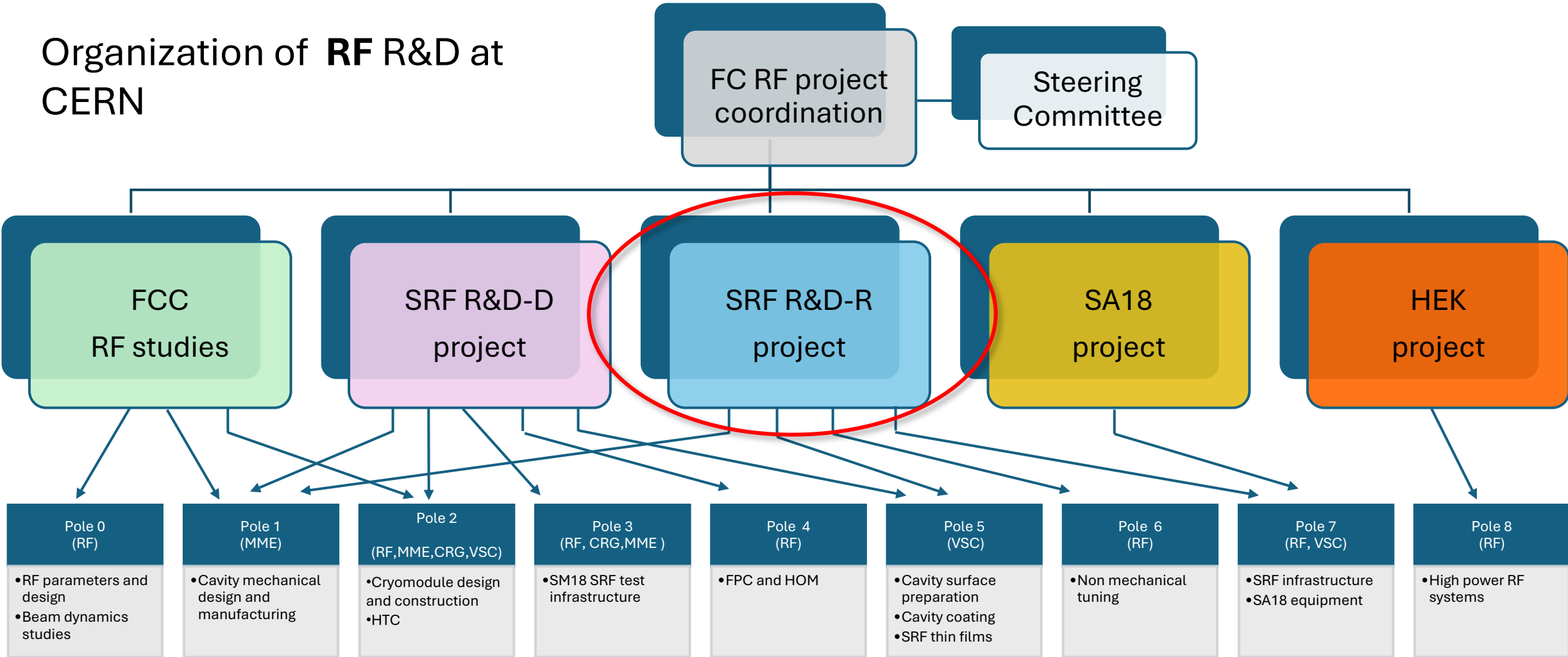


Strategy for SRF R&D at CERN

Walter Venturini Delsolaro

On behalf of CERN SRF R&D-R teams

Organization of RF R&D at CERN



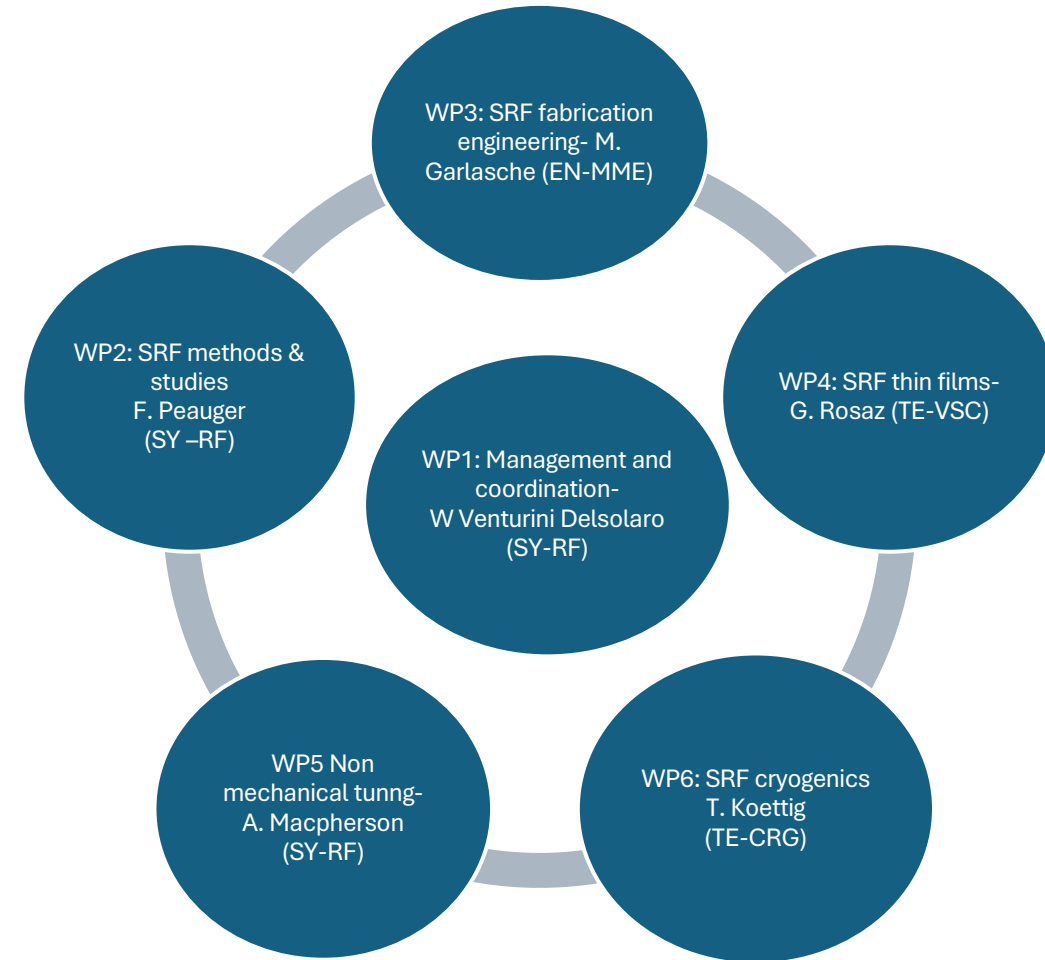
SRF R/D-R aims at strengthening the know-how, the facilities and in general the capabilities in the field of superconducting RF at CERN, for its present and future accelerators

- **The main direction is to push performance of thin films on copper cavities (Nb and Nb₃Sn):**
- **High Q (understand mechanisms of spurious losses/residual resistance)**
 - Tuning substrate preparation and coating parameters
 - thermal mapping + optical inspection
 - flux trapping in different SRF structures
- **High field:**
 - Improving cleanliness chain, SRF process infrastructure
 - Moderate activity on bulk Nb and SIS structures
- Explore **novel fabrication methods**: Bulk machining, Hydroforming, Electro-forming
- Develop **non mechanical tuning**
- Explore **novel cooling methods**

Work Package Structure

More highlights in talks by M. Garlasche, F. Peauger, K. Brunner, A. Miyazaki, G. Rosaz, L. Ferreira, and T. Koettig at this event

- **WP2** objectives:
 - Fundamental understanding of RF losses and surface field limitations in superconducting materials
 - RF tests and Diagnostics, particulate control
- **WP3** objectives:
 - Studying, benchmarking and pushing the limits of known fabrication technologies: seamless, EB welding, high precision machining.
 - Promote R&D Activities on alternative fabrication technologies, such as additive manufacturing, alternative welding processes, mechanical surface finishing and studies on corresponding surface quality
- **WP4** objectives:
 - Optimize surface preparation method on high conductivity substrates (Cu, Al)
 - Optimize Nb/Cu coating recipe at 1.3 GHz
 - Scaling of Nb/Cu on large cavities (400 MHz)
 - Synthesis of Nb₃Sn thin films on copper for RF applications, method optimization on samples
- WP5** objectives:
 - Transient Detuning demonstrator (TDD) applied to the LHC cavities at injection settings
 - FE-FRT use case applications including microphonics compensation, discrete tuning and cavity trip mitigation.
 - Development of SRF set ups for PBC and QTI:
- **WP6** objectives:
 - Develop cooling schemes alternative to helium baths
 - Diagnostics and calorimetry for SRF
 - Thin film contactless Tc determination



Cavity performance goals

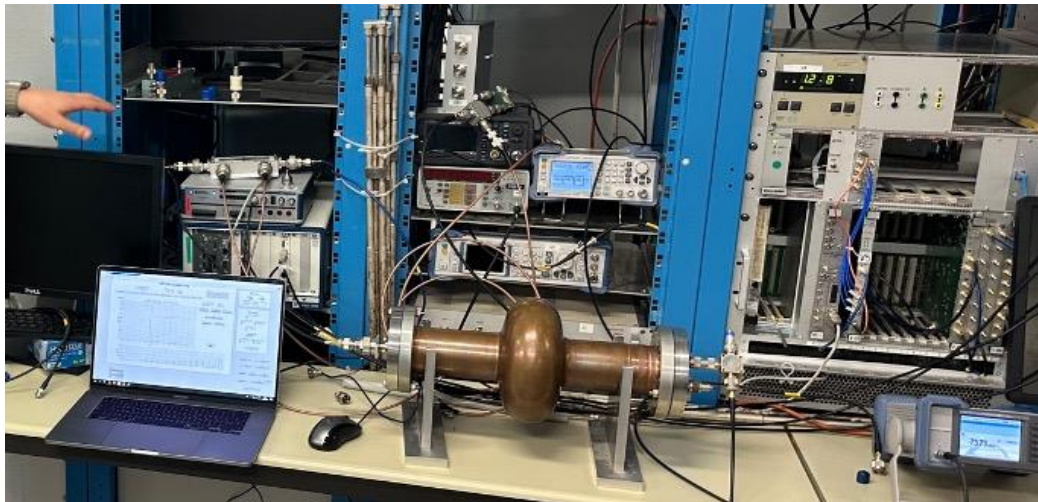
Frequency	Technology	T operation	Q _o	Ep (MV/m)	Bp (mT)	Ea (MV/m)
1.3 GHz	Nb/Cu	2 K	10 ¹⁰	50	106.5	25
400 MHz	Nb/Cu	4.5 K	3.3 10 ⁹	26	69.3	13
800 MHz	Nb ₃ Sn/Cu	4.5 K	10 ¹⁰	50	100	20
800 MHz	Bulk Nb	2 K	3 10 ¹⁰	50.8	108	25
800 MHz	Nb/Cu	2 K	2 10 ¹⁰	50.8	108	25

