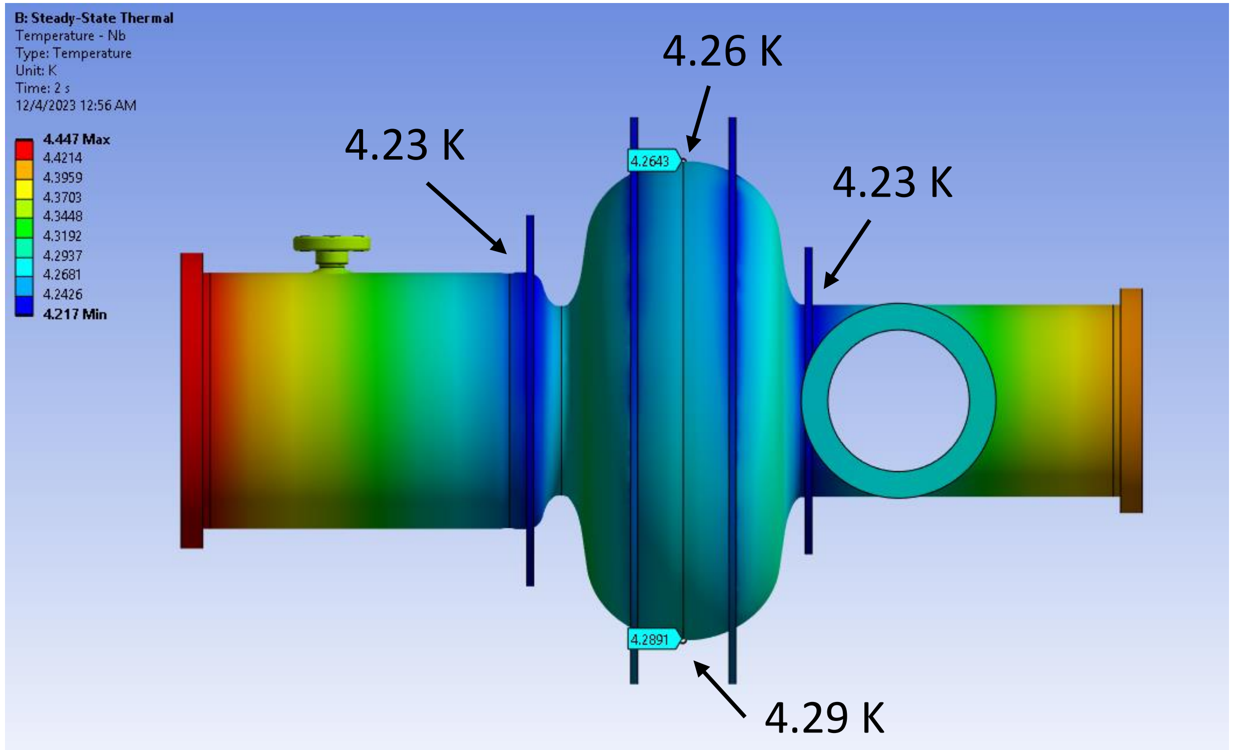
- Final design uses 5N Aluminum rings with copper braided thermal straps
  - High-purity Al offers high thermal conductivity with lower weight
  - Copper braided straps proved effective in previous experiments
- Cavity remains close to 4.2 K for high Q_0
- Uniform cooling around entire cavity cell → low thermal gradients







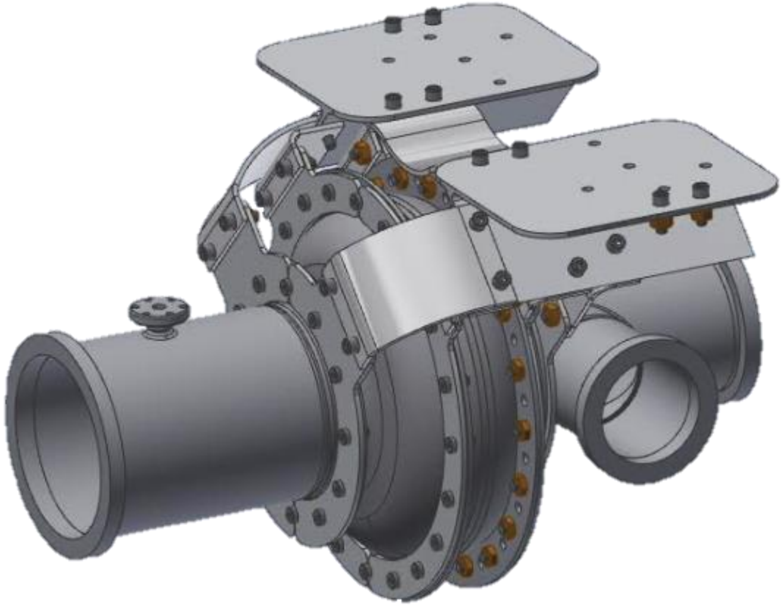
B: Steady-State Thermal
Temperature - 4K
Type: Temperature
Unit: K
Time: 2 s
12/4/2023 12:50 AM



B: Steady-State Thermal
Temperature - Nb
Type: Temperature
Unit: K
Time: 2 s
12/4/2023 12:56 AM

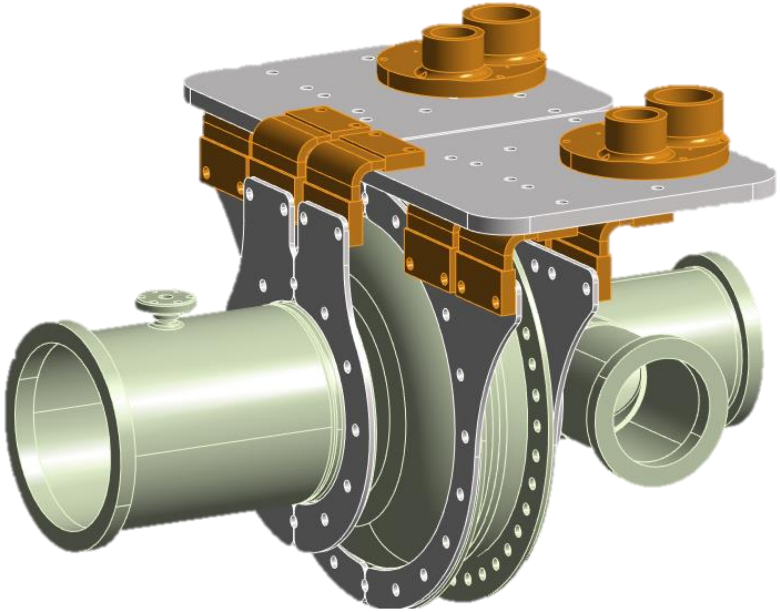
Primary Challenges

- Most challenges rise from practical limitations / obstacles
- Low contact resistance – requires good material, clean surfaces, improved with pressed indium
  - All become more difficult with full-sized systems
- Not much headroom at our operating parameters
  - Pushing fields much past 10 MV/m gets challenging
  - For constant ΔT across thermal link, required cross-section $\propto E_{acc}^2$
- Thermal link design may be restricted by technical limitations



Design iterations

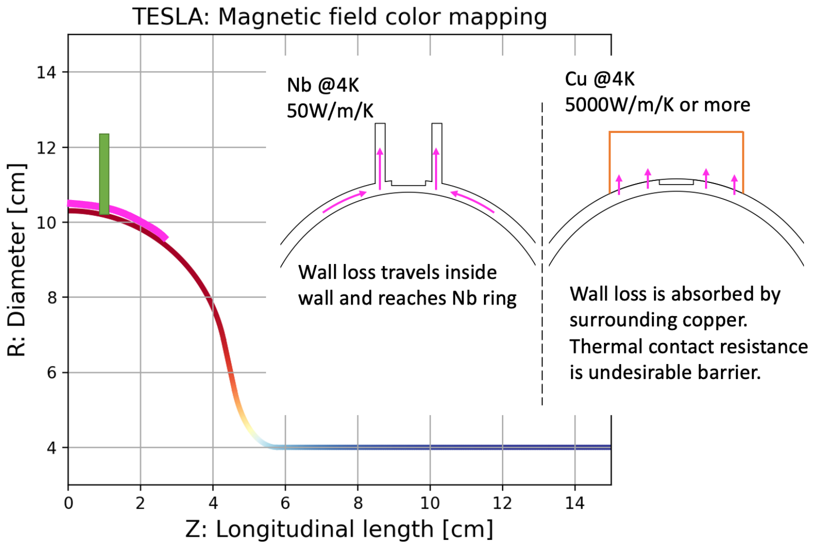
- Supply / vendor challenges
- Spatial requirements
- Simpler design (identical straps)
- Reduced cost



2b

Cooper ring strategy

- KEK adapted copper ring equator clamping as a first trial of conduction cooling.
- Reasons:
  - Cooling wide area of equator outside
  - Detachable system for Nb3Sn re-coating
  - (Short time implementation)

