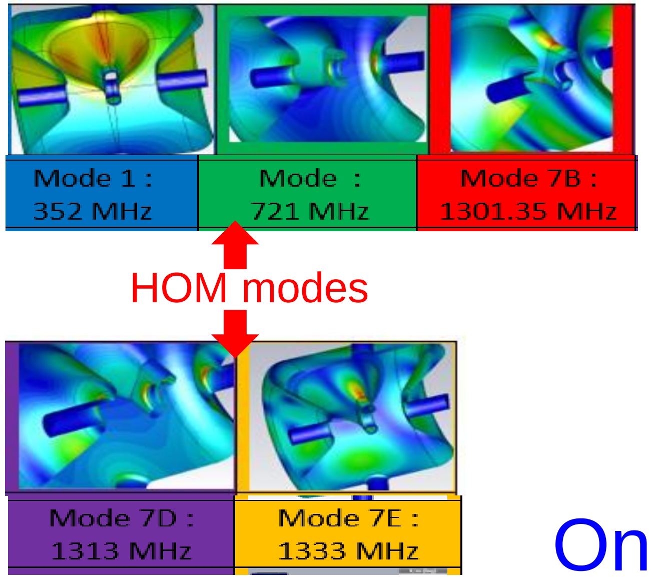
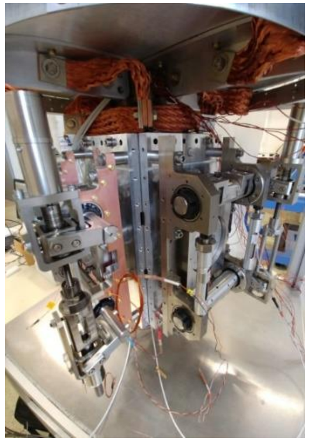


SRF R&D activity at IN2P3

M. Fouaidy

On behalf of IN2P3 SRF Teams (IJCLab, LPSC)



OUTLINE

- Why SRF and for SRF R&D?
  - ✓ Scope of SRF R&D topics
  - ✓ What is an SRF surface ?
  - ✓ SRF main goals

- SRF organization and overview of projects at IN2P3
  - ✓ Heat treatments and diagnostics for Niobium cavities (HELOISE)
  - ✓ Alternative fabrication and surface polishing (PACCAS, PICASU, AXE SRF)
  - ✓ Alternative SRF materials (ECOMI, AXE SRF)
  - ✓ Mitigation of multipacting (MULTIPAC)
  - ✓ Optimization of SRF ancillaries like Couplers, Tuners and LLRF (MYRRHA, PIP-II)

- Conclusion and perspectives

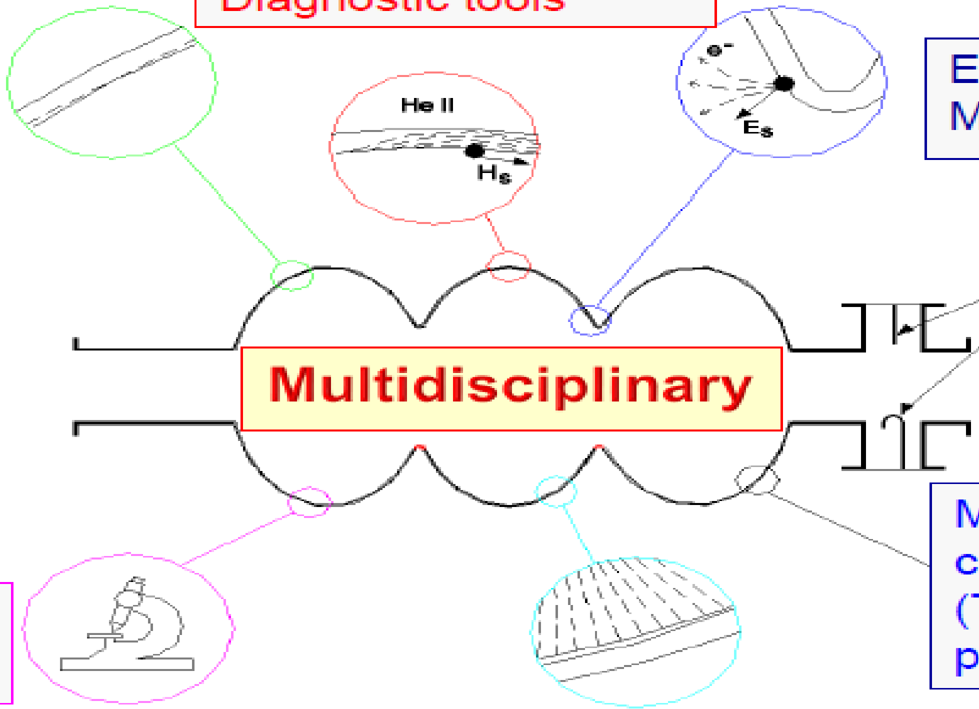
Scope of SRF R&D topics

Functional performance of SRF Accelerating Systems depends strongly on material and surface properties and their preparation and treatment processes

Residual surface resistance
Residual magnetic field

Heat transfer
Experimental studies
Numerical simulation
Diagnostic tools

Enhanced Field Emission
Multipacting



Development of RF components and hardware
FPC and HOM couplers
LLRF

Surface and Material characterization at RT

Material characterization at cryogenic temperatures (Transport and mechanical properties, superconducting prop.)

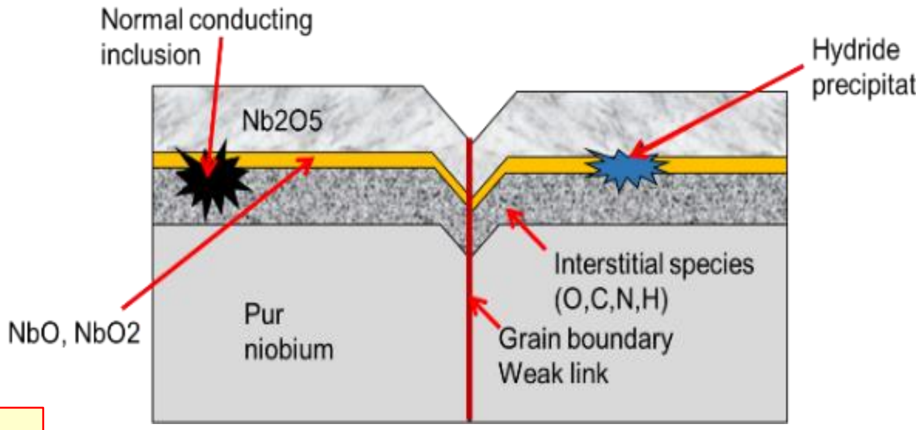
Material and Surface processing
Development of new materials
Surface engineering

Topics are addressed in the Master project SRF (Basics R&D) and/or driven by current construction projects

Real RF surface of SRF resonators are 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	

- ✓ 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



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

SRF R&D Main goals

Develop High functional performance SRF accelerating structures, at low cost with High production and process yield at large scale

- Optimum design of cavities
  - Acceleration efficiency
  - Lower anomalous RF losses (reduce Bpk/Eacc and Epk/Eacc)
  - High thermal stability
  - Mechanical stability (Lorentz detuning, microphonics)
  - Multipacting free
- New surface treatment new materials: Optimize bulk Niobium technology (doping, passivation layer, shielding multilayer) and find alternative superconducting materials and substrates
- Fabrication, preparation and processing: reliable manufacturing, preparation and processing at low cost
- Ancillaries : Cryostat and cryogenics, Power coupler, Cold tuner, Magnetic shielding, instrumentation