Strategy

- **Develop Nb/Cu HIPIMS through the 1.3 GHz program for fast turnaround from coating to RF test**
 - Scaling specs at 4.5 K to 400 MHz from theory and QPR results
 - Study separately surface resistance components
 - Study high field behaviour at 2 K in view of possible use at 800 MHz for ttbar
- **Scale up to 400 MHz using LHC single cells substrates until FCC prototypes are ready**
 - Transfer lessons learned (seamless, HIPIMCS, EP, mitigation of thermal currents, etc.)
 - Aiming at "proof of principle"
 - Measurement campaigns to define key specifications for the cryomodule (B_a , ∇T , etc)
 - The large cavity surface is prone to "random" defects: rationale behind integrated process in the new SRF building:
 - Push success yield and define protocol for industrialisation
- **Nb₃Sn/Cu: from small samples, to QPR**
 - Collaborations for sample studies (UNIGE, TUWIEN, CEA, ...)
 - Directly aiming at 800 MHz cavities as possible use case See talk by G. Rosaz at this event
 - Collaborations: INFN, Cornell
- **Nb bulk at 800 MHz, 2 K, through collaborations (FNAL, IJCLab, ...)**

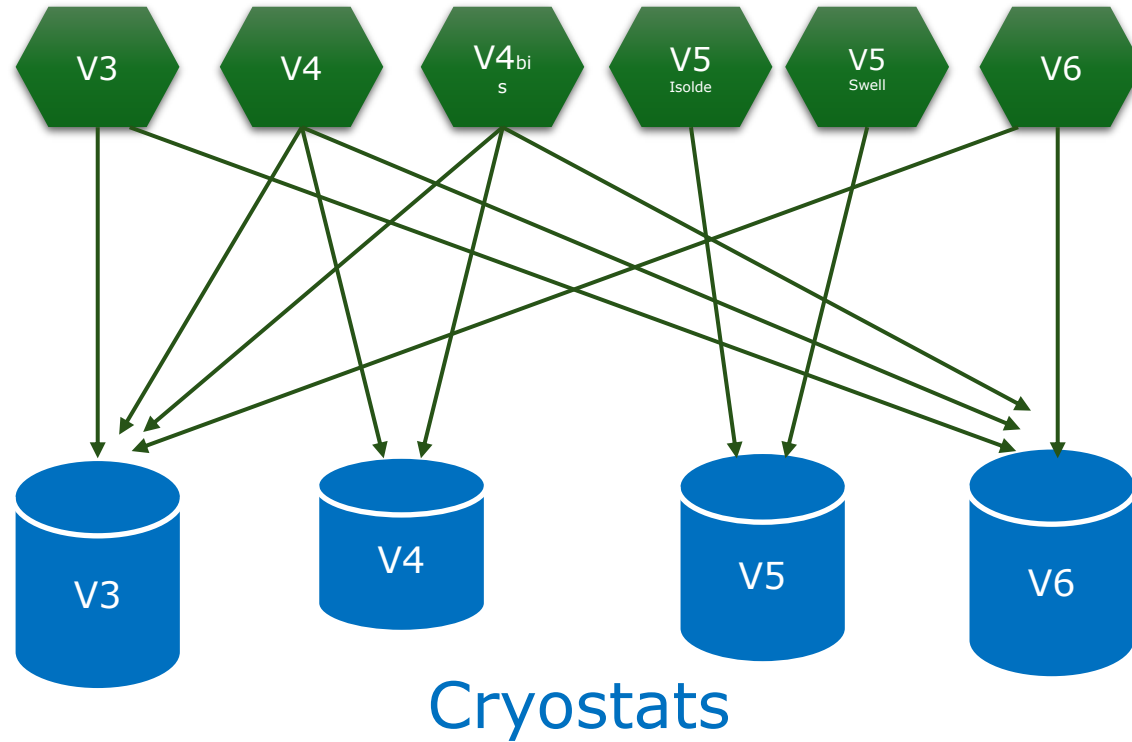
SRF facilities upgrades

- New clean booth with automatic washer
- New vertical cryostat with magnetic compensation and cavity thermal shield, dedicated to 400 MHz cavity testing
- Development of independent LLRF systems, based on different methods to reduce systematic uncertainties



Upgrades of RF cold testing facility

Vertical inserts



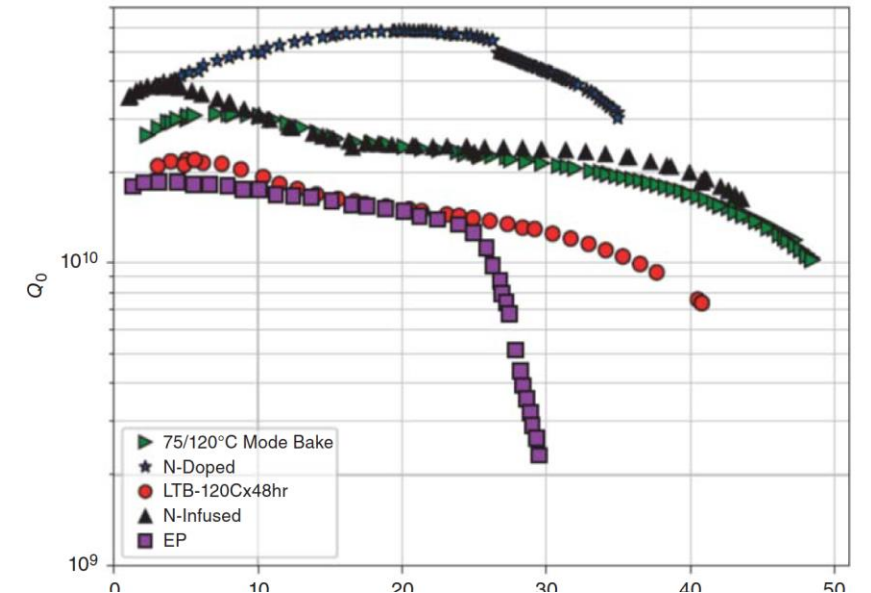
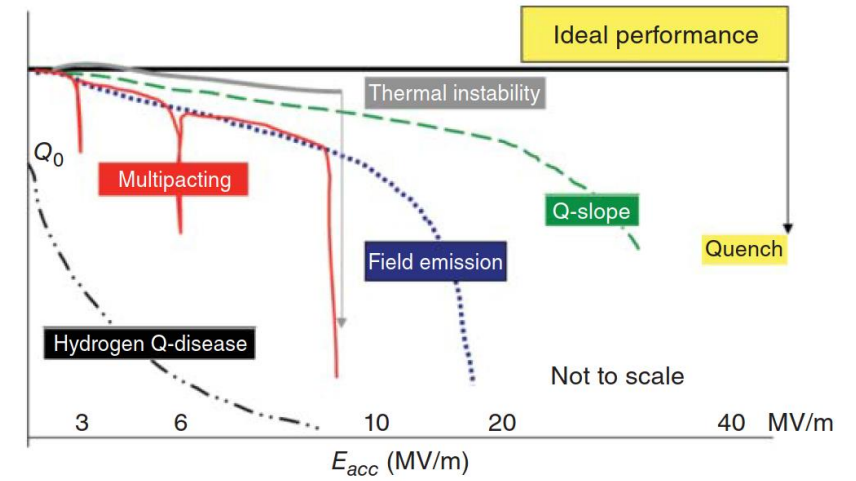
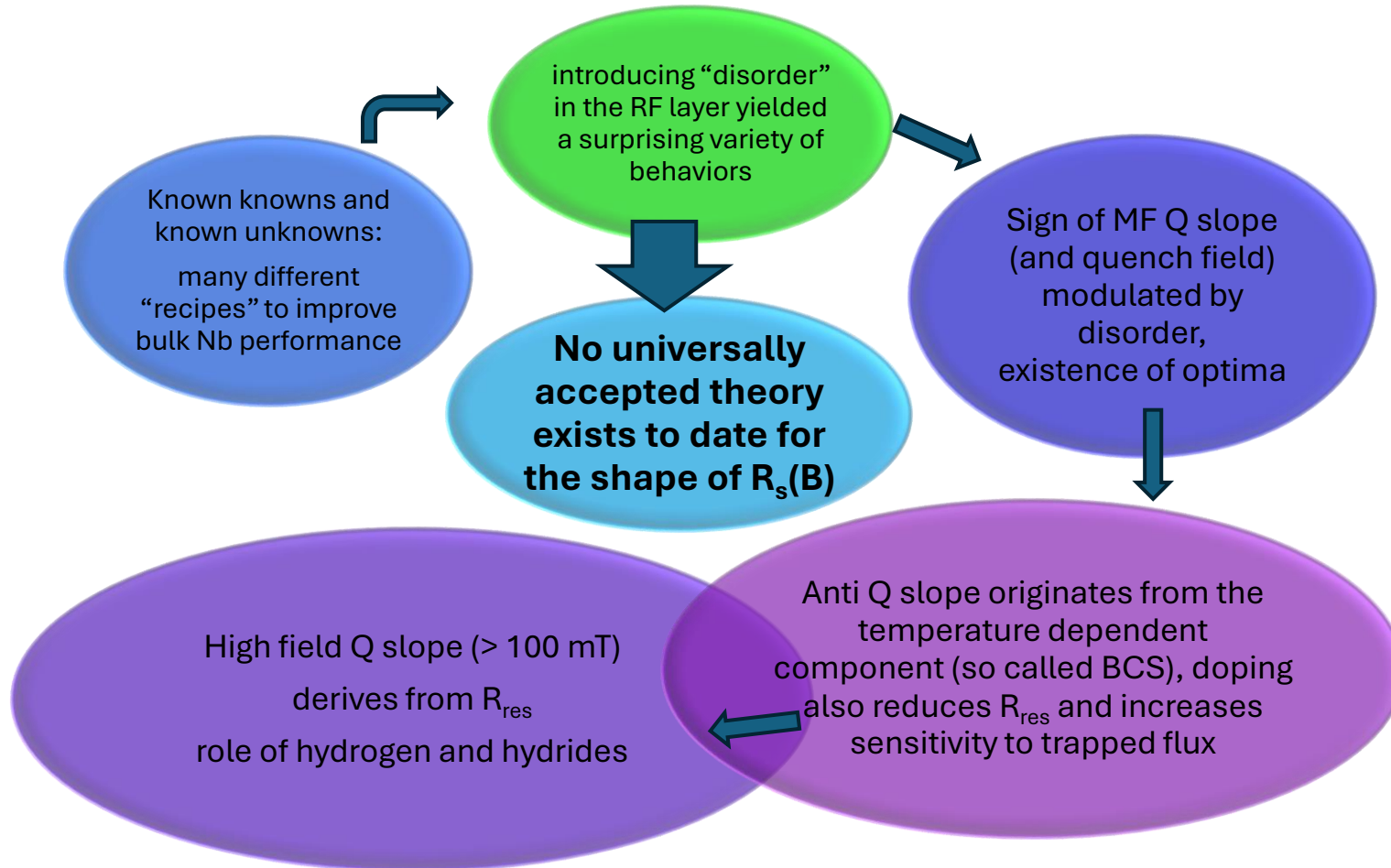
V3 / V6 insert with RFD crab bare cavity