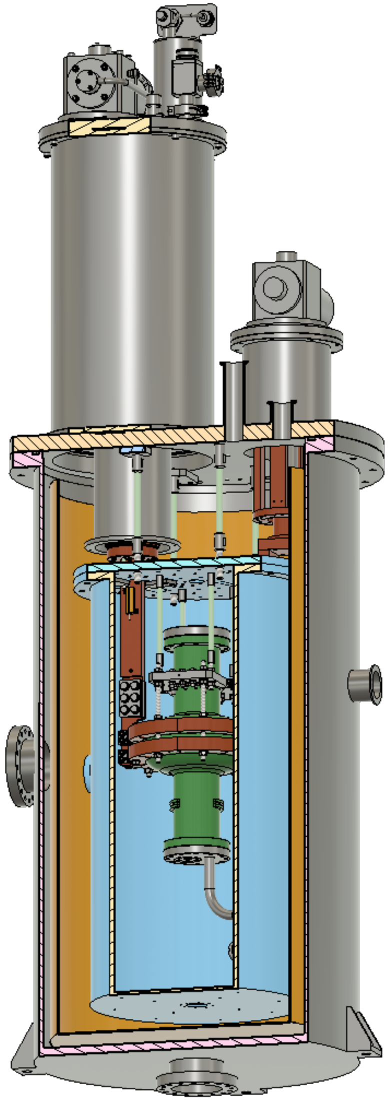

TESLA: Magnetic field color mapping

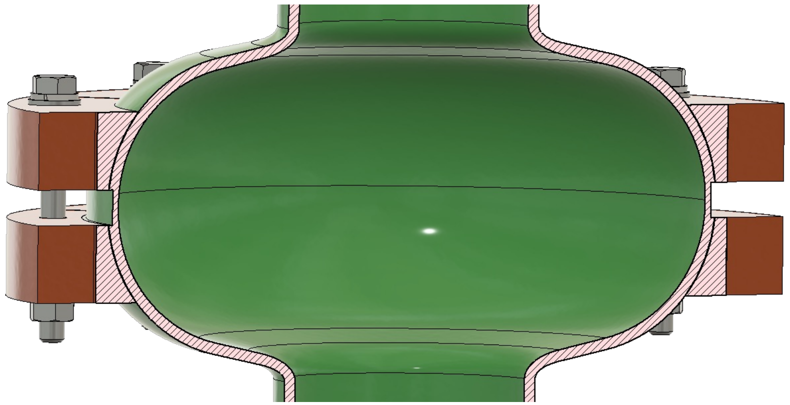
Nb @4K
50W/m/K

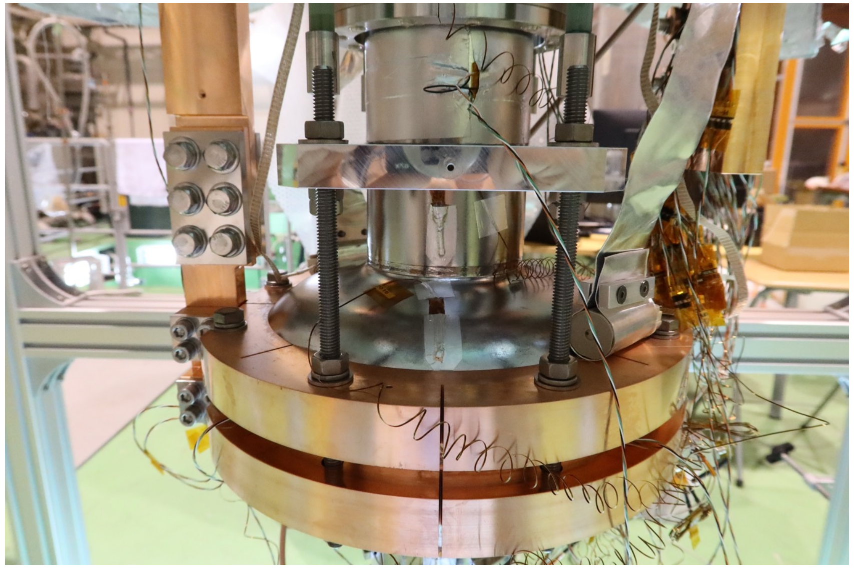
Wall loss travels inside wall and reaches Nb ring

Cu @4K
5000W/m/K or more

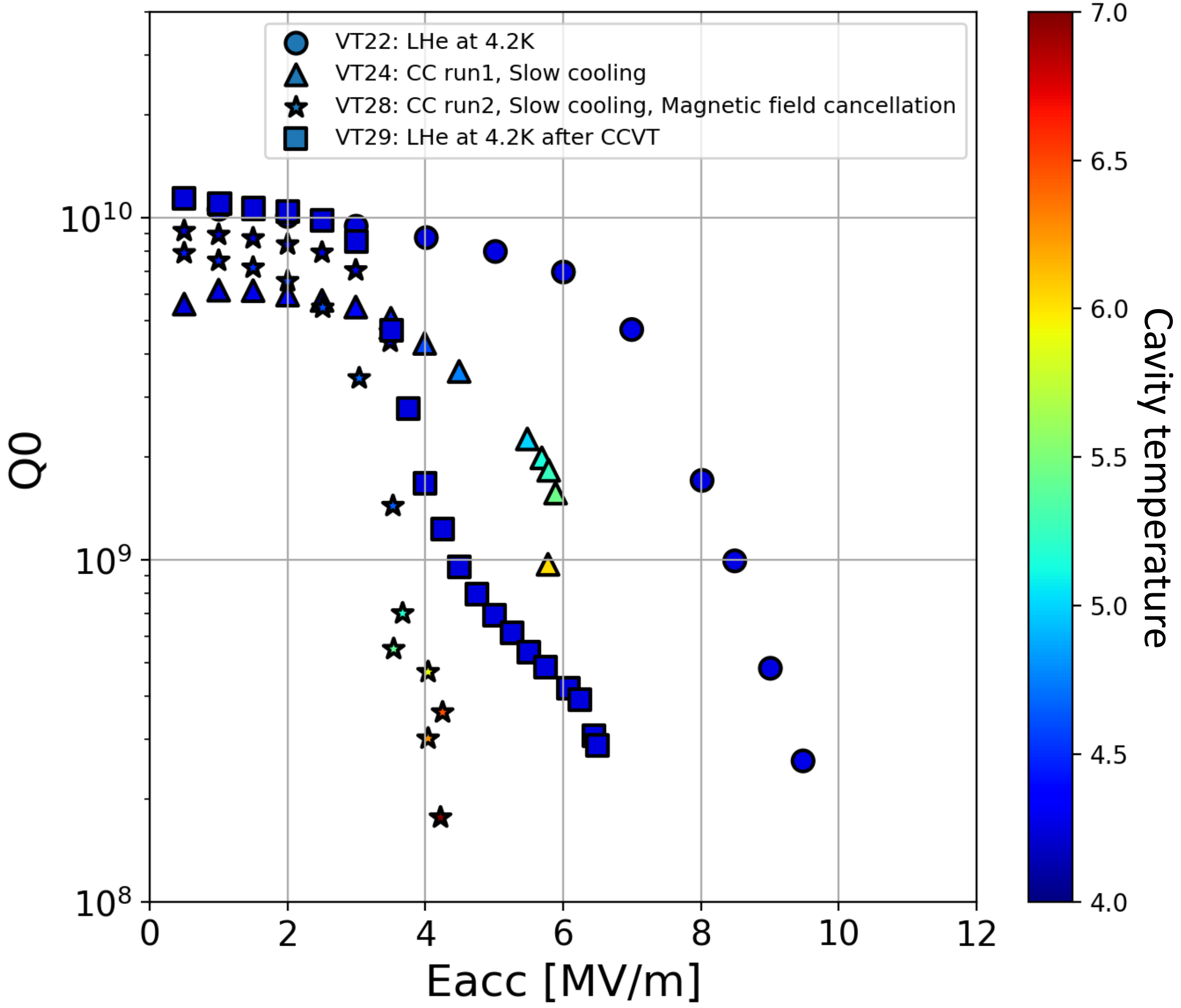
Wall loss is absorbed by surrounding copper.
Thermal contact resistance is undesirable barrier.







RF test with copper ring



Observation:

- Cooling speed (and temperature gradient) largely affected RF performance.
- Magnetic field was improved by cancelling magnetic field out.
- Nb3Sn film (~3um) was broken in the process of copper ring clamping. (It is possible to avoid film-breaking by assembly carefully.)

- The cavity was well cooled, however, the conduction cooling didn't show the QE curve as high as the LHe test. (Both residual magnetic field was almost same.)

