Cristian **Pira**

Superconductive Materials
Course Introduction

February 27, 2024

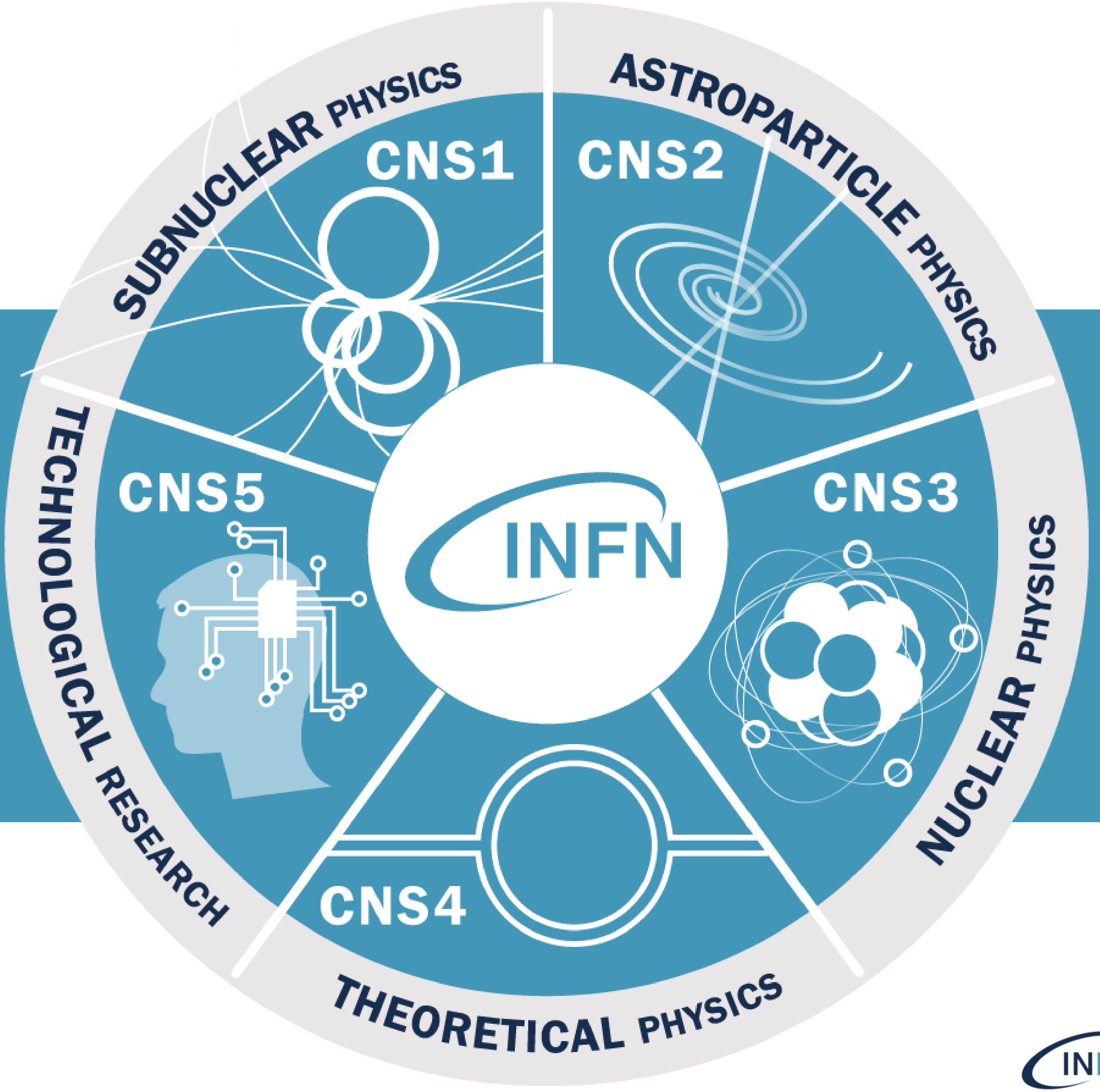
800 ANNI 1222·2022
UNIVERSITÀ DEGLI STUDI DI PADOVA

Few words about INFN

Superconductive Materials

Course Introduction

The **5 research lines**
and the National
Scientific Committee



INFN

INFN
facilities

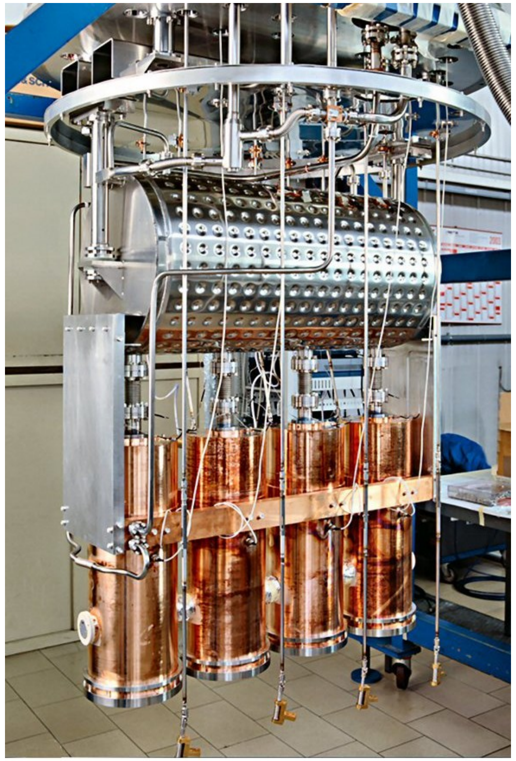
- 4 National Laboratories
- 20 Divisions
- 6 Associated groups
- 3 National Centres and Schools
- 1 International consortia

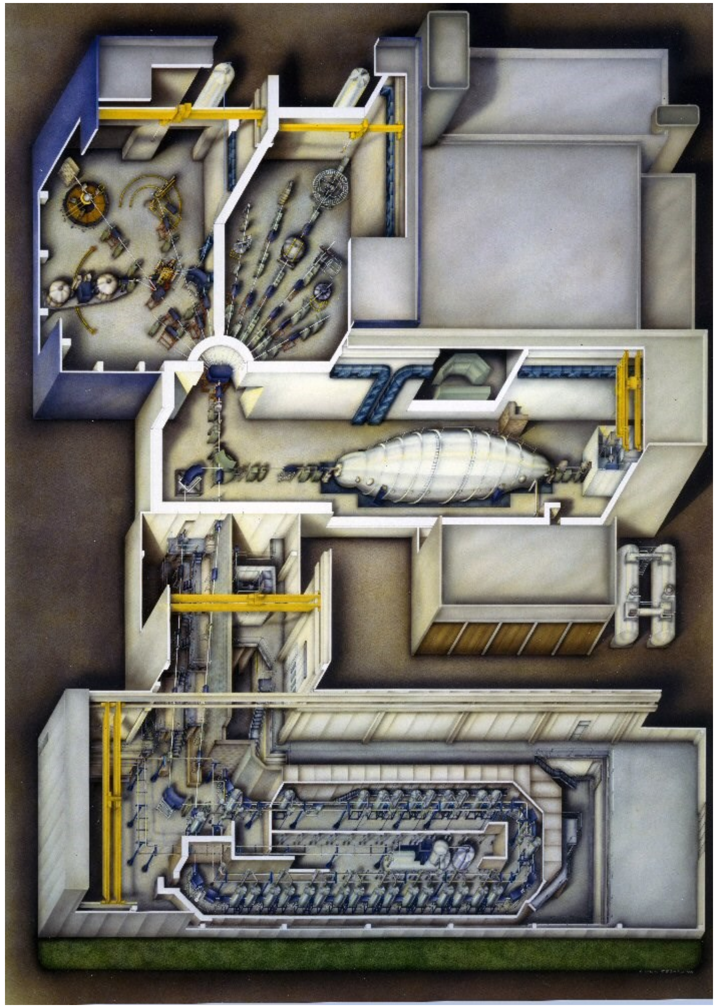
Legnaro National Laboratories (LNL)

- 4 National Laboratories
- 20 Divisions
- 6 Associated groups
- 3 National Centres and Schools
- 1 International consortia

INFN

ALPI (90's)

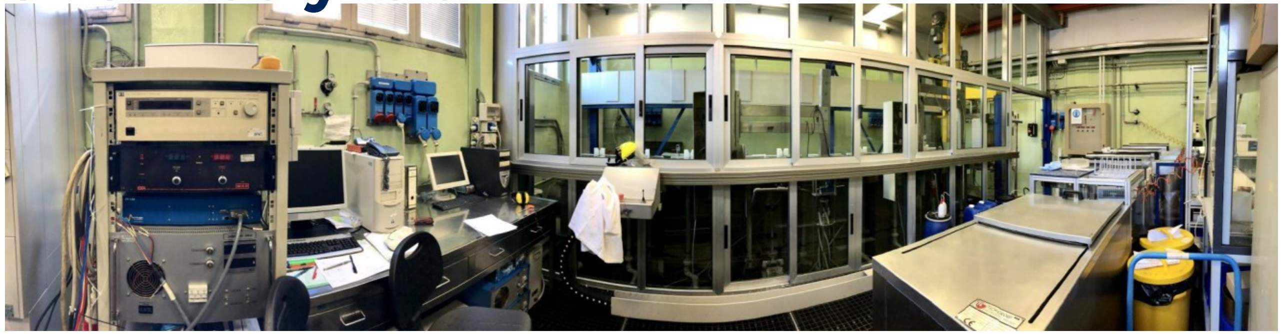




Thin Film Superconducting
LINAC
for heavy ions

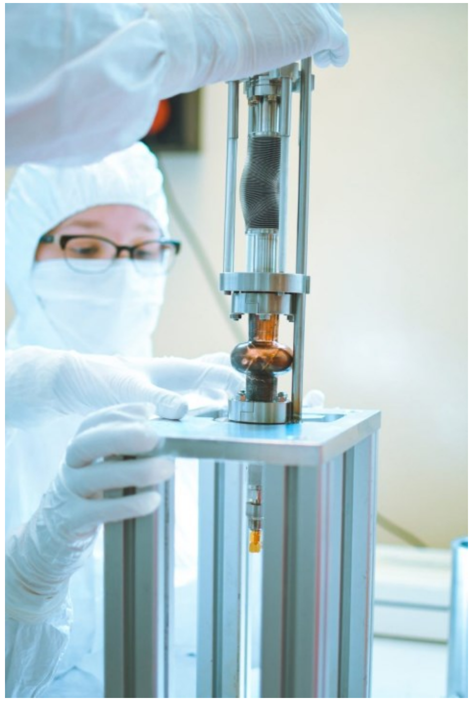
LNL Surface Treatments and Superconductivity Service