OUTLINE

- Why SRF and for SRF R&D?
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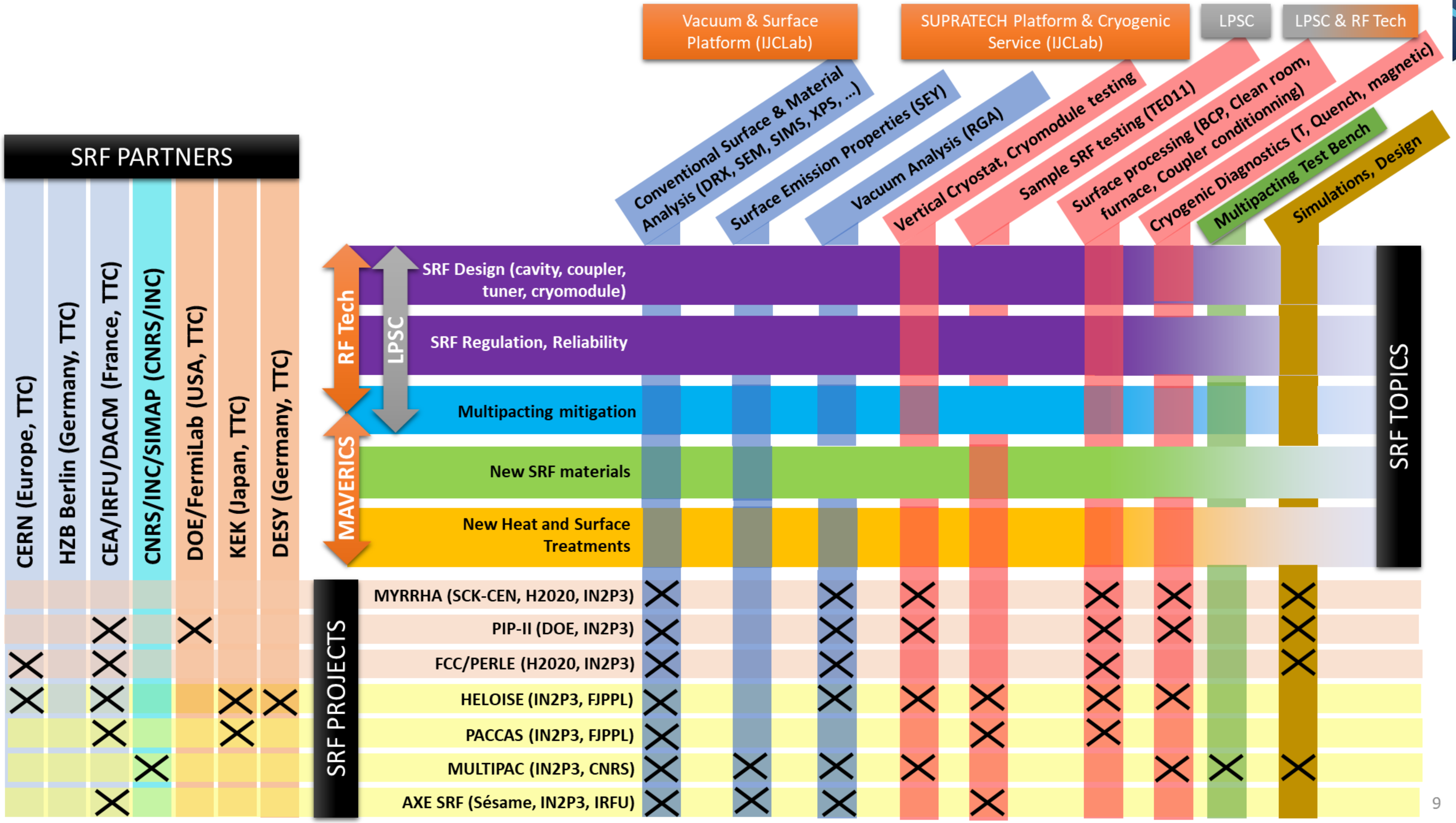
Overview of SRF R&D organization



HELOISE: objective and research topics

HELOISE

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

Objectif: Produce reliably and reproducibly at large scale SRF cavities

► High gradient (Increase E_{acc} by 25%)

► Low RF losses (Reduce losses by a factor 2 à 4)

HELOISE is focused on two main topics

Topic #1: Develop, master and optimize the parameters of thermal processes under vacuum (low temperature baking, high temperature annealing, Nitrogen infusion and doping) of low β SRF resonators.

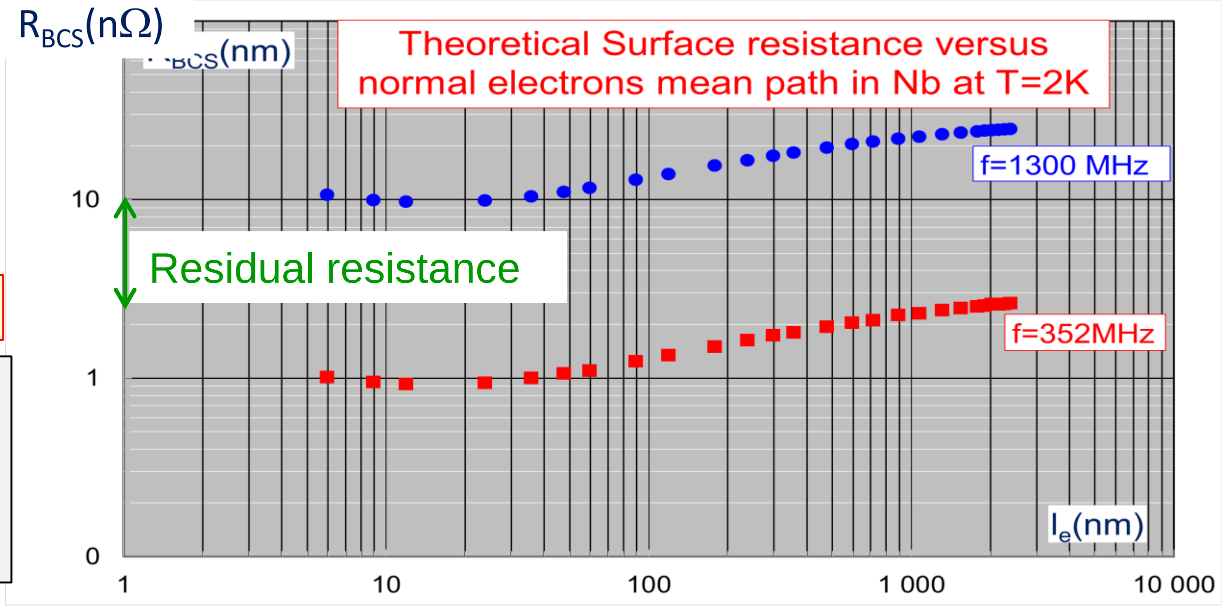
Topic #2: Develop diagnostics tools (quench , X-rays induced by field emission, magnetic field) and test stands for material characterization at cryogenic (measurement of electrical, superconducting, thermal and magnetic properties).

N-doping and N-Infusion of low frequency cavities

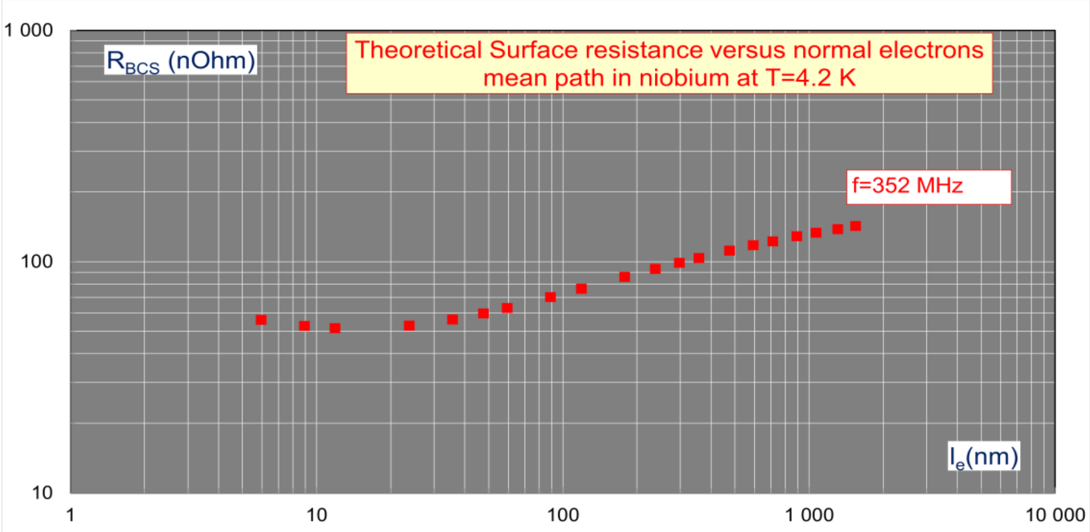
At T=2K, the gain of applying of N-doping or N_infusion at lower frequency is not obvious :
resonator is operated in residual surface regime
RF losses dominated by the frozen magnetic field: effort on magnetic hygiene is mandatory

Expected gain for high frequency cavities: reduce losses (factor ~3)

At 2 K, two important advantages:
Reduced micro-phonics (perturbations of cavity frequency)
Superfluid helium (He II) coolant @ 31 mbar Better pressure/Temperature regulation) Efficient heat transfer



