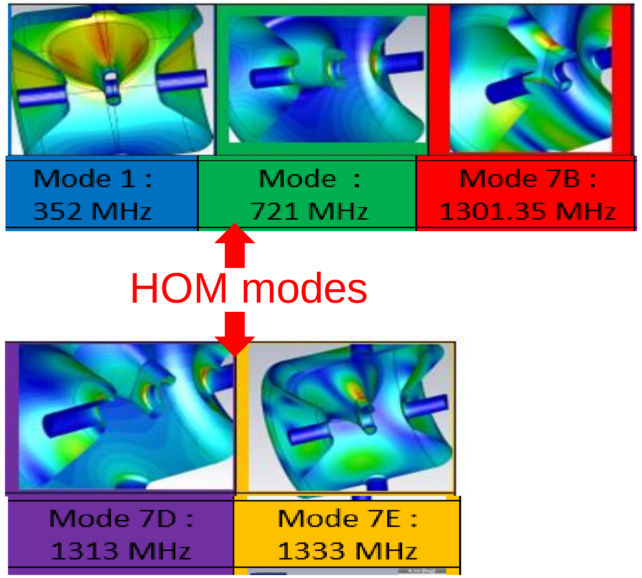
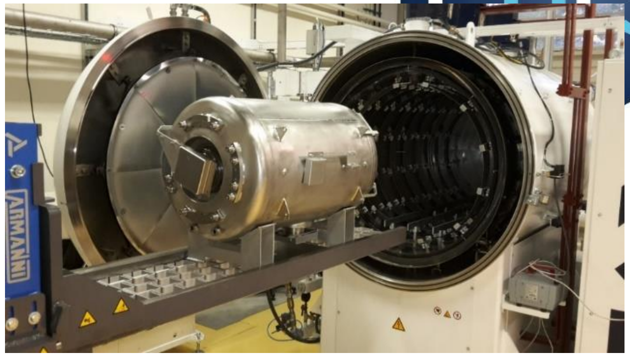
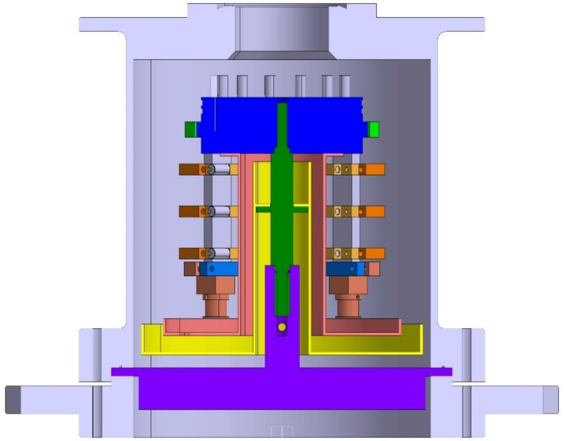




SRF/HELOISE

M. Fouaidy, IJCLab, Orsay

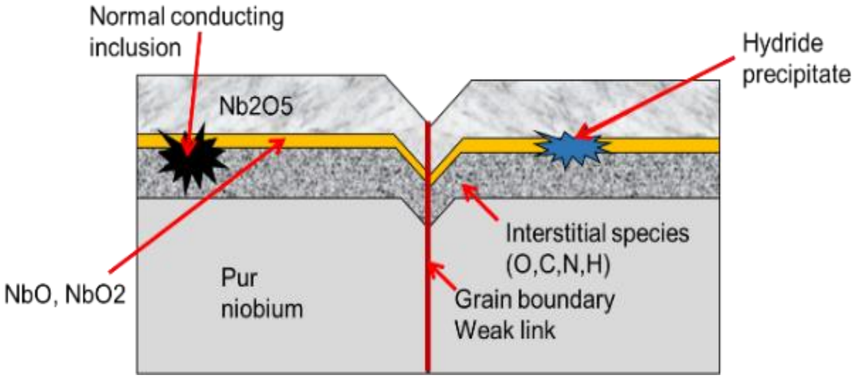


Plan

- Le surface RF d'une cavité supraconductrices n'est pas idéale: traitement nécessaire
- HELOISE: Objectifs et thématiques de recherche
- Motivations de la R&D sur nouveaux traitements thermiques des cavités
- Infusion azote pour réduire la résistance de surface en régime RF
- Premiers résultats Infusion azote à IJClab
- Amélioration de la qualité de l'azote à l'entrée du four
- Banc de mesure de conductivité thermique
- Développement d'outils de diagnostic des pertes RF anormales

Real RF surface of SRF resonators is not ideal

Type of contamination, impurities or surface damages	Layer	Cleaning Method
oils, dirt, … →	**Surface Contamination**	Dissolution (solvents + detergents +ultrasound)
C_xH_y, H_2O, Cl, … →	**Adsorbates (≈nm)**	
Nb_xO_y, →	**Oxides layer (1-10 nm)**	Buffered Chemical Polishing
Excess dislocation, voids →	**Hardened layer (100-200 µm)**	Buffered Chemical Polishing Electro-polishing
	Clean Niobium	



- ✓ Nb RF surface and sources of anomalous RF losses
- ✓ Complex Physico-Chemical phenomena need to be understood

- ✓ Processing of RF surface is mandatory to ensure good RF performance
- ✓ Surface and Heat Treatment of SRF cavities : a key technological process to be mastered for a good reliability and high yield rate for large scale projects

HELOISE: objectifs et thématiques de recherche

Projet R&D SRF soutenu par l'IN2P3 (Master projet SRF)

HELOISE

High tempErature anneaLing, Low Temperature baking and dOpIng for low LoSses CavitiEs

Recuit haute température, étuvage, infusion et dopage pour cavités à faibles pertes RF

Objectif: Production fiable et répétable de cavités
- ► A haut gradient (Augmenter E_{acc} de 25%)
- ► Faibles pertes RF (Réduction des pertes RF: facteur 2 à 4)

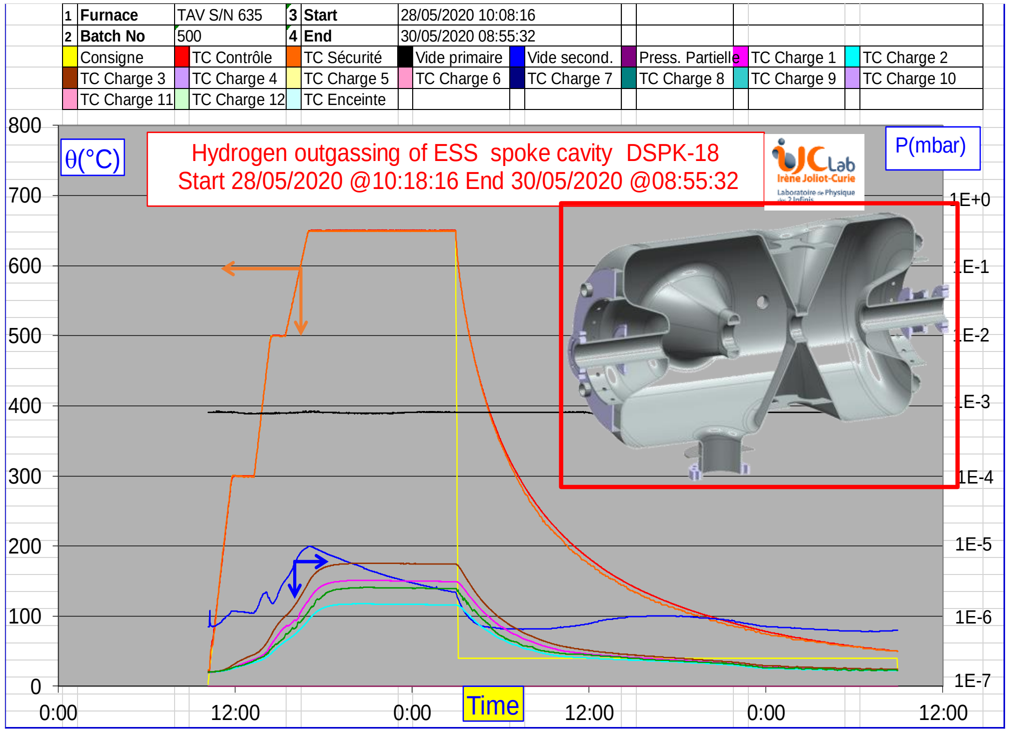
HELOISE est focalisé sur deux axes principaux