Question:

- *Do we need to cover wider surface area of the cell?*

2c

The use of high purity aluminum for conduction cooling of SRF cavities

Ram C. Dhuley on behalf of Fermilab's conduction-cooled SRF project team

2023 TTC Meeting at Fermilab

07 December 2023

Fermilab's conduction-cooled SRF program is built on the use of high purity aluminum thermal links

Superconductor for Fermilab's CDF solenoid

Minemura, Kephart*, et al. (1985) https://doi.org/10.1016/0168-9002(85)91023-X

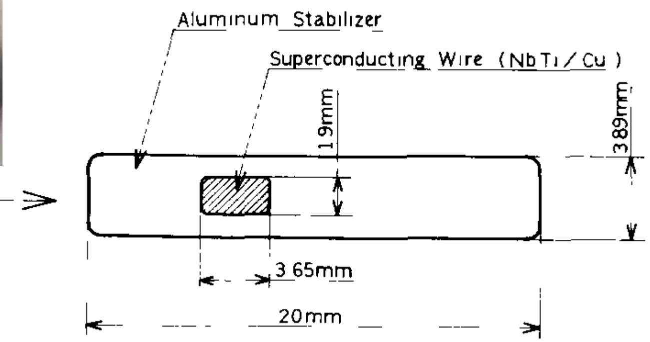
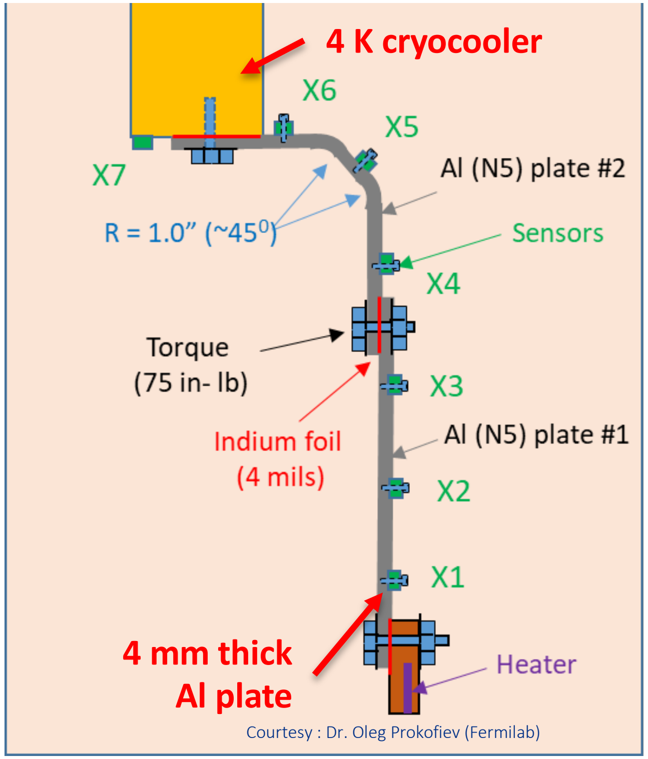


Fig. 3. Schematic diagram of the conductor cross section. The volume ratio of NbTi : Cu : Al is 1 : 1 : 21. The NbTi composite consists of 1700 × 50 μm diameter NbTi superconducting filaments. High purity aluminum of 99.999% is used. The orientation of the conductor in the coil is also shown.

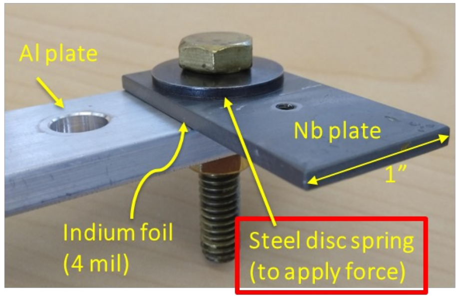
*R.D. Kephart is also the founding member of Fermilab's conduction cooled SRF program

High purity Al thermal conductivity, Al-Al and Al-Nb contact resistance near 4 K



Courtesy : Dr. Oleg Prokofiev (Fermilab)

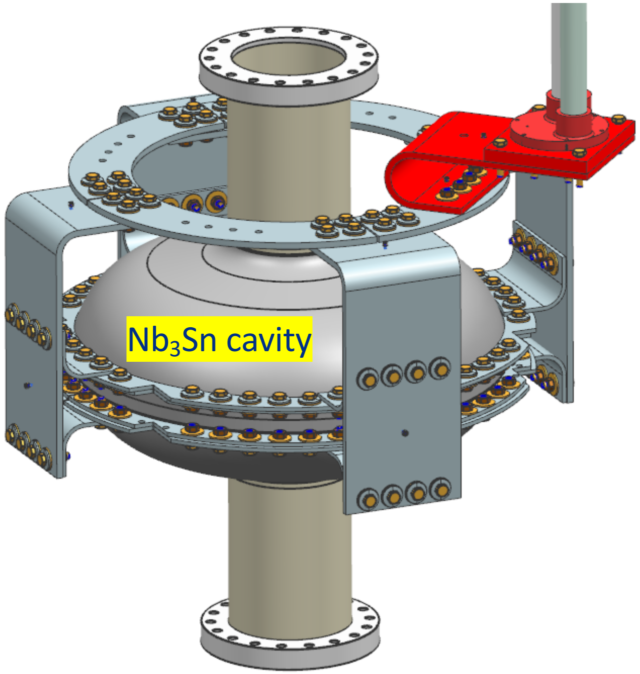
Nb-Al bolted contacts



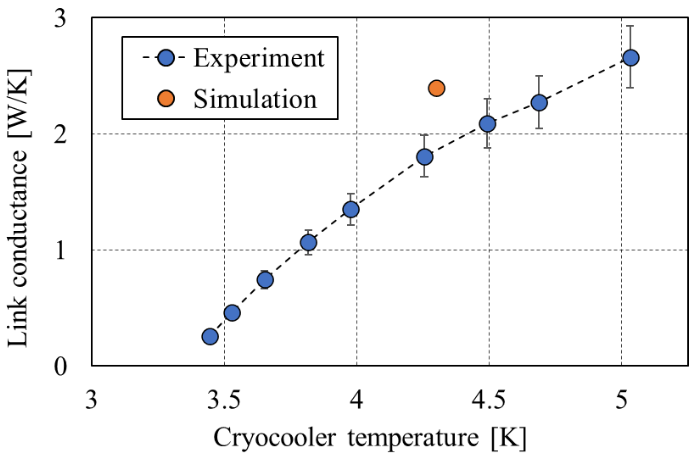
Data available at:
R.C. Dhuley, et al. (2018)
https://doi.org/10.1016/j.cryogenics.2018.06.003

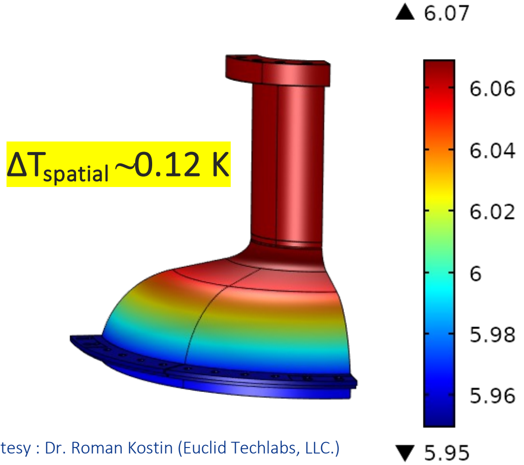
Fermilab’s conduction-cooled SRF program is built on the use of high purity aluminum thermal links

Al conduction link bolted to the Nb rings welded to the cavity



Comparison of measured and simulated link thermal conductance





Courtesy : Dr. Roman Kostin (Euclid Techlabs, LLC.)

Computed cavity surface temperature at steady state with ~10 MV/m cw

- Ring temperature = 5.95 K,
- RF dissipation = 2.4 W

R.C. Dhuley *et al* 2022 *IOP Conf. Ser.: Mater. Sci. Eng.* **1240** 012147

2d

Cooling link design for conduction cooled SRF cavity*

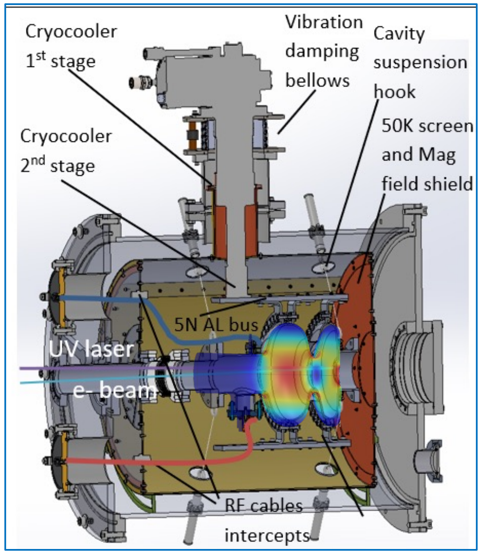
Roman Kostin, Euclid BeamLabs, Bolingbrook, IL, USA