To be experimentally demonstrated/confirmed



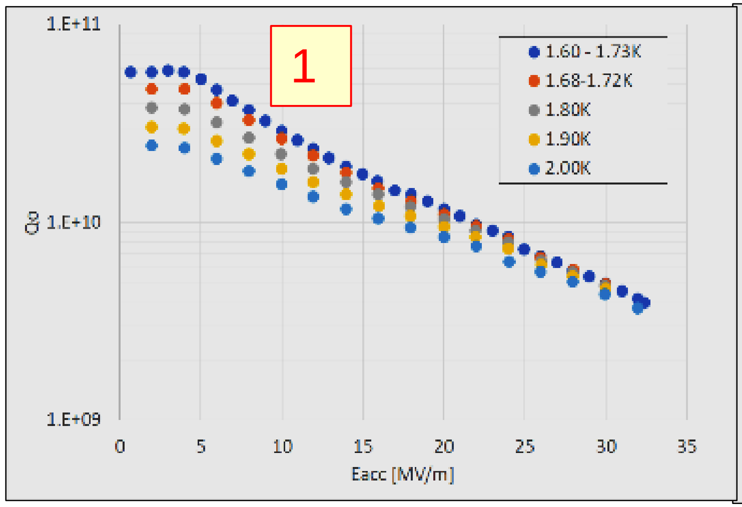
At T=4.2K: Potential gain of performing N-Doping or N-infusion: reduction of RF losses (factor 2-3).
Advantages
Reduced refrigeration cost (investment & operation)
Reduced leak risk (atmospheric pressure)
Cheaper and simpler cryostat, cold box and cryogenics

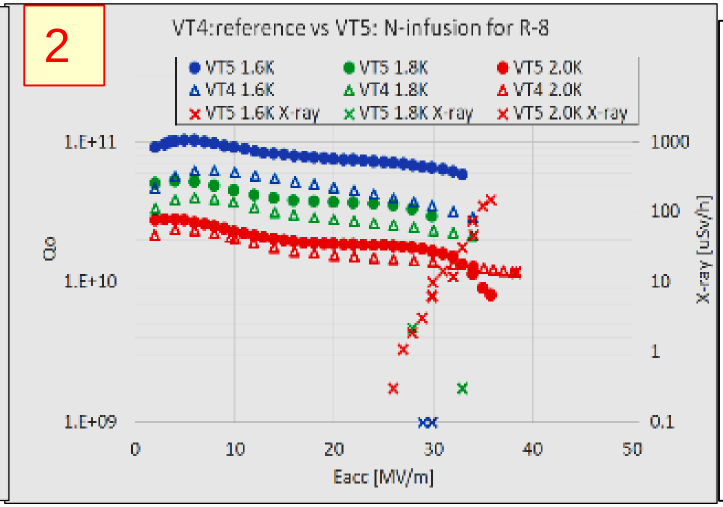
Heat Treatments for Low Losses High Gradient SRF Cavities

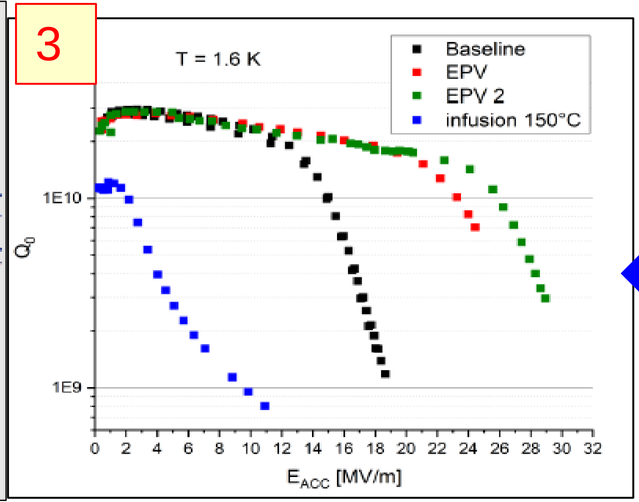
M. Fouaidy (Leader), D. Longuevergne, G. Martinet (IJCLab/IN2P3), E. Cenni(IRFU/CEA)
K. Umemori(Leader), E. Kako, H. Sakai, T. Konomi, M. Omet, R. Katayama, H. Itoh(KEK), T. Okada, K. Takahashi (SOKENDAI)

Collaboration CNRS-CEA-KEK TYL FJPPL Project ARD_19

Investigate New surface and material Heat Treatment (HT) processes for improving RF performance (Q_0 and E_{acc}) of SRF cavities. Study of 4 processes : 1) N-infusion, 2)N-doping, 3) Middle-T baking and 4) Two step baking.







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

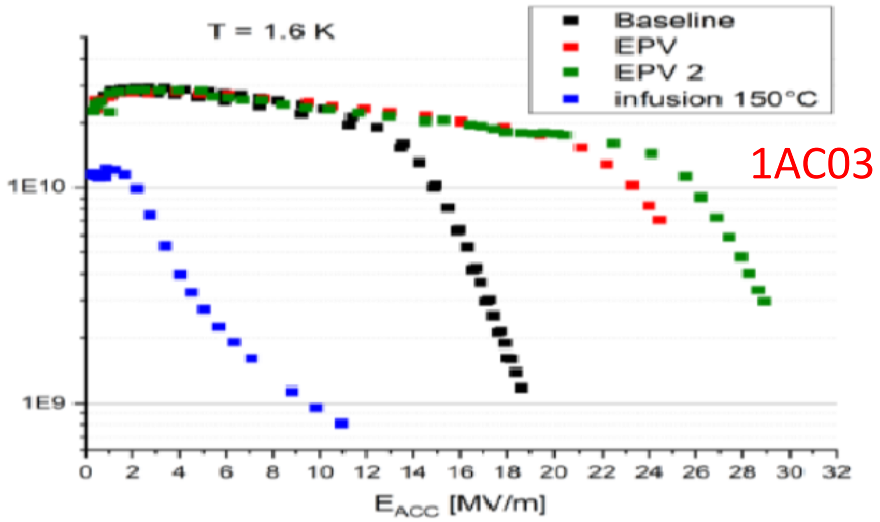
Main issue: Lack of repeatability and reproducibility of results between institutes.
Results for N-infusion at KEK / IJCLab depend strongly on furnace and detailed process.

Main objective :

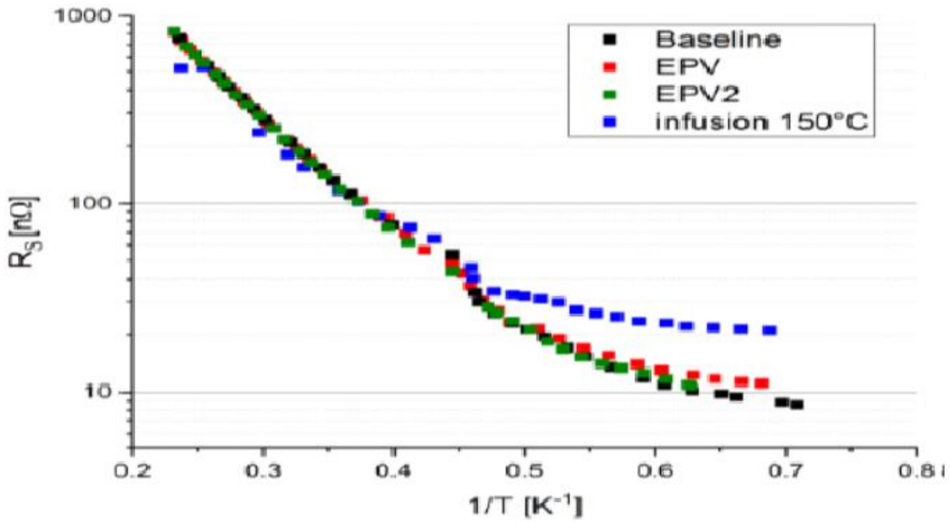
- ✓ Master the process and **optimize process parameters** (collaboration) and **develop new HT recipe** for high performance SRF resonators.
- ✓ In depth understanding of the correlations between Qo, Eacc and material/surface properties using dedicated Nb surface analysis of samples and vertical tests of cavities at different frequencies

