DE LA RECHERCHE À L'INDUSTRIE

3D additive fabrication of Cu cavity with cooling channeling at CEA.

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

18/09/2024

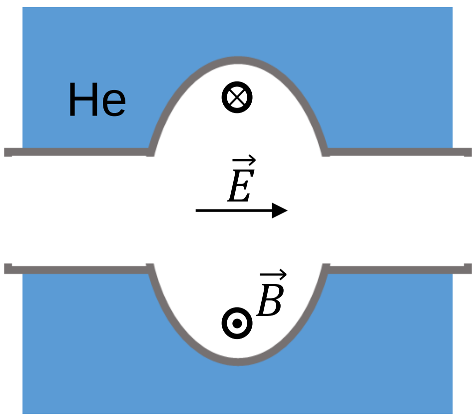
MOTIVATIONS

ADDITIVE MANUFACTURING

CRYOGENIC TESTS

CONTEXTE

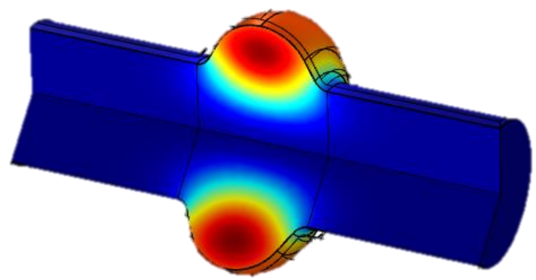
Current Technology



- **Material :** Niobium
- **Fabrication :** Mecanics-welded
- **Cooling :** Liquid He bath

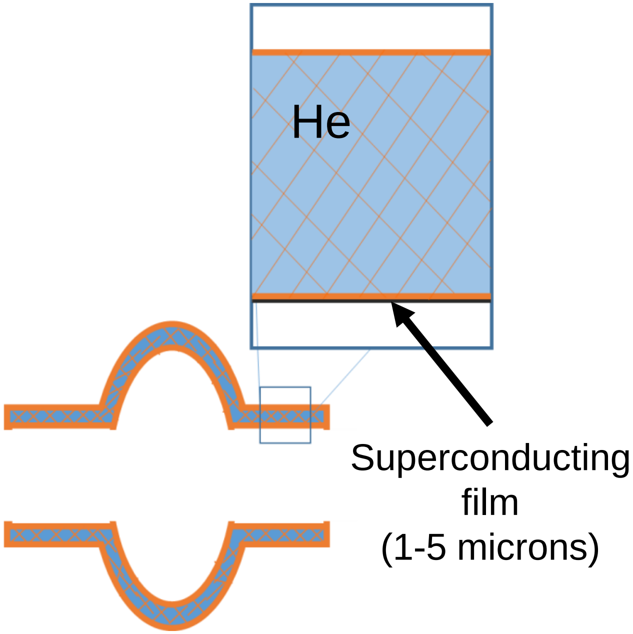
$$P = \frac{1}{2} \int r_s * H^2 \, ds$$

Non-homogeneous dissipation



- **Cryogenic cost reduction**
- **No welding.**

Objective



- **Materials :** Copper (substrat) + superconducting film (Nb, Nb_3Sn, MgB_2…)
- **Fabrication :** additive manufacturing + thin film deposition
- **Cooling :** Liquid He / cryocoolers

CONTEXTE

- *European strategy for particle accelerator: Yellow report CERN – RF/cavities*.

- Lower cost and environnemental footprint:
  - Material (Al, Fe, Mg, Si…): lower quantities of Cu, Nb, Sn…(thin films)
  - Helium consomption: use only necessary quantities in closed loop.
  - Chemistry: less toxic and costly chemicals.

- Technical challenges for 3D printing:
  - High vacuum (leak tests).
  - Surface roughness.
  - Thermal conductivity.
  - What cooling strategy?

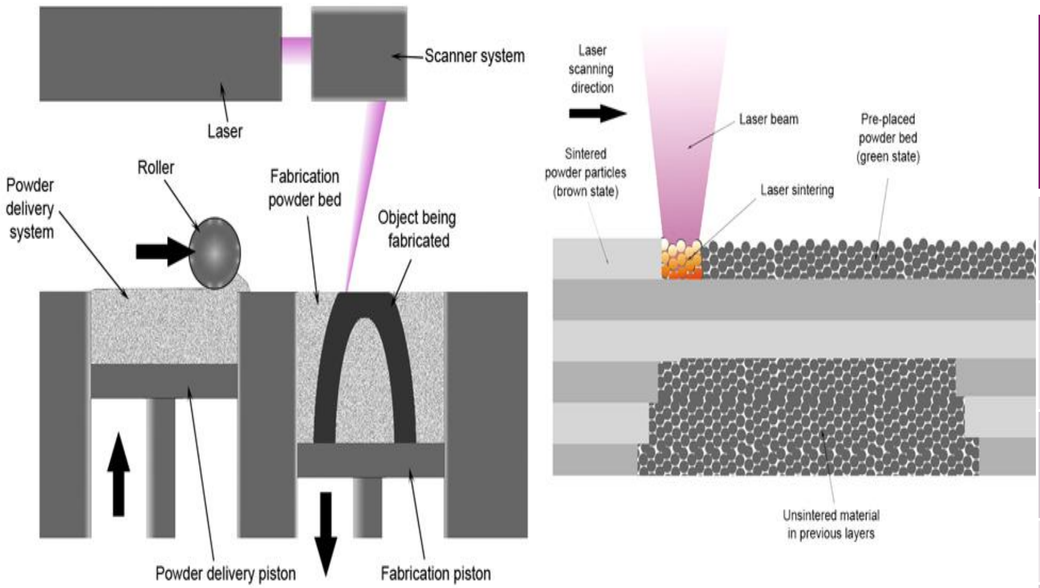
MOTIVATIONS

ADDITIVE MANUFACTURING

CRYOGENIC TESTS

Freedom of design with additive manufacturing

SLM Principle



	Conductivité thermique à 293K (W/m/K)	Conductivité thermique à 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

SLM PROCESS OPTIMIZATION– DENSITY

- Process parameters:

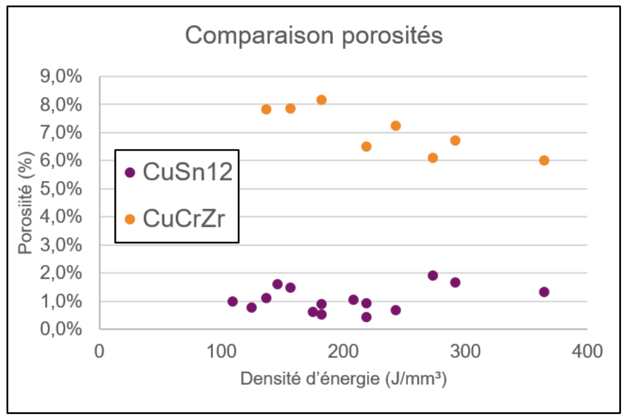
P: Puissance Laser	v : Vitesse laser	t : Épaisseur de couche	h :Écart vecteur	E : Densité d'énergie	Densité
(W)	(mm/s)	(µm)	(µm)	(J/mm^3)	%
175	700	30	60	139	**~85%**
175	250	30	70	333	**~95%**

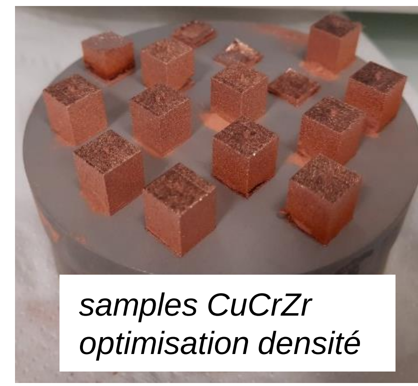
Principal paramètre :

$$E = \frac{P}{v\,t\,h}$$

- alloys CuCrZr, CuSn
  - Hands on experience with SLM of metals.
  - CuCrZr density ~ 94%
  - CuSn density ~ 99%

Plateforme Samantha (CEA-DES)
Red Laser (1070 nm)