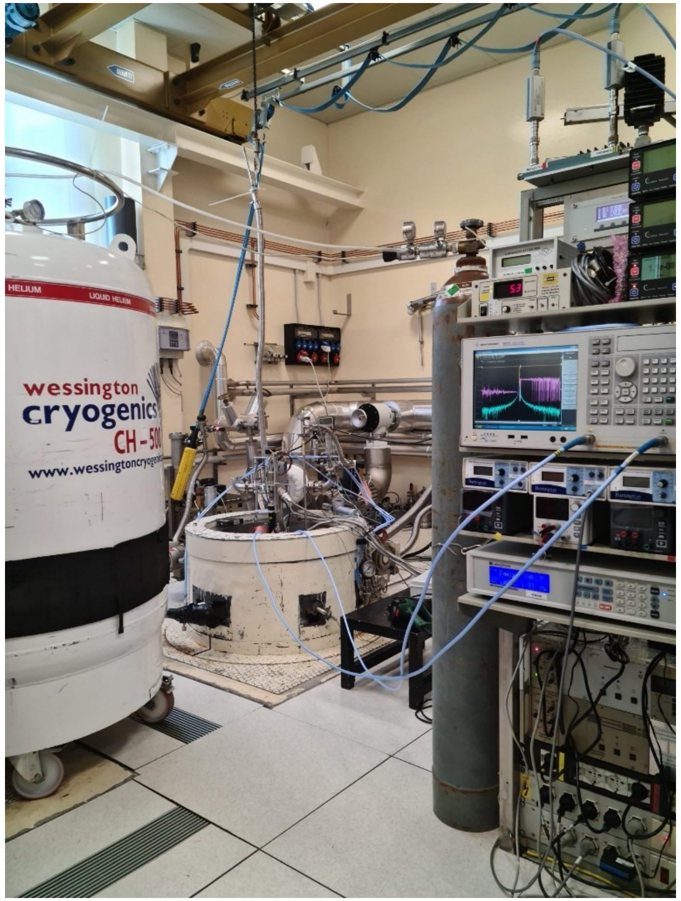
Chemistry lab



Coating lab

Clean room





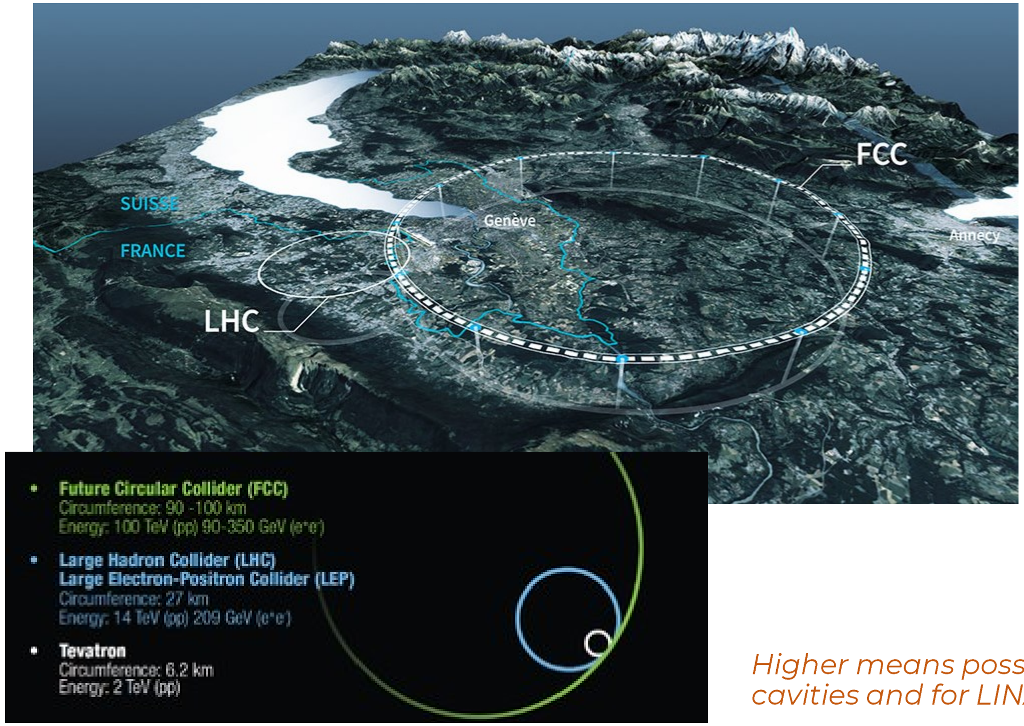
Cryo-RF test lab

https://surfacetreatments.infn.it

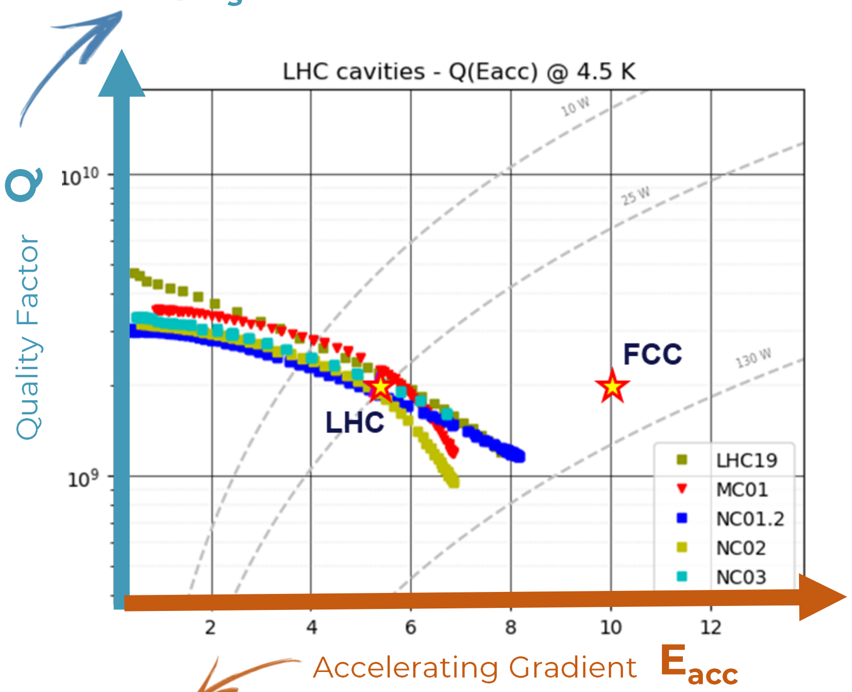
Thin film SRF cavities R&D @LNL

Continuous development to **maximize the performance** of superconducting cavities: **reducing cryogenic consumption** and **increasing the accelerating field**

An example: **Future Circular Collider @CERN**



Inversely proportional to cryogenic consumption



Higher means possibility to reduce number of cavities and for LINAC the facility length

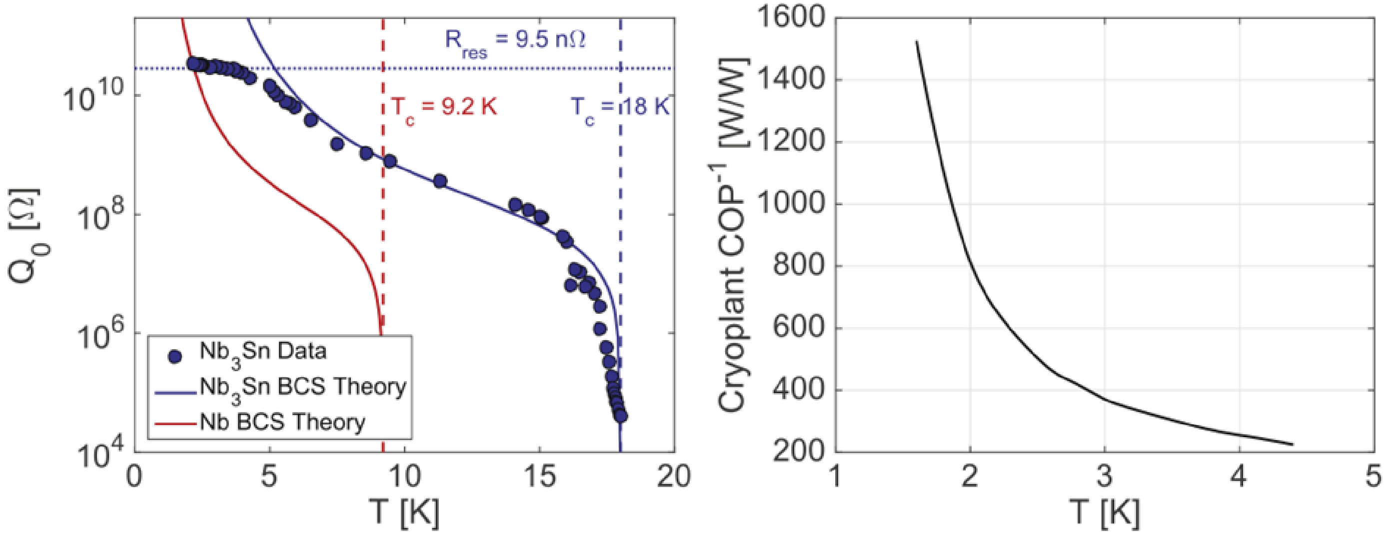
Nb on Cu cavity

FCC-ee requires **higher cavities performances** rather than LHC

Different projects, one main goal:
Nb_3Sn on Cu

Energy saving *is mandatory for the* ***next generation accelerators****…*

*…****cryogenics*** *is one of the* ***larger energy cost*** *in modern SRF accelerators*