Axe #1: compréhension des mécanismes physiques , développement, maitrise et optimisation des paramètres des procédés thermiques sous-vide (Etuvage, recuit à haute température, dopage et infusion azote) pour des cavités RF supraconductrices bas β .

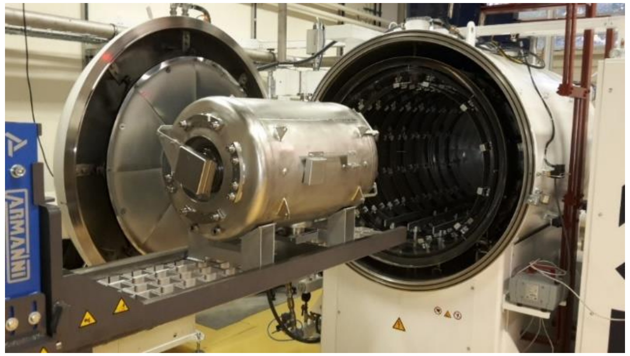
Axe #2: Développement d'outils de diagnostics (quench , Rayons X électro-émis (effet de champ), champ magnetic résiduel) et de bancs d'essais dédiés à la caractérisation des matériaux aux températures cryogéniques (mesure des conductivités électriques et thermiques, paramètres critiques des supraconducteurs)

IJClab High Temperature Vacuum furnace dedicated to Heat Treatment of SRF Nb Resonators

$\beta = 0.5$, $f_0 = 352$ MHz
E_{acc} : 9 MV/m $B_{pk}/E_{acc} = 6.9$ mT/MV/m
$E_{pk}/E_{acc} = 4.3$
r/Q = 426 Ω G= 130 Ω



Furnace developed in the framework of ESS
For hydrogen outgassing of ESS SRF resonators

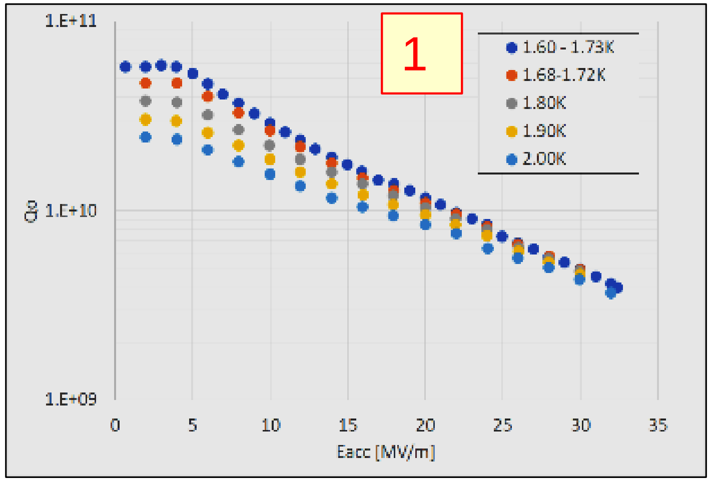


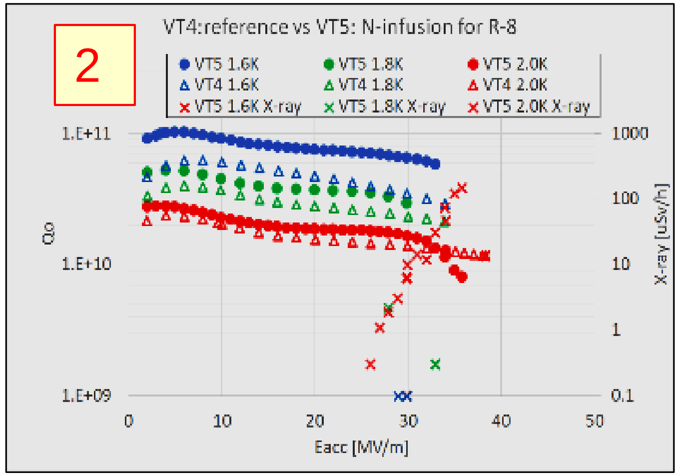
Furnace description and commissioning results

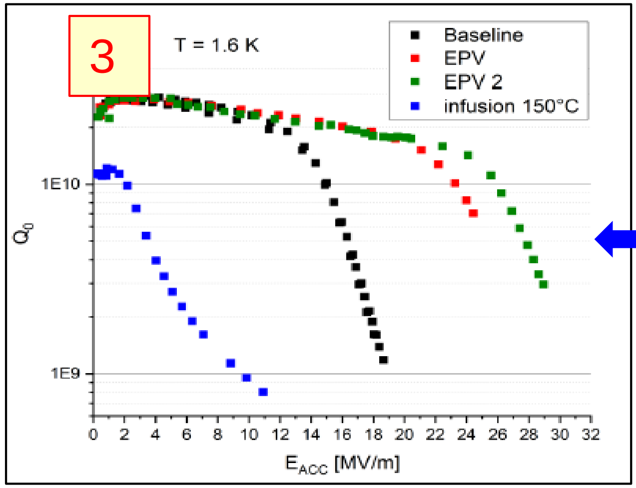
Commissioned in May 2016
Heating: Mo heaters, up to 1400 °C
Temperature uniformity: +/- 2 °C
Cryopump: 14000 std l/s hydrogen
Roots (2050 std m^3/h)
Pumps: Screw pump (650 std m^3/h),
N-Doping valve- Gas flow @300K: 10^{-10} et 500 mbar.l. s^{-1}

Motivation et objectifs principaux

Etude de nouveaux procédés de traitement thermique (surface et cœur du matériau) afin d'améliorer les performance RF (Q_0 et E_{acc}) des cavités RF supraconductrices.
Etude de 3 procédés : 1) N-infusion, 2) N-doping, 3) Etuvage.