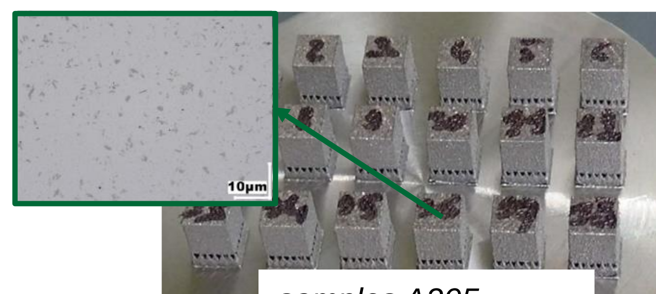


samples CuCrZr optimisation densité

- Cu pur: SLM, 485 W, 600 mm/s, powder Cu-OFE – 30 microns
  Densité > 99,5 %

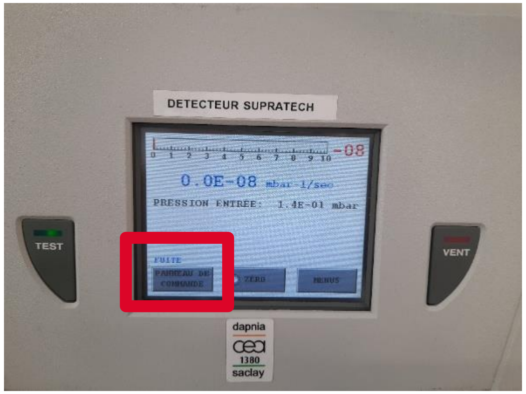
- Alliage Al 205: FLLP, 300 W, 1350 mm/s
powder Al 205 (1,5% de TiB_2 + Cu 4,6%) – 45 microns –
Densité > 99,5 %

Plateforme UTBM
Laser vert (515 nm)



samples A205 optimisation densité

FLLP PROCESS OPTIMIZATION– LEAK TESTS



Test UHV

Feasibility studies of complex shapes (internal lattices)

Double wall CuCrZr pot

- Machining CF 40 flanges.
- Leaks for a density of 94 % - wall thickness: 2mm

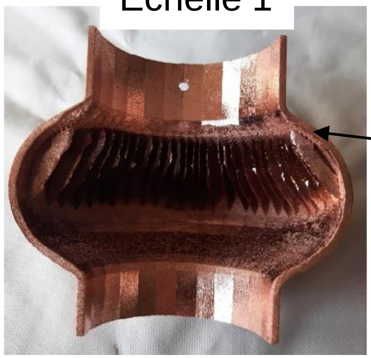
- Cu pur, Al 205 densité > 99,5% no leak between all volumes/walls and under prolonged He exposure (1/2 hrs).

Pur Cu 3,9GHz cavity

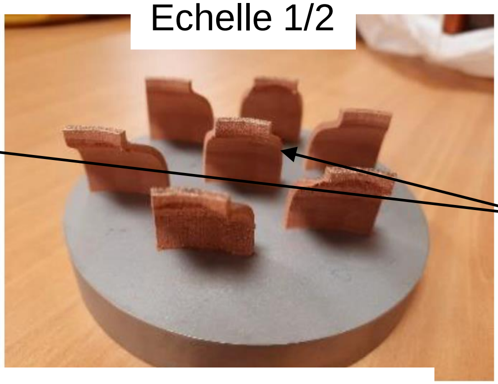
SLM BUILD UP STRATEGIES - SUPPORTS

- Test different construction strategies for a cavity (3,9 GHz) - CuCrZr

Echelle 1



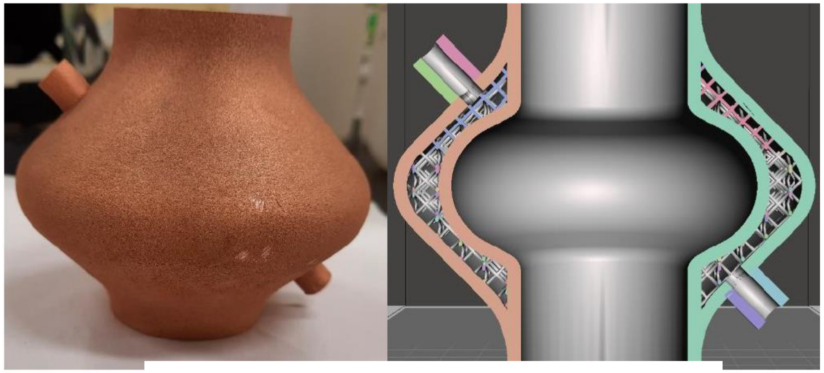
Echelle 1/2



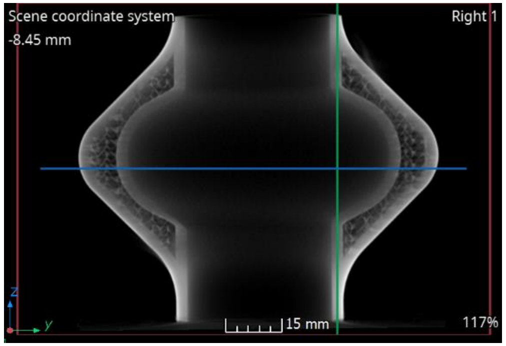
- Critical angle 30° (45° Ok)
- FLLP optimised for a support free build up
- CuCrZr (CEA-platforme Samantha)

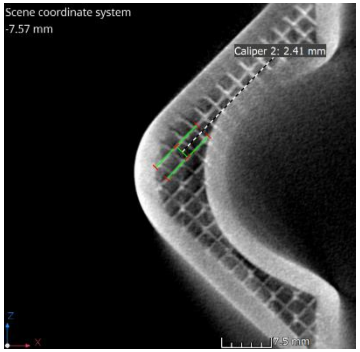
FLLP strategy, with (left) et without (right) supports

- Application to a« real » cavity. OK .



Cavité 3,9 GHz without supports





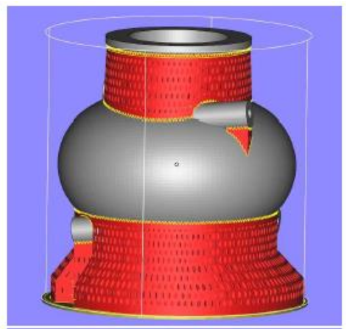
- Tomography Digitéo-Saclay.

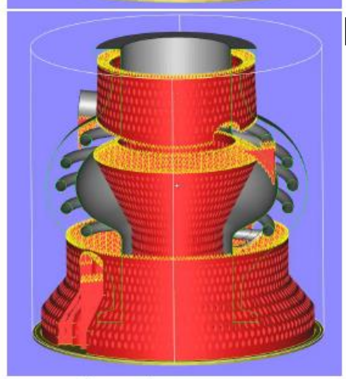
FLLP BUILD UP STRATEGIES - SUPPORTS

➢ Test different construction stratégies for a cavity (3,9 GHz) – Cu pur et Al 205

- Failure upon apply the strategies to pur Cu at UTBM (or Al 205) with 515 nm laser.
- Support Optimization inside the cavity