Move from bulk Nb @2K to Nb_3Sn @4.5 K

reduces cryogenic power by a factor of 3

Nb_3Sn on Cu: Multiple challenges

- A15 are Brittle materials
- Complicate Phase Diagram
- Substrate preparation
- Low melting point substrate
- Interface diffusion
- Target Production
- Necessity of Test RF properties on simple geometry
- …

INFN LNL SRF R&D Supported by

Collaboration-Projects on Accelerators:

iFAST

iSAS

SAMARA
INFN CSN5 Experiment

SRF cavities R&D for FCC-ee
INFN Accelerators European Strategy Program

Collaboration-Projects on Quantum Applications:

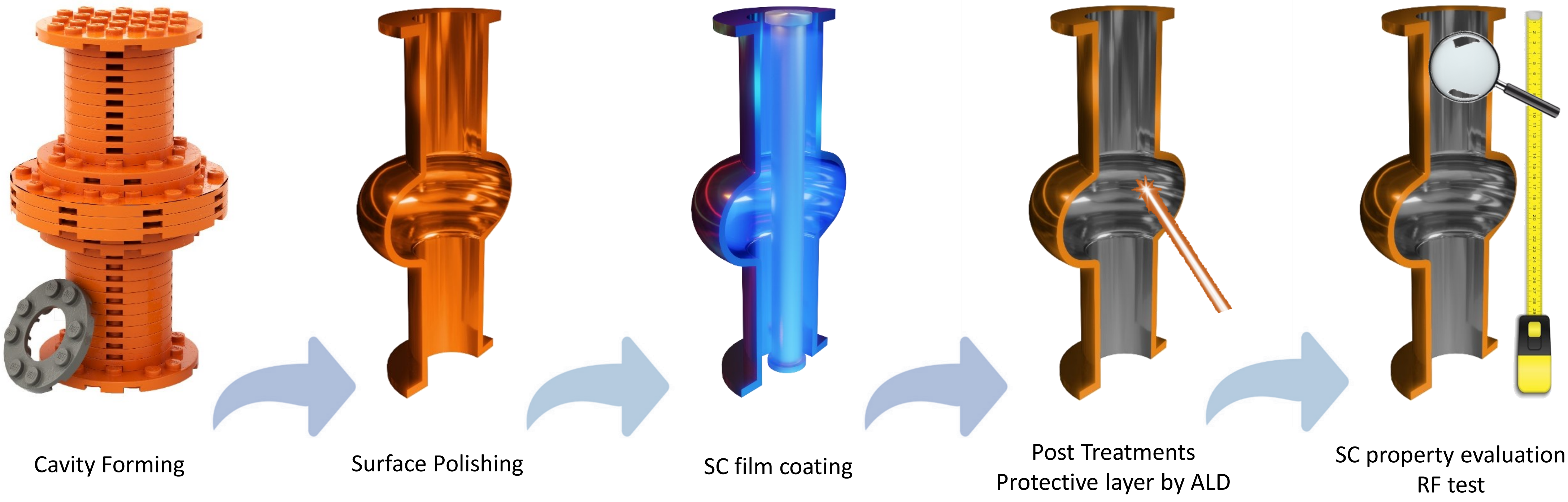
NQSTI
National Quantum Science and Technology Institute

SQMS

Partners:

cea · IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis · UKRI Science and Technology Facilities Council · CERN · HZB Helmholtz Zentrum Berlin · HZDR Helmholtz Zentrum Dresden Rossendorf · Rīgas Tehniskā Universitāte · Jefferson Lab · Fermilab · Universität Siegen · ELÚ · PICCOLI srl Torneria in lastra metallica · Universitas Studii Paduani · INFN Torino · INFN Roma Tre · INFN LNF · INFN Milano · INFN Padova

All the production chain must be developed and optimized



Cavity forming

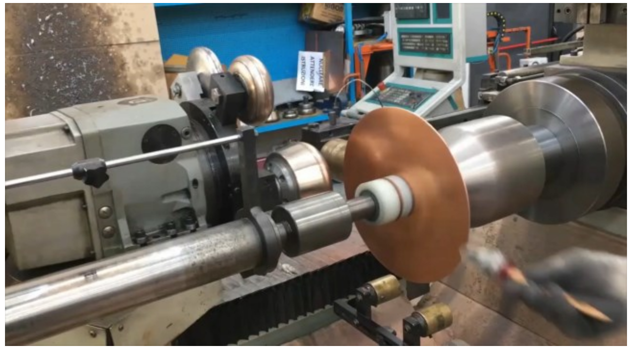
Seamless Spinning

in collaboration with

Forming technology adopted to produce 1.3 GHz and 6 GHz elliptical seamless Cu R&D substrates

PRIMARY GOAL:

High internal surface quality



OPTIMIZED PRODUCTION PROTOCOL:

- CNC machine
- Reduced Annealing Temperature (400 °C, previous 500 °C)
- New intermediate Deep Drawing Step

Cavity Forming

Additive Manufacturing

in collaboration with

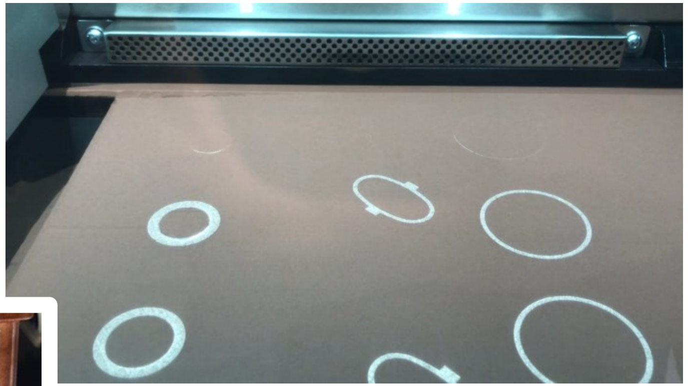
INFN PADOVA

AM can open to a new way to design RF cavities

GOAL: Prove the possibility to polish properly the surface and get SRF state of the art performances

COPPER

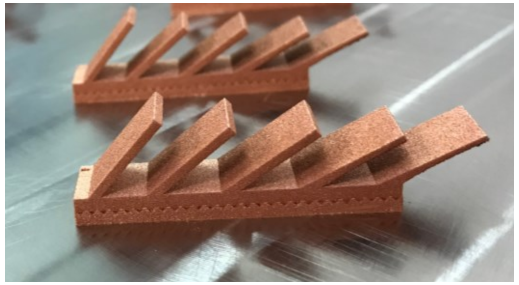
- Density 99.9%
- High quality surface after Vibrotumbling + EP
  Ra < 400 nm
- Production of new optimized prototypes ongoing



6 GHz seamless copper cavities via Additive Manufacturing

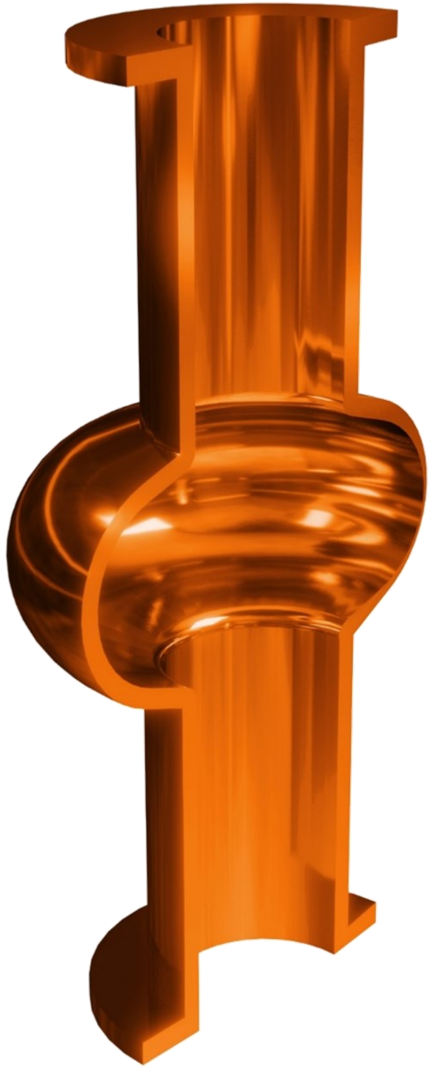
2 prototypes produced using TRUMPF TruPrint 5000

AM Cavity cutted after VB + EP of the cell



Despite the lower surface quality, Cu can be manufactured with low inclination angles