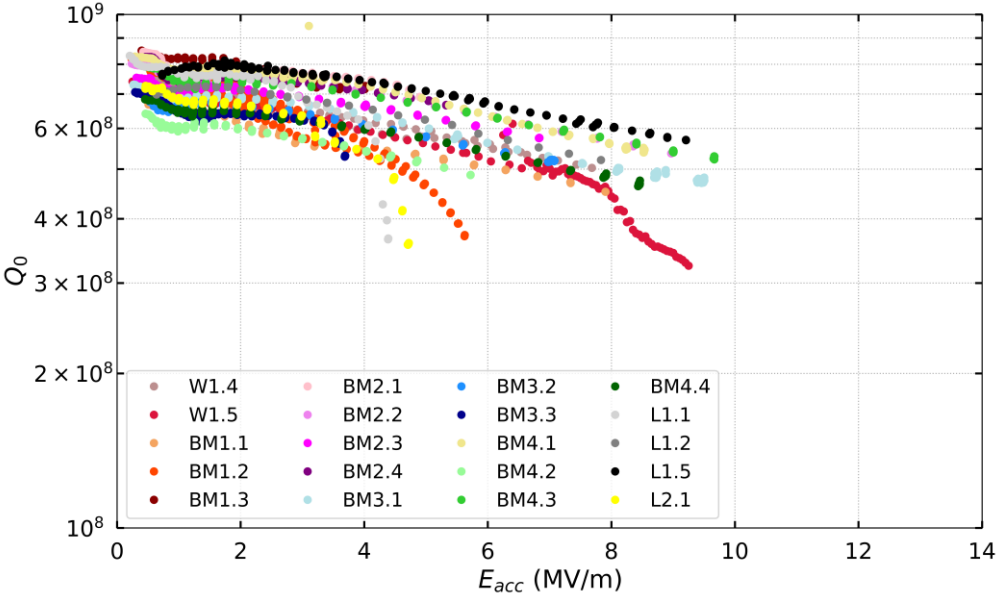
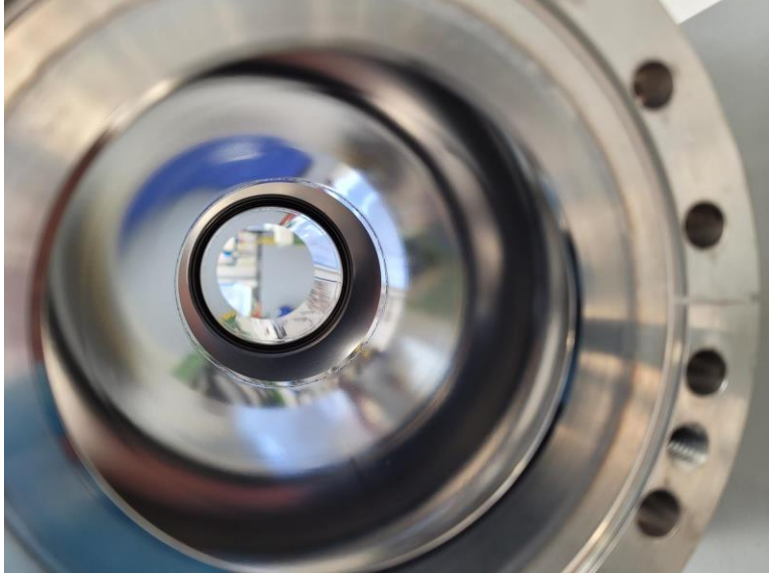
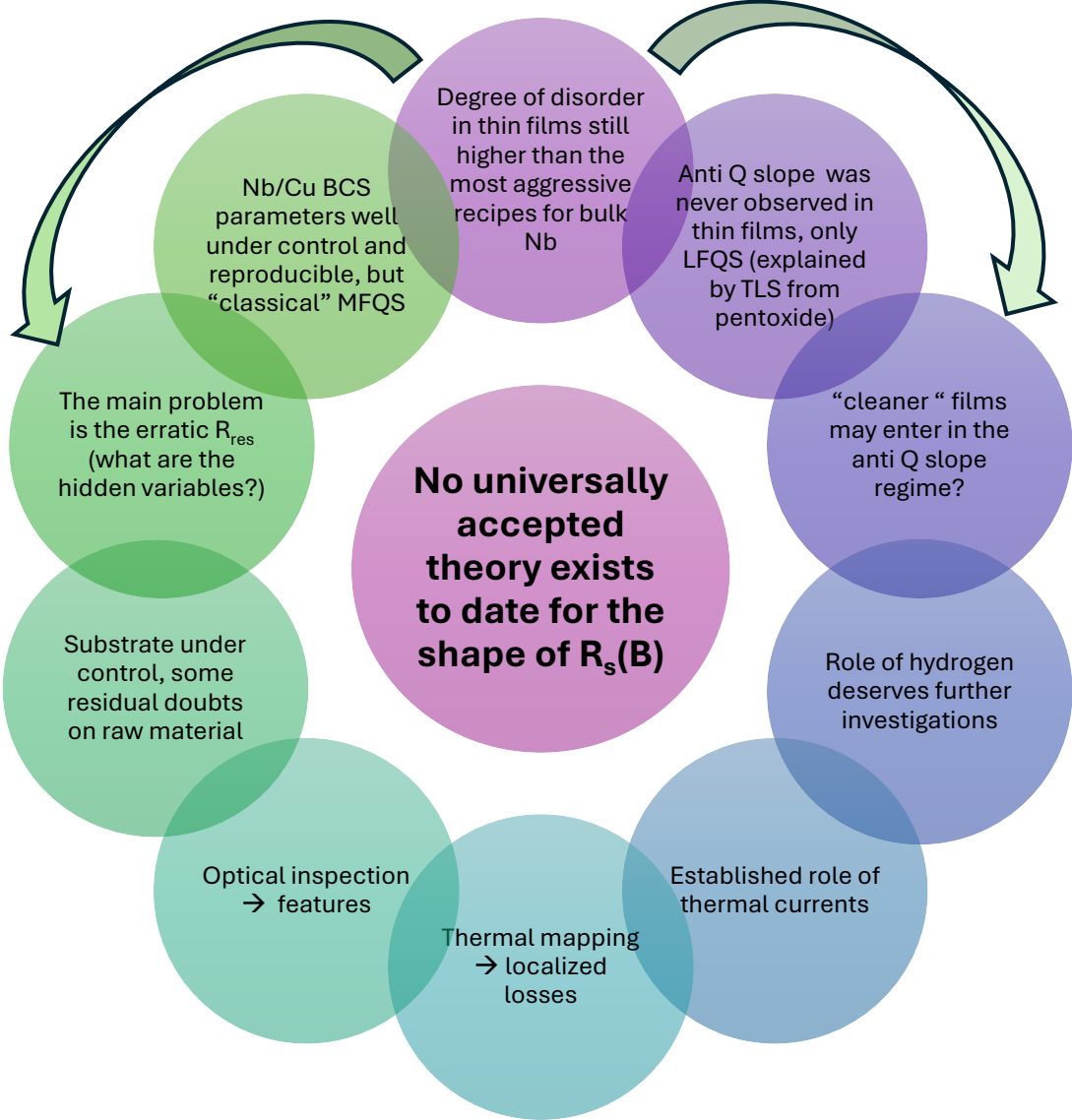
New V4bis insert and preparation area

⇒ This will allow to have a stock of prepared cavities "ready to be tested"

Scientific challenge: understand and control $R_s(H)$: bulk Nb



Scientific challenge: understand and control $R_s(H)$ in Nb thin films



Sample studies of HIPIMS Nb on QPR

QPR measurements of complex surface impedance versus T , B_{rf} , B_a , f

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IOP Publishing

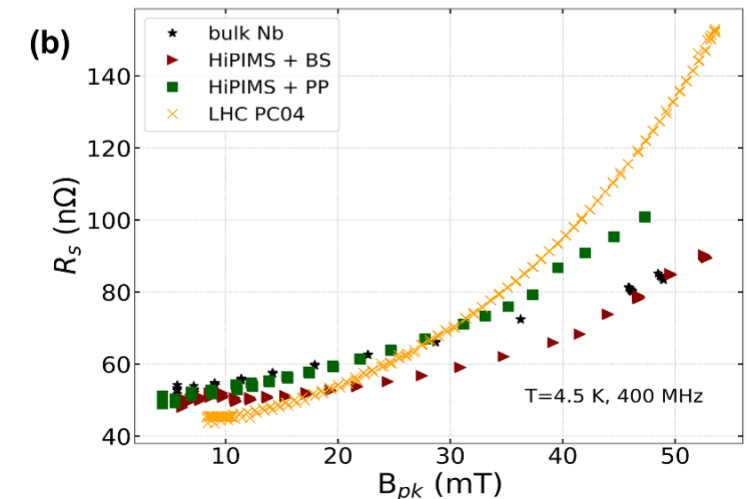
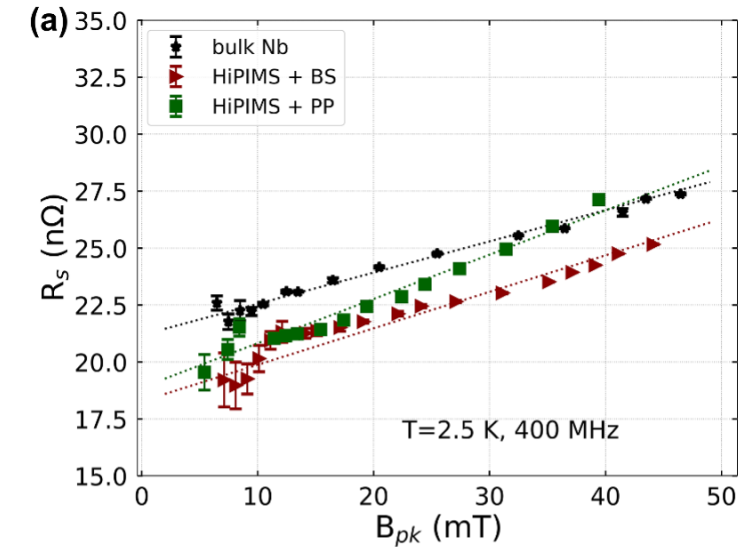
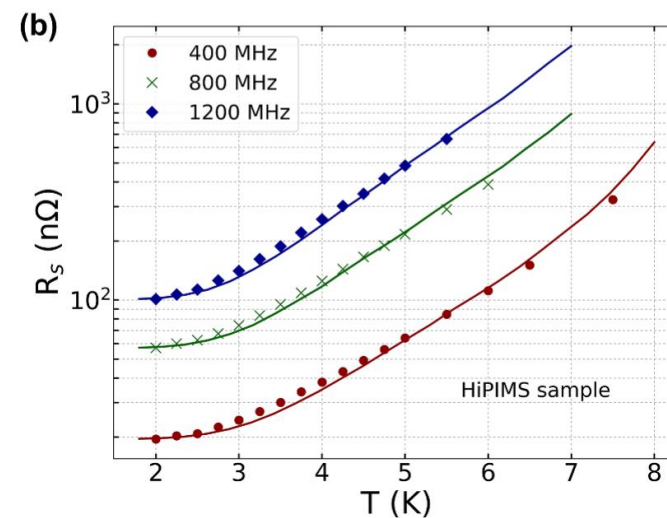
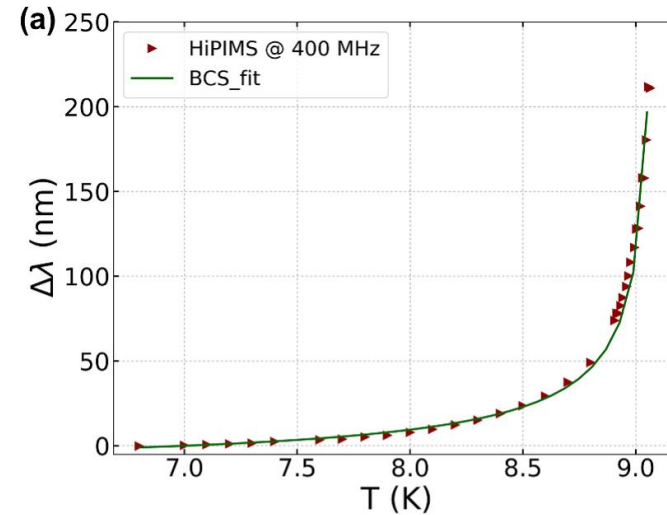
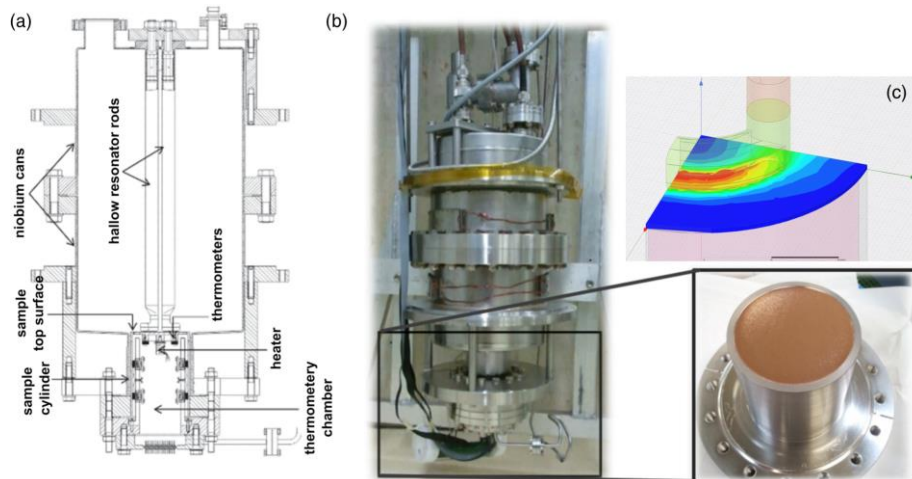
Supercond. Sci. Technol. 35 (2022) 054008 (9pp)