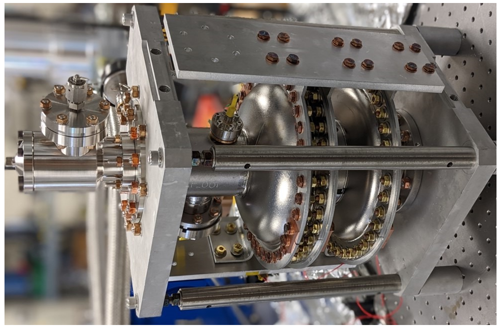
*Work supported by US DOE SBIR grant DE-SC0018621

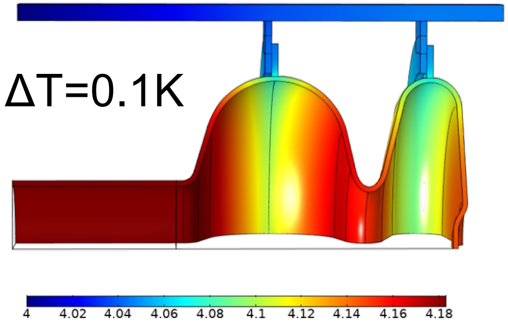
Cooling link design based on Nb equator ring and high purity AL

- Euclid develops Conduction cooled Nb_3Sn SRF photo-gun for UED/UEM
- Eacc=10 MV/m should be achievable with single cryocooler
- Cooling link design – Fermilab's approach:
  - EBW Nb equator ring + bolted 5N AL link
  - Differential thermal expansion safe
  - Simple manufacturing
- Stable operation regimes was simulated: 0.9 [W] dissipation; 1.1 [W] excess of cooling power

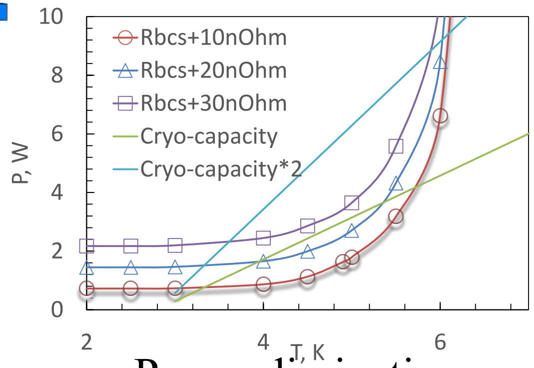
Parameter	Value
Frequency	1.3 GHz
Length	1.45cell (166.54mm)
Q0 at 4° K (Rs = 20 nΩ)	1.16×10^{10}
R/Q	176.9 Ω
Geometry factor	232 Ω
Wall Power dissipation	0.9 W
E on axis	20 MV/m
E max	23.5 MV/m
B max	43.3 mT
E acc	10 MV/m



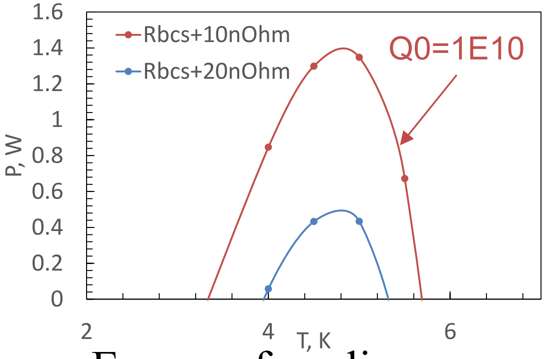

Cavity with the links



T [K] at Eacc=10 MV/m



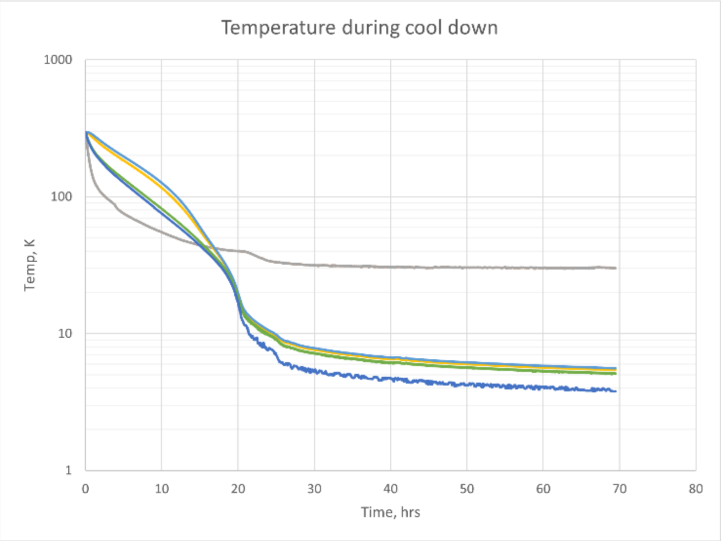
Power dissipation

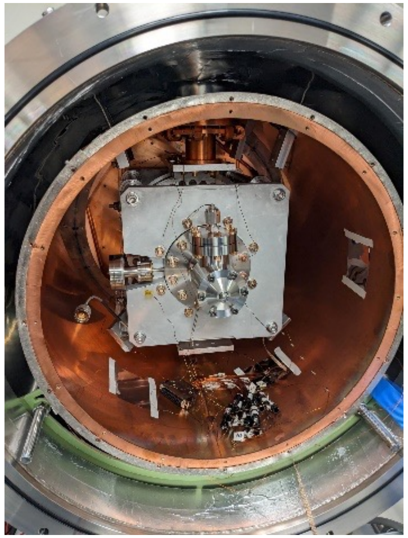


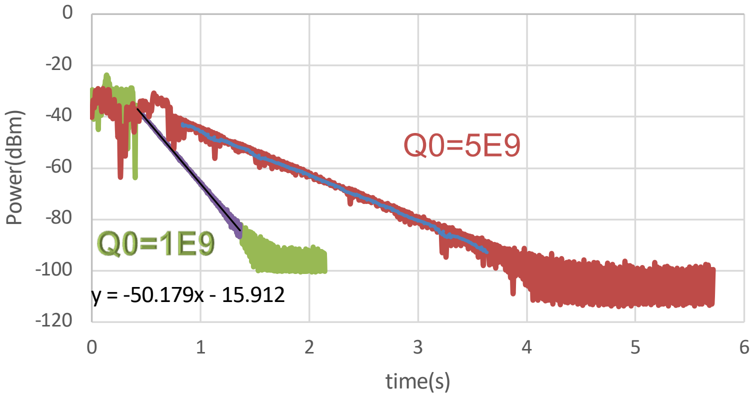
Excess of cooling power

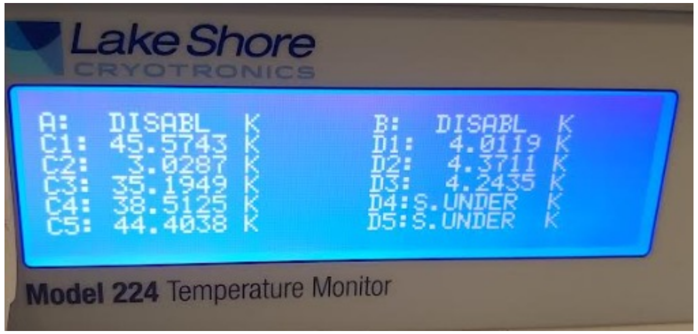
Cavity was cooled to 4.2 [K] in the conduction cooled cryomodule

- Nb3Sn Cavity in VTS: Q0=7e9
  - Contaminated during deposition
  - Recoat is planed
- 1st Cryomodule results:
  - Q0=1E9 - fast cool down
  - Q0=5E9 – controlled cool down
  - Cavity temperature ~4.2 [K] w/o Apiezon or Indium
  - Links polishing and Apiezon to improve contact are underway









```
A:  DISABL   K        B:  DISABL   K
C1: 45.5743  K        D1:  4.0119  K
C2:  3.0287  K        D2:  4.3711  K
C3: 35.1949  K        D3:  4.2435  K
C4: 38.5125  K        D4:S.UNDER   K
C5: 44.4038  K        D5:S.UNDER   K
```

- C1 - Back of the radiation screen
- C2 - 2nd Stage of the cryocooler
- C3 - Inner Braid ring: screen to chimney
- C4 - 1st Stage of cryocooler
- C5 - Front of the radiation screen
- D1 – Cavity Top
- D2 – Cavity Bottom
- D3 – Cavity Middle

2e

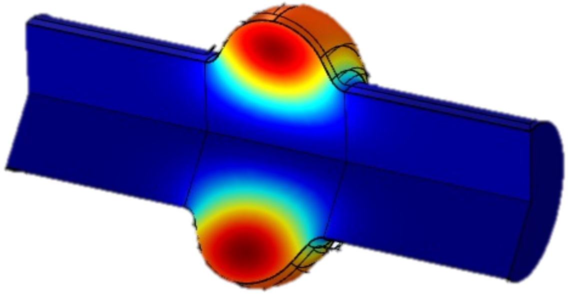
DE LA RECHERCHE À L'INDUSTRIE

Funding P2IO « projets émergents »

3D printing R&D of Cu SRF cavities

Q. Ponchon[1,2], F. Lomello[1], C. Verdy[3], J. Drant[1], K. Danfakha[1], J. Rathore[4], F. Eozenou[1], G. Devanz[1], F. Miserque[1], N. Delerue[2], C. Marius[4], V. Stepanov[1], B. Baudouy[1], T. Proslier[1].