Cavity Forming



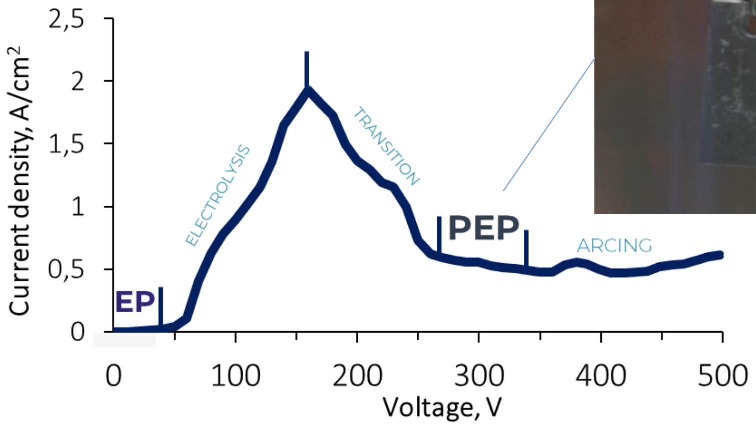
Surface polishing

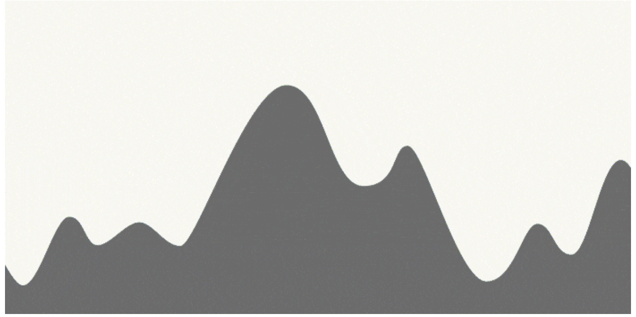
SAMARA
INFN CSN5 Experiment

SRF cavities R&D for FCC-ee
INFN Accelerators European Strategy Program

Plasma Electrolytic Polishing PEP

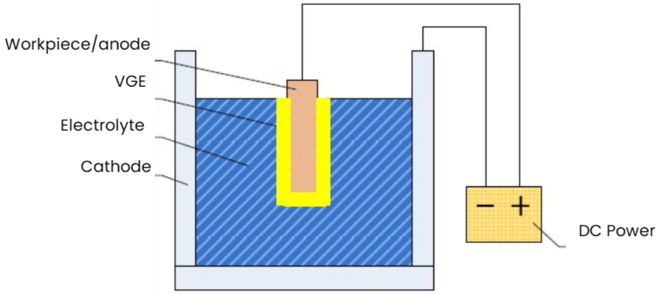
Mechanism





Same EP set-up

Different regime



J. Wang et al., AMR, 2012

Advantages

Green
Diluted water solutions, enviromentally friendly

Fast
The fastest non-destructive polishing

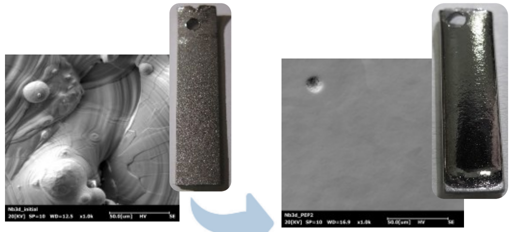
Equal thickness removal yield lowest roughness among competitors
Efficiency

Less sensitive to the cathode shape!
AM compatible
Versatility

Plasma Electrolytic Polishing PEP
Results

1x Nb 3x Cu
Solution Patentees by INFN

Additive Manufacturing



Initial
Ra= 13 µm

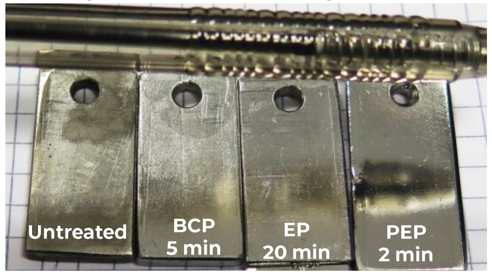
PEP 30 min
Ra= 1.5 µm

QPR Samples HZB Helmholtz Zentrum Berlin

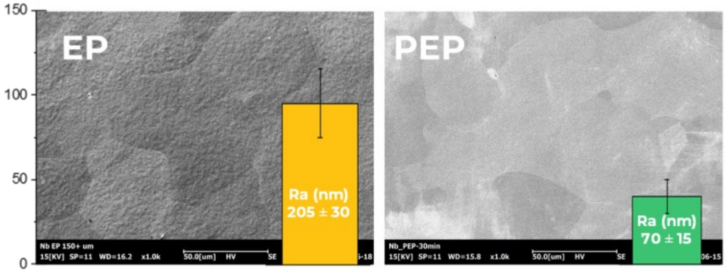
Nb QPR polishing optimizaztion on-going

Full Cu QPR ready for coating

Nb planar samples



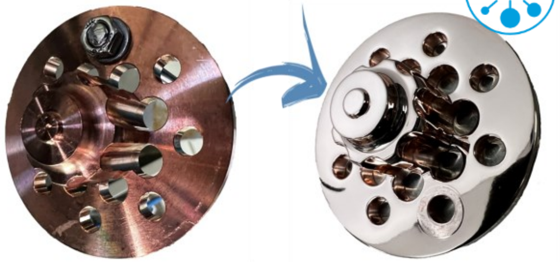
6.5 µm removed



150 µm removed in ~ 5 h

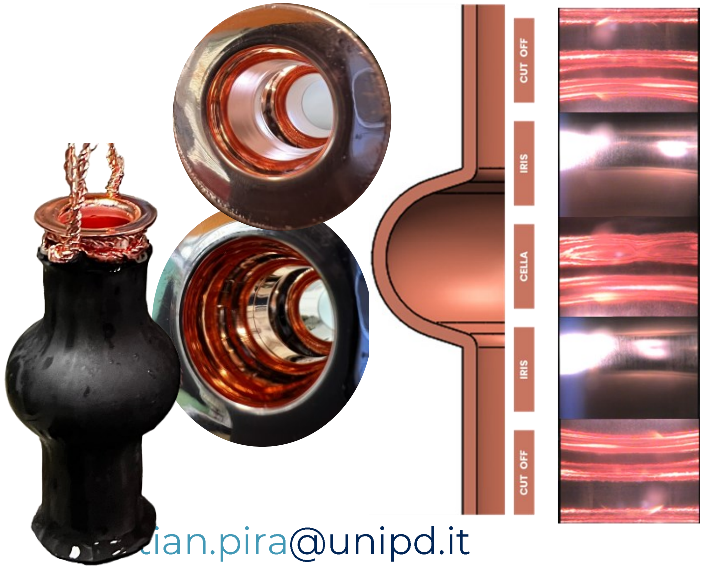
150 µm removed in ~ 40 min

Cu Photocatodes



Ra ~ 8 nm!!!

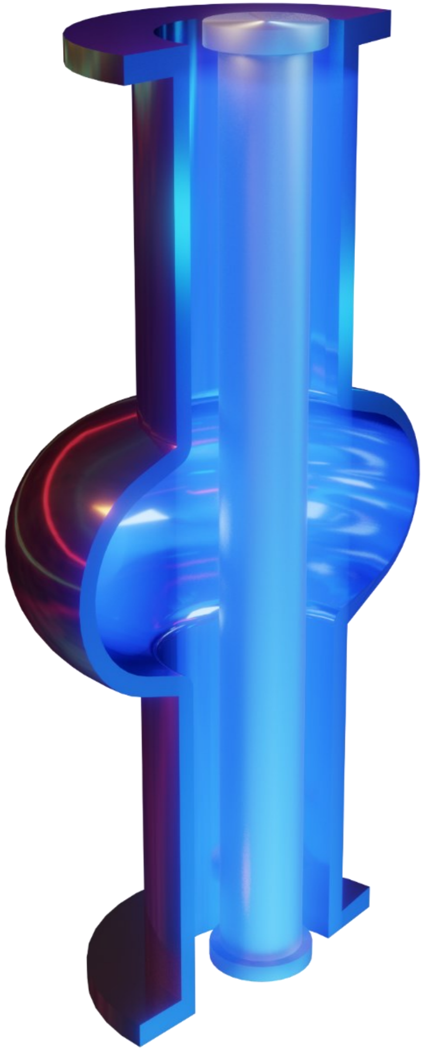
6 GHz Cu cavity



No internal cathode!

70 µm removed in 10 minutes
30 A (100 cm2 → 1.3 GHz ~ 300 A)

Surface Polishing



SC Coatings

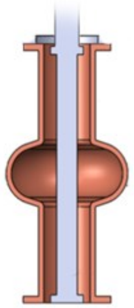
iFAST

iSAS

SRF cavities R&D for FCC-ee

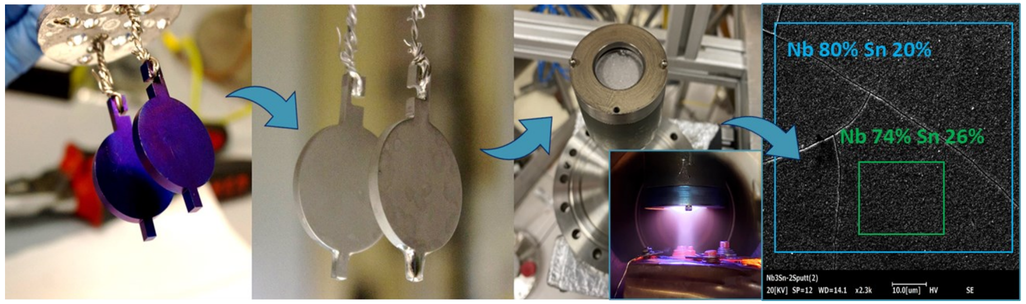
INFN Accelerators European Strategy Program

Nb_3Sn coatings: target production



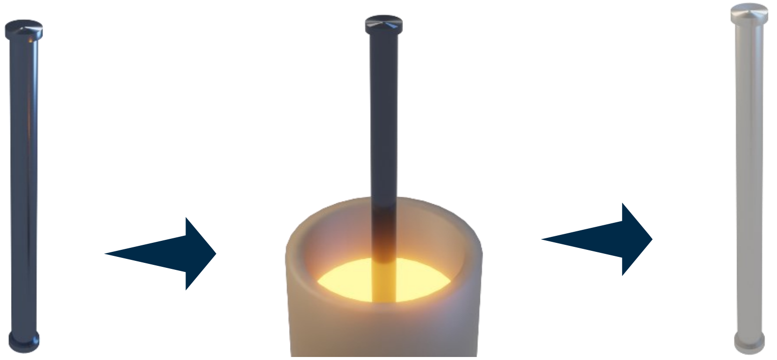
Single target configuration easiest to scale onto elliptical geometry