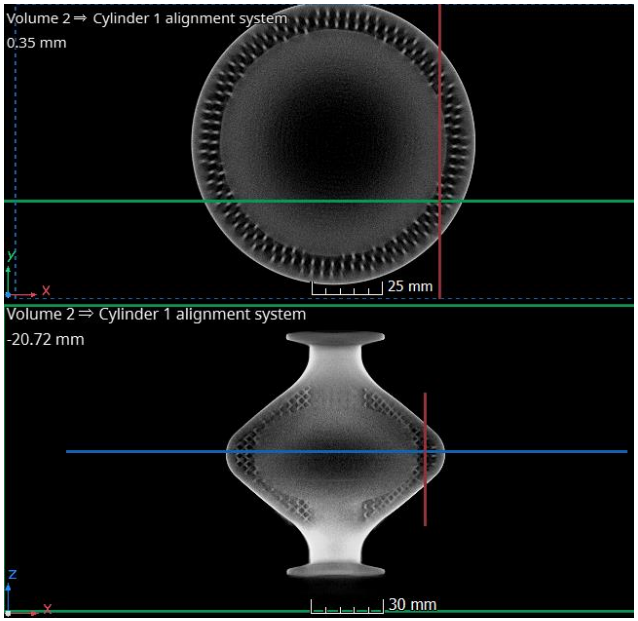
Tries for a 30° cône





Selected Supports

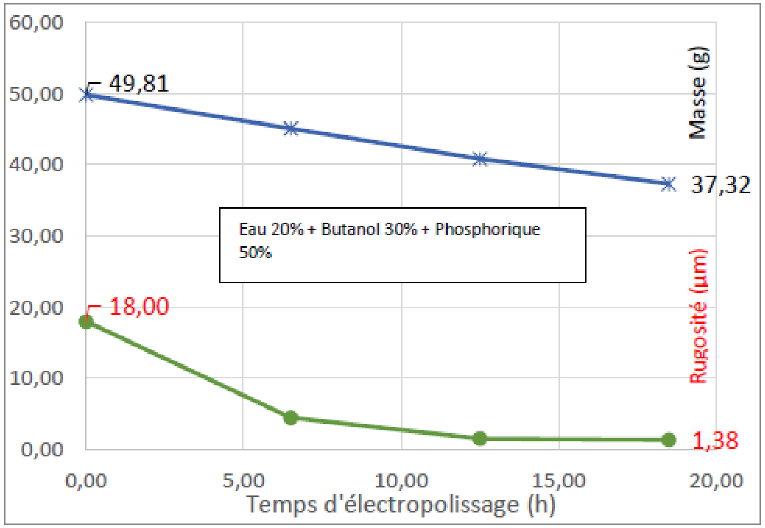
Tomography

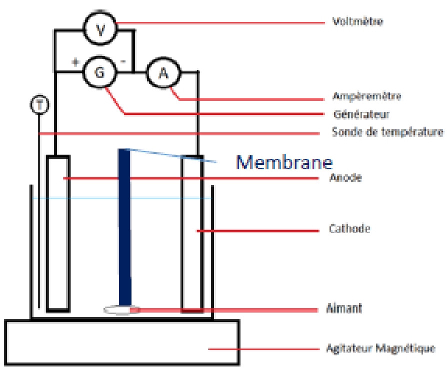


- Very little impact on the internal wall surface.

POST-TREATMENT : ELECTROPOLISHING

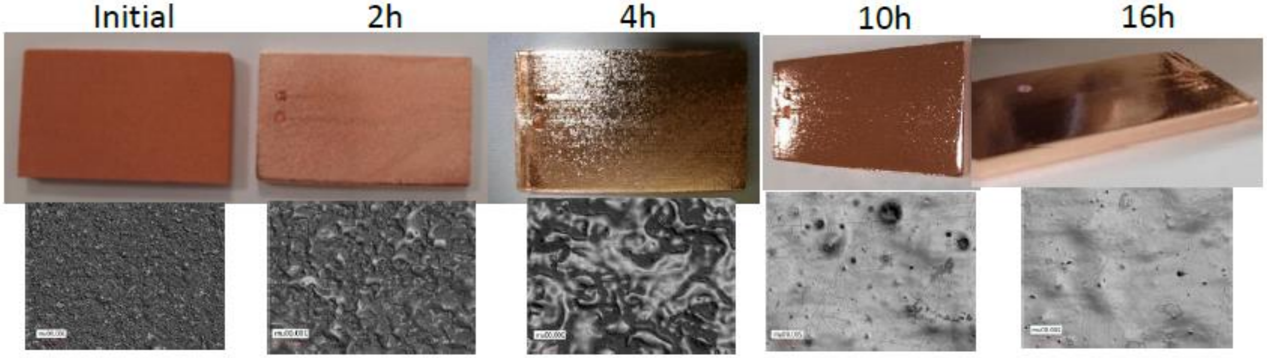
- Lower surface roughness (futur films): Electropolishing – Goal: roughness ~ 1 µm





- Internship:
Optimisation of EP comp. speed:
water (20%)
+ Buthanol (30%)
+ Phosphoric acid (50%)

CuCrZr et Cu pur

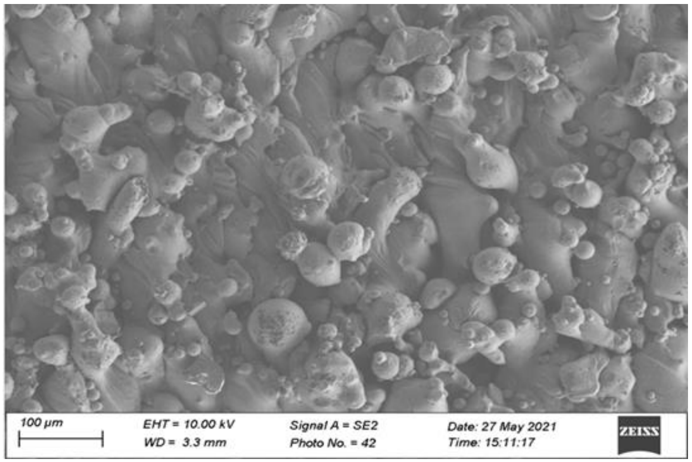


- Confocal microscope roughness measurements at IJCLab.
- Final roughness ~ 1,4 µm.

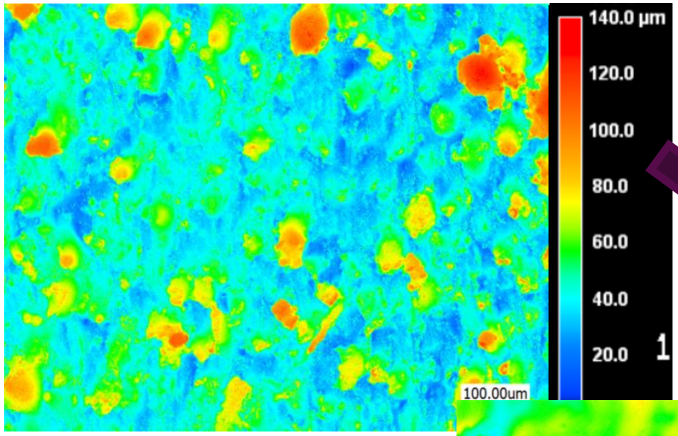
- Ongoing tests on Cu tubes and cavities

POST-TREATMENT : ELECTROPOLISHING

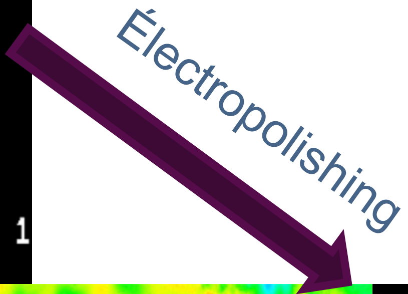
- Rough surface with partially melted particles

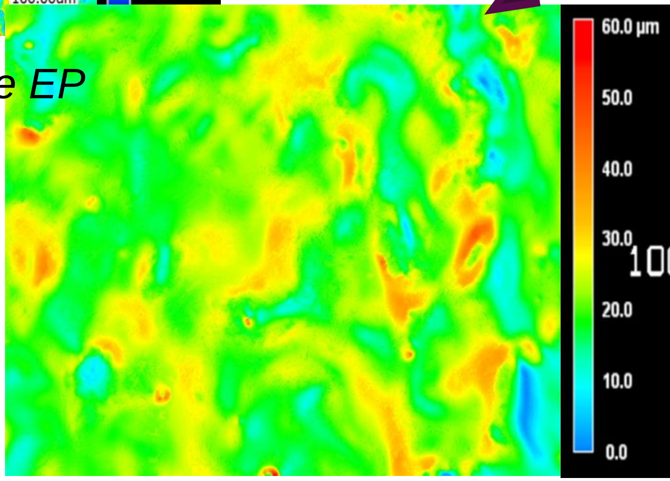


Surface post fabrication FLLP – CuCrZr / Cu



Post-fabrication – Before EP





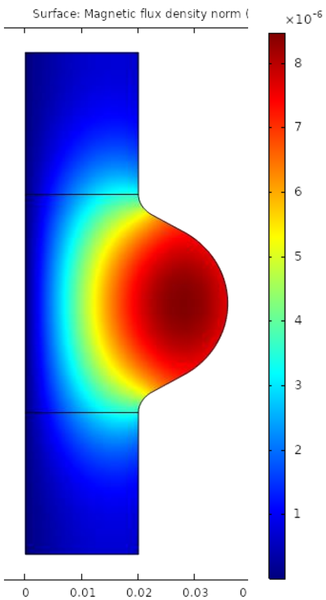
After EP

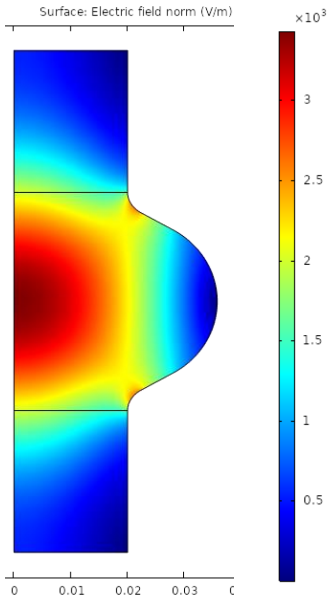
	Sa (µm)	Sz (µm)	Ssk
As made	12,9	186	1,51
After EP density 99.9%	1.4		
After EP density 95%	3,9	62	0,14
After EP density 85%	16	163	/