Superconductor Science and Technology

<https://doi.org/10.1088/1361-6668/ac5646>

Enhanced radio-frequency performance of niobium films on copper substrates deposited by high power impulse magnetron sputtering

M Arzeo^{1,2,*}, F Avino^{1,3}, S Pfeiffer, G Rosaz¹, M Taborelli¹, L Vega-Cid¹ and W Venturini-Delsolaro¹

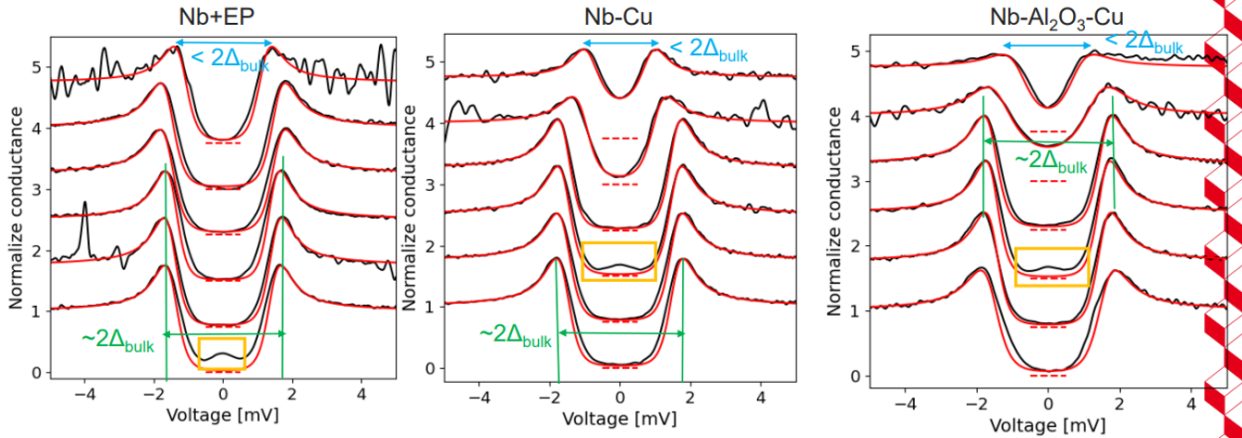


Point contact Tunneling study of Nb films

G. Rosaz (CERN), T. Proslie (CEA),
S. Leith (CERN), I. Curci (CEA)

PCT tunneling spectra

$$\rho(E) \sim \text{Re} \frac{E - i\Gamma}{\sqrt{(E - i\Gamma)^2 - \Delta^2}}$$

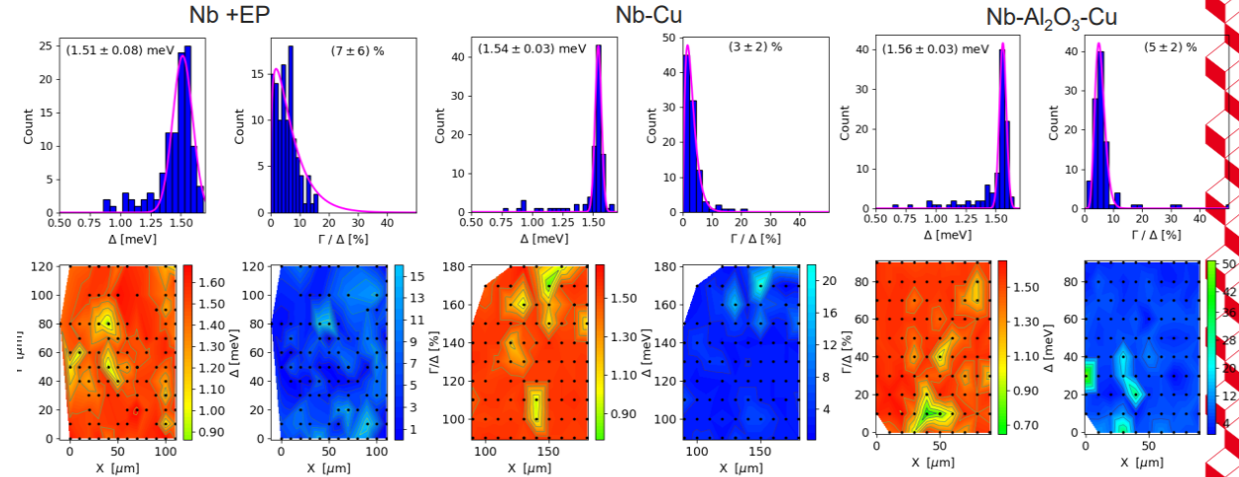


1. PCT measurements reveal similar tunneling conductance spectra for the three samples.
2. Evidence of **magnetic impurities**, which may originate from Nb native oxides.
3. **Bulk Nb gaps** ($\Delta \sim 1.5\text{-}1.6$ meV) were found in most of the spectra, **but also smaller gaps**.

13/11

Δ and Γ/Δ distributions

$$\rho(E) \sim \text{Re} \frac{E - i\Gamma}{\sqrt{(E - i\Gamma)^2 - \Delta^2}}$$



1. Similar homogeneous distributions for the 3 samples.
2. Peaked and narrow distribution of Δ values around the standard bulk Nb of ~ 1.55 meV.
3. Small Γ/Δ values $\sim 3\text{-}7\%$ and narrow distribution: close to ideal
4. For Nb +EP, slightly larger Δ and Γ/Δ distributions than the Nb films.

14/11

Confirms no differences in fundamental SC properties between Nb bulk and Nb/Cu

$$R_s = R_{BCS} + R_{\text{flux}} + R_{\text{res}}$$

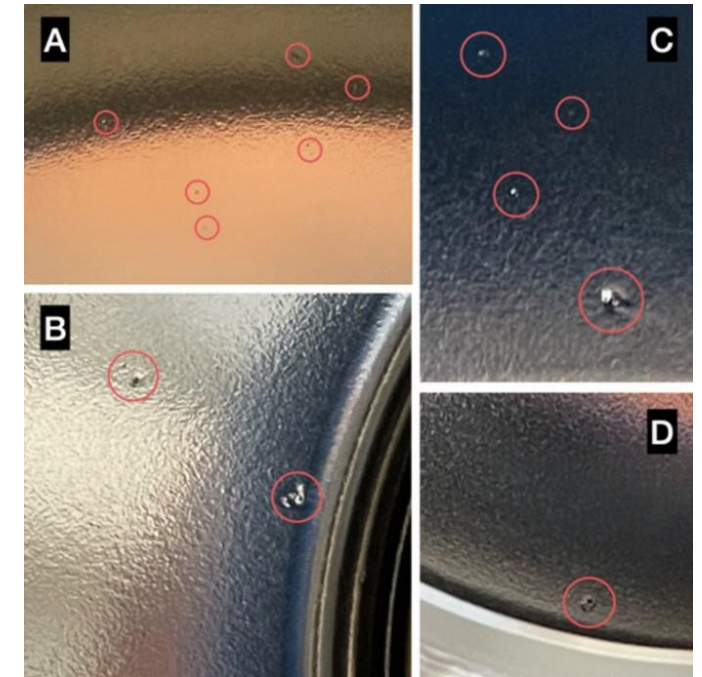
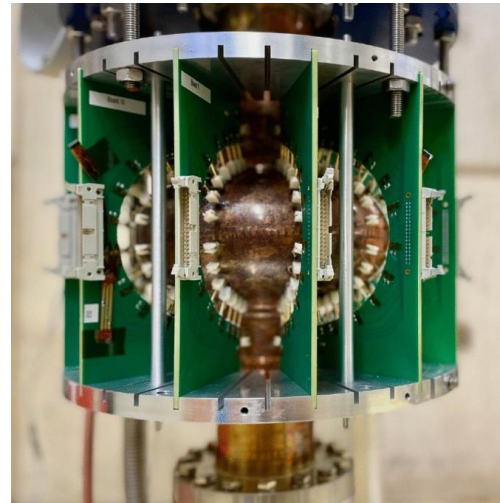
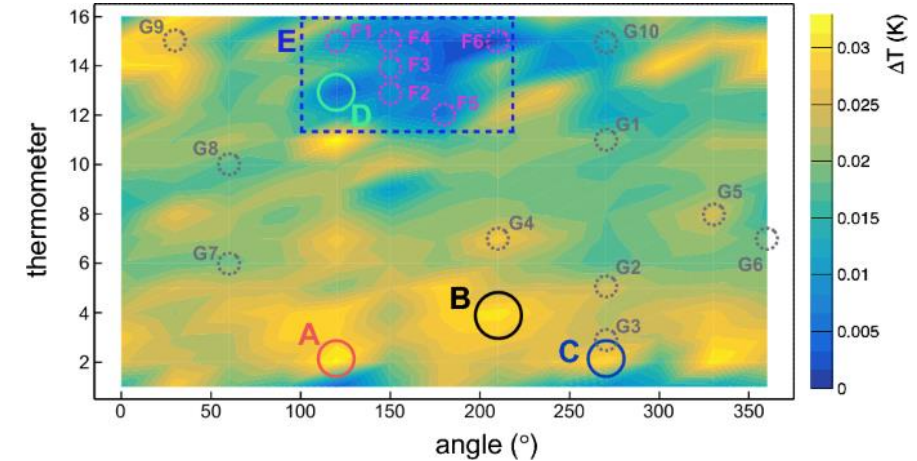
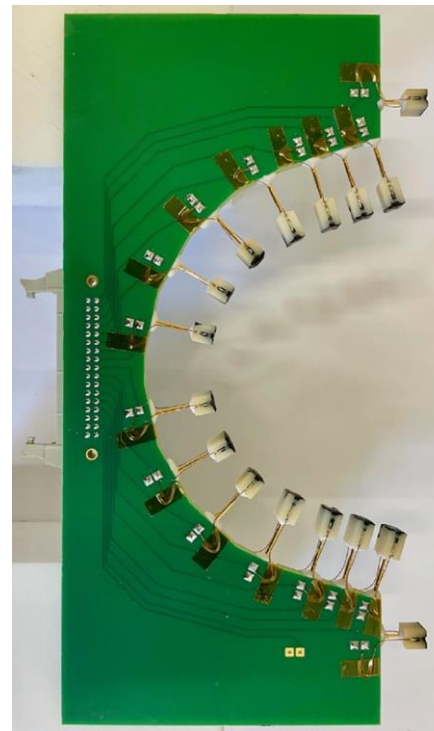
Temperature mapping and spurious losses