Nb_3Sn cylindrical target are not commercially available

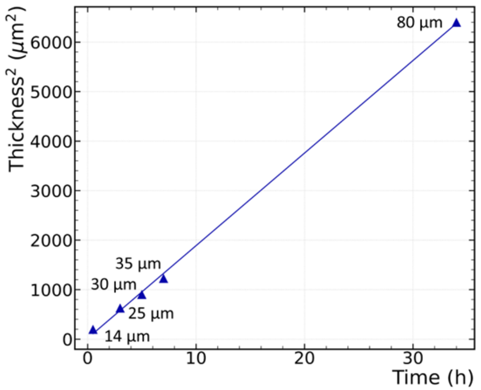


Proof of concept

LNL Strategy for Nb_3Sn cylindrical target production for 6 GHz cavities



Raw Nb target → ***Dipping in liquid Sn*** → *Nb_3Sn cylindrical target*



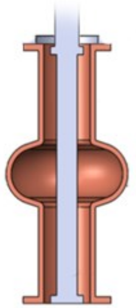
Nb_3Sn **thickness** related to **dipping time**

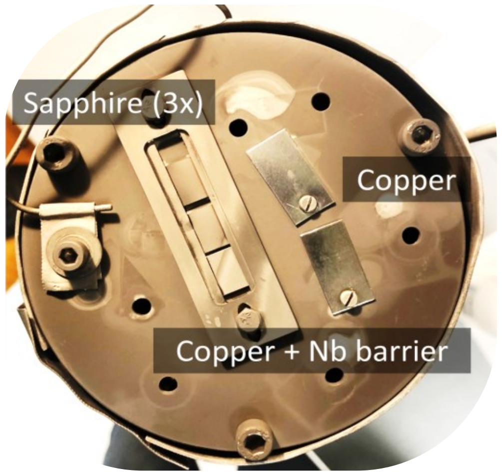
Possible **tin content modulation**

Nb_3Sn coatings

Sputtering parameter optimization

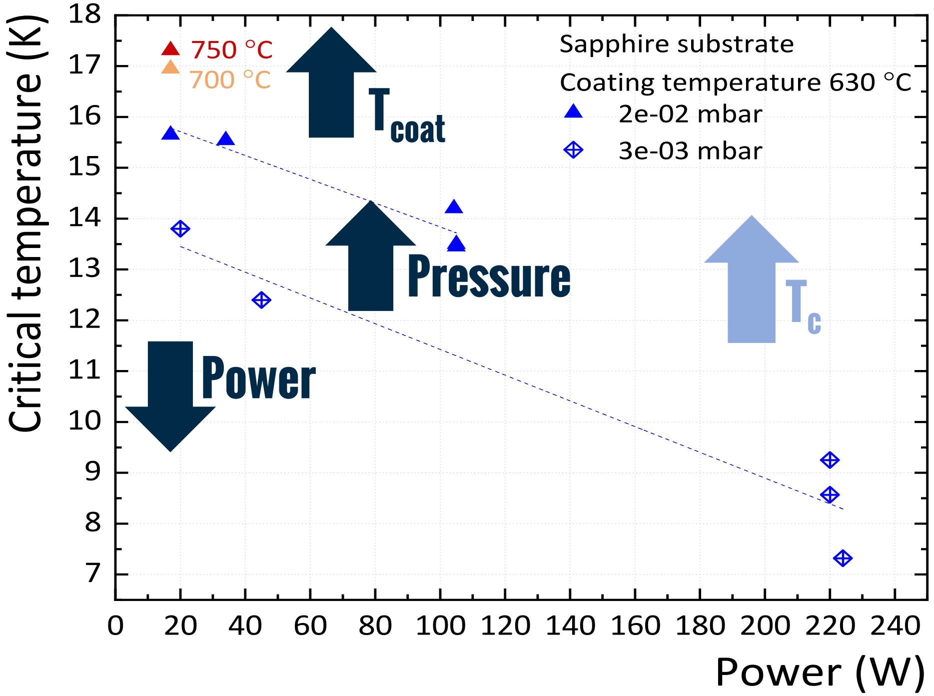
Nb_3Sn deposited via DCMS from 4’’ planar **stoichiometric target** in Ar atmosphere → **Single target configuration easiest to scale onto elliptical geometry**