Higher material density lead to smoother surfaces

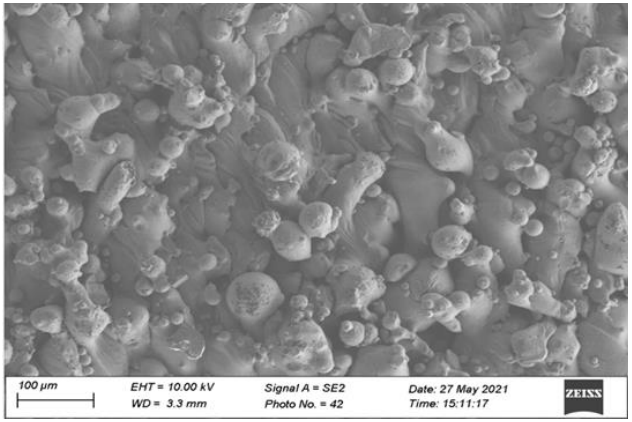
RF TEST AT ROOM TEMPERATURE

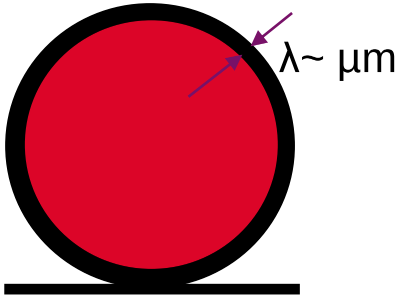
➢ Conception type XFEL: G = 312.83 Ohm, f_0 = 3,8962 GHz





- Roughness -> increase the effective surface if λ < characteristic grain size (~ 30 µm)





Estimation ~ facteur 4

cavity	**F_0 (GHz)**	**Q_0**	**Rs (mΩ)**	**ρ (µΩ.cm)**	**λ (µm)**
Cu + US	3,9904	9200-**35000**	*34* – **8,5**	*46* – **2,8**	*13.5* – **3,3**
Cu + léger EP	3,999	13 000	*24*	*23*	*9.5*
Al 205 + Alcool	4,0018	6500	*48* - **12**	*92* – **5,7**	*36* – **4,7**

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

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

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

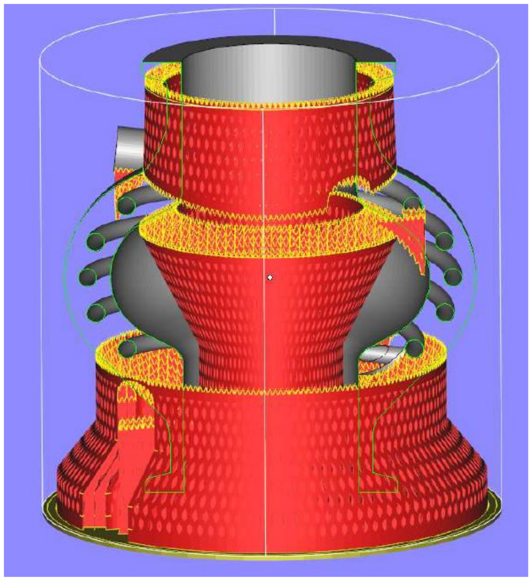
MOTIVATIONS

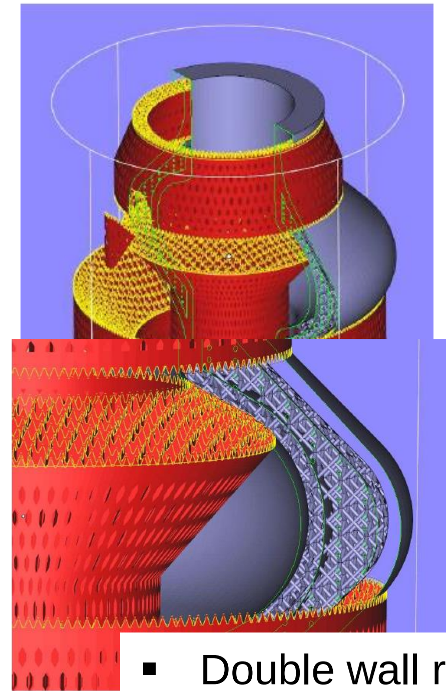
ADDITIVE MANUFACTURING

CRYOGENIC TESTS

CRYOGENIC TESTS – WHAT STRATEGY?

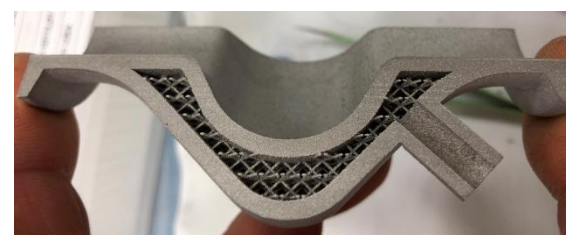
➢ Two proposed approaches for He circuit:





- Two pairs of tubes wrapped around the cavity
  5° minimum Angle for He flow.

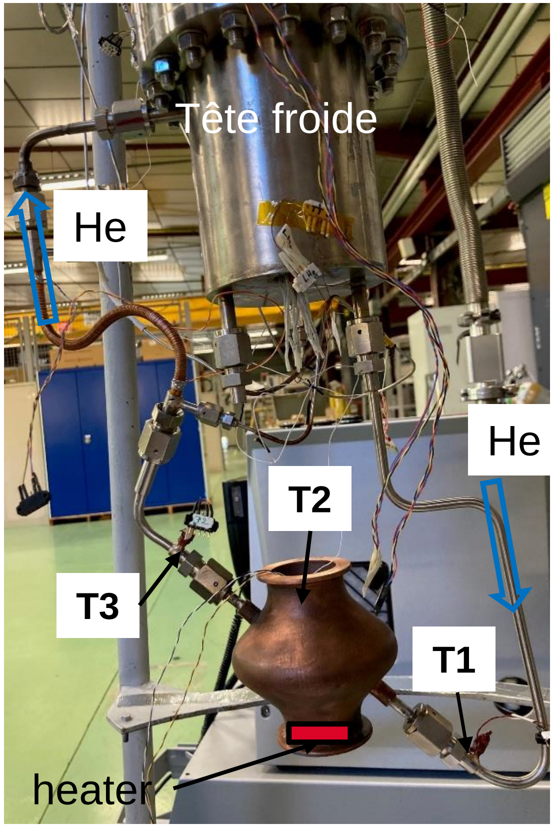
- Double wall reservoir with lattices



➢ For Pur Cu
  RRR = 77
  Thermal conductivity at 6,9K: 835 W/m.K (RRR = 80)

CRYOGENIC TESTS – PUR CU

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

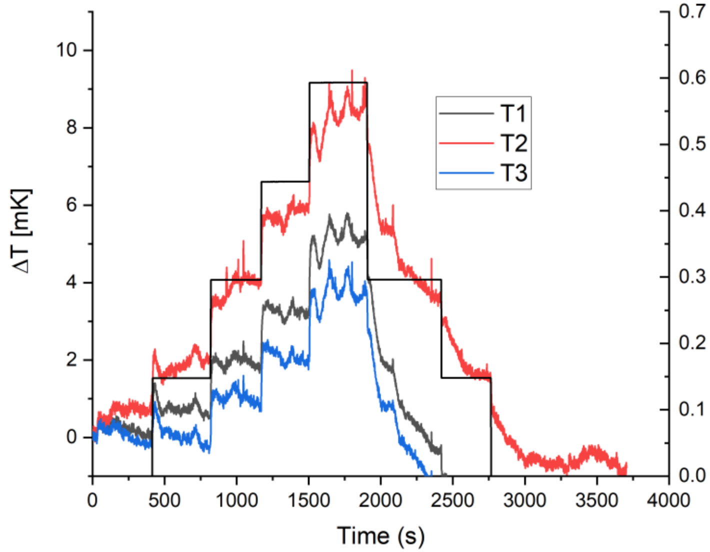


- Tests at 4,2 and 4,5 K. Cryocooler power: 1,1 W and 1,5 W– cold head (reservoir).
- Closed gravity circulation loop with vapor recondensation.
- Thermal insulation around the cavity + cold head.
- P= 1 Bar at 4,2 K et 1,3 bar at 4,5 K.
- Static vacuum (5.10^{-7} mbar) during cryogenic test.
- Heater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