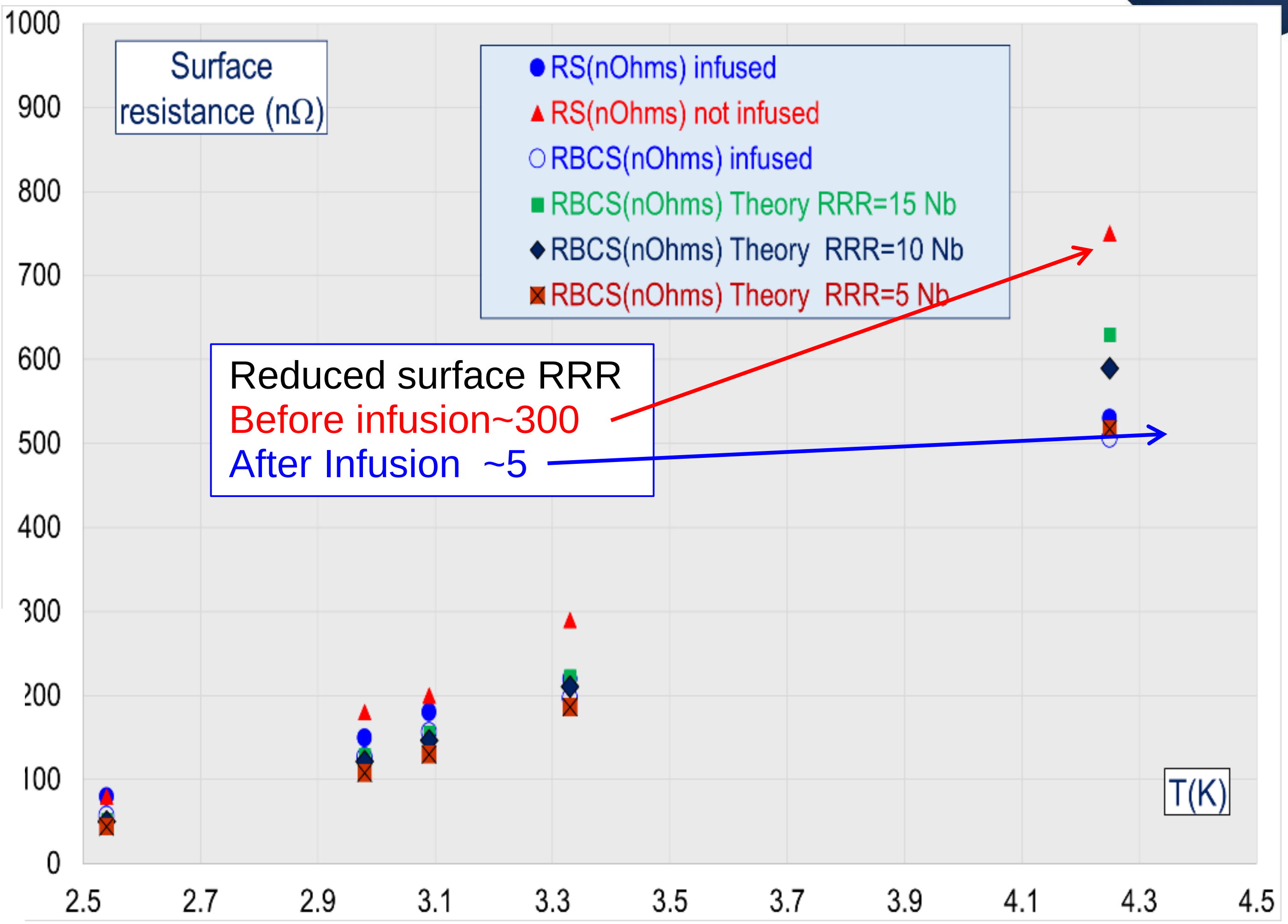
First infusion run at IJCLab Saclay 1.3 GHz cavity

Collaboration CEA



Residual Surface resistance increased due to Nb2C





BCS Surface resistance decreased

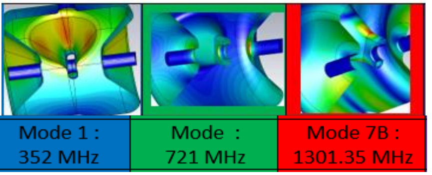
Multimode spoke cavity studies

Motivation of multimode tests

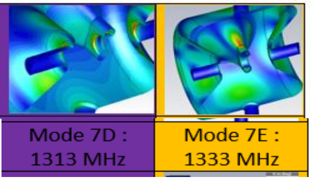
- ✓ Anomalous Q_0 vs E_{acc} variations (degradation) depend on frequency (f)
- ✓ Sensitivity to magnetic field depend on f ($\sim f^{1/2}$)
- ✓ Residual surface resistance depend on f
- ✓ N-infusion & N- doping effect on surface resistance depend on f

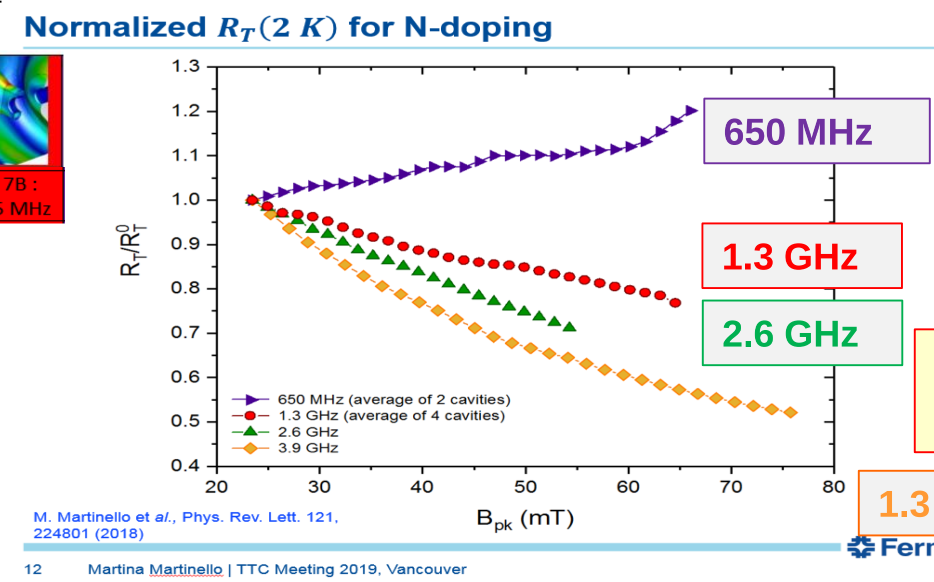
How

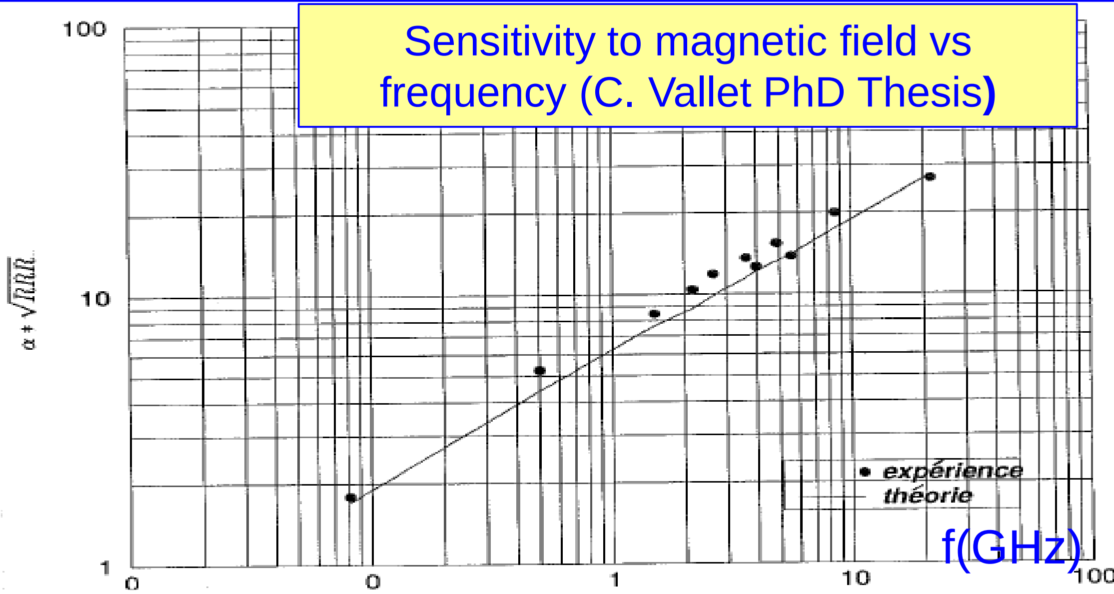
Study the above effects as function of frequency on the same cavity : process the cavity and perform the RF tests without resetting the surface.