1- KEK N-infusion
2 KEK N-infusion,
3 IJCLab N-infusion

Problématique: Manque de répétabilité et de reproductibilité des résultats
Résultats N-infusion à IJClab, Desy et au KEK dépendent fortement du four (propreté, pompage, qualité de l'azote à l'entrée du four) et de la procédure (régulation pression azote et température four ou cavité)
Objectifs : Bonne compréhension des corrélations entre Qo, Eacc et les propriétés matériau/surface: 1) analyse de surface d'échantillons, 2) Tests RF de cavités à différentes fréquences

Collaborations : CEA , Desy (TTC) , KEK (TYL-FJPPL ARD-19)

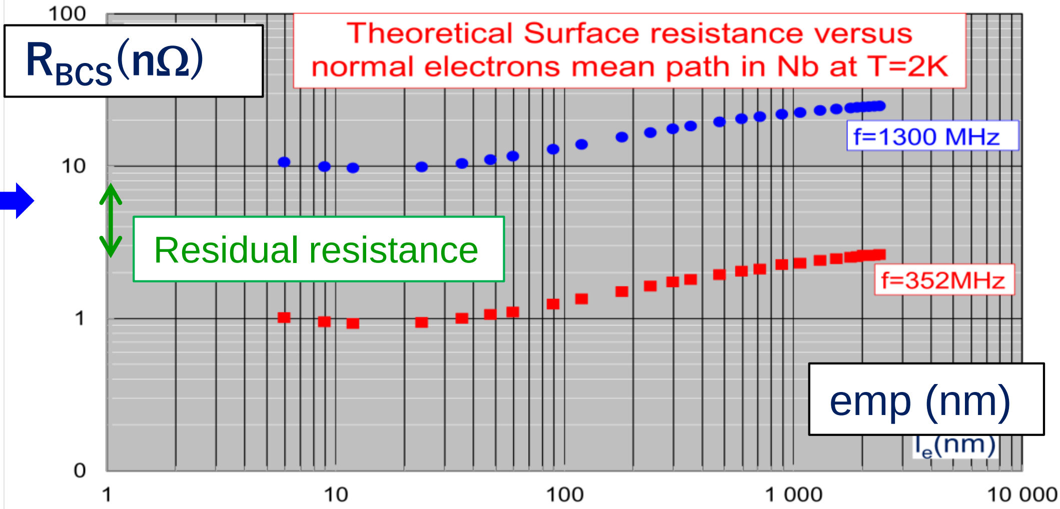
Nitrogen Infusion for reducing surface resistance of Niobium SRF cavities

Irène Joliot-Curie
Laboratoire de Physique

Nitrogen–Infusion (N-Infusion) is based on the strong dependence of the BCS surface resistance R_{BCS} as function the mean free path l_e of normal electrons.

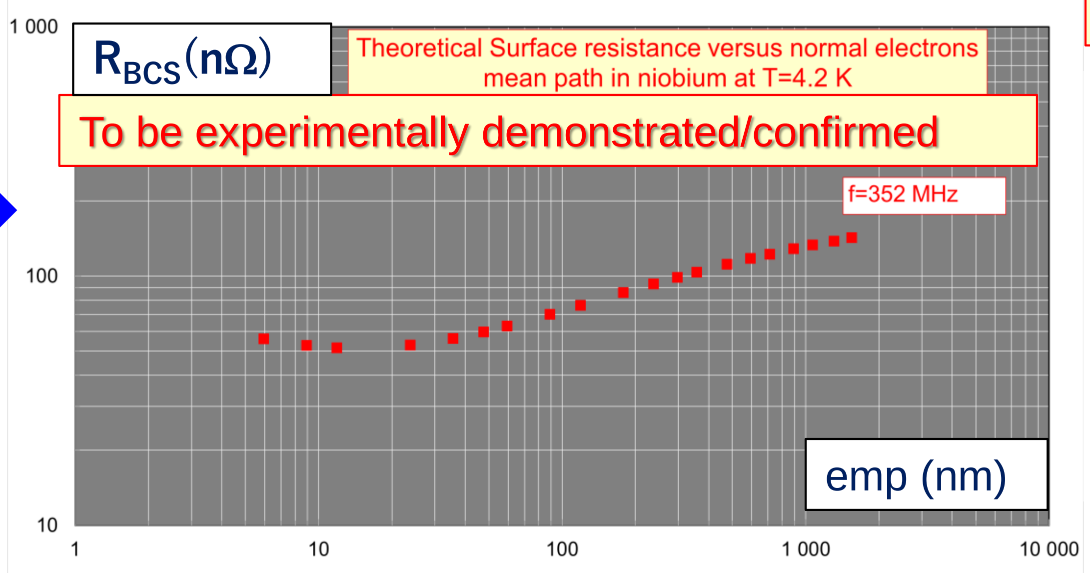
Principle: Reduce surface resistance via reduction of electron mean path

How: Controled pollution of the Niobium RF surface (dept: 0.5 -1 µm) with a dopant (Nitrogen)



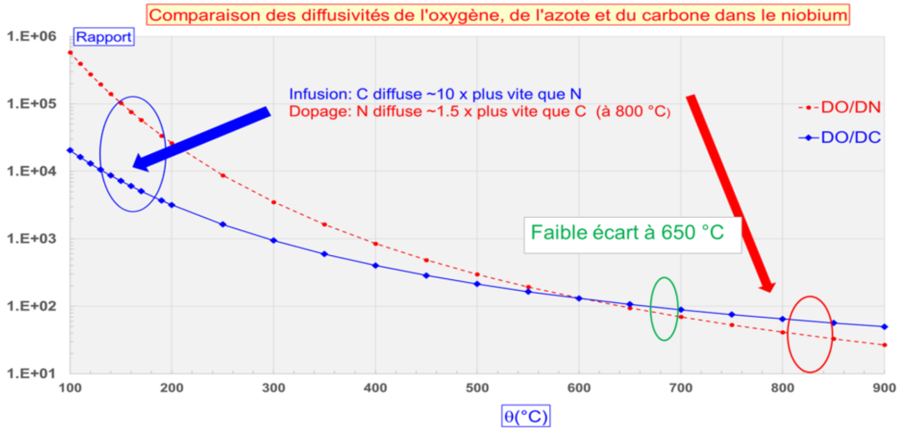
BCS surface resistance vs. e^- Mean free path at T=2 K

At T=4.2K: Potential gain of performing N-Doping or N-infusion: reduction of RF losses (factor 2-3).



BCS surface resistance vs. e^- Mean free path at T=4.2K

Expected gain 1.3 GHz cavities (e.g ILC) : reduce losses (factor ~3)



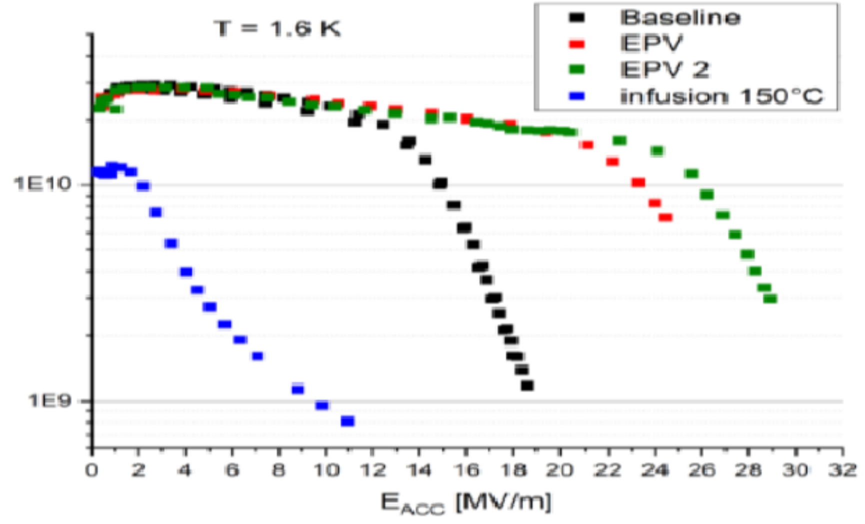
Diffusion of Nitrogen, Oxygen and Carbone in Niobium

For temperature in range 160°C-200 °C In niobium carbone diffuse ~10 time faster than Nitrogen