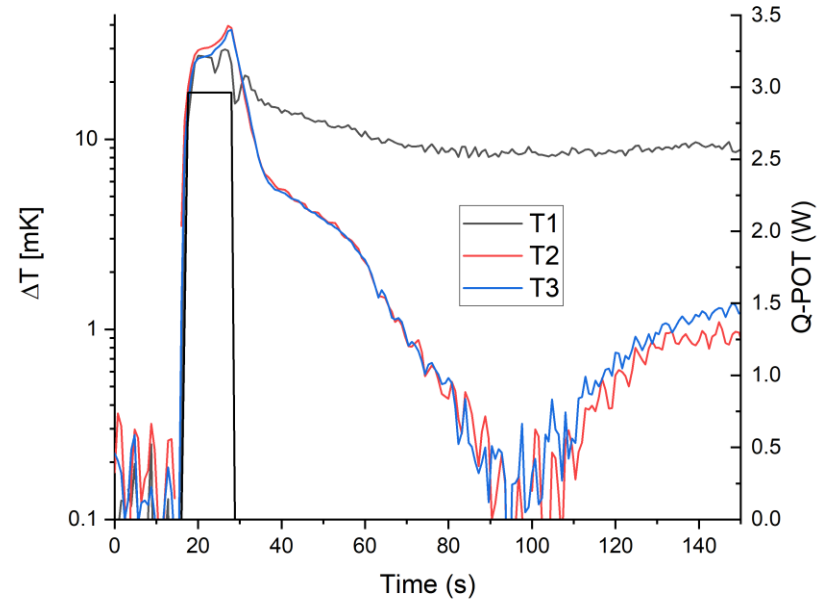
Cryogenic tests – Pur Cu

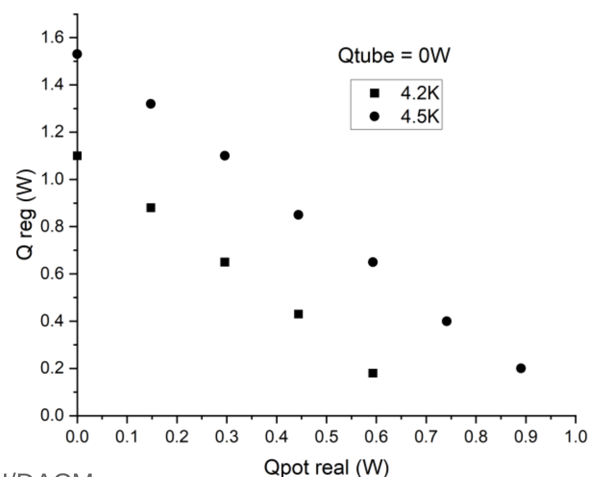
➢ Two power regimes delivered to the cavity:

continuous mode



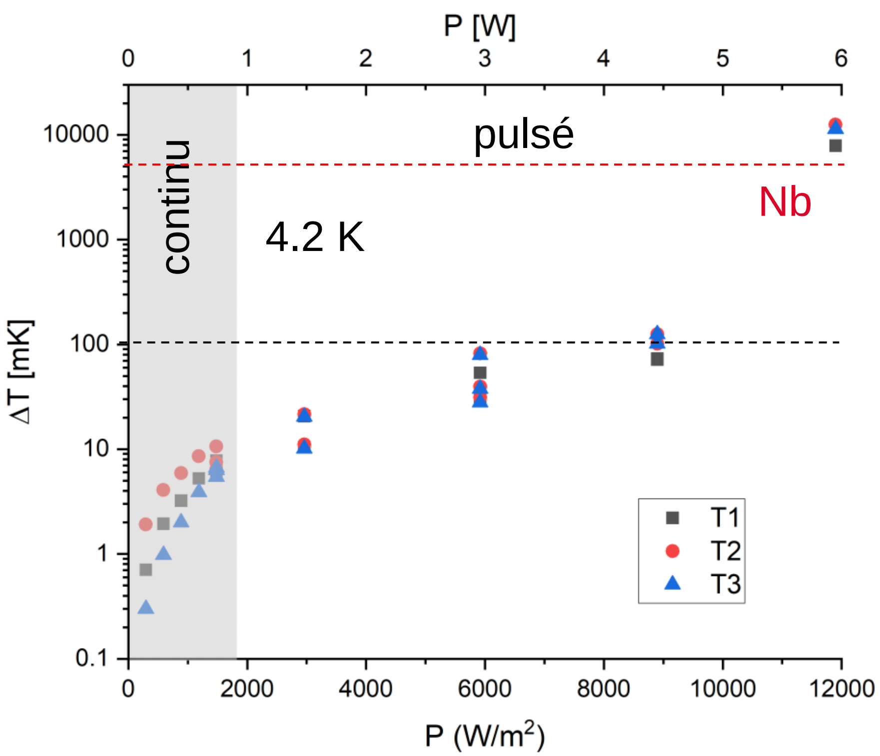
Pulsed mode

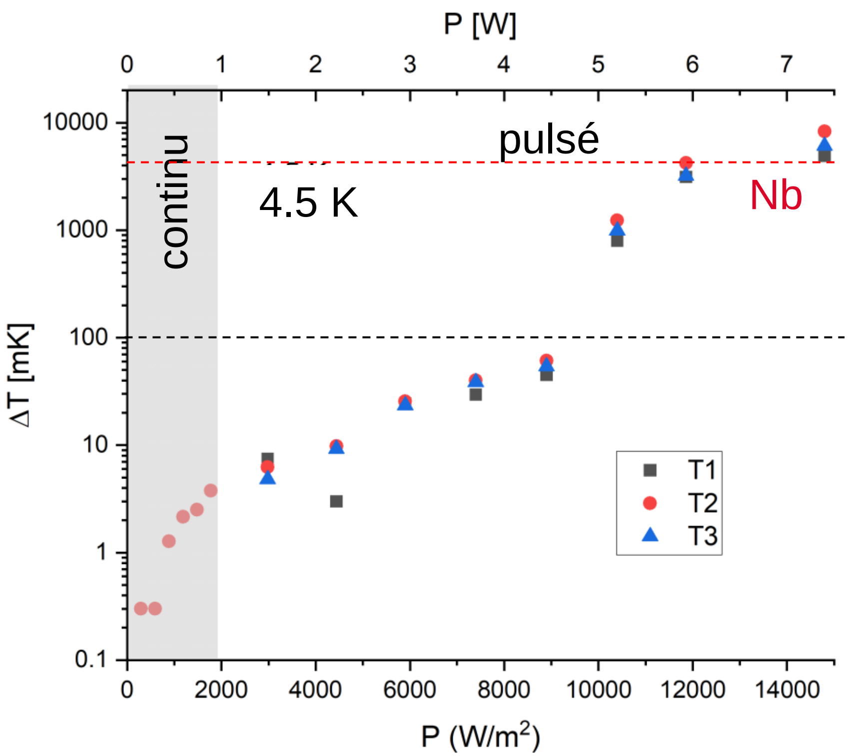




- Continuous: equilibrium of temperatures. t=408 s, P = 0.15, 0.3, 0.44, 0.6, 0.75 W. Limitation: power of the cryocooler.
- Pulsed: Out of equilibrium– 8-15 s, 1.5, 3, 4.5, 6 W.
- $\Delta T_i = T_i$ - 4,2 K (or 4,5K)