HOM modes







- ✓ Slope of R_S vs B_S depend strongly on f
- ✓ Opposite sign of slope for low frequencies

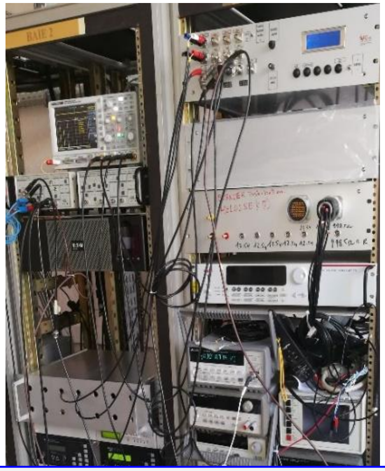
Successful test at 2K (baseline) prior to N-doping

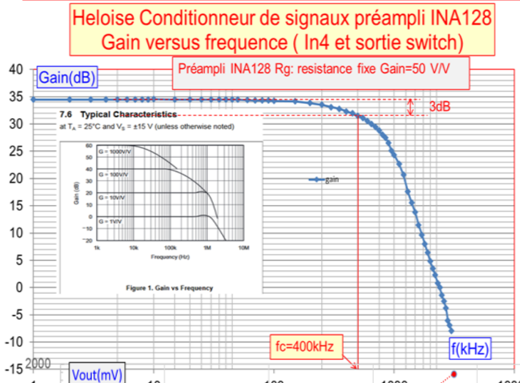
Cryogenic Diagnostic Tools

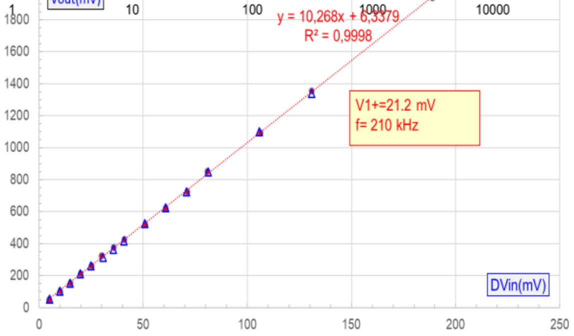
Goal: Development of sensors and electronics dedicated to diagnostics and characterization of anomalous losses and dissipation sources in SRF cavities

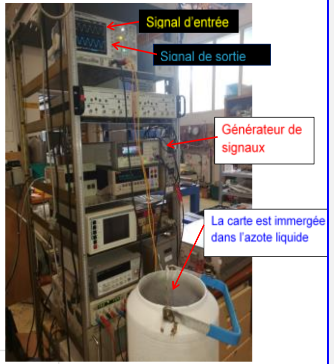
Second sound quench detectors

BW: 1-3 MHz
Resolution: 10^{-6}-10^{-5}









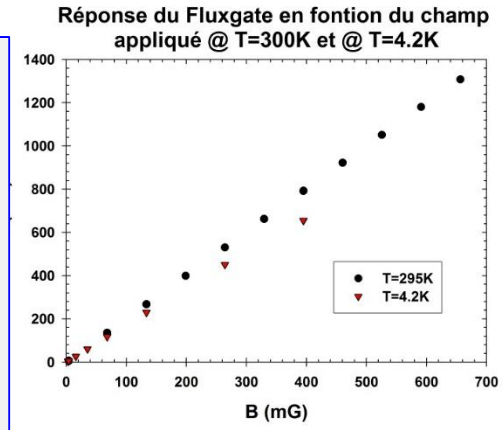
Qualification test done: dynamic characteristics , calibration, sensitivity/resolution measurements

Good linearity Repeatability: 99.95%
Successful qualification tests
Reay for cryogenic test with real signals

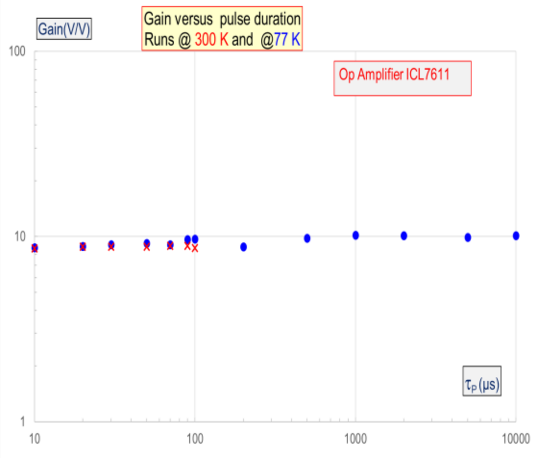
AMR sensors for magnetic mapping

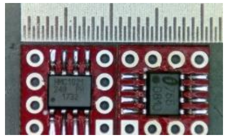
Objective:

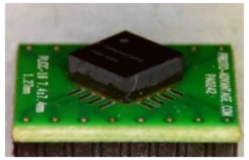
1. Characterization of magnetic sensors for measurement at cryogenic temperatures
2. Measurement of residual magnetic field on supperconducting sample surface (ECOMI)
3. Compact system for magnetic mapping of SRF cavities at T <4.2 K

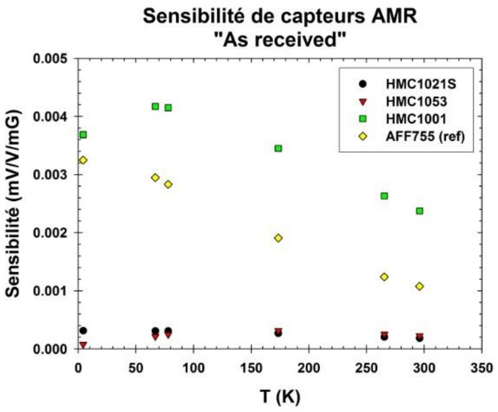


PACCRYO









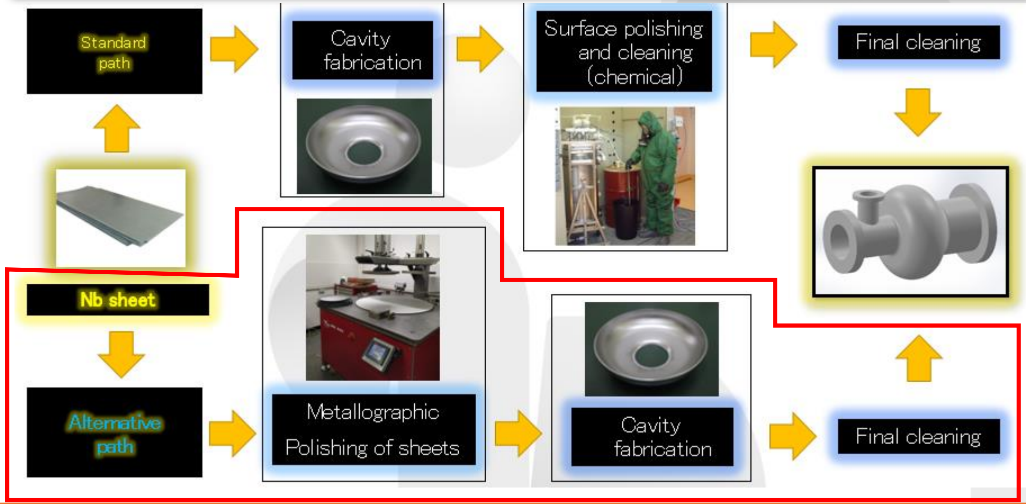
Investigation of an alternative path for SRF cavity fabrication and surface processing (PICASU, PACCAS, AXE SRF)

Motivations

- Possible cost reduction of cavity fabrication & surface processing (ILC, FCC, …)
- Achieve better surface roughness than standard chemical cleaning & study impact on SRF properties
- Substrate preparation for thin films deposition (prepare for future technology)
- Improve enviromental footprint and worker safety (reduce usage of acids)

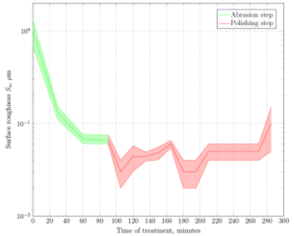
ON-GOING COLLABORATIONS & ROLES

- **IJCLab**: Niobium polishing & material characterization
- **IRFU** (H2020, Axe SRF): Expertise in metallurgy
- **KEK** (FJPPL): Niobium forming & welding. Cavity fabrication
- **LAMPLAN**: company specialized in lapping & polishing