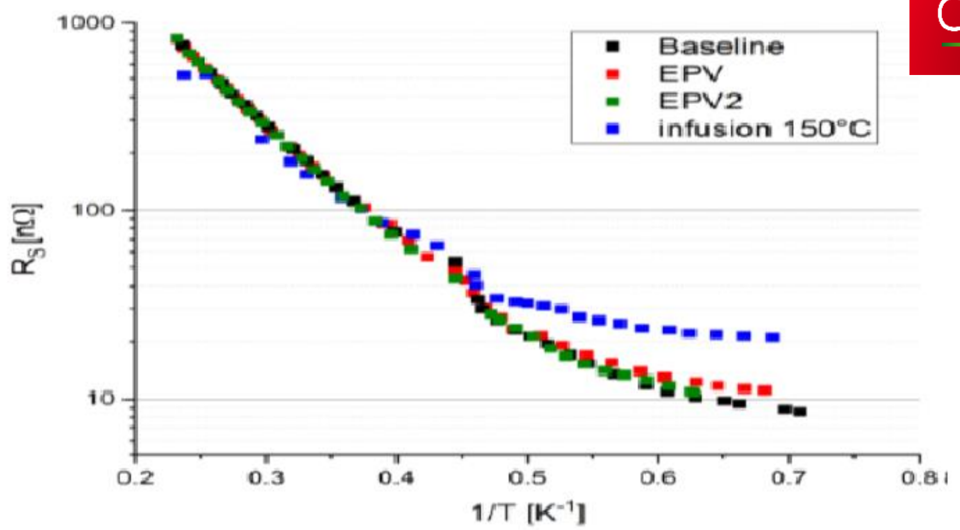
Process should be performed in very clean conditions

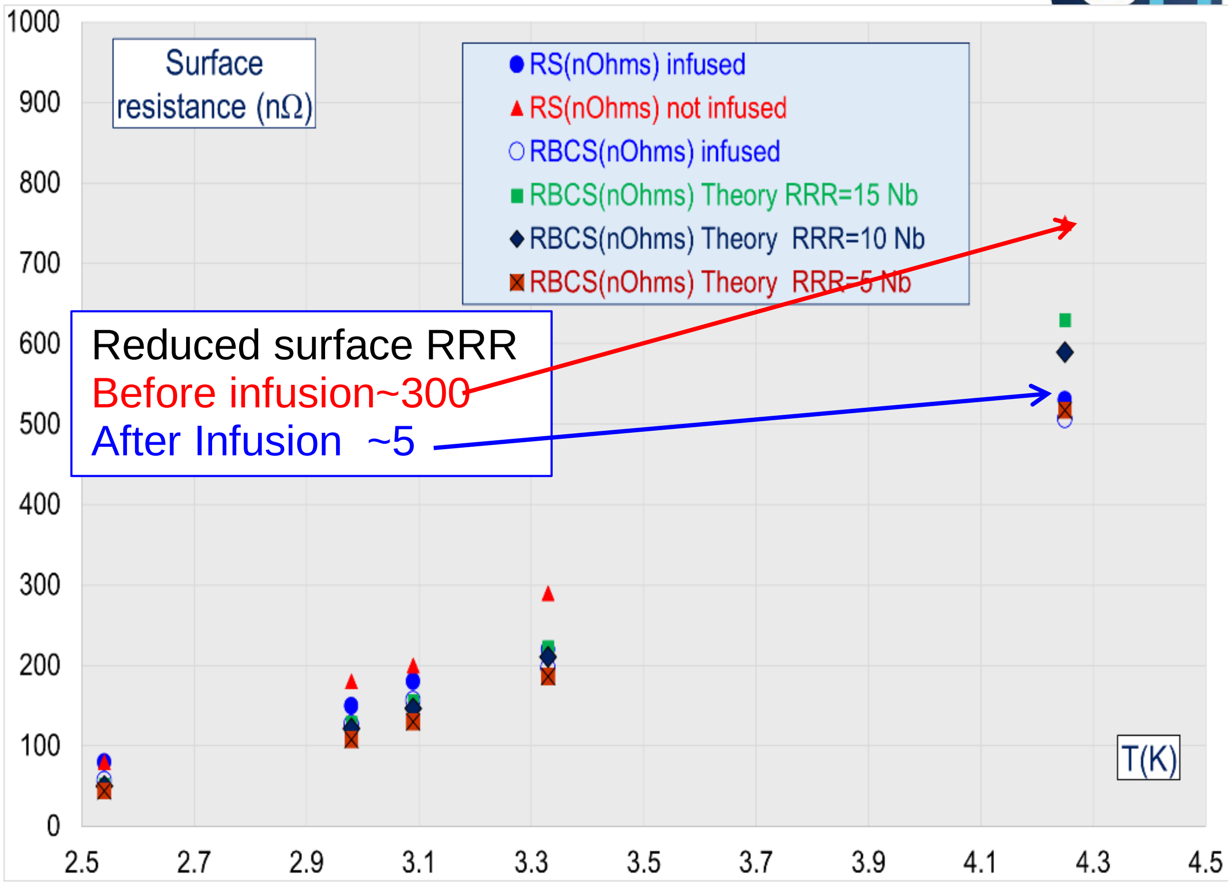
First infusion run at IJCLab Saclay 1.3 GHz cavity

1AC03 Saclay cavity



Residual Surface resistance increased due to Nb2C



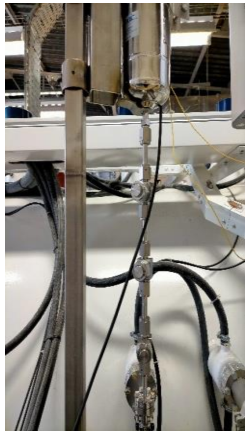


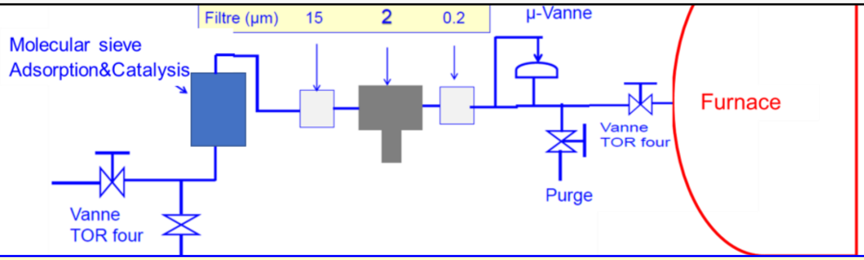
BCS Surface resistance decreased: promising results

M. Fouaidy et al. 'Recent results of High Temperature Vacuum Heat Treatment program of SRF Resonators at IJCLab', IEEE Transactions on Applied Superconductivity Vol. 31 , Issue 5
DOI: 10.1109/TASC.2021.3062788