- New T mapping system adapted for copper substrates (hot spot detection more challenging)

Bianchi, A., Vandoni, G. & Venturini Delsolaro, W. **Temperature measurement on copper surfaces for superconducting thin film cavity applications.** *Meas. Sci. Technol.* **35**, 015901. <https://doi.org/10.1088/1361-6501/acfba2> (2024)

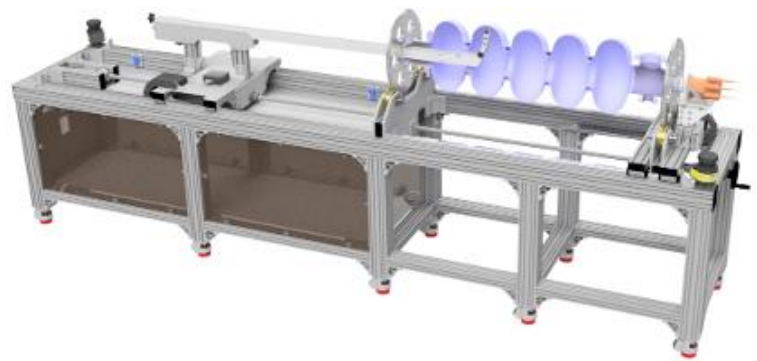
- Established correlation between hot spots, cold spots and surface defects

A. Bianchi, W. Venturini Delsolaro **Temperature mapping on a niobium-coated copper superconducting radio-frequency cavity** *Scientific Reports* volume **13**, Article number: 17075 (2023)

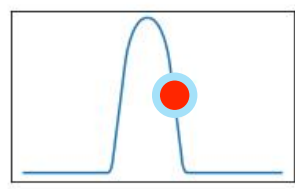
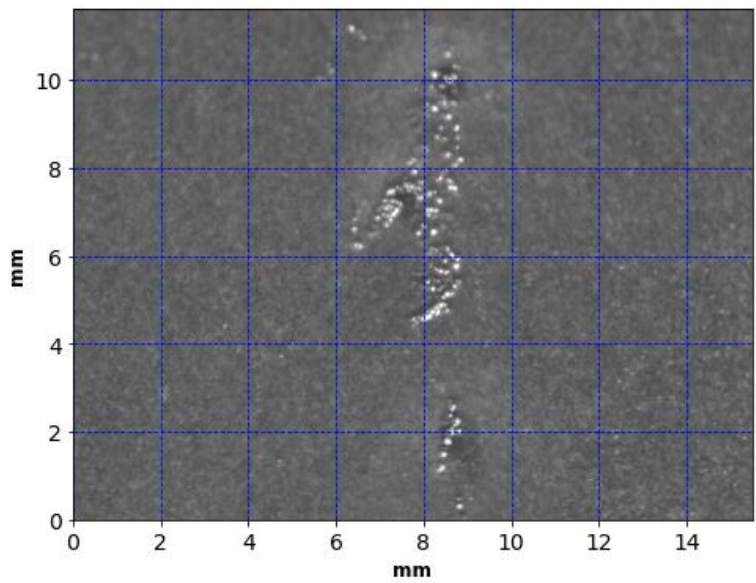
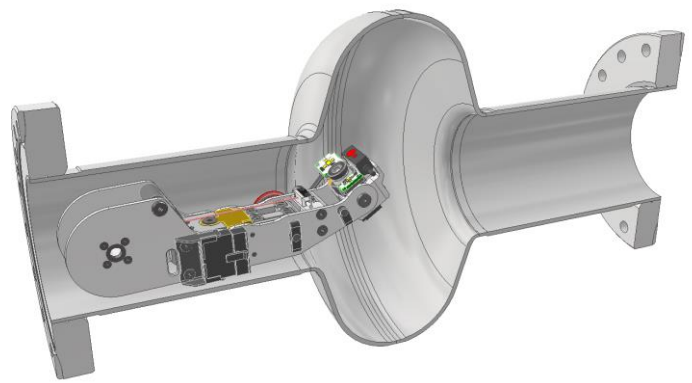
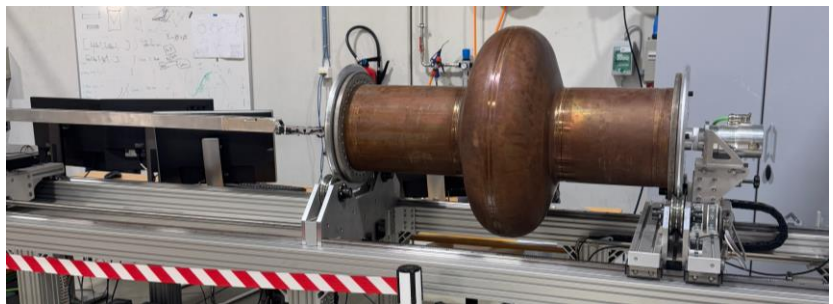


Optical inspection bench

S. R. Mathews, A. Macpherson, et al.

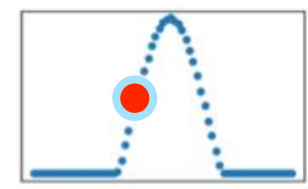
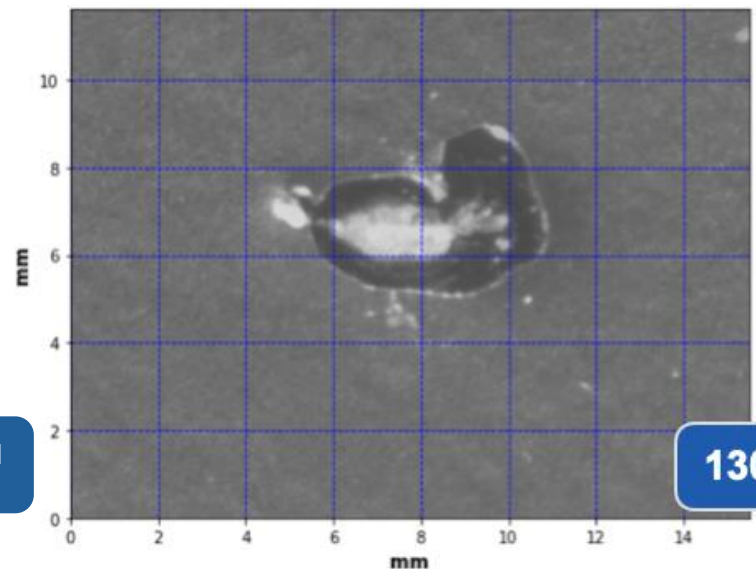


- Fixed short focus camera mounted on robotic arm
 - Precision imaging over full RF surface
- System capable of scanning Elliptical Cavities
 - LHC cavity: ~30000 images for full coverage
- Defect Analysis: AI driven defect detection in development