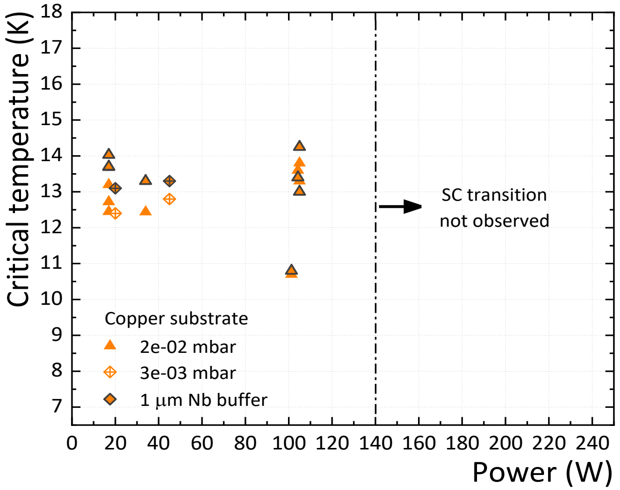




In the same run different substrates are coated in the same conditions

Tc clear trends visible on Sapphire



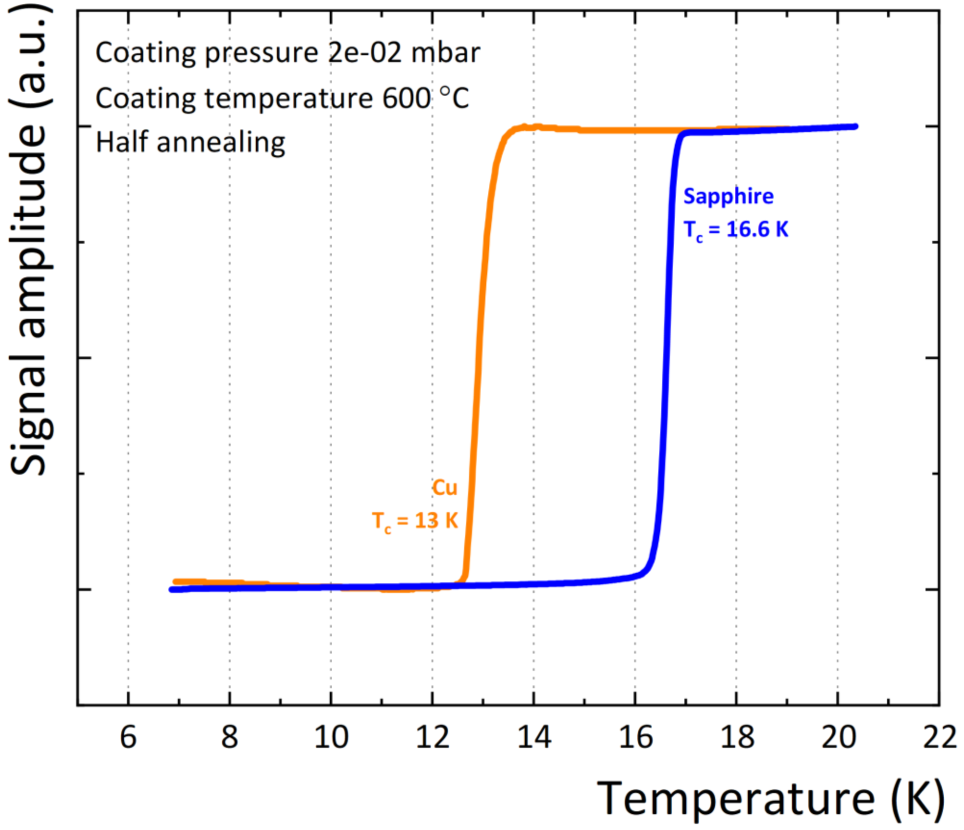


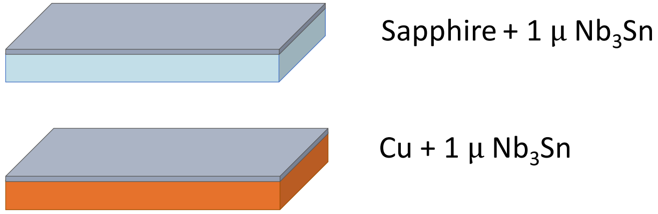
Nb_3Sn Tc stucks at 14 K on Cu

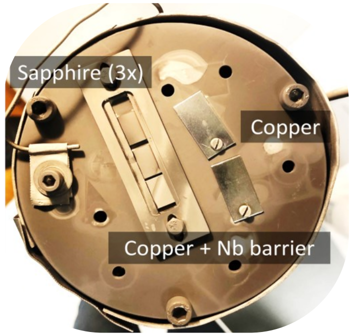
Interface effect

Nb_3Sn coatings

Sputtering parameter optimization

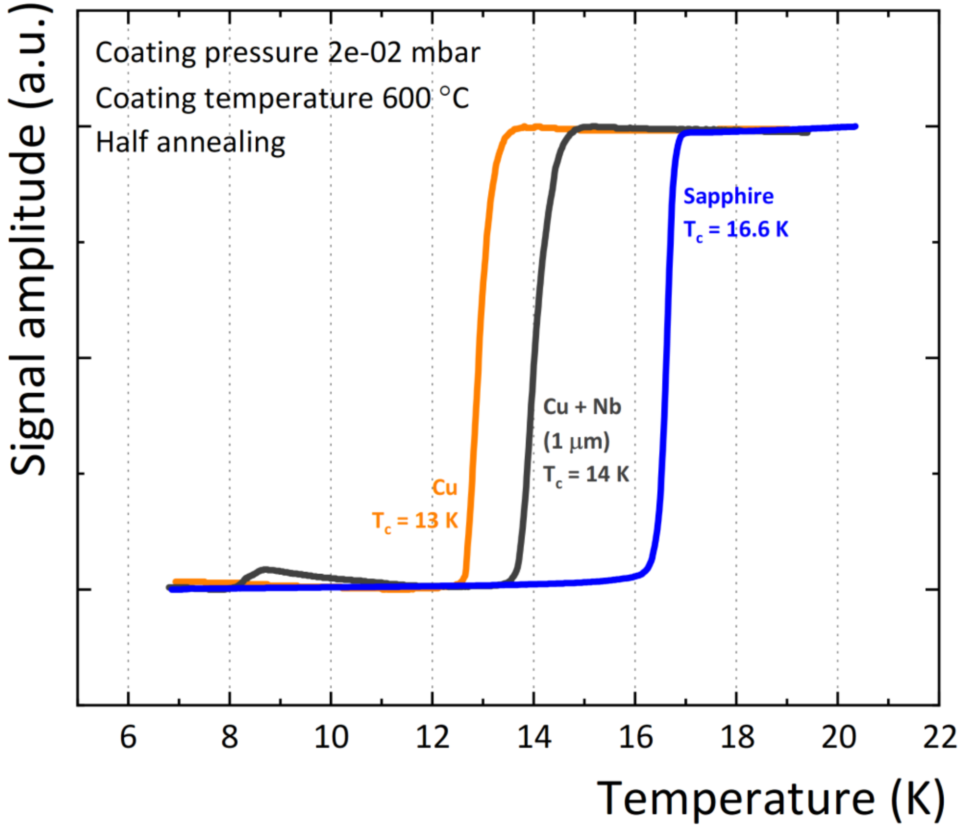


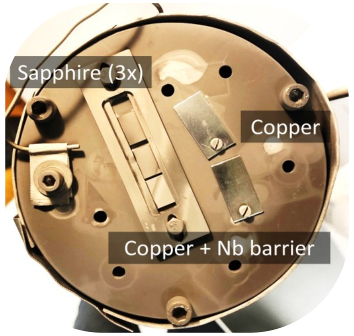


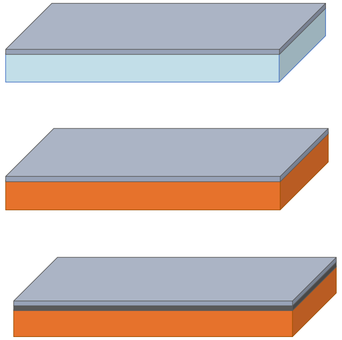


Nb_3Sn coatings

Sputtering parameter optimization







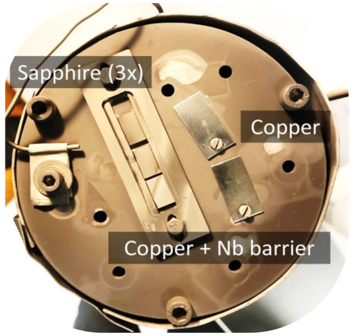
Sapphire + 1 μ Nb_3Sn

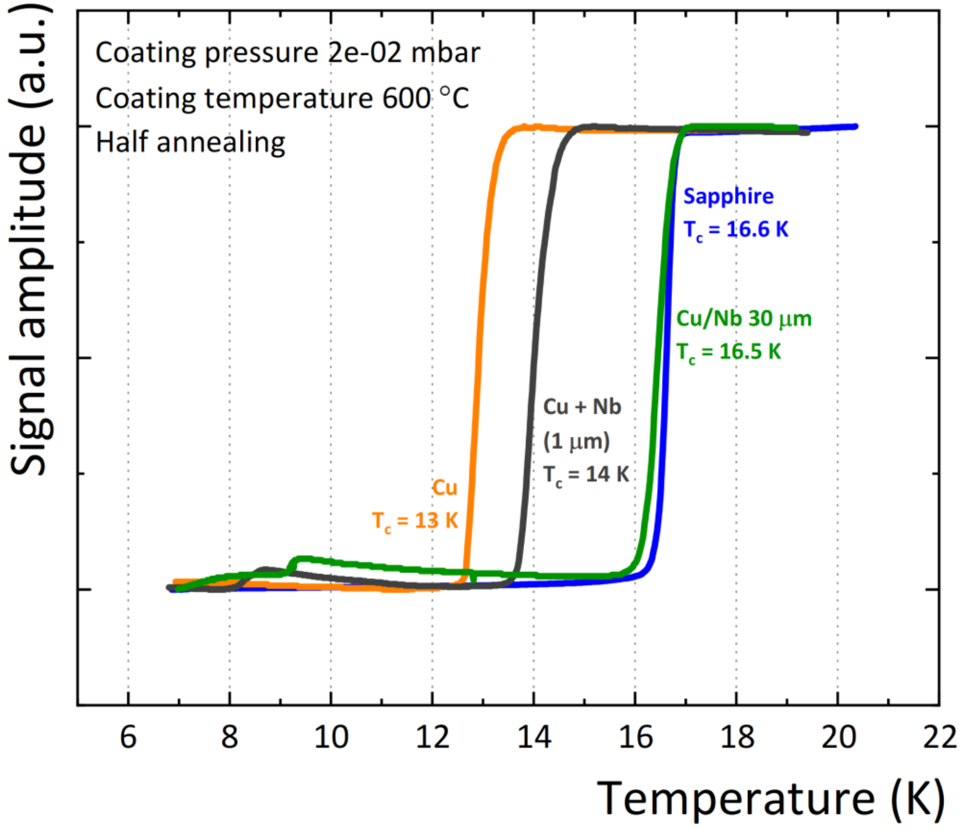
Cu + 1 μ Nb_3Sn

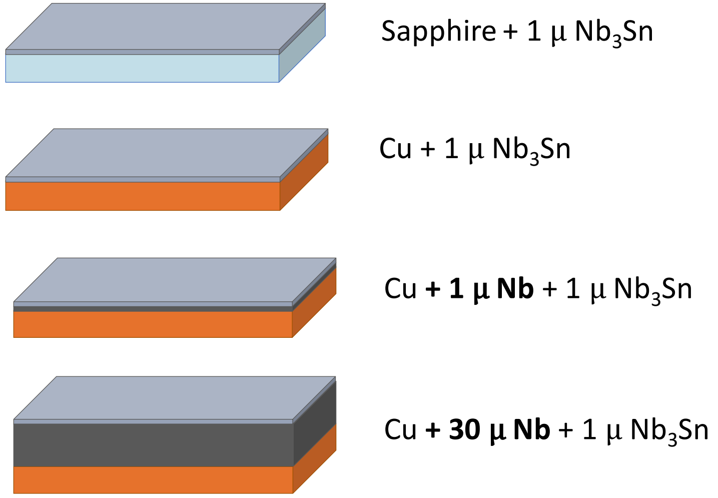
Cu **+ 1 μ Nb** + 1 μ Nb_3Sn

Nb_3Sn coatings

Sputtering parameter optimization







A very thick Nb layer enhance Tc close to Nb_3Sn nominal values

T_c = 17.3 ± 0.25 K
on Cu+50 um BL @T_{dep}=600 °C

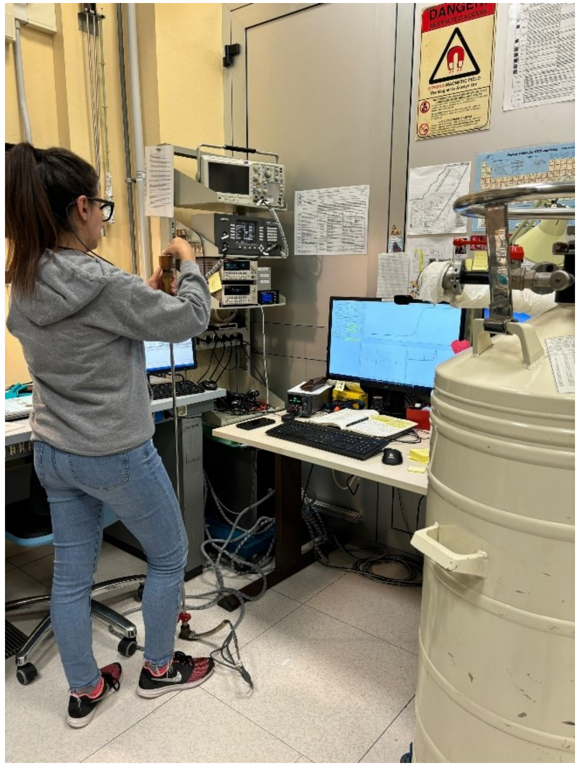
Barrier or accommodation effect?