Upgraded Nitrogen injection line and next runs

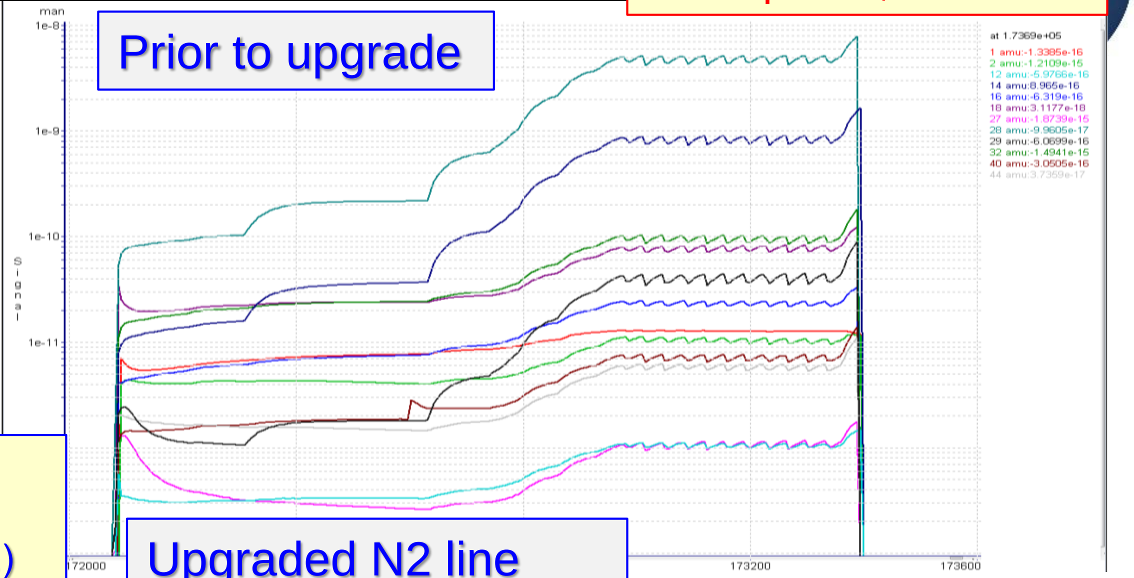
Improved cleanliness of nitrogen at furnace inlet:
- ✓ Molecular sieve (adsorption& chemical reaction)
- ✓ Particle filters (avoid/reduce particulate contamination)



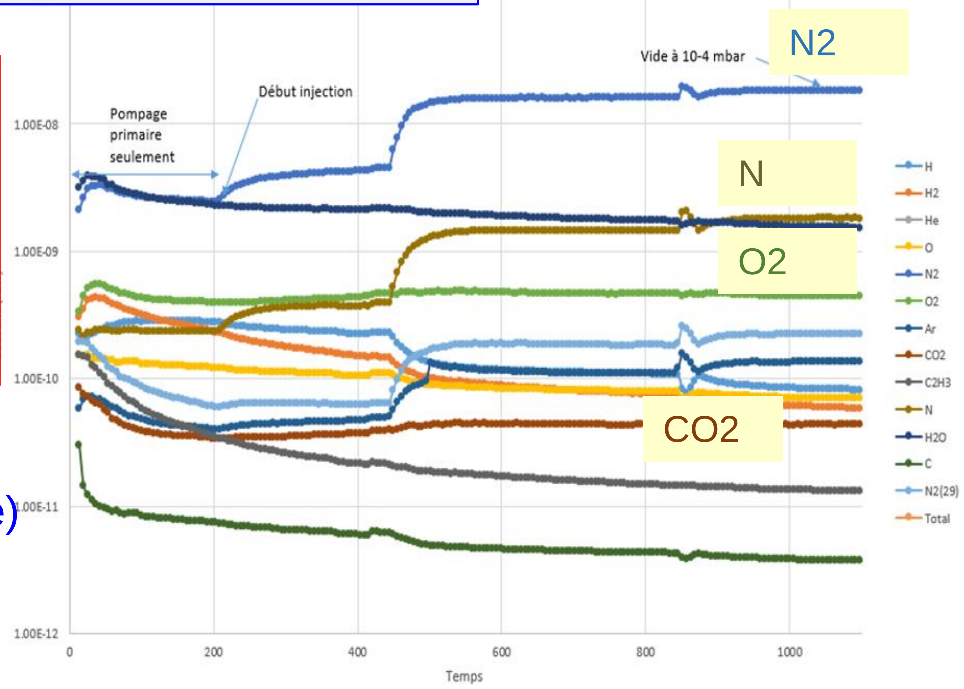
Run April 28, 2021

Prior to upgrade

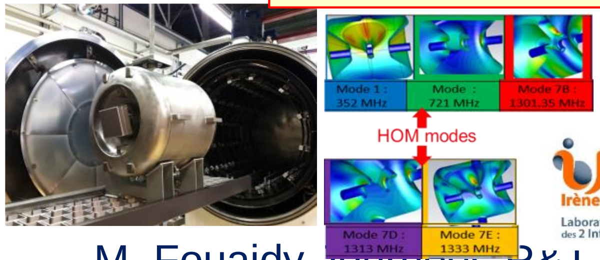


In contrast to previous results prior to the upgrade of Nitrogen injection line, this assembly of filters is efficient :
Partial pressure of unwanted species (H, H2, H2O, CO, CO2, …) don't increase when N-Infusion micrometric valve is opened

Upgraded N2 line

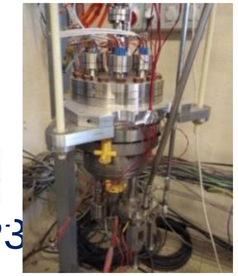


Next runs :
- Commissioning of N-infusion with samples
- N-infusion of a 1.3 GHz cavity
- N-infusion of a MYRRHA Spoke multi-mode cavity : f=352 MHz, 704 MHz and 1300 MHz
- N-infusion of a TE011 cavity sample : f=3,85 GHz and 5.12GHz



IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

spoke multimode IJClab cavity



TE011 cavity :
- Removable end plate (sample)
- Thermometric system

Motivations for developing thermal conductivity test facility

Irène Joliot-Curie
Laboratoire de Physique

✓ High purity Niobium material for high RF performance SRF cavities

Cold work
Heat treatments
Nitrogen doping/Infusion
Low temperature Baking

Strongly impact

Crystallization
Dislocation, defects density
Hydrogen and impurities concentration