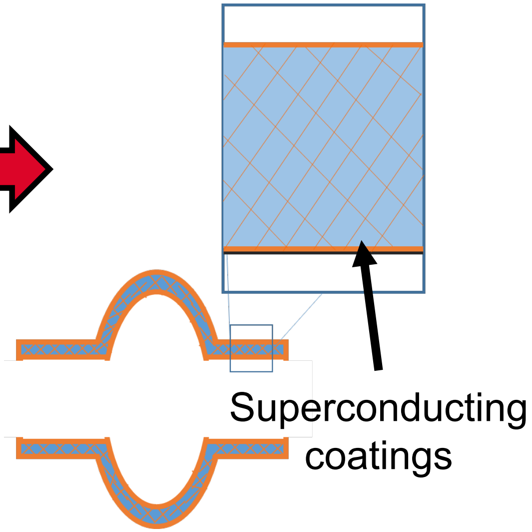
1) CEA (IRFU, DES), 2) IJCLab, 3) UTBM, 4) DIGITEO-Saclay,



$$P = \frac{1}{2}\int r_s * H^2\, ds$$

Inhomogeneous dissipation

Proposed approach:



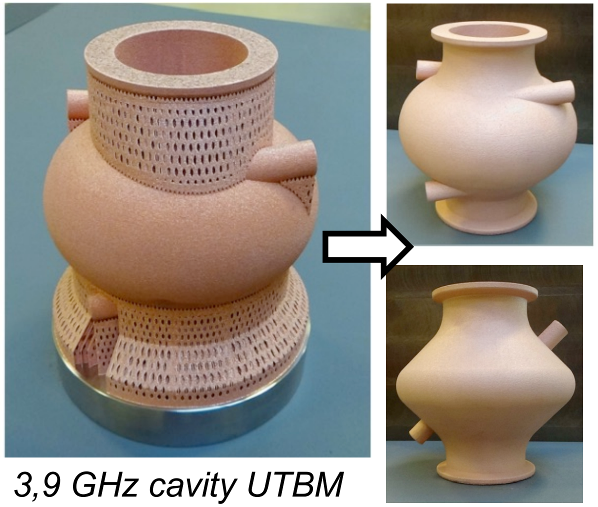
- ➢ **Cryogenic cost optimisation.**
- ➢ **No welds.**

- ➢ **Matérials :** Cu + superconducting films (Nb, Nb_3Sn, MgB_2)
- ➢ **Fabrication :** additive manufacturing + coatings.
- ➢ **Cool down :** « dry » cavities – Cryocoolers

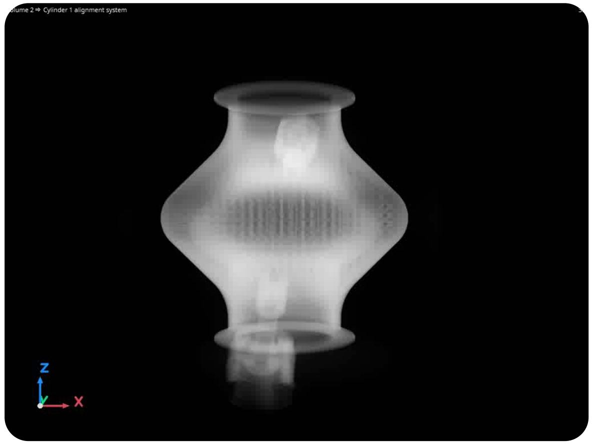
OPTIMISATION OF SLM PROCESS - SUPPORTS

- ➢ SLM pur cooper parameters:
- ▪ Density > 99.5%
- ▪ Leak test successfull (≤ 10^{-11} mbar.l.s^{-1})
- ▪ RRR = 77
- ▪ Thermal conductivity at 6,9K: 835 W/m.K (RRR = 80)

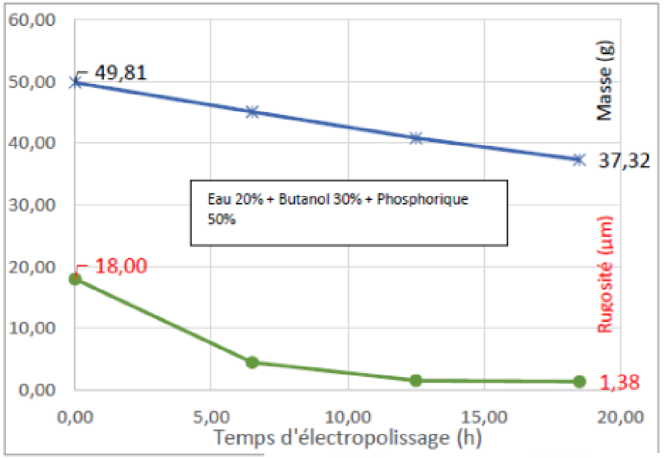
- ➢ Test different construction strategies of a 3,9 GHz cavity – pur Cu
- ▪ Optimisation of the support for the cavity inside walls

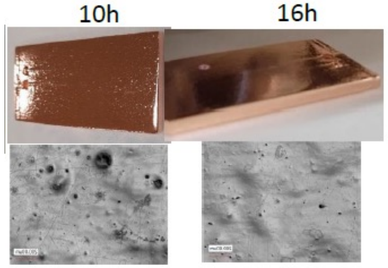


3,9 GHz cavity UTBM



X-Ray Tomography, Plateforme Digitéo.



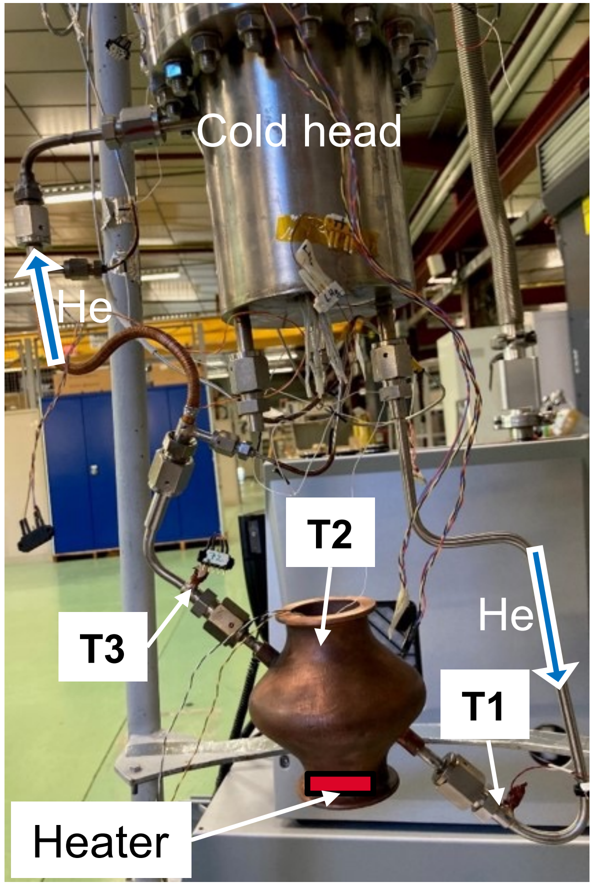


Confocal PANAMA

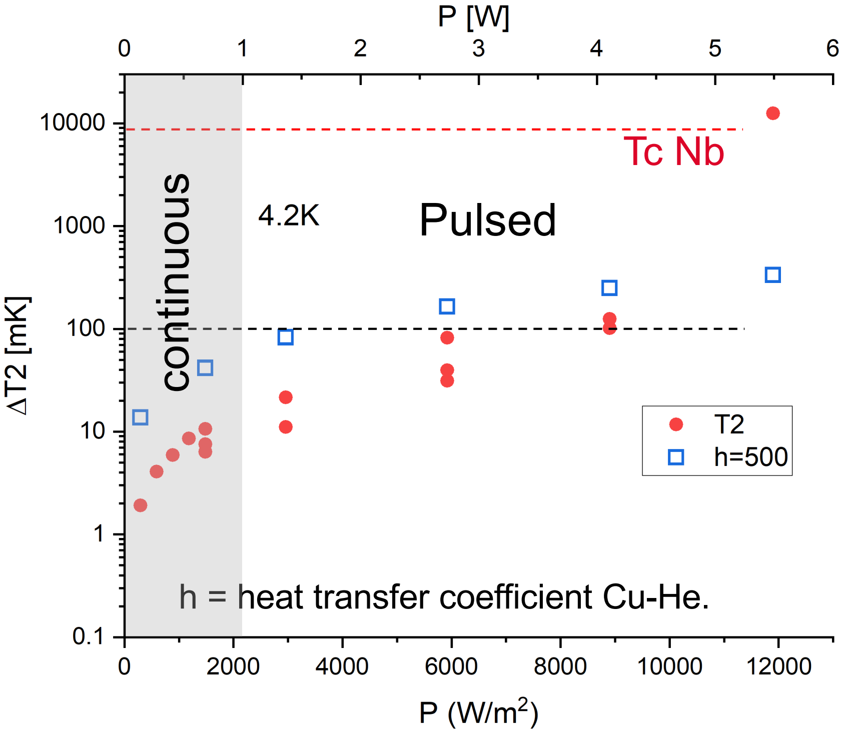
- ➢ Chemistry: EP Water (20%) + Buthanol (30%) + Phosphoric acid (50%)
- ▪ Roughness down to 1.3-1.4 µm (avoid mechanical poslishing).
- ▪ Tests on Cu cavities ongoing