z: 618 mm,
 ϕ : 205.9°

400 MHz Nb-on Cu
Nb-on-Cu

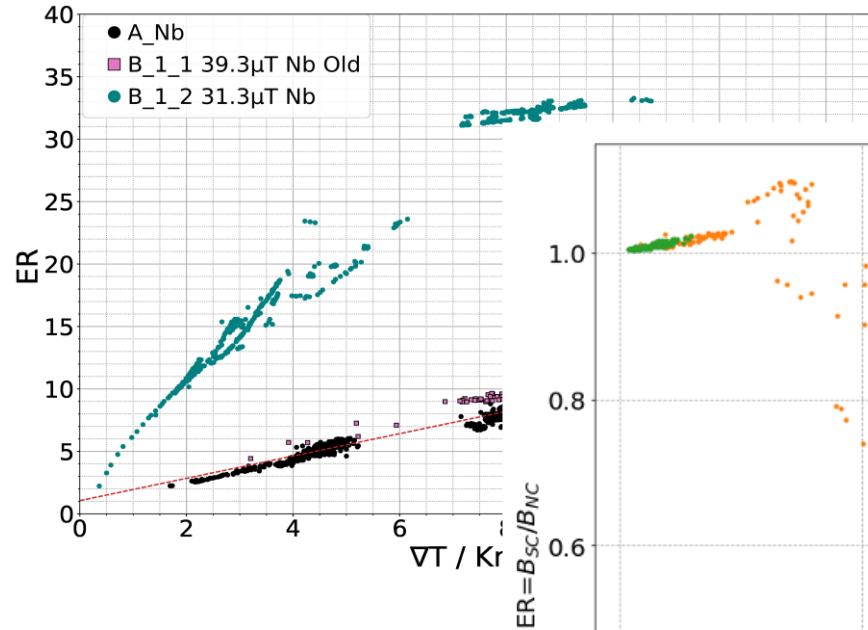


z: 157.34 mm,
 ϕ : 226.12°
size: 0.47 mm²

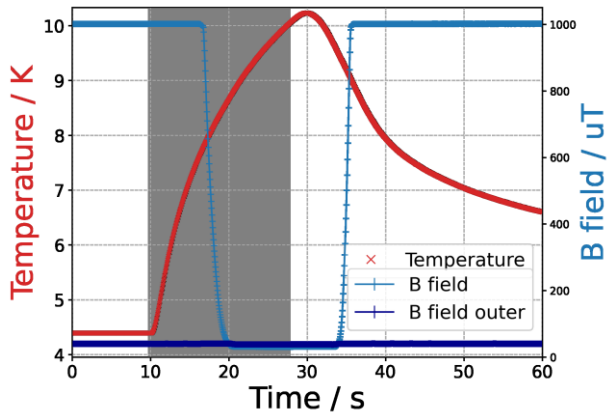
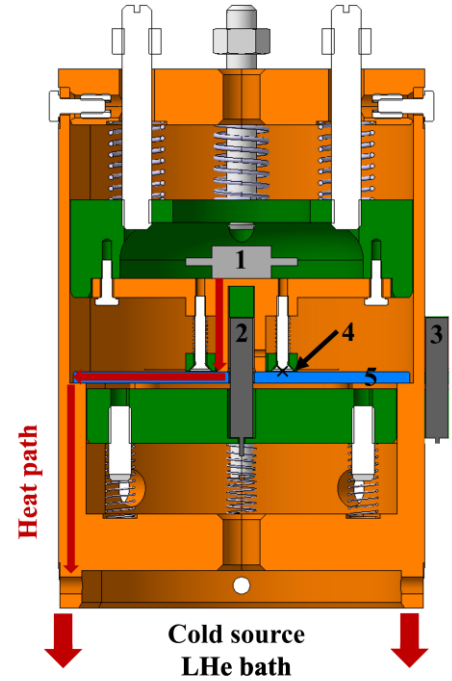
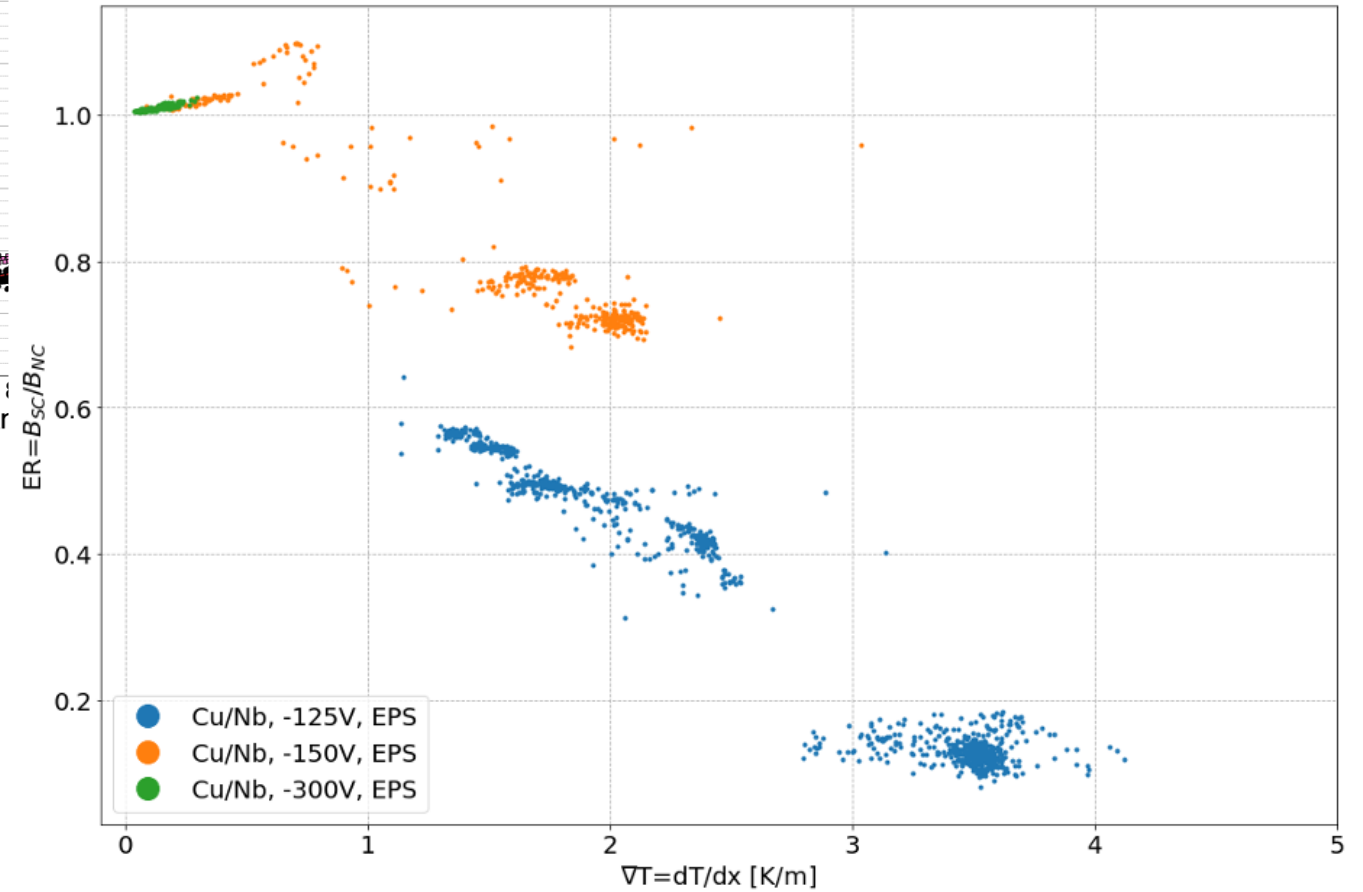
1300 MHz Nb-on-Cu

Flux expulsion studies with flux lens

Normal behavior for Nb: expulsion ratio $\sim \nabla T$

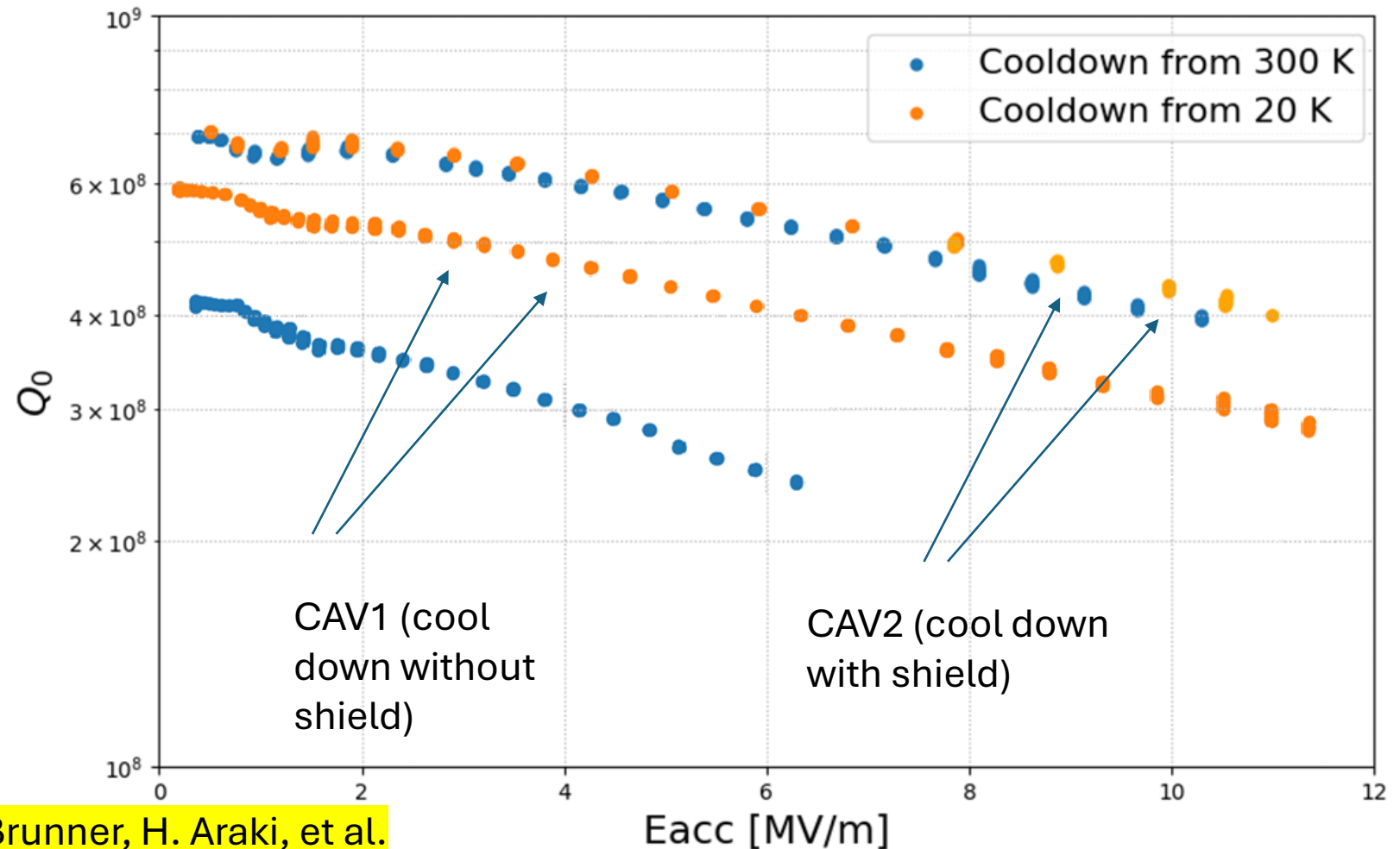


Evidence of thermoelectric currents in Nb/Cu : flux trapping at high ∇T

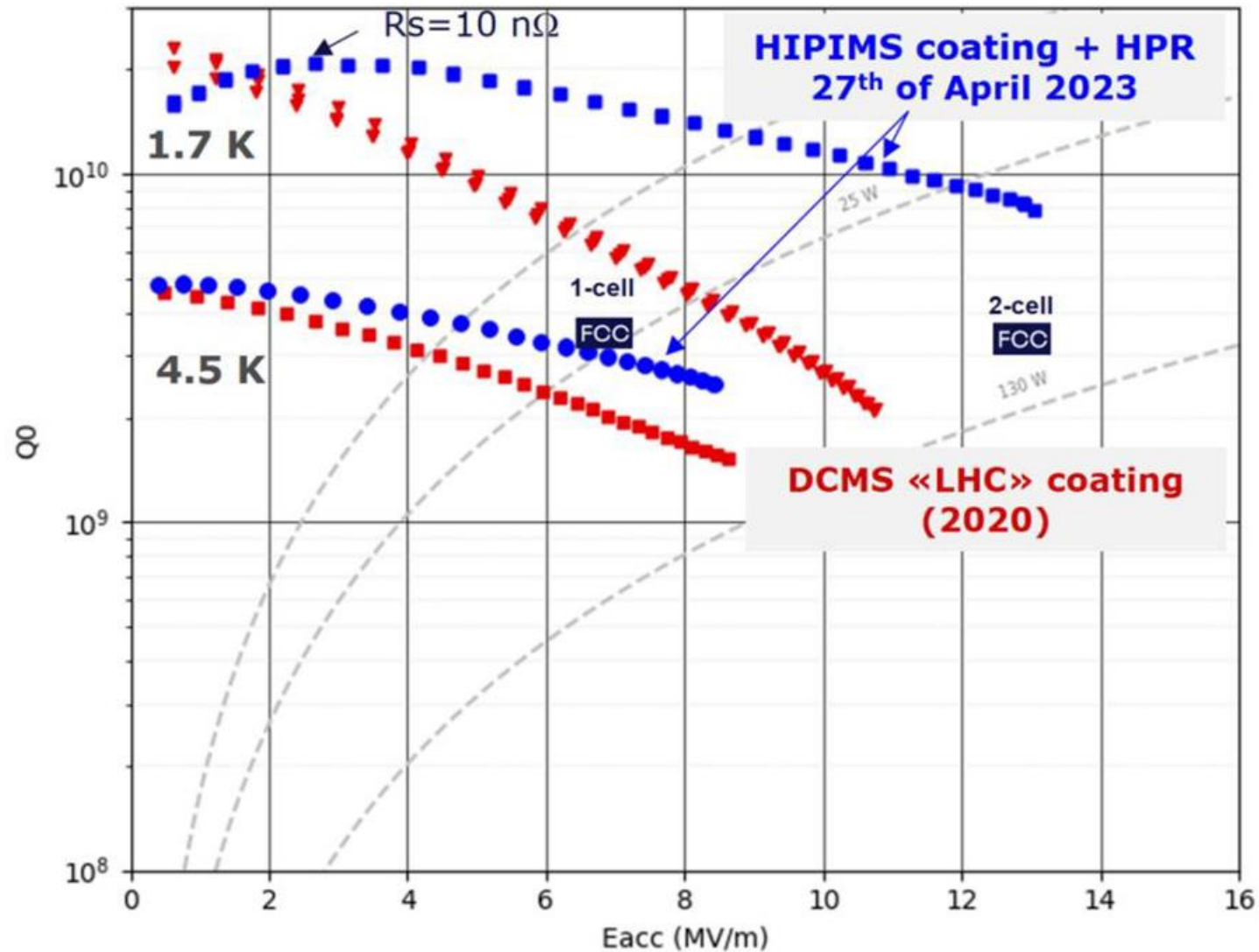


Importance of controlling thermal currents

Contrary to bulk Nb, minimizing T gradient at T_c is required to optimize performance