Electrical resistivity (RRR)
Thermal conductivity
Phonon peak at T ~2 K

Quench field
Thermal stability
RF performance

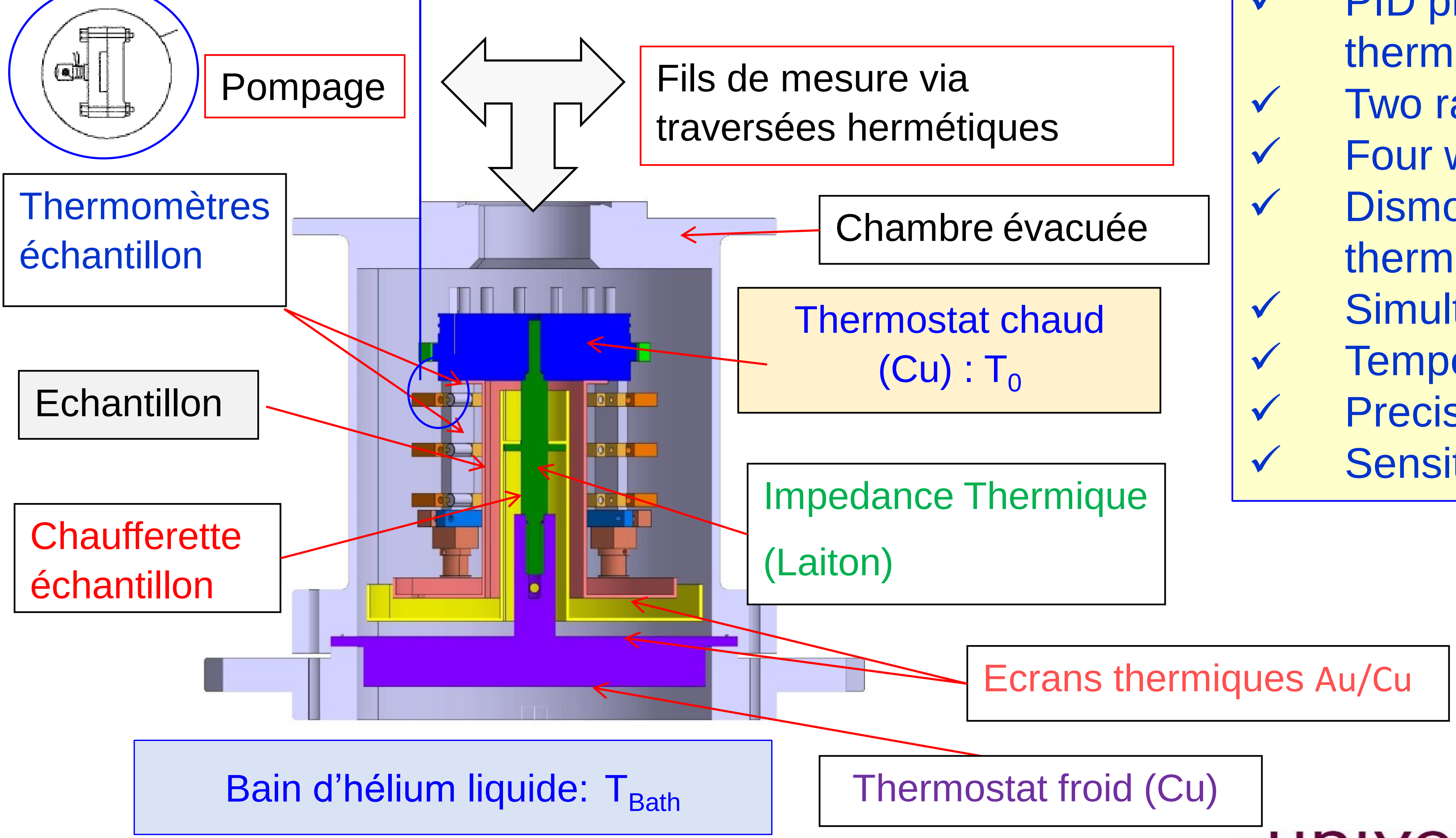
✓ Lack of data about the effect of Heat treatments on the transport and superconducting properties of high purity bulk niobium for High performance SRF resonators

Development of New material and new fabrication method (3D printing, thermal spraying) for SRF cavities and ancilaries : Nb, NB3Sn, NnTiN thin films (µm), multilayers (~10 nm thick)

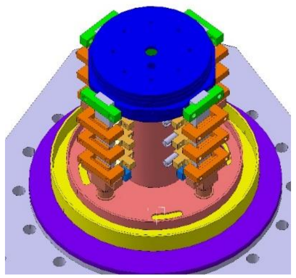
Test stand description (1)

Main features

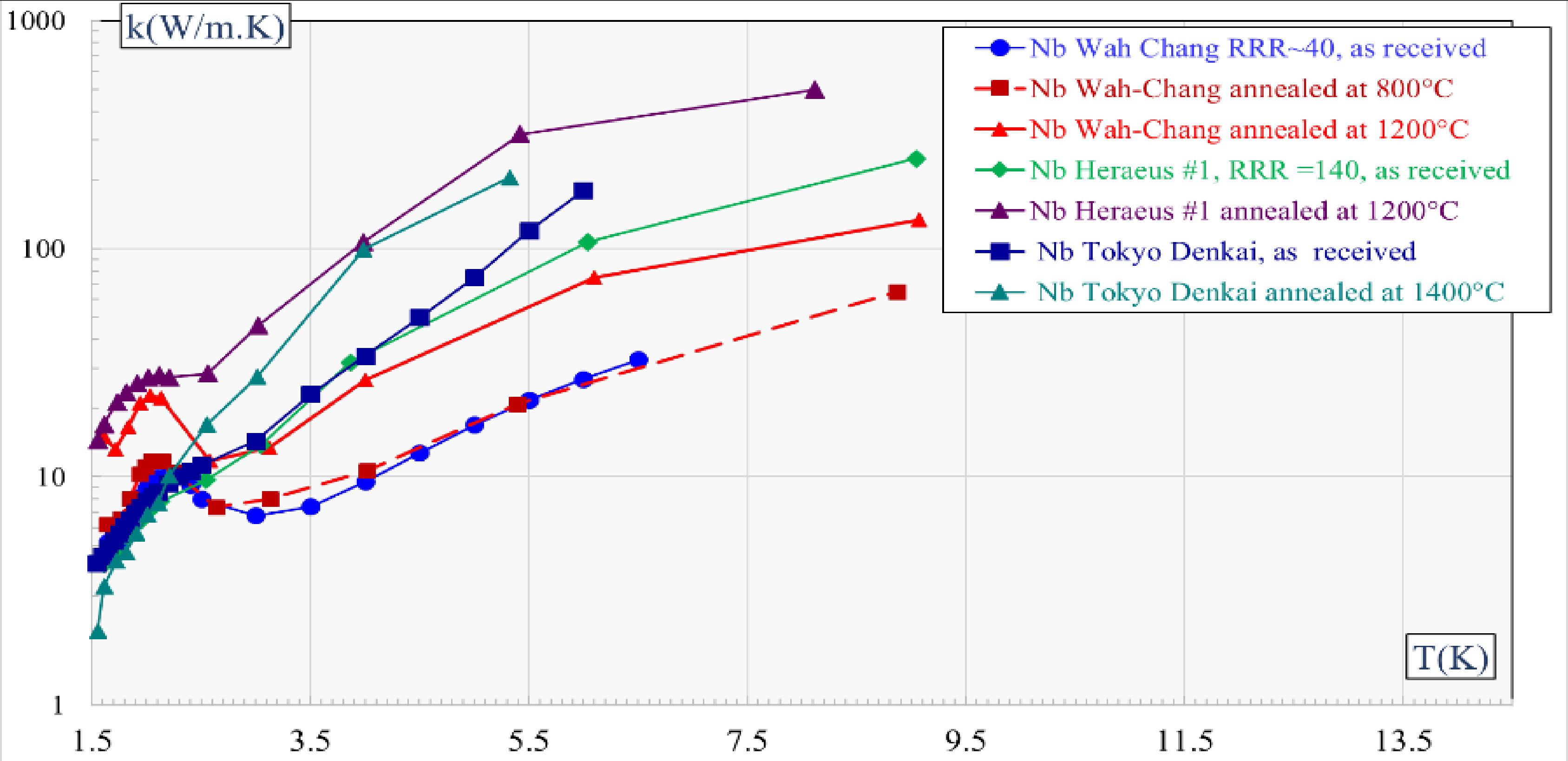
Cellule d'essais



- ✓ Steady-state axial heat flux
- ✓ PID precise regulation of Tbath and thermostats temperature
- ✓ Two radiations shields
- ✓ Four wire measurements
- ✓ Dismountable samples heaters and thermometers
- ✓ Simultaneous tests of four samples
- ✓ Temperature range: 1.55 K- 30 K
- ✓ Precision: +/-12%
- ✓ Sensitivity over a wide range of k(T)