CRYOGNEIC TESTS – PUR CU

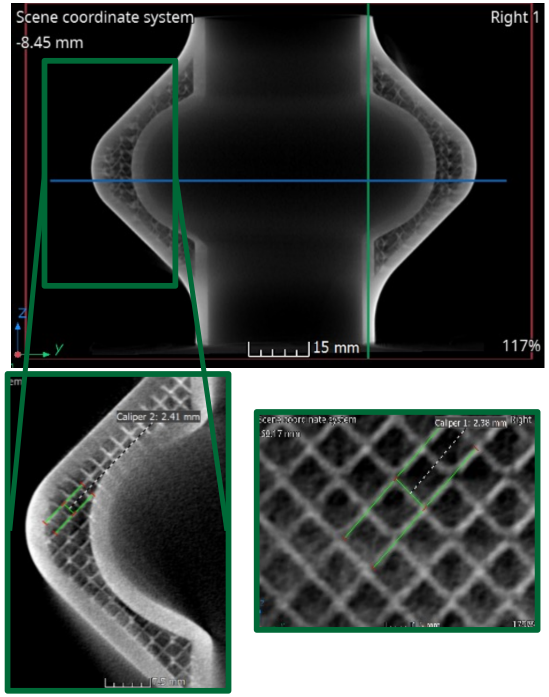
- First closed loop cryogenic test on a « lattice » 3,9 GHz cavity.
- VCR connectors brazed on Cu.



- Tests at 4,2 and 4,5 K. Cryocooler power: 1,1 W and 1,5 W– cold head (reservoir).
- Thermal insulation around the cavity + cold head.
- P= 1 Bar at 4,2 K et 1,3 bar at 4,5 K.
- Static vacuum (5.10^{-7} mbar).
- Heater simulate the RF power.
- Cernox: T1 et T3 before and after the cavity, T2 inside the cavity.



h = heat transfer coefficient Cu-He.



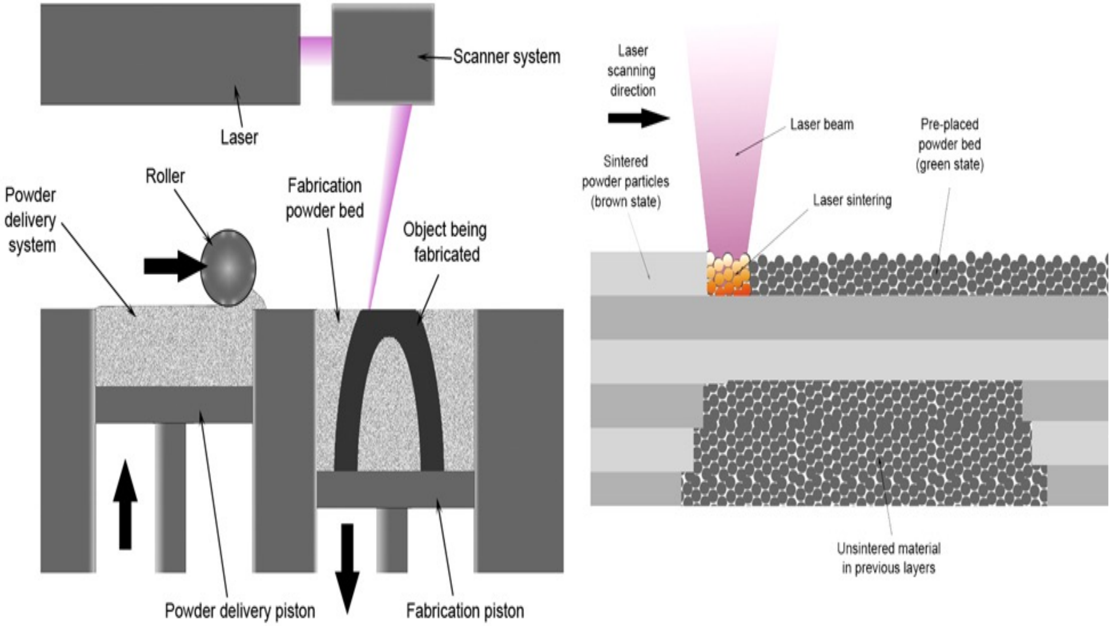
Thanks for you attention !

Questions?

SELECTIVE LASER MELTING - COPPER

Freedom of forms with SLM

Principle of SLM



material selection – thermal conductivity

	Thermal conductivity at 293K (W/m/K)	**Thermal conductivity at 4K (W/m/K)**
Cuivre (RRR =30)	380	183
Niobium (RRR = 200)	60	40
Aluminium (RRR = 30)	220	110
316L	12	<1
TiAl6V	7	<1

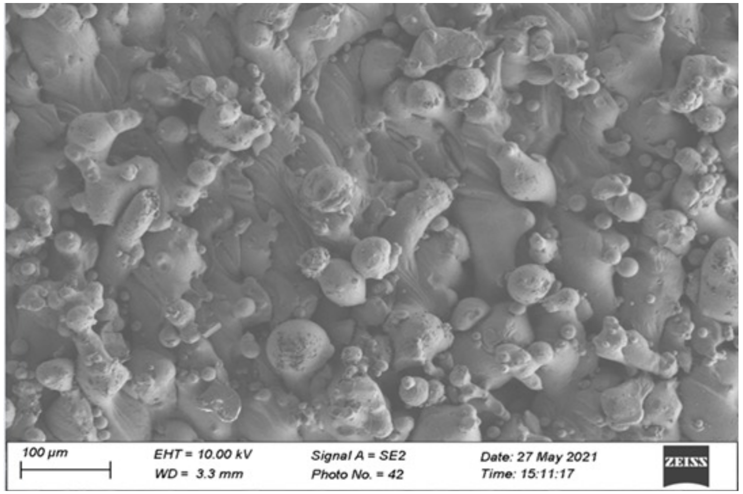
Known problem of Copper SLM

- Bad energy absorption by the powder (λ = 1070nm)
- High thermal conductivity that dissipate rapidly the energy