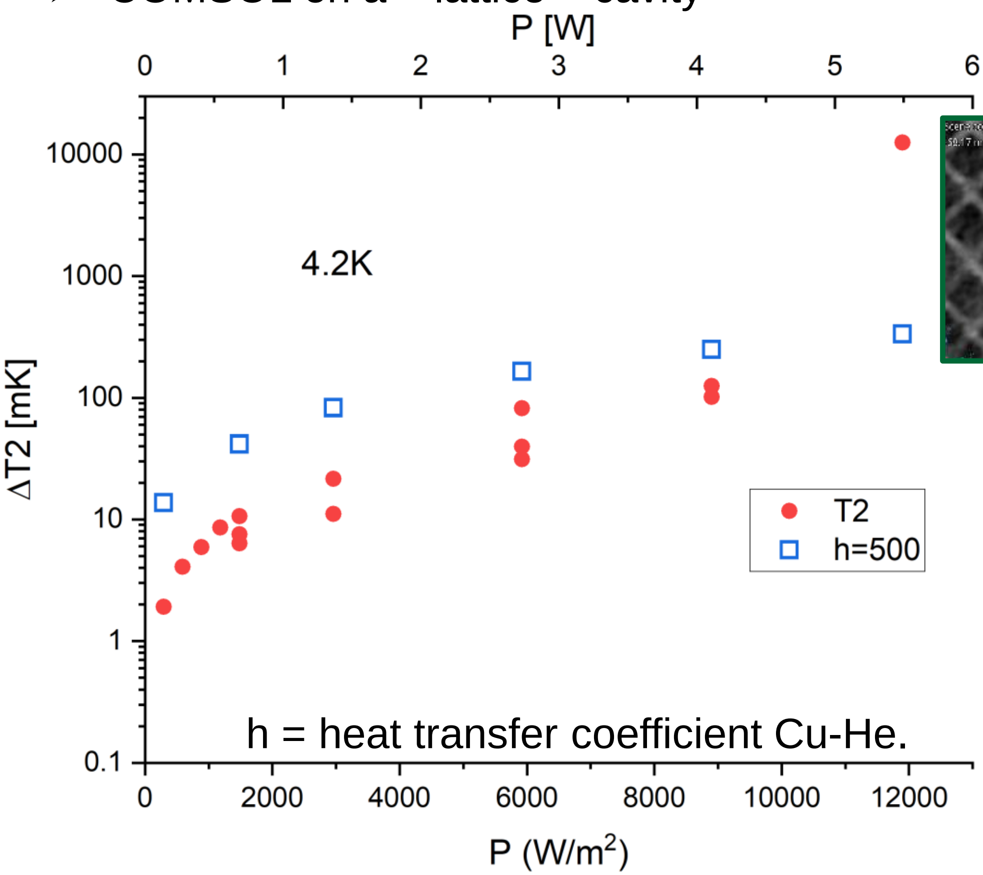
➢ Measurements summary:

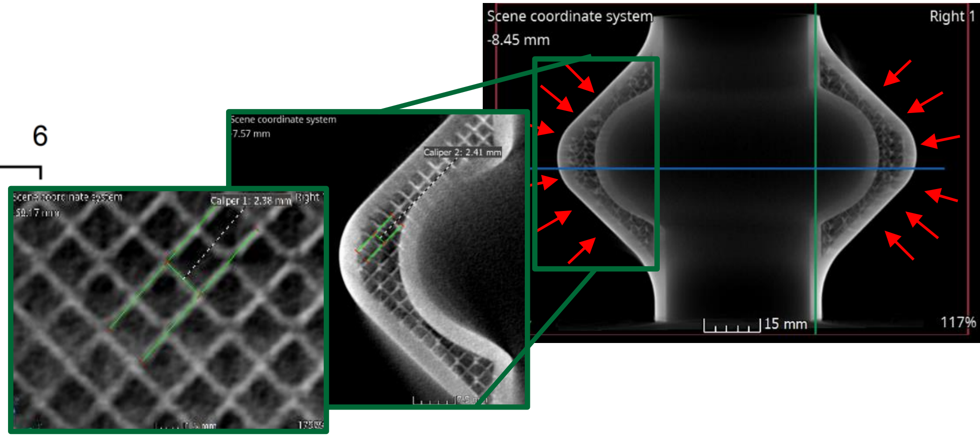




- acceptable ΔT (?) < 0,1 K - > 4-5 W in pulsed mode with P_{Cryo} ~1,1W à 4,2K

- COMSOL on a « lattice » cavity





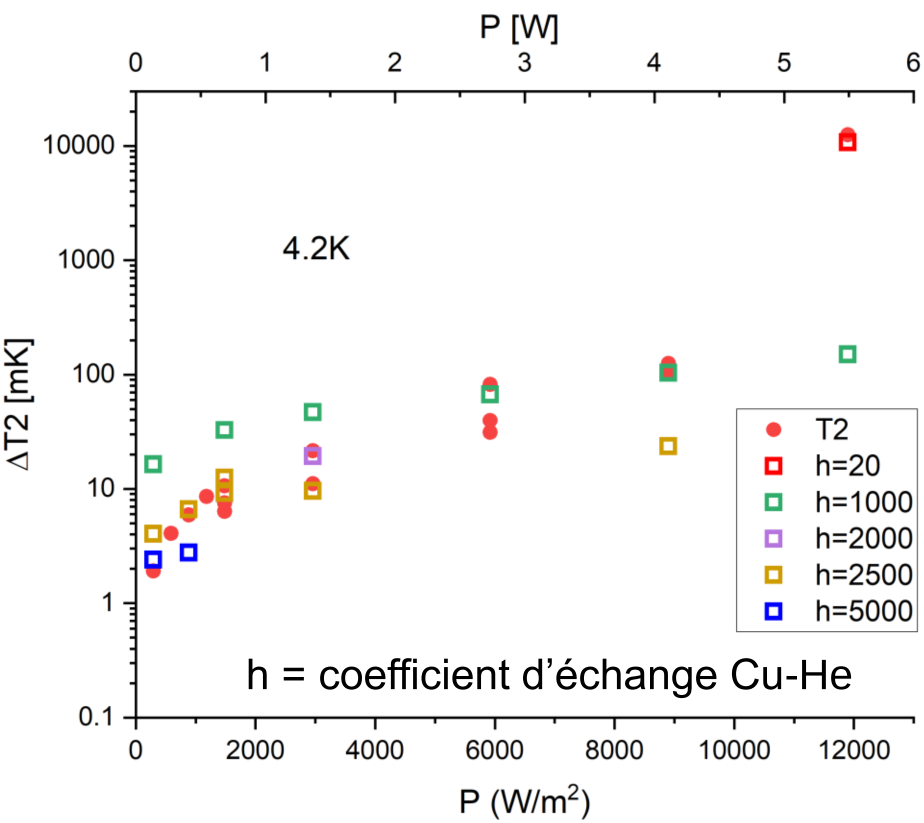
- Influence of the lattice on ΔT.
- External radiative heat source: 0.1 W/m^2

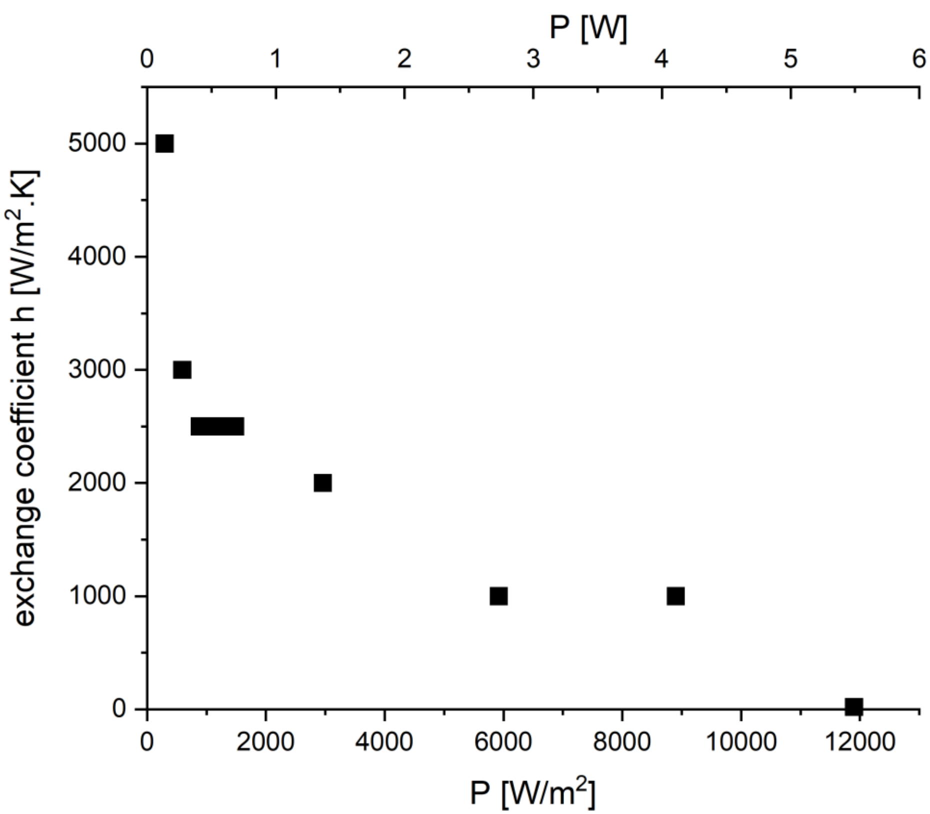
# lattice COMSOL	Exchange surface gain [%]	ΔT2 [mK]
0	0	69,16
850 (17x50)	32	61,7
1785 (17x105)	50	70,7
4250 (17x250)	70	105,85