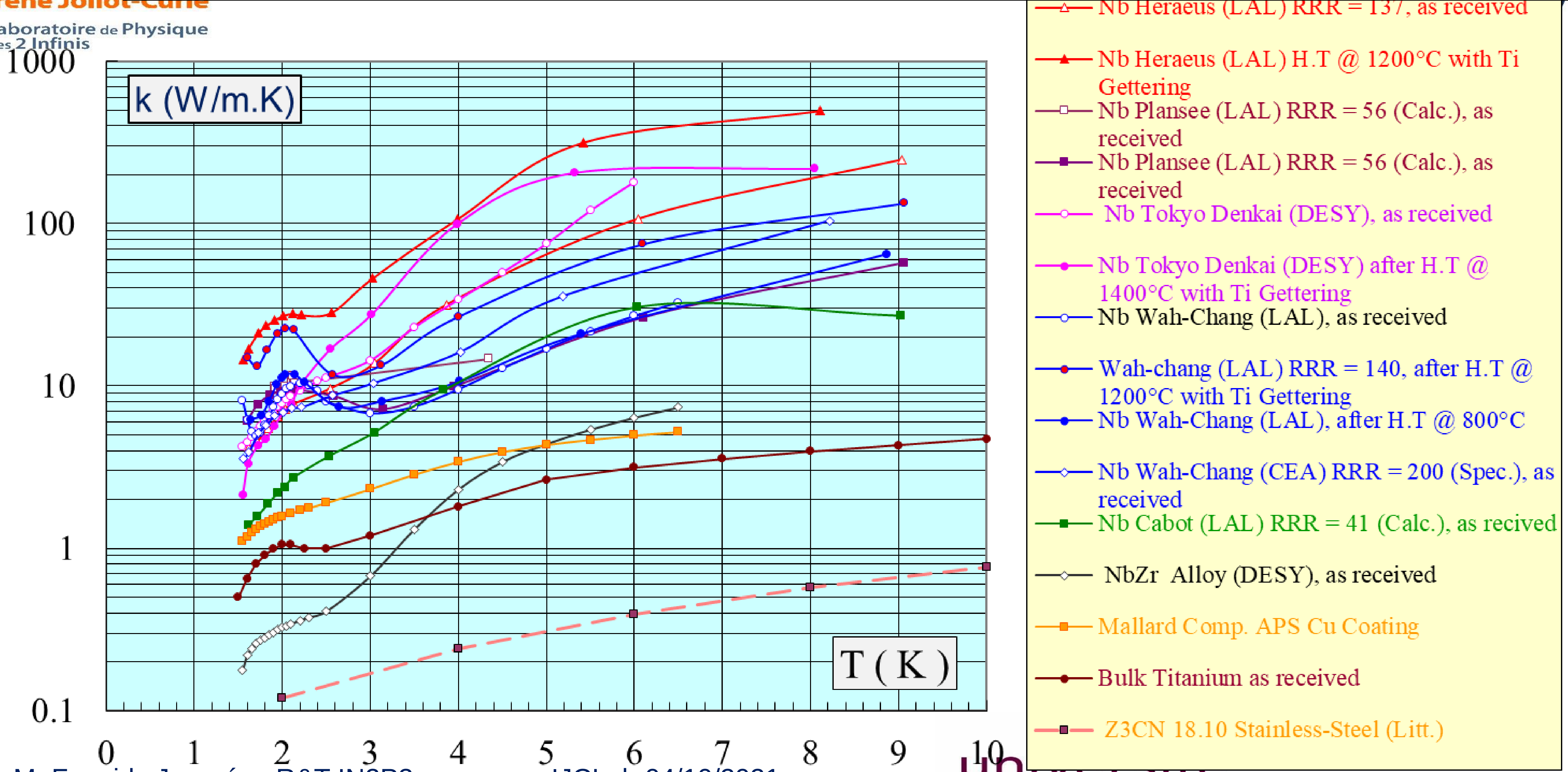
Heat treatment increases niobium thermal conductivity



- ✓ Shape of niobium thermal conductivity vs temperature (e.g phonon peak at 2K,) depends strongly on supplier, production process (raw material, rolling, annealing,..) and post processing
- ✓ High temperature annealing at 800 °C for Hydrogen outgassing increases the thermal conductivity
- ✓ Phonon peak at T~2 K depends on impurities content including H and plastic deformation
- ✓ Post-purication with Ti gettering à T>1200 °C (Reduction of C, O and N concent. in Nb) imcreases the thermal conductivity
- ✓ Reduction of quench field subsequent to heat treatment and/or baking could be attributed to reduction of k(T) phonon peak

Summary of IJClab thermal conductivity experimental data

Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis



Cryogenic Diagnostic Tools

Goal: Development of sensors and electronics dedicated to diagnostics and characterization of anomalous losses and dissipation sources in SRF cavities

Second sound quench detectors in superfluid helium (He II)

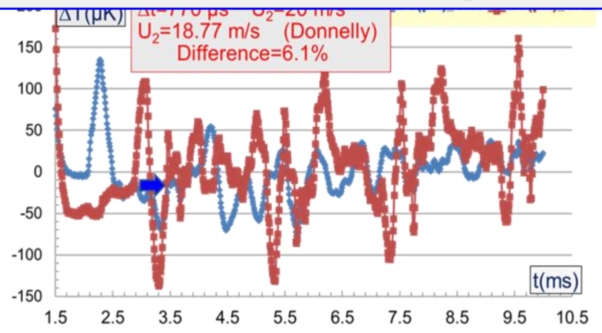
Measurement of 2nd sound thermometric signals is challenging

Low level <100mV: difficult to measure transient (<<1 ms)

Expected transient heatings ~50 µK-200 µK

V_S(mV)	Sensitivity (Ω/mK)	DV(µV) for dT= 100 µK	DV/V
81.5	7	7.7	$9.4\ 10^{-5}$

2nd sound thermometric signals in He II



➡ High resolution needed < 10^{-5}

BW: 1-3 MHz

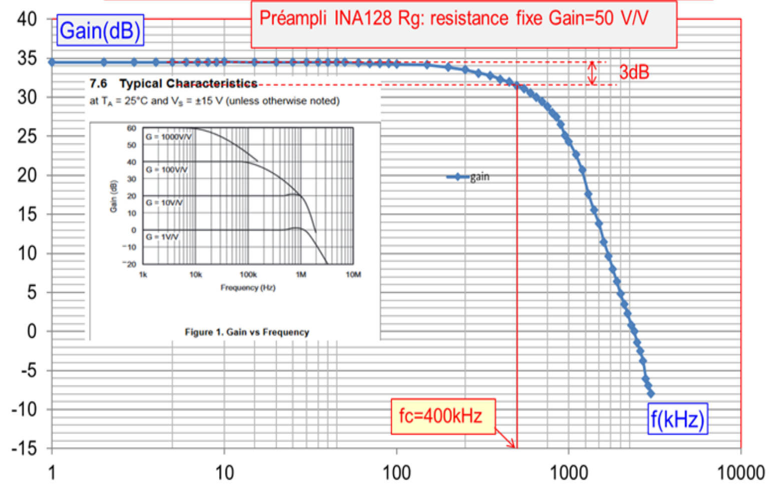
Resolution: 10^{-6}-10^{-5}

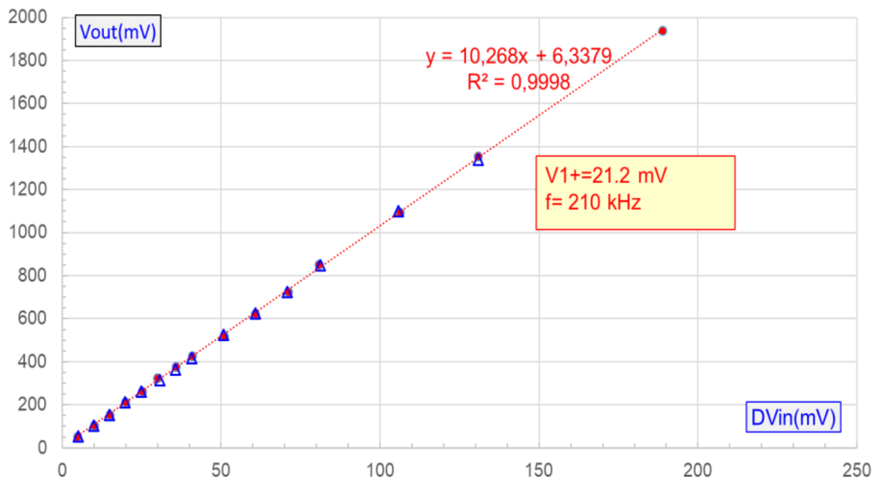
Qualification test finished:

- Dynamic characteristics
- Calibration,
- Sensitivity/resolution
- S/N Ratio
- Spectral response

Heloise Conditionneur de signaux préampli INA128

Gain versus frequence (In4 et sortie switch)



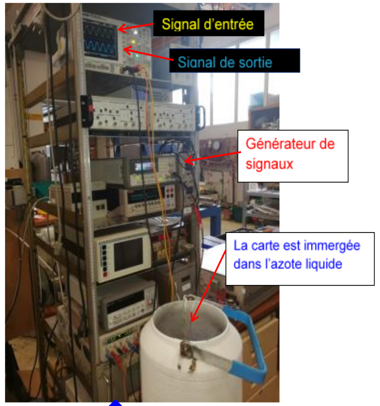


- ✓ Good linearity Repeatability: 99.95%
- ✓ Successful qualification tests
- ✓ Ready for cryogenic test with real signals

Cryogenic Diagnostic Tools (2)

Motivations développement électronique cryogénique

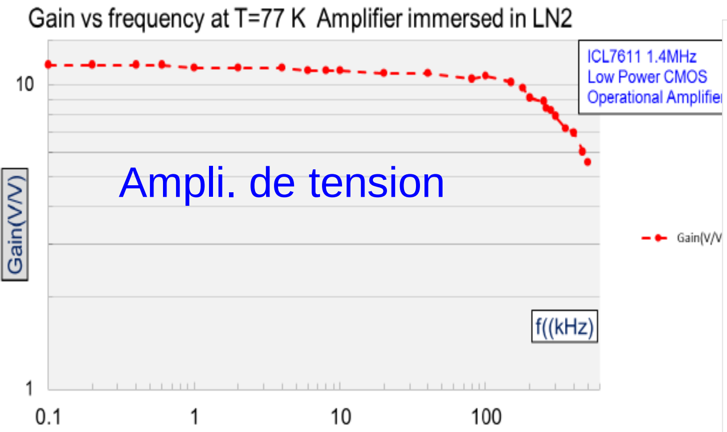
1. Intégration capteur et électronique
2. Simplification & réduction coût câblage (multiplexage cryo.)
3. Meilleure performances (BW, moindre bruit,…)
4. Développement compétences en électronique cryo.
5. Se renforcer en instrumentation bas niveau)
6. Synergie avec NGCRYO (Bolomètres, Kids, TES)

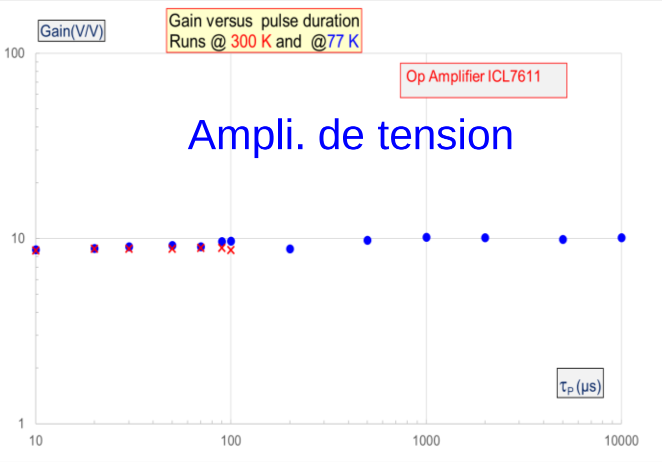


Test en azote liquide à 77K

Développement en cours PACCRYO

Premier tests réussis

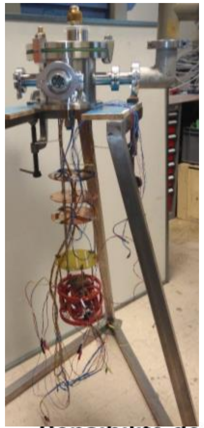


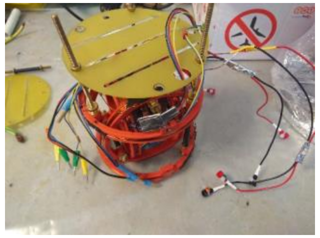


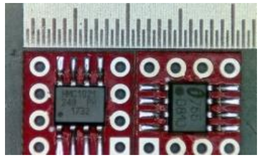
Capteur AMR : cartographie champ magnétic

Objectifs:

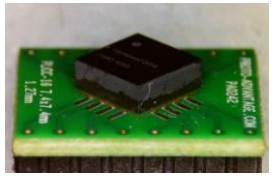
1. Caractérisation de capteurs magnétiques opérant aux températures cryogéniques
2. Mesure champ magnétique résiduel sur échantillon supraconducteur (cabité TE011 – banc ECOMI)
3. Système compacte pour cartographie champ magnét sur cavités RF supraconductrices à T <4.2 K

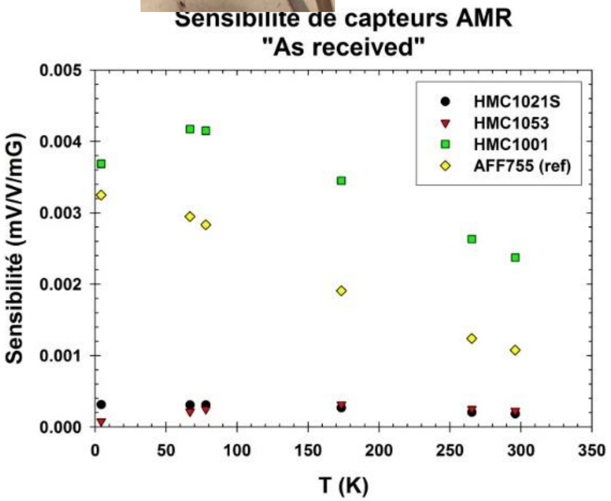


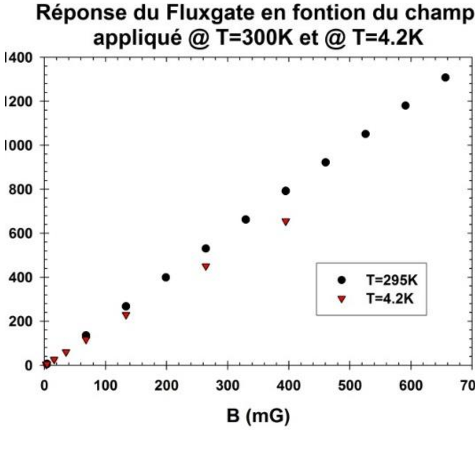




New test facilty for full characterization of AMR sensors







M. Fouaidy Journées R&T IN2P3