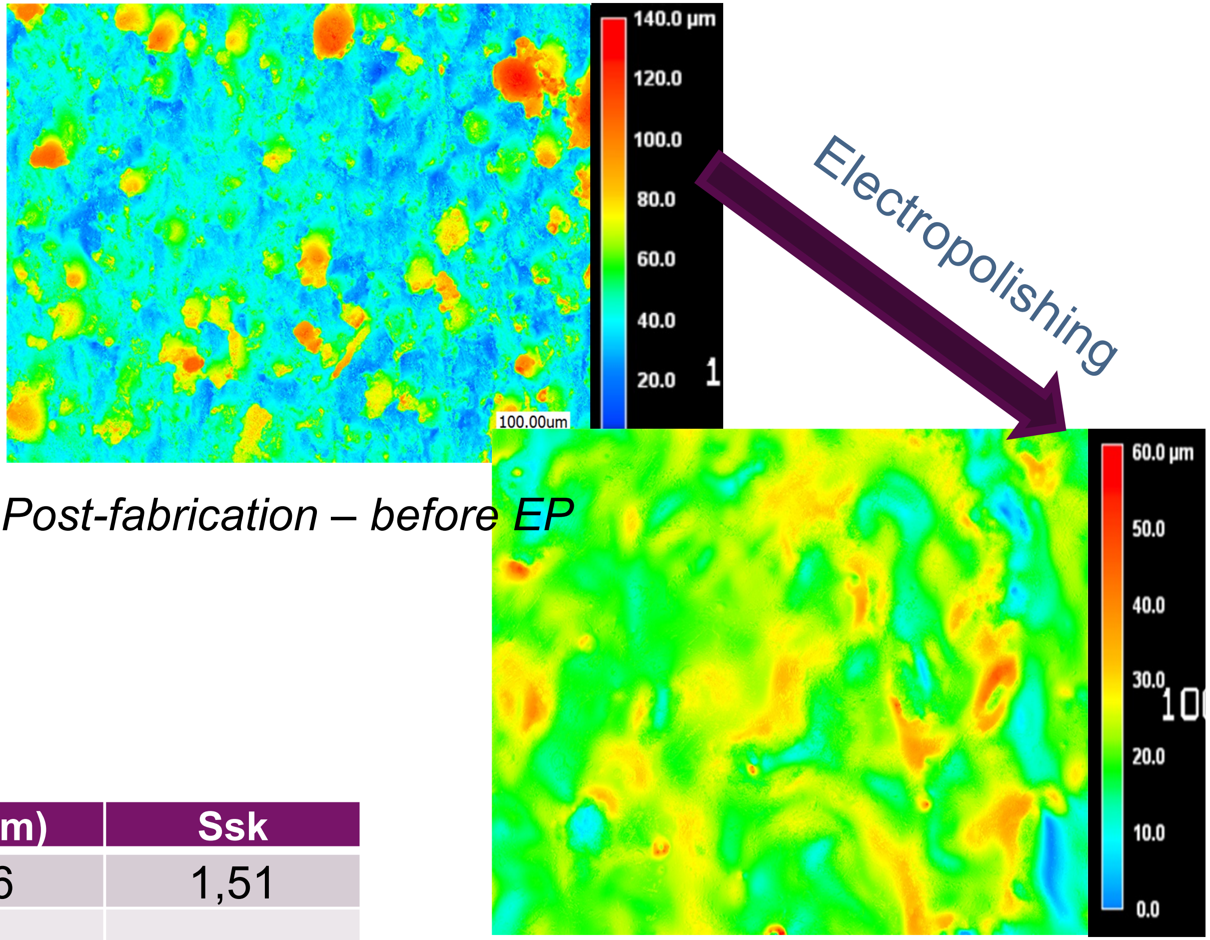
POST-TREATMENT : SURFACE ROUGHNESS AND ELECTROPOLISHING

- ➢ Improve roughness (future coatings): EP – Goal ~ 1 µm

- ▪ Rough surface with partially melted particles



As built surface state– CuCrZr / Cu/ A205



Post-fabrication – before EP

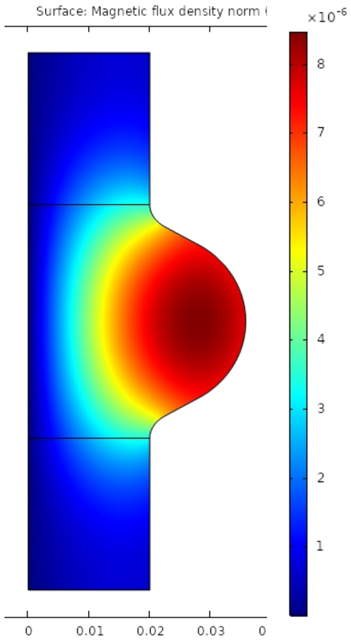
After EP

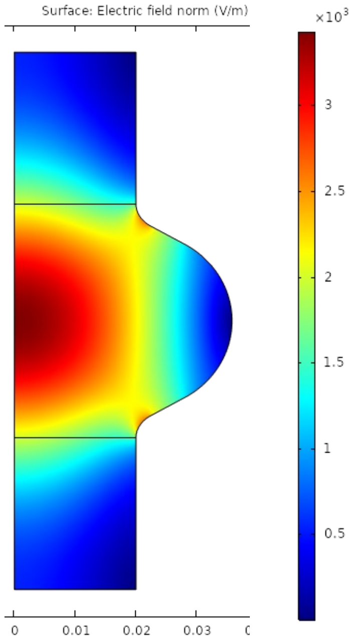
	Sa (µm)	Sz (µm)	Ssk
Before EP	12,9	186	1,51
After EP 95 % density	3,9	62	0,14
After EP 85% density	16	163	/

- ➢ Increased density of the material improve the effectivness of Electropolishing.

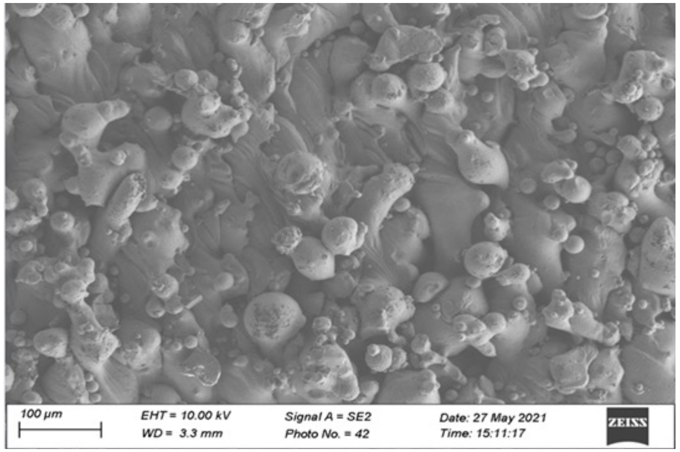
WARM RF TESTS

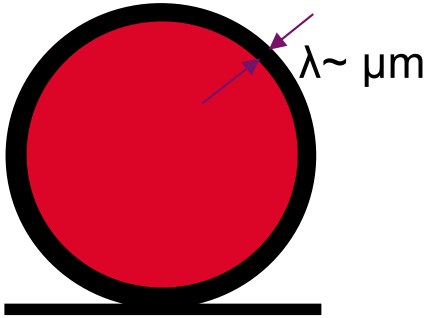
- Design type XFEL: G = 312.83 Ohm, f_0 = 3,8962 GHz





- Roughness -> increase the effective surface area if λ < surface structure size (grains ~ 30 µm)





Estimation ~ facteur 4

cavité	F_0 (GHz)	Q_0	Rs (mΩ)	ρ (µΩ.cm)	λ (µm)
Cu + US	3,9904	9200	*34* – **8,5**	*46* – **2,8**	*13.5* – **3,3**
Cu + light EP	3,999	13 000	*24*	*23*	*9.5*

$$R_S = \frac{G}{Q_0}\ ;\ \rho = 2\frac{{R_S}^2}{\omega.\mu_0}$$

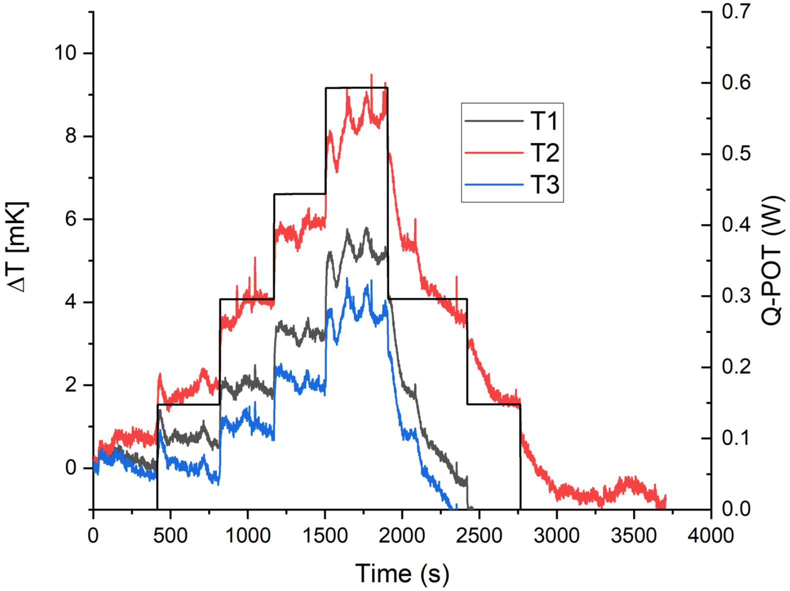
$$\lambda = \frac{\rho}{R_S}$$

- Mesure ρ_{Cu} = 2,5 µΩ.cm at 300K (ref ~ 1,6 µΩ.cm)
- Surface state -> $G_{effectif}$~ G/4; after light EP $G_{effectif}$~ G/2,85