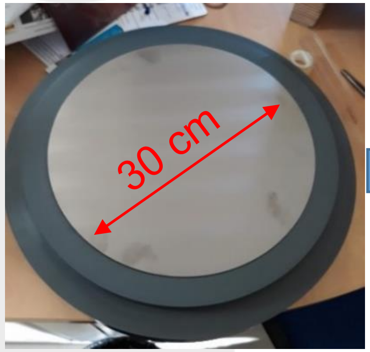


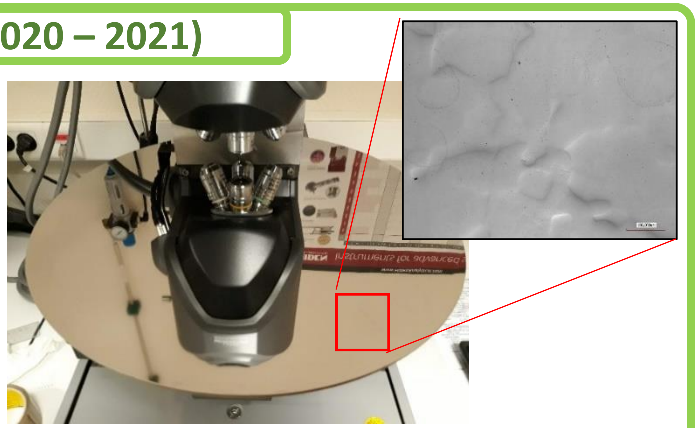
PHASE 1 : PICASU : Optimization of Polishing on small samples (2016-2019)

- Supported by IN2P3, H2020 (Ensar2)
- 1 PhD : Oleksandr Hryhorenko

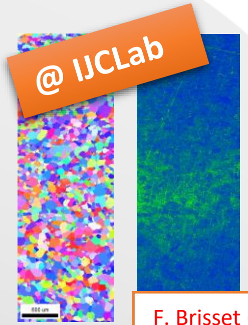


PHASE 2 : PACCAS : Large disks polishing (2020 – 2021)





PHASE 3 : PACCAS : Optimized forming of pre-polished sheets (2020 – 2022)



F. Brisset (ICMMO)

Investigation of alternative SRF materials (ECOMI, AXE SRF)

Motivations

- Go beyond bulk Niobium technology.
- Improvement of accelerator gradient (Eacc) and quality factor (Qo)
- Dope Niobium surface (remove deleterious oxide layer) to improve superconducting properties
- Study several pathways : thick films (Nb3Sn) or multilayers (S–I–S structures)

Multilayer path (SIS)

- 2 layers of superconductor separated by a thin layer of isolator (S-I-S)
- Suggested by Gurevich in 2007
- Shielding by multilayer still not fully demonstrated under intense RF fields
- ALD (Atomic Layer Deposition) very promising as very uniform nanometric layers required
- TODAY investigated at IN2P3

Thick films (A15 compounds)

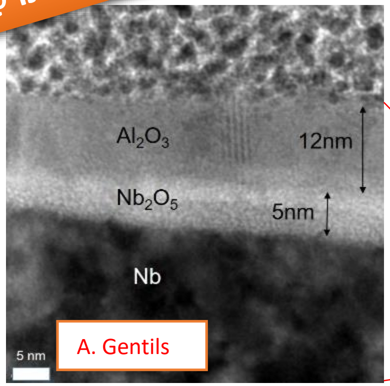
- A15 : Nb3Sn, V3Si
- Operation at 4.2K (Tc > 15K)
- Accelerating gradient doubled
- But limitation today at B~80 mT because of granular superconductivity
- Several paths : Sn diffusion on Nb (USA), Nb/Sn deposition on copper (CERN), « bronze route » (China).
- NOT investigated at IN2P3

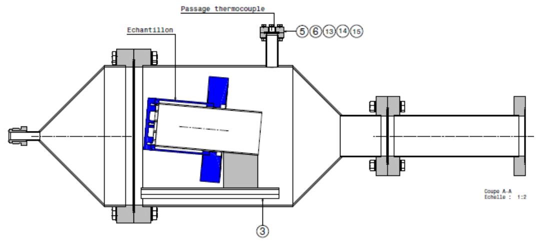
ON-GOING COLLABORATIONS & ROLES

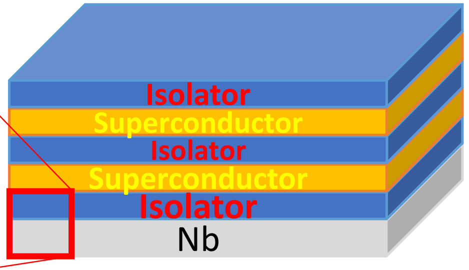
- **IJCLab** : Material characterization & SRF testing (TE011)
- **IRFU** (Axe SRF, I-FAST): Expertise in ALD & SRF testing (1.3 GHz elliptical cavities)
- **HZB** (TTC): SRF testing in Quadrupole Resonator (QPR)

AXIS 1 : AXE SRF : Production of thin films by ALD at IRFU (2018-2022)

- Supported by IN2P3, IRFU, Ile de France Region
- 2 PhDs : Sarra (IJCLab), Yasmine (IRFU),

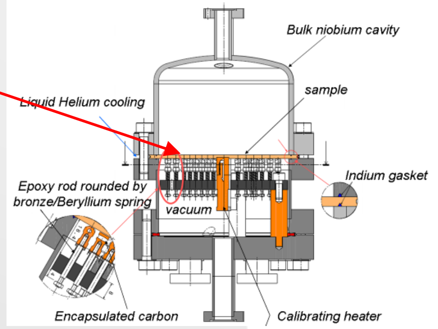


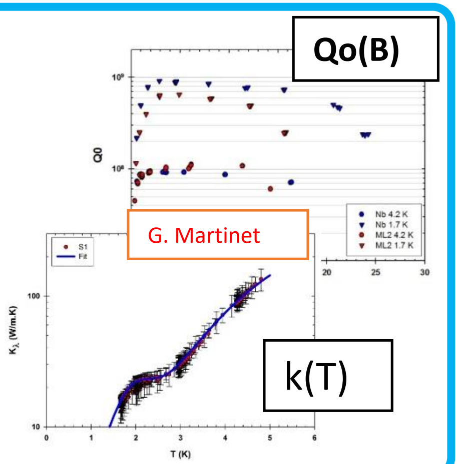




AXIS 2 : ECOMI : SRF testing of flat disks (2012 – 2020)

- TE011 resonator (RF and calorimetric measurement)





Mitigation of multipacting phenomenon in accelerators (MULTIPAC)

Motivations

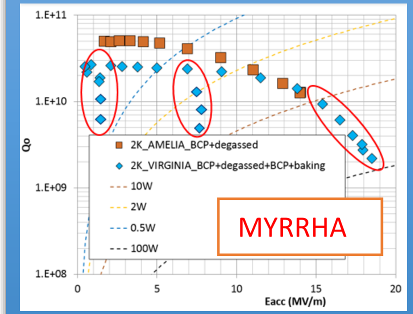
- Multipacting is a general problem/limitation in SRF structures (cavity and couplers)
- Causes vacuum degradation (e− clouds) in synchrotrons (limitation of luminosity in LHC)
- Mitigation of multipacting helps mitigating risks of failure and improvement of reliability in accelerators

ON-GOING COLLABORATIONS & ROLES

- **IJCLab** : Material characterization & Simulations
- **LPSC** : Simulation & Dedicated multipacting test bench
- **IRFU** : TiN coating by ALD & Plasma processing
- **SIMAP** (to be initiated): Expertise in thin film deposition (ALD, PVD, …)