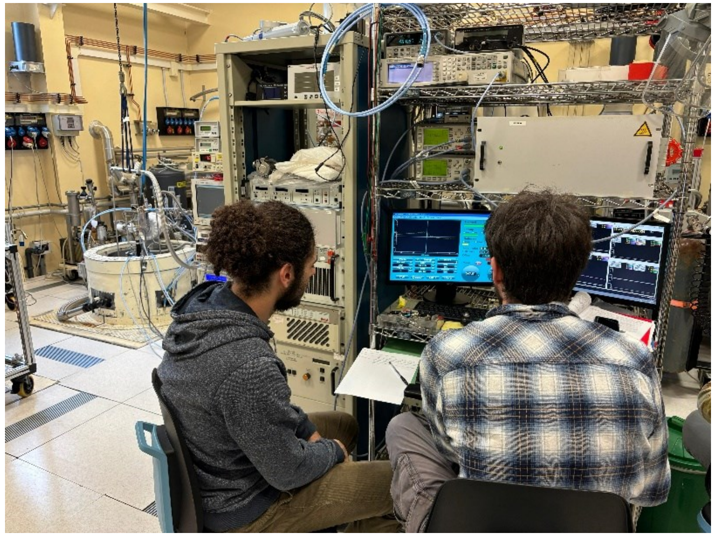
RF Measurements
Material Characterization

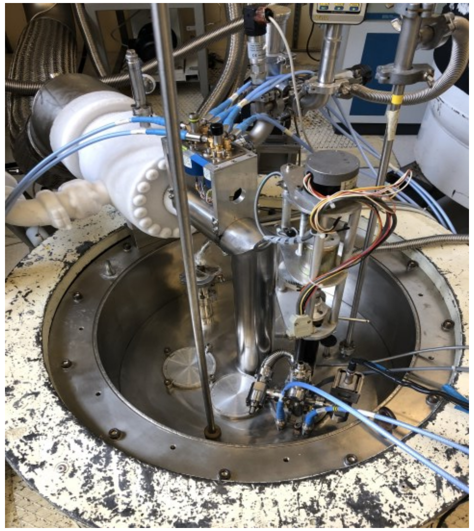
SRF cavities R&D for FCC-ee

INFN CSN1 Experiment

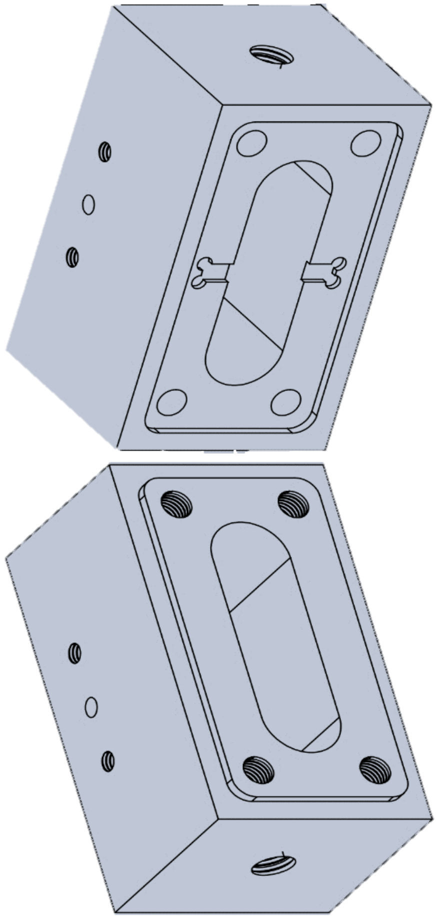
Testing Facilities @LNL







- **6 GHz RF test**
  (possibly QWR and 1.3 GHz too)
- **Tc inductive and resisitive measurement**
- **SEM, EDS, XRD characterization**



SRF for Quantum Applications

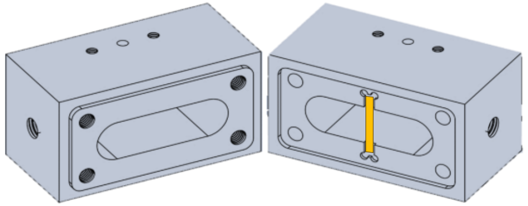
NQSTI National Quantum Science and Technology Institute

SAMARA INFN CSN5 Experiment

SQMS

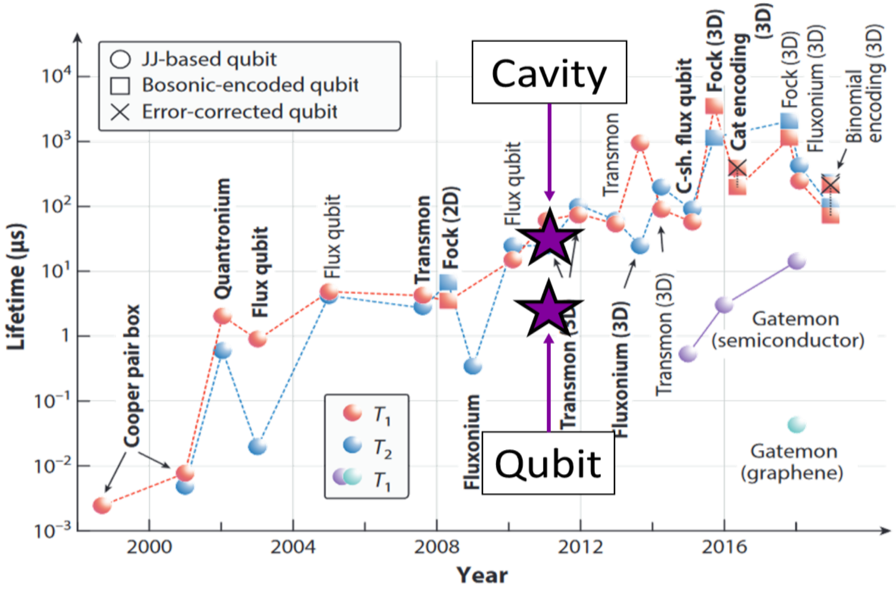
Quantum Computing

3D Architecture to enhance Coherence Time



Improve cavities Q-value

- Study different materials (Nb and Al)
- Surface Treatments



M. Kjaergaard *et al.*, *Annu. Rev. Condens. Matter Phys.*, vol. 11, fasc. 1, mar. 2020

Quantum Sensing

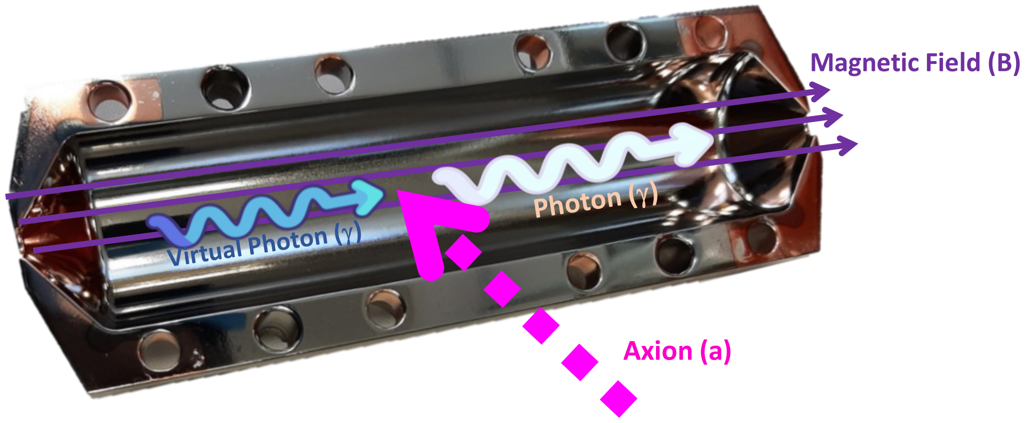
Axion Haloscopes

- The axion haloscope was designed to scope microwave photon signals from the axions in our galactic halo
- The signal power can be enhanced by the resonance effect that occurs when the axion mass matches the natural frequency of the detection system

$$P_{a\gamma\rightarrow\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 \omega_0 V C \frac{Q_a Q_c}{Q_a + Q_c}$$

Conversion Power ($P_{a\gamma\rightarrow\gamma}$); Coupling Constant ($g_{a\gamma\gamma}^2$); Dark Matter Axion Density (ρ_a); Axion Mass (m_a); Magnetic Field (B^2); Resonant Frequency (ω_0); Volume (V); Cavity Quality Factor (Q_c); Axion Quality Factor (10^6) (Q_a)