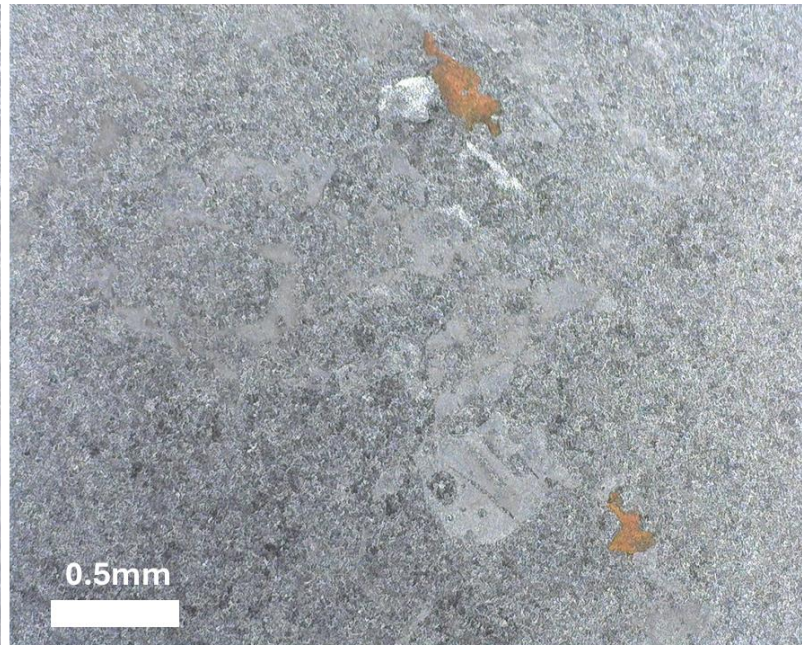
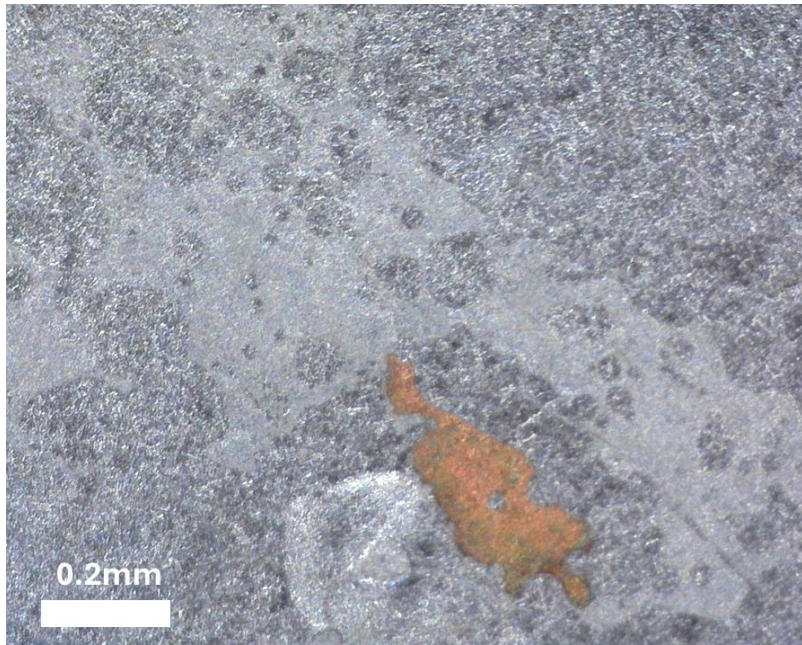


State of the art: 400 MHz



Situation of 400 MHz tests

- Of the four good practices so far identified (use seamless substrates, electropolishing, HIPIMS, thermal shield) until end 2024 only HIPIMS was implemented.
- Recently two cavities received EP, PC04 and PC06 (with HOM ports)
- PC04 was tested with thermal shield. It had poor performance, explained by localized peel off
- PC06 is presently under test in SM18 (with TS)
- Crab cavities will now use the chemical lab until end of June at least....



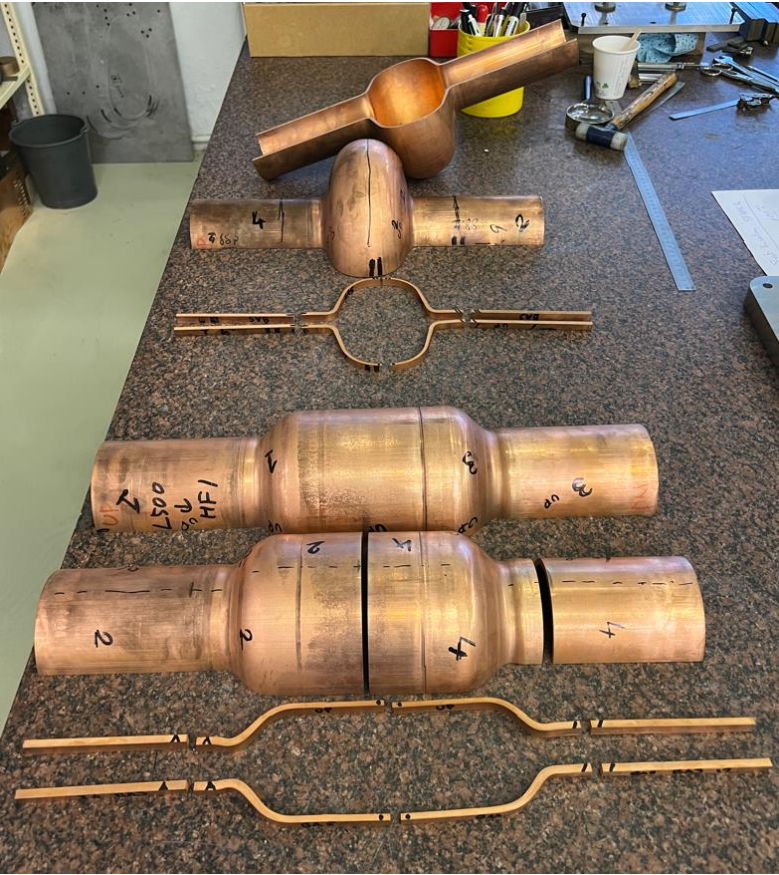
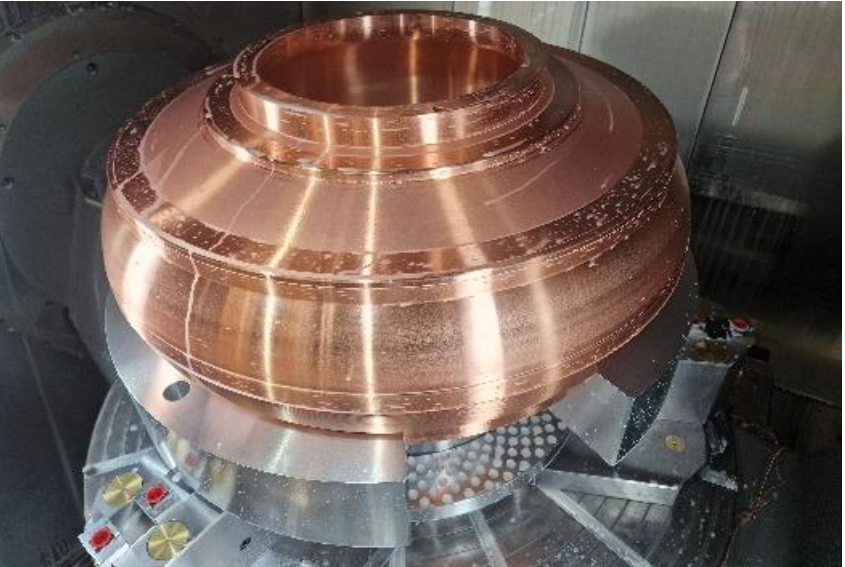
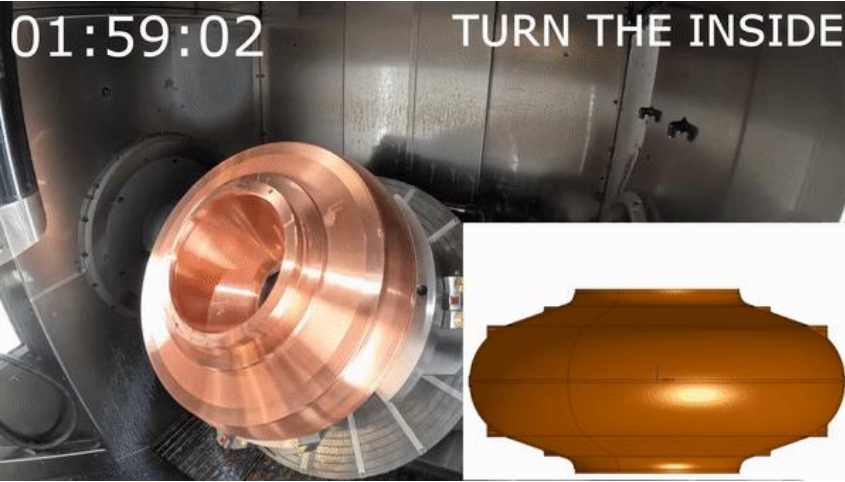
Peeled-off surface: 0.08 mm²