Multipacting in cavity

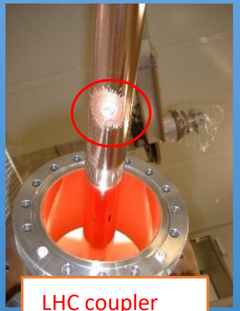
Qo degradation and field limitation



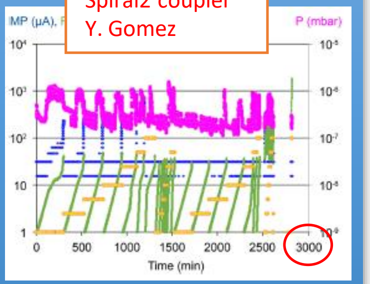
MYRRHA

Multipacting in coupler

Surface damages and long conditionning time



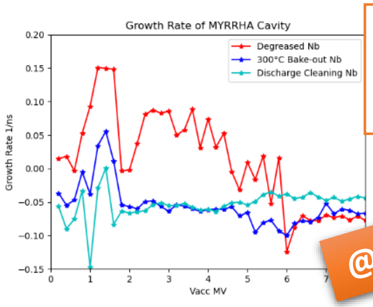
LHC coupler
E. Montesinos



Spiral2 coupler
Y. Gomez

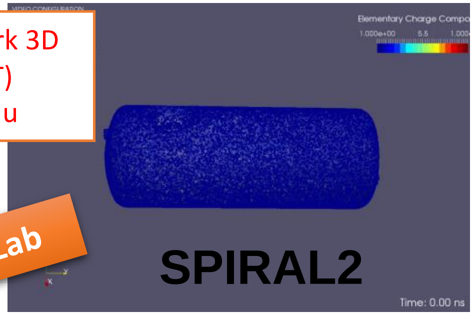
AXIS 1 : SIMULATION : Identification & localization of multipacting)

- Several 3D codes available (CST PIC & SPARK3D)
- Code developed @ IJCLab (MUSICC3D). 1 PhD (2015).
- Integrated in design phase of cavities and couplers
- Essential for new accelerator projects : risk mitigations



Spark 3D
(CST)
N. Hu

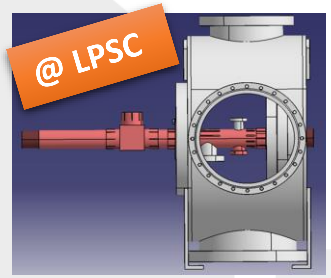
@ IJCLab



AXIS 2 : TESTING : dedicated test bench

- Test in nominal conditions

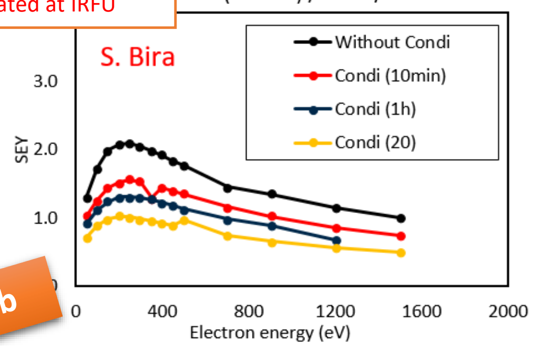
@ LPSC



- Measure SEY

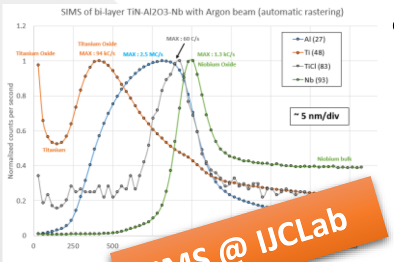
@ IJCLab

Coated at IRFU



AXIS 3 : MITIGATION : Improve TiN coating & surface processing (plasma, UV, …)

- Thin film deposition (TiN) on ceramics (Al_2O_3)
- Companies (HEF, PMB, Thalès-RI)
- IRFU (ALD)
- Investigate several coating techniques, thicknesses, …
- Investigate new materials (SIMAP)



SIMS @ IJCLab

- Specific surface processing as plasma and UV (Activity to be initiated)

Fast Active Cold Tuning Systems Piezo tuning System

Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

FACTS Program driven by the needs of ESS (pulsed), PIP II and MYRRHA (CW)

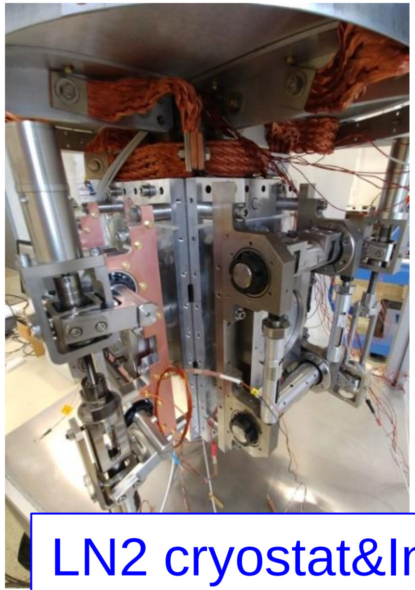
Main goals

Dynamic Lorentz Detuning Δf_{LD} compensation

Reduction/damping of vibrations & microphonics

High Reliability needed
Test of Fault Tolerance strategy: fast detuning

Motivations
Beam quality (Phase&Amplitude)
Energy stability against perturbation
Reduce RF power ($\sim \Delta f_{LD}^2 \sim E_{acc}^2$)



LN2 cryostat&Insert (T=77 K)
Testing of four FACTS

Test stand dedicated to reliability and lifetime studies at cryogenic temperatures

PARIS-SACLAY

Fundamental Power Coupler (FPC)

Main function : efficient transfer, in matched condition, of the RF power from the source through the waveguide network to the particle beam.

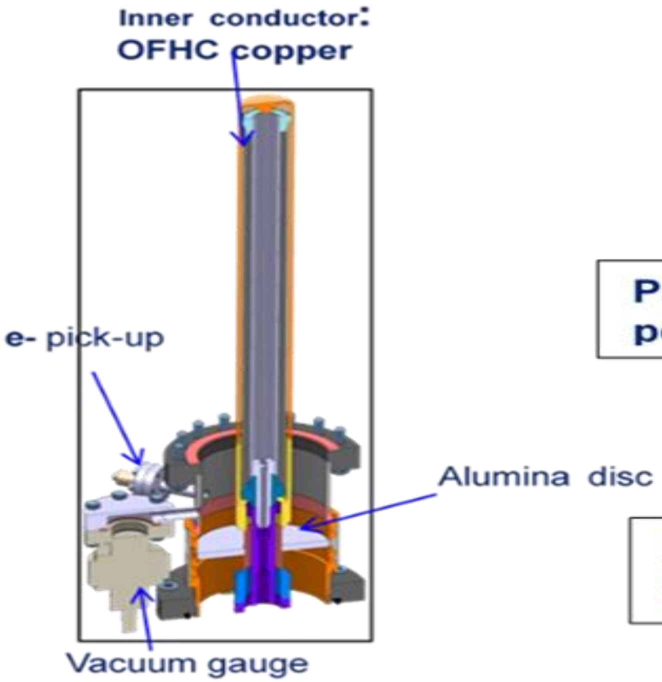
FPC is a complex device operating in stringent conditions:

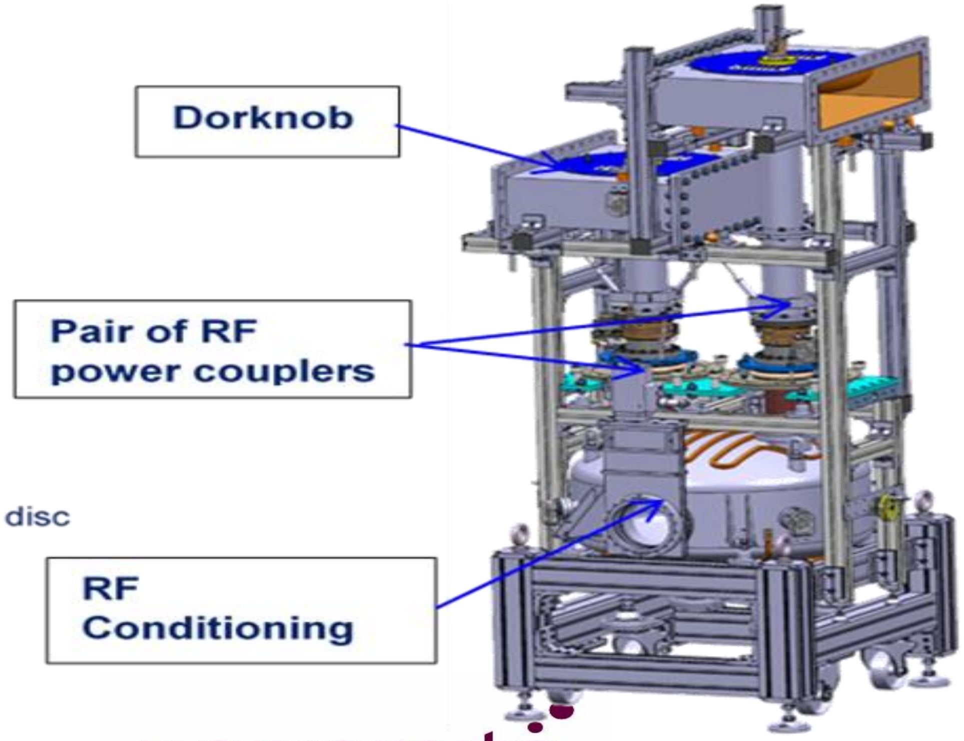
- Handle and transmit a high RF power (10 kW-500 kW) through a ceramic window,
- Thermal interface between warm (T = 300 K) and cold parts (T = 2–4.2 K) of the cryomodule
- RF transparent vacuum barrier between 1 bar (WG @300 K) and UHV in the SRF cavity at T= 2 K.