D. Kim *et al*. JCAP03(2020)066



Q factor of Cu haloscope limited by anomalous skin effect

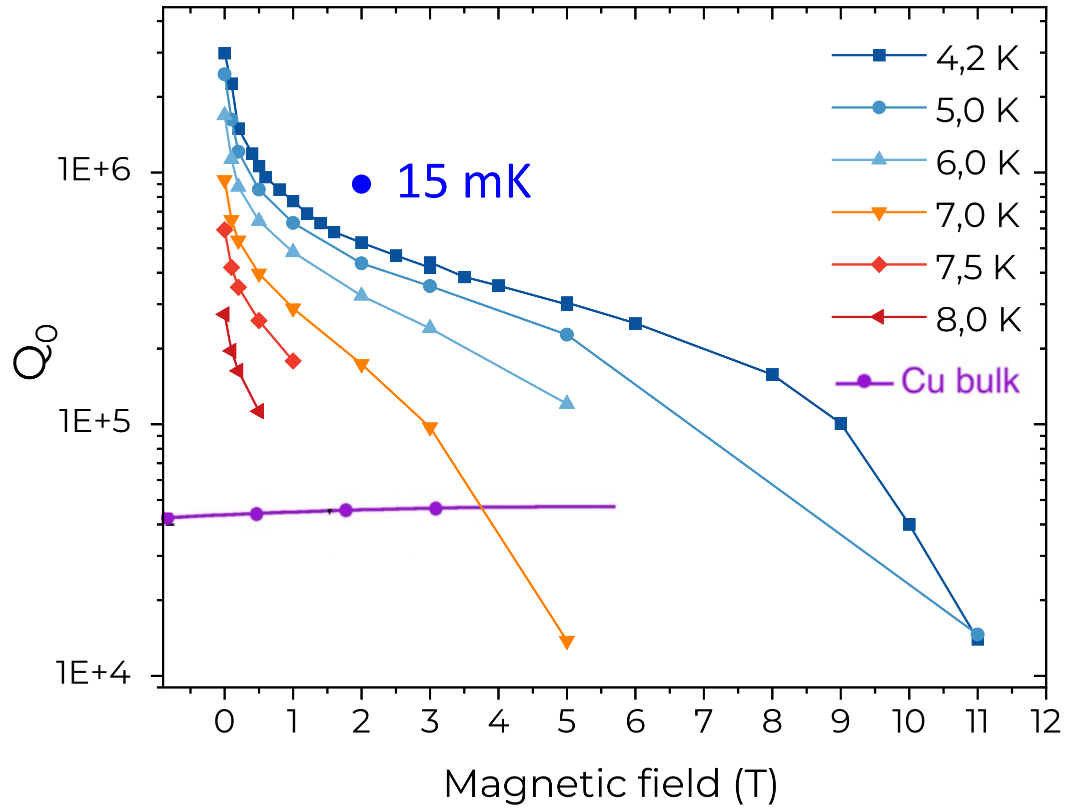
to improve Q

SRF in High Magnetic Field *(Mixed State)*

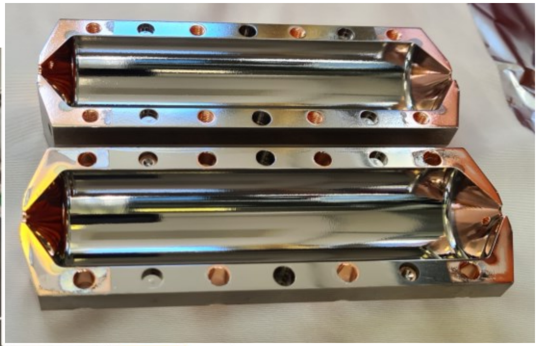
cristian.pira@unipd.it

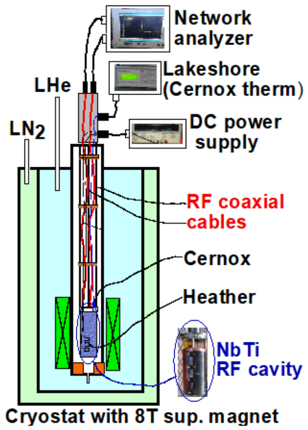
Quantum Sensing

NbTi Hybrid Haloscope



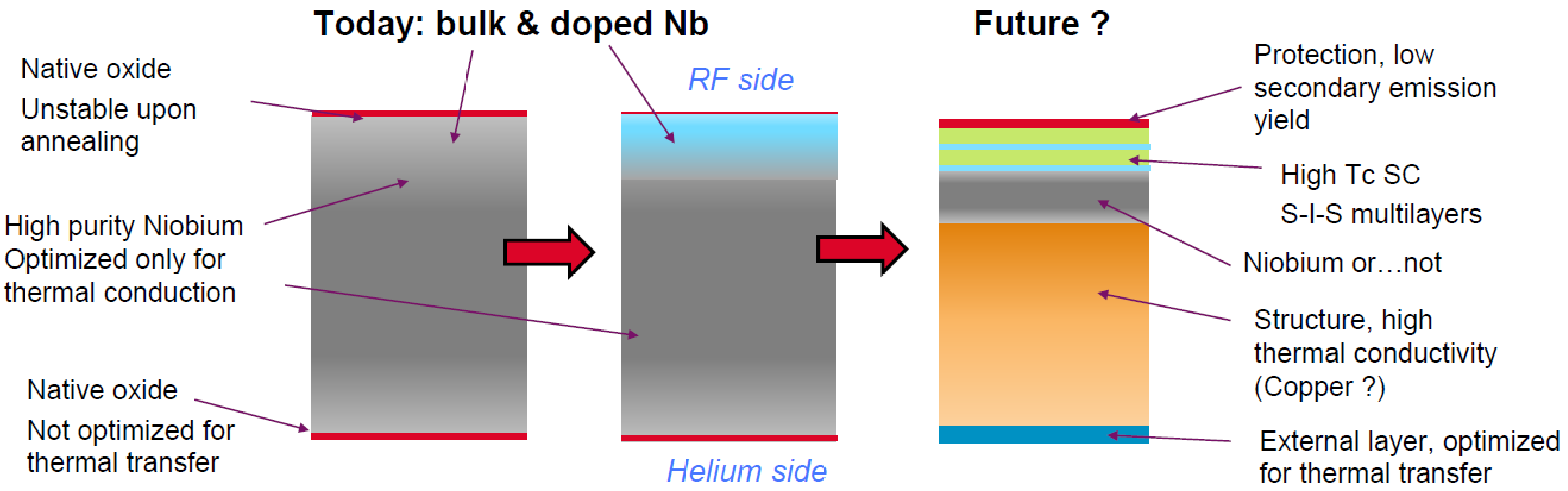
- $Q_0 \approx Q_0$ **simulation** → limited by Cu cones
- $Q_{0\ NbTi}$ **> 20 *** $Q_{0\ Cu}$ @ 15 mK, 2T
- $Q_{0\ NbTi}$ **> 10 *** $Q_{0\ Cu}$ @ 4K, 5T
- $Q_{0\ NbTi}$ **>** $Q_{0\ Cu}$ up to 9 T @ 4K





Next Step: Nb_3Sn

Conclusion



Courtesy of C. Antoine

Vision of the future for SRF

Course Contents

Superconductive Materials

Course Introduction

Course **Contents**

- Basics of **cryogenics**
- **Phenomenological** description of SC properties
- Principal **theories** (London, GL, BCS)
- **Low T** and **High T** superconductors
- Superconductive Radio Frequency (**SRF**)
- **Material preparations** for Magnets and RF applications
- Principal **Applications** of SC

Visit to LNL INFN

International expert guests

Flipped lectures

Applications of Superconductors

- Superconducting Magnetic Coils
- Superconducting Cables and Tapes
- Superconducting Permanent Magnets
- Nuclear Magnetic Resonance
- Magnetic Resonance Imaging
- Particle Accelerators
- Nuclear Fusion
- Energy Storage Devices
- Motors and Generators
- Magnetic Separation
- Levitated Trains
- Superconductors for Power Transmission: Cables, Transformers and Current-Limiting Devices
- Resonators for Particle Accelerators
- Resonators and Filters for Communications Technology Superconducting Detectors
- Superconducting Quantum Interference Devices (SQUID)
- Superconductors in Microelectronics
- Voltage Standards
- Digital Electronics Based on Josephson Junction
- Quantum computing

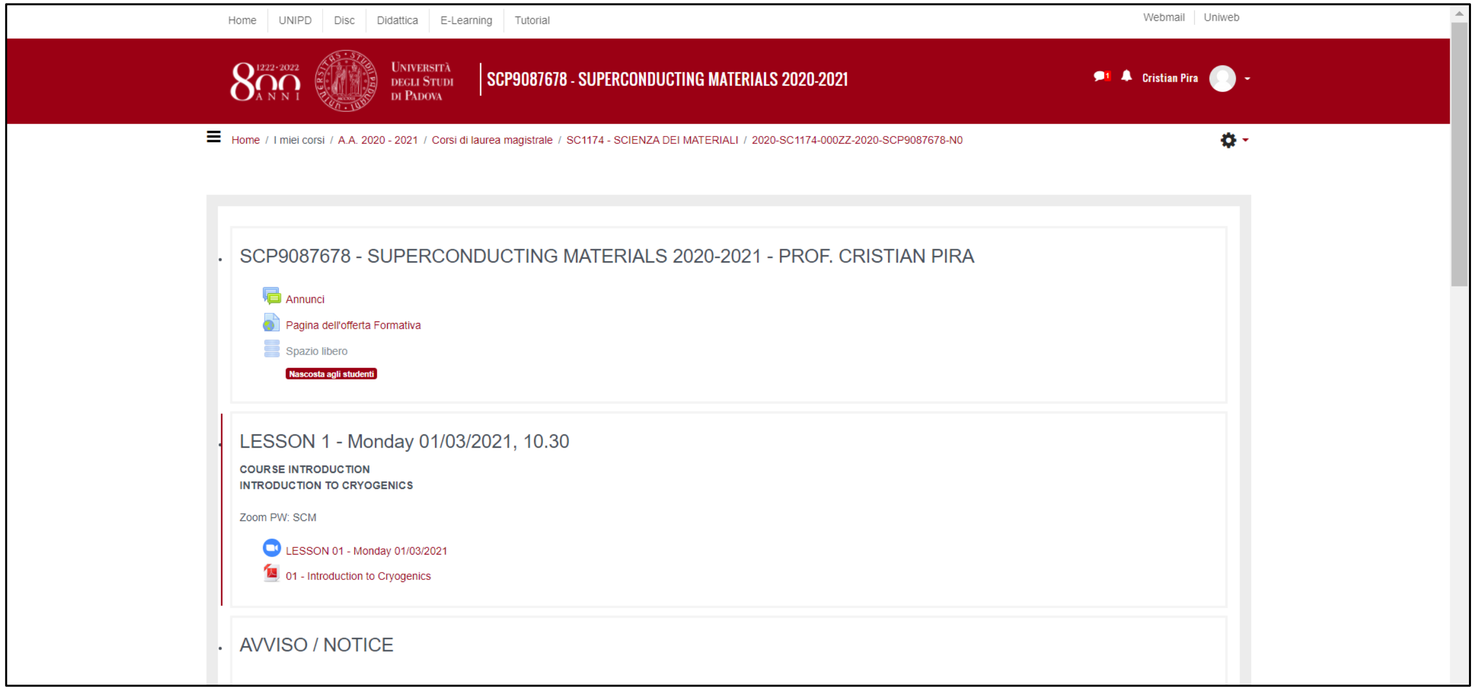
Course Organization

Superconductive Materials

Course Introduction

Comunications

- For communications the **Moodle** of the course will be used
- Please, stay tuned!



Lectures & Exam

Flipped Lectures

Student lectures on SC applications *(free topic)*

Oral exam

Student lectures are part of the exam

Bibliography (more at the end of each lesson)

- **Lesson Slides** (available on Moodle)

- W. Buckel, R. Kleiner, "*Superconductivity - Fundamentals and Applications*", Wiley
- K. Fossheim, A. Sudbø, "*Superconductivity - Physics and applications*", Wiley
- CERN Accelerating School (CAS): Course on Superconductivity for Accelerators (2013) https://cds.cern.ch/record/1507630
- CERN Accelerator School on SC and Cryogenics for Accelerators and Detectors (2004) https://cds.cern.ch/record/503603