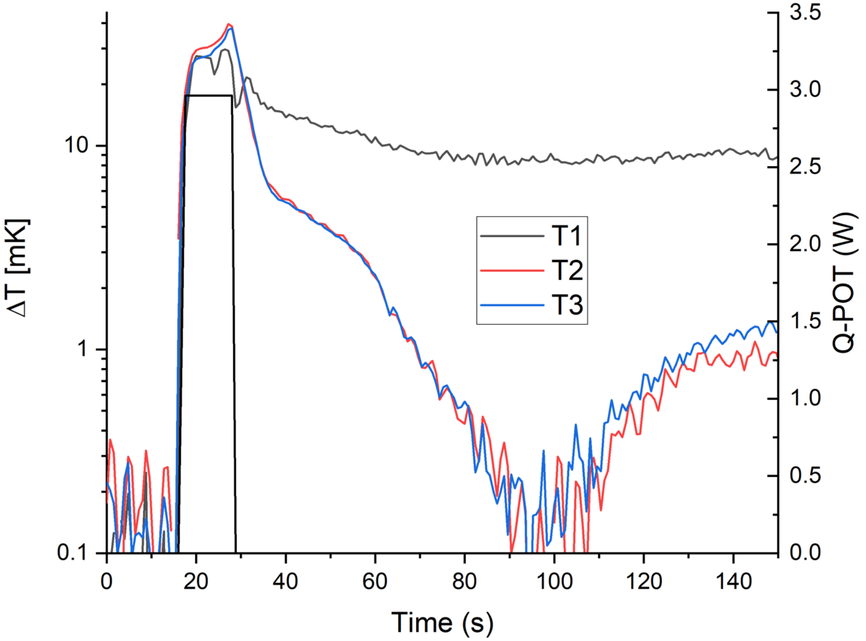
TESTS CRYOGÉNIQUES – CU PUR

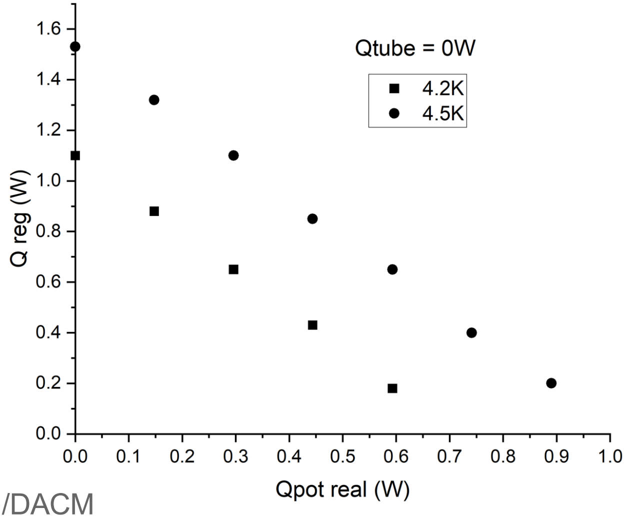
- Deux régimes de puissances délivrée à la cavité:

Mode « continu »



Mode « pulsée »

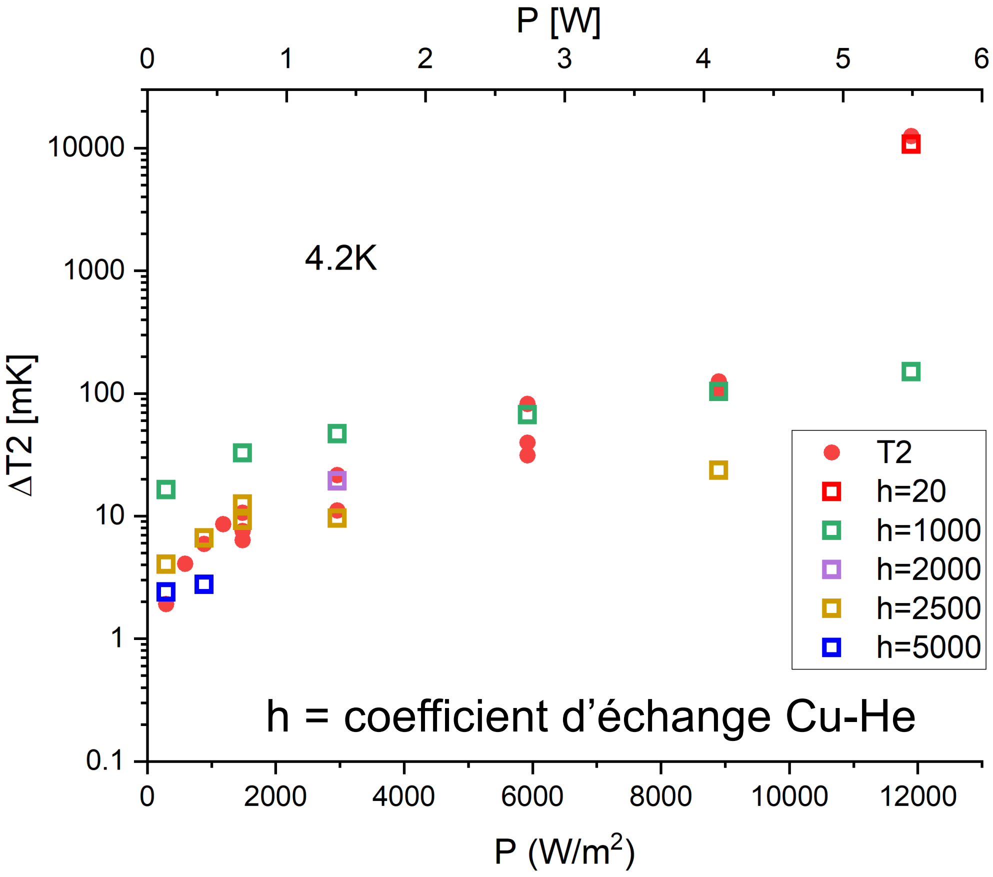




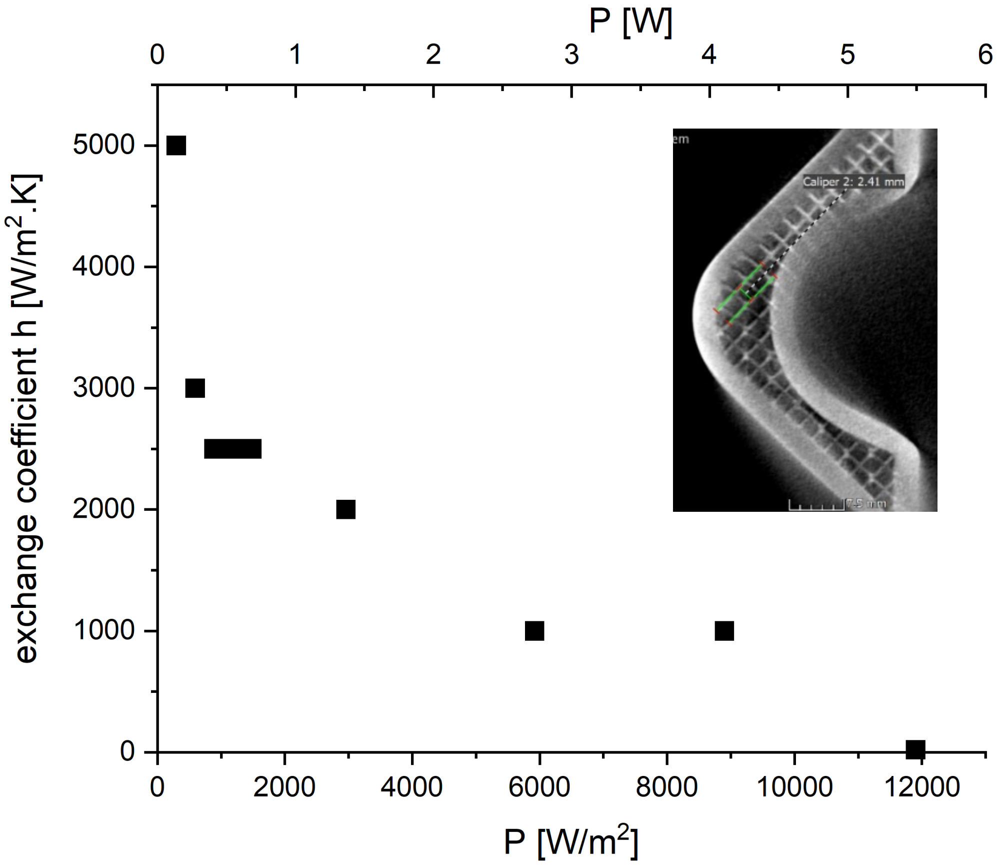
- Continu: équilibre des températures. t=408 s, P = 0.15, 0.3, 0.44, 0.6, 0.75 W. Limitation: puissance du cryocooler.
- Pulsé: Hors équilibre – 8-15 s, 1.5, 3, 4.5, 6 W.
- $\Delta T_i = T_i - 4{,}2$ K (ou 4,5K)

THERMAL NUMERICAL SIMULATIONS

- COMSOL on a « lattice » cavity



h = coefficient d’échange Cu-He



- Cu-He exchange coefficient h decreases as P increases

  -> effective exchange surface decreases (vapor surfaces increases – roughness?)

CONCLUSIONS & PERSPECTIVES

Conclusions:

- Material choice: Cu pur
- SLM : maximal density + internal structure support + flexibility but slow.
- Surface roughness: "simple" approach - acid less toxic/corrosive, roughness ~1,3 µm.
- Good quality Cu (RRR~ 80 and thermal conductivity 835 W/m.K at 6,9K)
- Leak tests successfull.
- Cryogenic tests successfull.

Perspectives:

- Cryogenic tests (RRR et Cryo loop).
- Optimisation of the structure.
- Other 3D printing approaches ?
- Coating – surface interactions ?

Futur challenges:

- Vibrations cryocooler
- Connections to HOM/couplers