MYRRHA FPC : reliability very demanding.

Power: 80 kW CW @ 352 MHz)

MYRRHA FPC





Fully Digital LLRF for MYRRHA

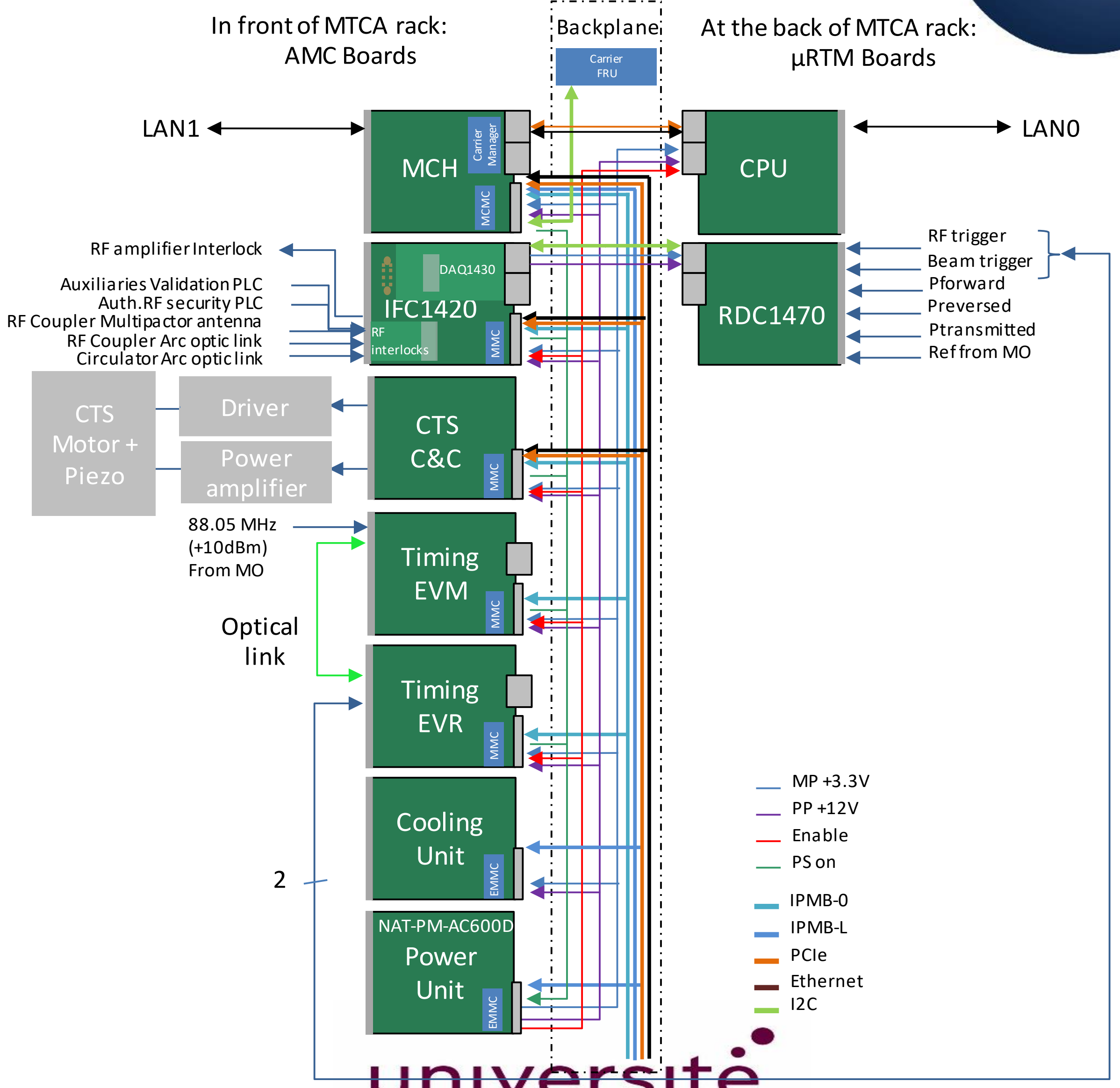
Features

- ✓ Fully digital
- ✓ Use of a standard platform MTCA

  Reliability, Compactness, …
- ✓ IOXOS solution main board IFC1420
- ✓ Collaboration with IOXOS company

On shelf HV solution with a long term availability,…

- ✓ Signal processing development upgraded and improved version of the software new functions including fault tolerance compensation
- ✓ Simulations of the whole system for easy tuning and optimization of regulation parameters



SRF landscape and IN2P3 focus

SRF landscape and IN2P3 focus		High Gradient	High Qo Low RF losses	High reliability in machine configuration (Coupler, tuner, multipacting)
Bulk Niobium @ 2K @ 1.3 GHz	Theoretical limit	~220 mT	~9E10	Performance en CV
	Best achieved	~206 mT (CORNELL) ~166 mT (ANL 72MHz) ~156 mT (IPNO 352 MHz)	~7E10 (N_2 doping)	~3E10 (N_2 doping) ~160 mT
	Commonly achieved	~100 mT	~2E10	~1E10 >110 mT
Alternative materials (MgB_2, Nb_3Sn) @ 4.2K @ 1.3 GHz	Theoretical limit	Nb_3Sn : 511 mT MgB_2 : 425 mT	Nb_3Sn : ~1E11 MgB_2 : ~1E15	Anti-multipacting coating (TiN)
	Best achieved	Nb_3Sn : < 100 mT MgB_2 : samples only	Nb_3Sn : 2E10	
	Commonly achieved	X	X	
Multi Layers (SIS)	Theoretical limit	?? > 1 T	Qo (4.2K) = Qo	X
	Best achieved	X	X	X
	Commonly achieved	X	X	

Projects — High Gradient (Bulk Niobium): PACCAS, AXE-SRF, HELOISE
Projects — High Qo (Bulk Niobium): PERLE, PIP-2, AXE-SRF, HELOISE
Projects — High reliability (Bulk Niobium): PIP-2, MYRRHA, PACCAS, MULTIPAC
Projects — High reliability (Alternative materials): EPISAMA, MULTIPAC
Projects — Multi Layers (High Gradient, High Qo): AXE-SRF, AXE-SRF

Behavior du size effect
Transport properties
Critical temperature

R&D supported by IN2P3

R&D supported by Projets (MYRRHA, PIP-II)

R&D not supported

IJCLab

LPSC

External Collaboration (DESY, KEK, FNAL

Conclusion & perspectives

- ✓ IN2P3 is involved in SRF R&D since 30 years with a continuous and increased effort
- ✓ IN2P3 moved from embryonic and young teams to well experienced and skilled staffs
- ✓ IN2P3 moved from cryomodule prototypes (MACSE,TTF) to major contribution to large projects
- ✓ World class dedicated Facilities allowed IN2P3 to major contribution to the development and construction of large SRF based accelerators
- ✓ A sustainable and well coordinated R& D effort (New material and advanced surface treatment) is needed in order to be ready for facing challenging and very demanding future machines (ILC, FCC)
- ✓ The scope of IN2P3 SRF R&D activity is large including major topics
- ✓ PACIFICS will boost R&D activity : Additive manufacturing &New Cooling Scheme, New high performing materials
- ✓ Upgrade of Vacuum&Surface platform : equipment and installation of D3&D4 test facility
- ✓ Continue R&D advanced Heat Treatments processes for near future projects
- ✓ SRF accelerating systems functional performance are determined by material and surface science and technology : MAVERICS team well skilled . Young scientist or engineer needed (SRF, Vacuum& Surface activities)