P=0.7415W t=10s

- h=500 W/(m^2.K). simulation over estimate the ΔT.
- Number of lattices: volume available for LHe decreases.
- Adding thermal shields to the cavity structure.

- COMSOL on a « lattice » cavity





- Cu-He exchange coefficient h decreases as P increases
  -> effective exchange surface decreases (vapor surfaces increases – roughness?)

Conclusions & Perspectives

Conclusion:

- Material choice: Cu pur ou Al 205
- FLLP parameters: maximal desnity + internal supports
- Surface roughness: « simple » approach, less toxic acid, roughness ~1.3-1.4 µm.
- Good quality Cu (RRR~ 80)
- Leak tests conclusive.
- Successfull cryogenic tests.

Perspectives:

- Cryogenic tests (RRR and Cryo loop) on Al205.
- **RF tests with cryocoolers.** Funding PACIFICS (Equipex – ANR)
- Scale up: 1,3 GHz -> Cold Spray.
- Masterise EP on cavities**.** Funding PACIFICS (Equipex – ANR)
- **HIPIMS deposition (Nb…).** Funding PACIFICS (Equipex – ANR)

Thanks for your attention
Questions ?

Commissariat à l'énergie atomique et aux énergies alternatives
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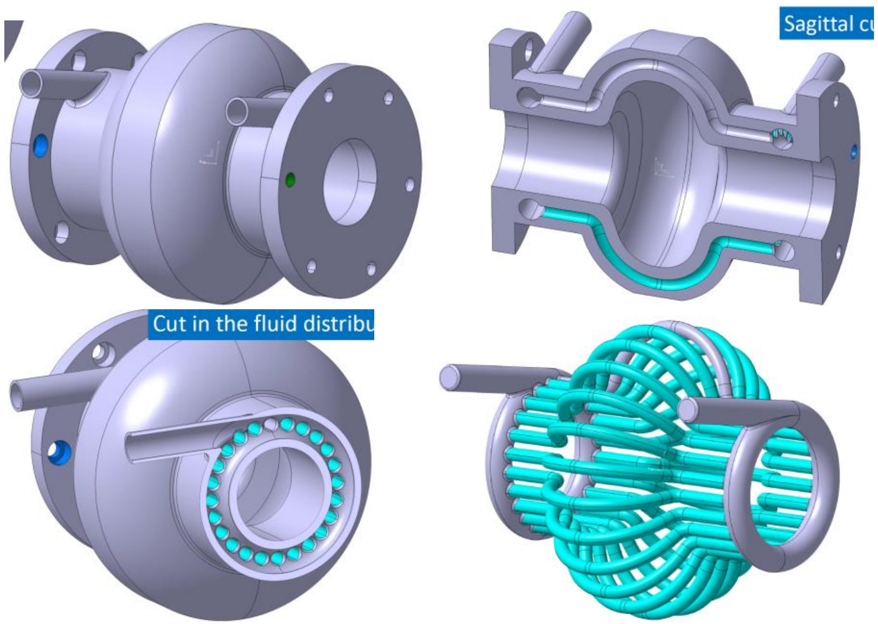
Direction de la Recherche Fondamentale
Institut de recherche
sur les lois fondamentales de l'Univers
Service

COLD SPRAY

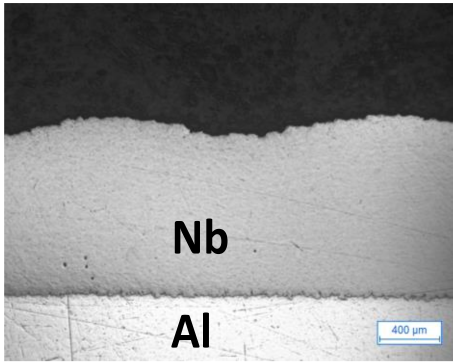
- Méthode par projection de poudre sous flux de gaz inerte sur mandrin d'Alliage Al.
  - symétrie de pièces cylindriques (elliptiques).
  - + Bcp plus rapide que FLLP.
  - + différent matériaux (bride, tube, « films » ~ 500 µm)
  - - moins flexible sur la géométrie (refroidissement).



Impact innovation@

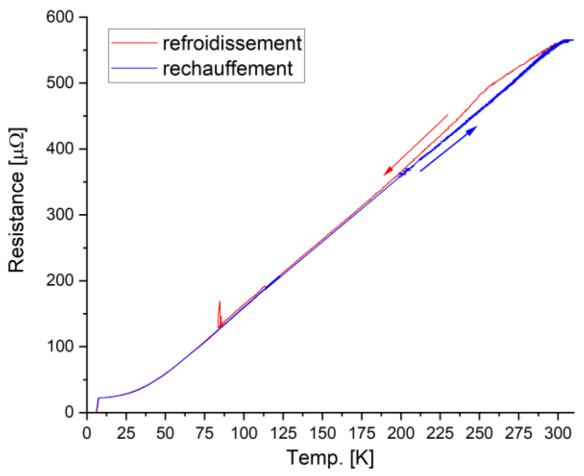
Test fuite pièce Cu (CuC2)

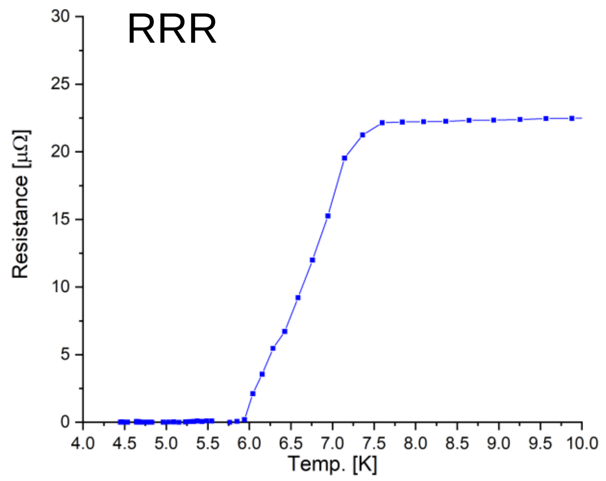
Films de Nb



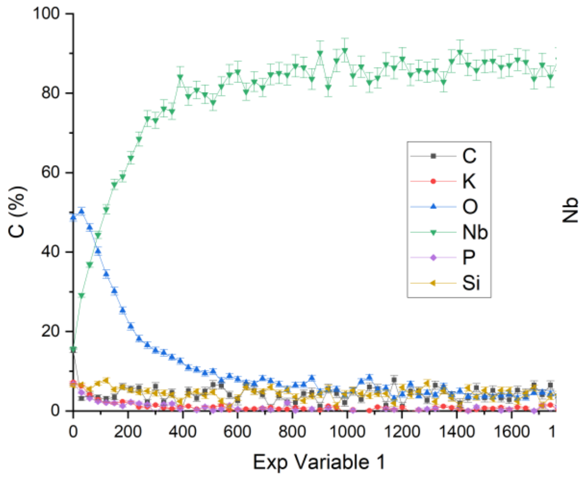
- Test fuite Cu < 10^{-11} mbar.l.s^{-1}
- Test films de Nb