Cavity manufacturing

M. Garlasche, S. Atieh, et. al

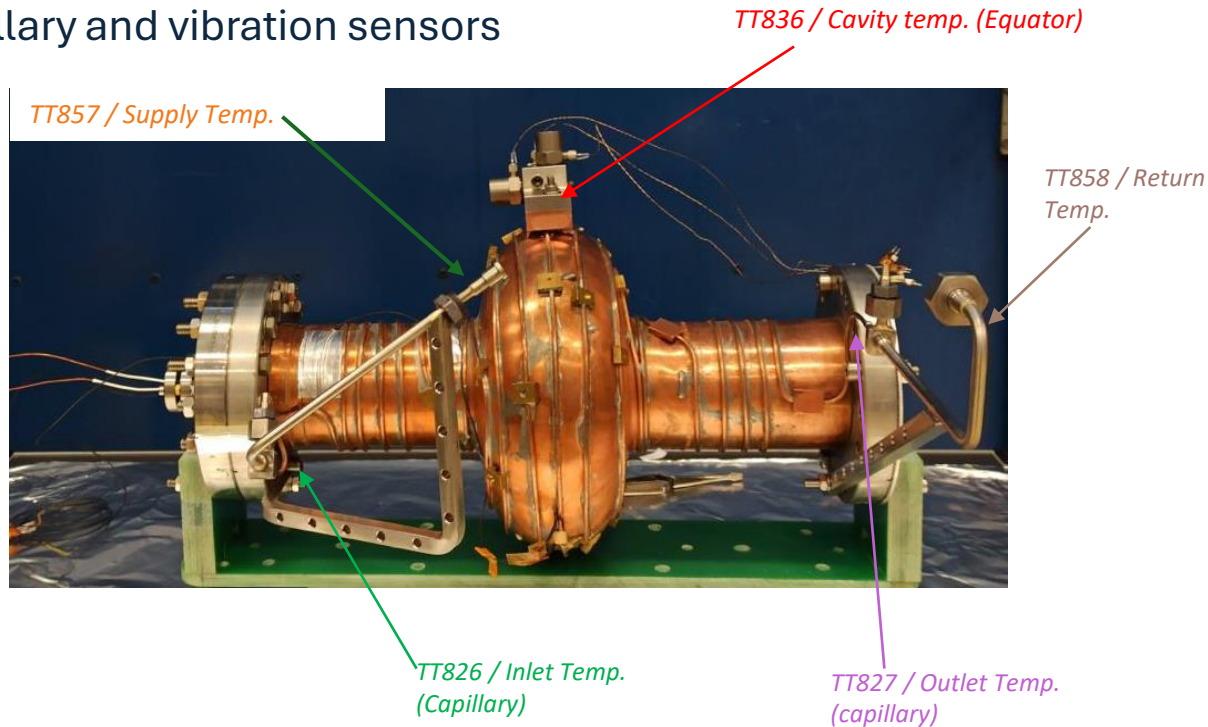
400 MHz Monoblock prototype

1.3 GHz hydroforming (KEK Collaboration)



Dry cavity cooling

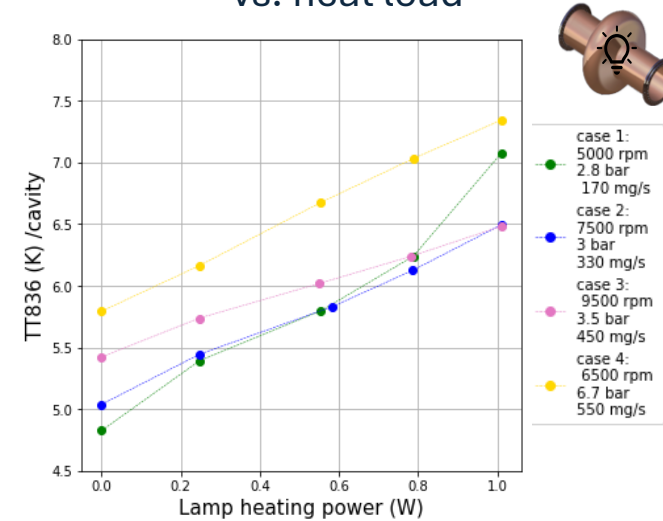
1.3 GHz Cu cavity with cooling capillary and vibration sensors



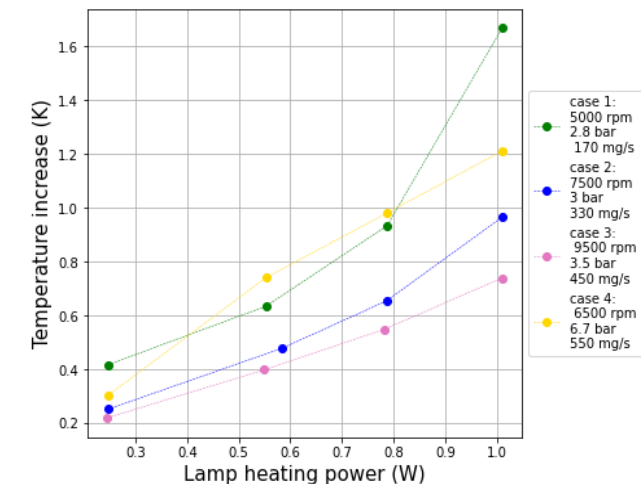
- Demonstrated **feasibility of remote cavity cooling** systems
- Tested different flow conditions for cooling (pressure, temp. and mass flow)
- **Low noise** cooling achieved
- **6.5 K cavity temperature** reached with 1 W + residuals
- **Integration of booster HEX finished**
- **Week 5 '24 => Start calibration procedure/pump down**

T. Koettig, M. Chioteli, et. al

Cavity absolute temperature vs. heat load

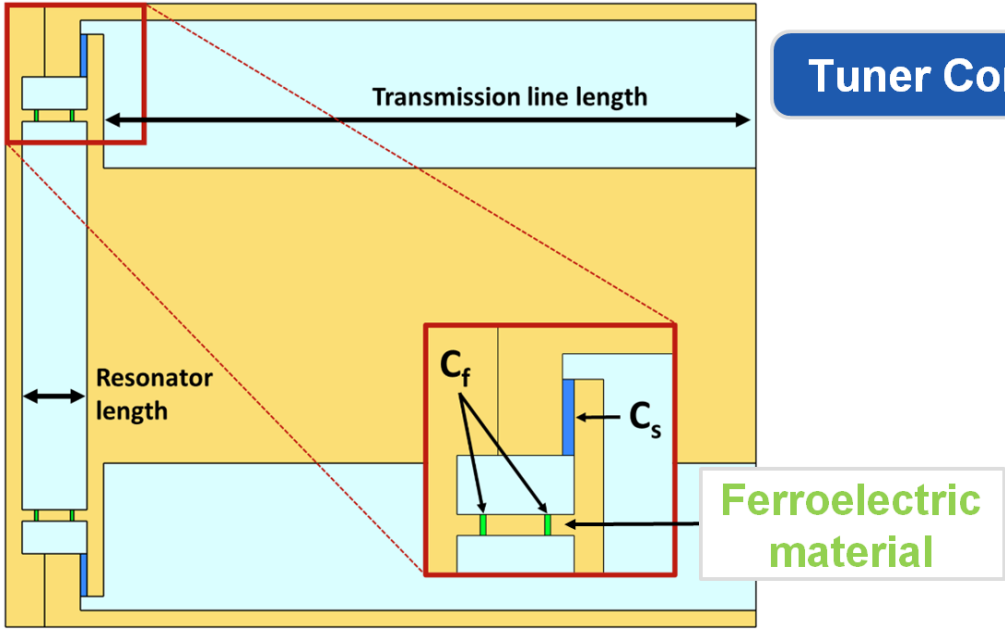
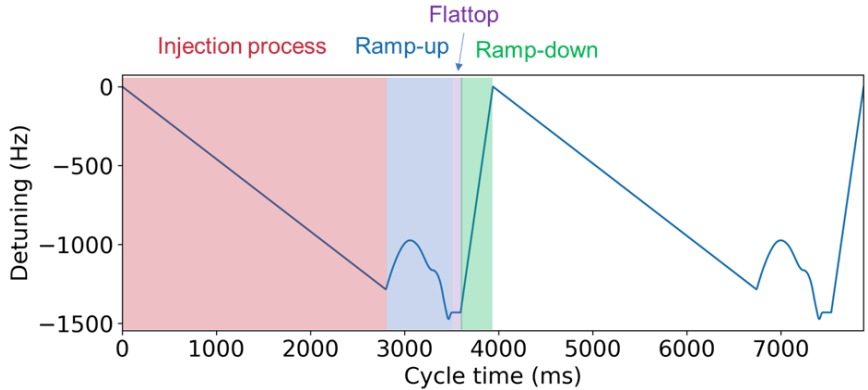


Cavity temperature increase vs. heat load



FE-FRTs: FCC use case

- **Task: compensate beam loading on 6-cell 800 MHz booster cavities @ injection**
 - RF power kept below 50 kW limit if cavities with detuned increased beam current.
 - Tuning range of 1.5 kHz with 25 J stored energy.
- **FE-FRT Solution: 1st Conceptual design exists**
 - Needs dedicated tuning port on cavity

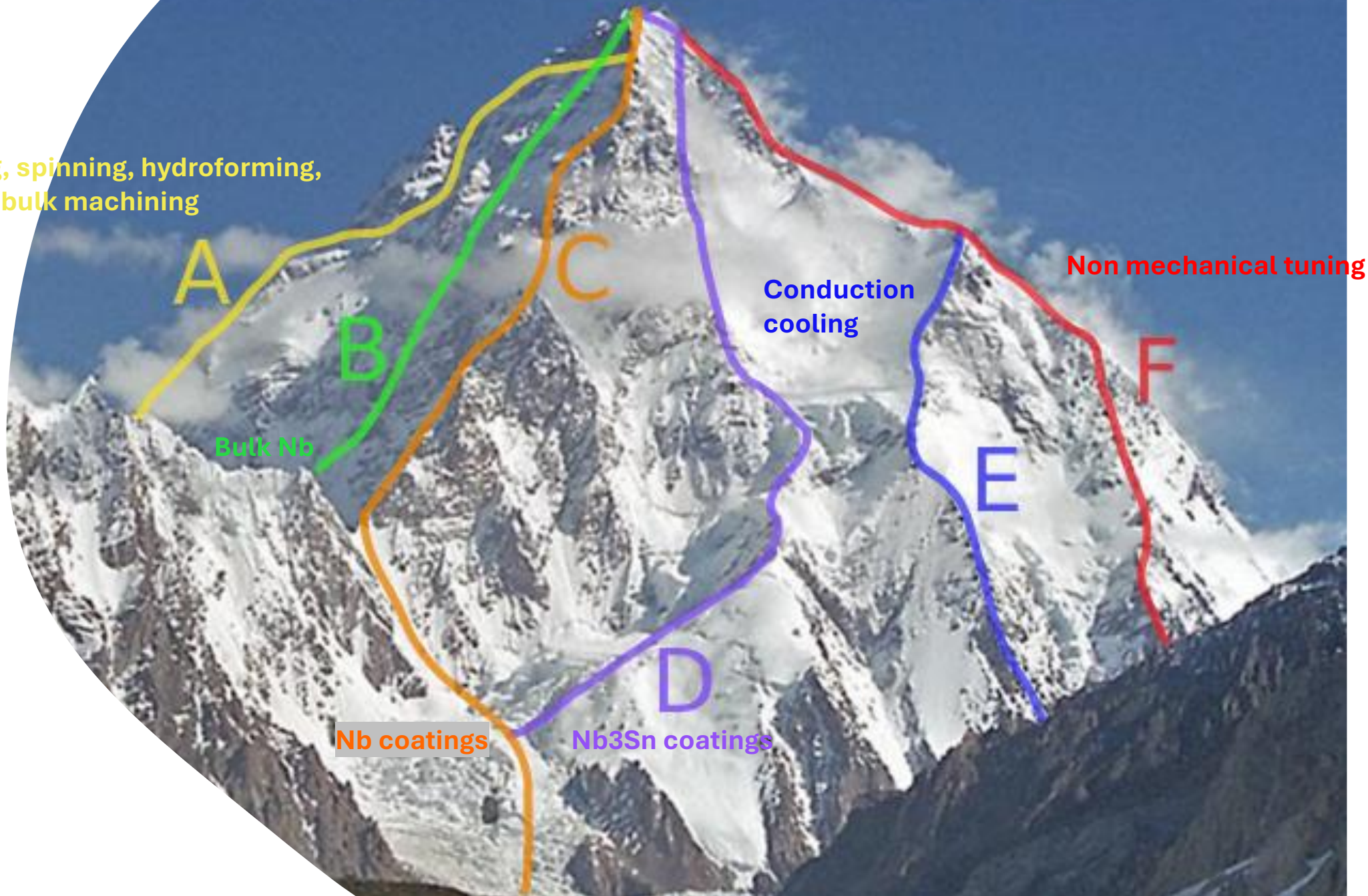


Tuner Concept

Parameter	Analytical	CST
f_0	801.58 MHz	801.58 MHz
U	24.3 J	-
Δf	1.5 kHz	1.5 kHz
FOM	56	48
$\Delta P_{\text{reactive}}$	458 kW	-
Q_e FRT	4.9×10^6	

$Q_0 > 3 \cdot 10^9$, $E_a > 10$ MV/m @ 400 MHz and 4.5 K

internal welding, spinning, hydroforming,
electroforming, bulk machining



A

B

C

Conduction
cooling

Non mechanical tuning

Bulk Nb

F

E

Nb coatings

Nb₃Sn coatings

D