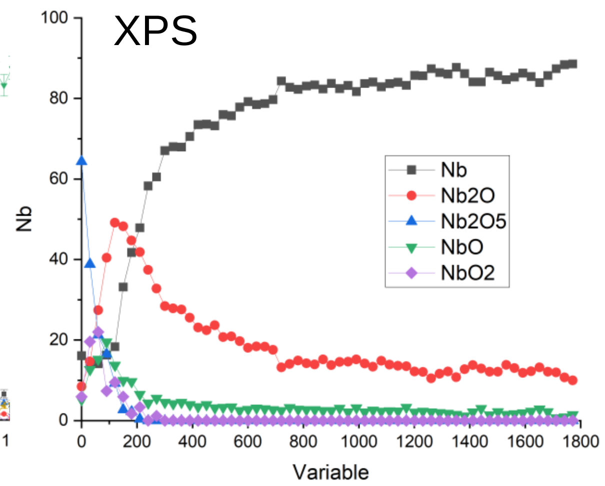
➢ Détermination des propriétés du Nb





- RRR ~ 20
- Tc = 6,8 ± 1 K

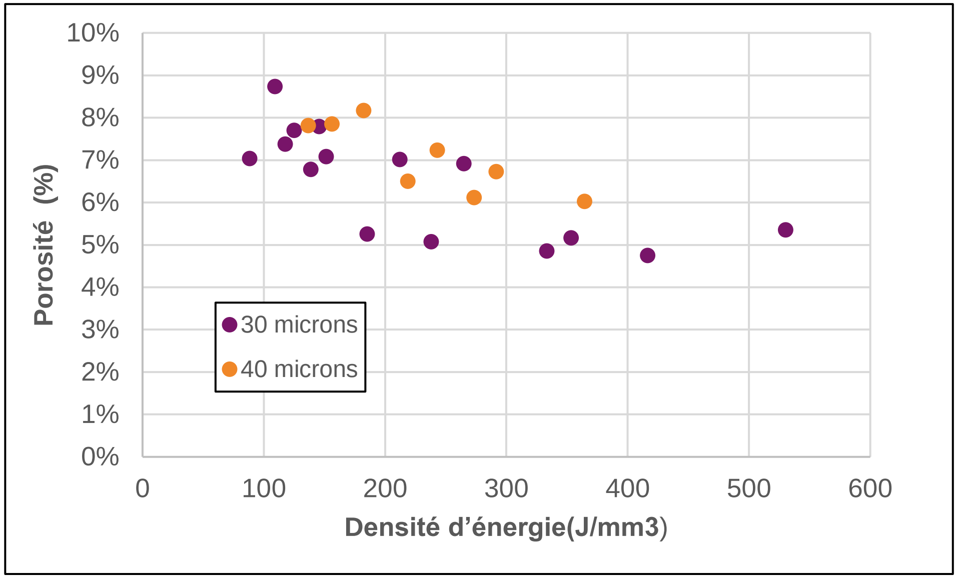




- Impuretés d'oxygène à 3-4% sous forme de NbO_X.
- De Sorbo (70s) : Tc ↘ 1K/%d'O

Densification du cuivre dépend surtout de l'énergie absorbée➔ Limite machine 175W

P: Puissance Laser	v : Vitesse laser	t : Épaisseur de couche	h :Écart vecteur	E : Densité d'énergie	Densité
(W)	*(mm/s)*	*(µm)*	*(µm)*	*(J/mm^3)*	%
175	700	30	60	139	**~85%**
175	250	30	70	333	**~95%**



Principaux paramètres :

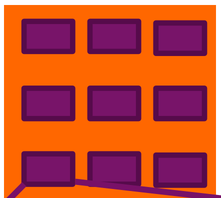
$$E = \frac{P}{v\,t\,h}$$

Résultats :

- La densité maximale atteinte est d'environ 95%, la puissance laser est insuffissante pour obtenir des cordons de fusion stables
- L'augmentation de la densité d'énergie augmente la densité finale de la pièce

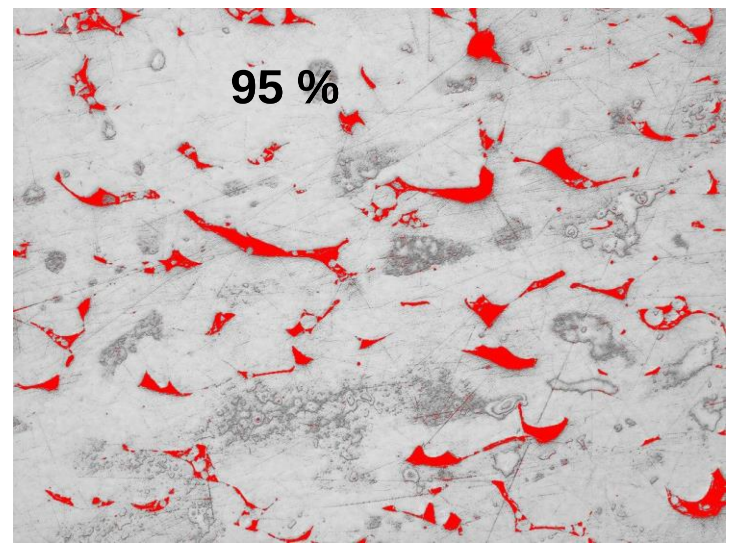
FABRICATION D'ÉCHANTILLONS EN CUCRZR

Méthode 1 : Mesure optique



9 positions différentes
pour prises de mesures

Analyse d'images →



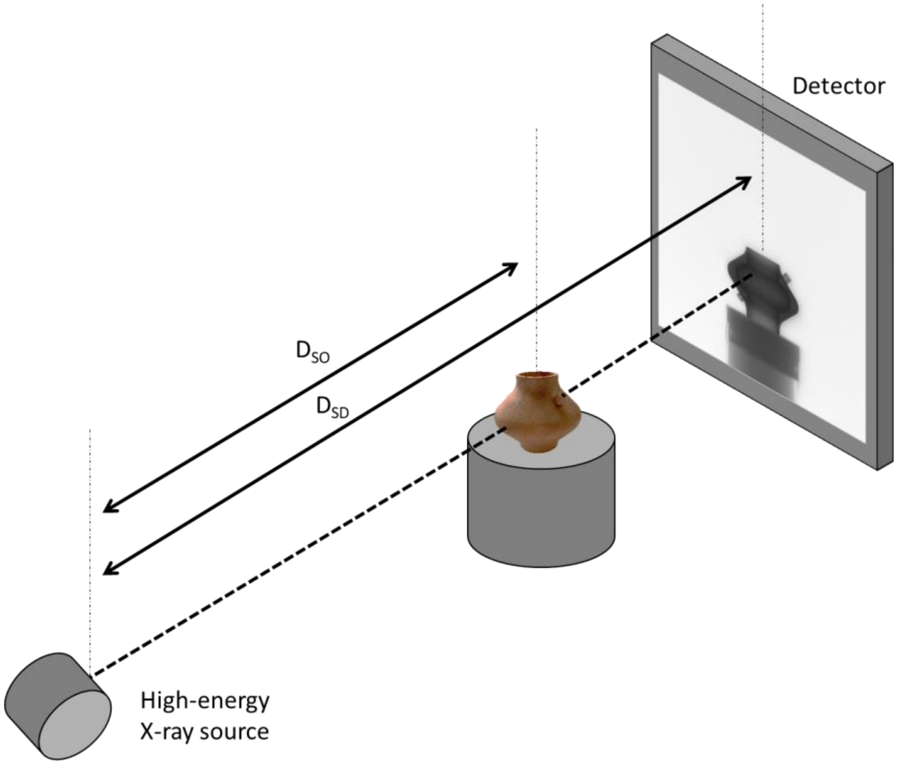
P 175 W – V 250 mm/s – T 30 µm – H 70 µm

27

Méthode 2 : Pésée hydrostatique (Archimède) : 95 %

➔ **Les 2 méthodes correspondent**

CT Scanning setup and parameters: 450kV



Parameter	Value
Voltage, kV	400
Current, mA	1,75
Filter, mm	4,2 Cu
Detector pixel	2048 × 2048
Projection,-	1440
D_{SD}, mm	1330
D_{SO}, mm	970
Voxel size, µm	146