

I.FAST

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DELIVERABLE REPORT

Thin-Film SRF Roadmap Report

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ABSTRACT

This Report proposes a comprehensive approach focused on the expertise and collaborative network that has been built in Europe and in the entire world over the past years. The IFAST WP9 team has developed a program aligned with the priorities deemed essential by the TF SRF community for continuous progress in this field. Ten priority topics have been identified on TF developments: 1 - Niobium on copper, 2 - Nb₃Sn on Cu and Nb, 3 - Other superconductors (other A15, MgB₂, Other) on Cu and Nb, 4 - Multilayers (SIS structures), 5 - Surface functionalization), but also on key activities that enable these developments, 6 - Cu cavity production and surface preparation, 7 - General Characterization / Surface science, 8 - Deposited cavities preparation and RF testing, 9 - Theory, 10 - Industrialization).

This Report is structured into 4 parts:

- (1) Introduction, where the challenges of the SRF technology are described
- (2) Detailed Topics, where the context and challenges are described in detail for each of the 10 topics

(3) Main recommendations. For each topic:

- A R&D program is detailed by priority order
- A global budget and manpower are recommended
- Additional targeted programs and investments are proposed

4) General conclusion

By addressing the challenges outlined in this document and fostering a collaborative research environment, the global community can benefit the full potential of this technology for applications from high-energy collisions and high-intensity hadron/neutron sources to light sources, cavity detectors, quantum computing or emerging fields like compact accelerators poised to revolutionize industrial processes and medical diagnostics.

I.FAST Consortium, 2025

For more information on IFAST, its partners and contributors please see <https://ifast-project.eu/>

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Executive summary

This document proposes a comprehensive approach focused on the expertise and collaborative network that has been built in Europe and in the entire world over the past years. The IFAST WP9 team has developed a program aligned with the priorities deemed essential by the TF SRF community for continuous progress in this field. Ten priority topics have been identified on thin film developments (1 Niobium on copper, 2 Nb₃Sn on Cu and Nb, 3 Other superconductors (other Al₁₅, MgB₂, Other) on Cu and Nb, 4 Multilayers (SIS structures), 5 Surface functionalization), but also on key activities that enable these developments (6 Cu cavity production and surface preparation, 7 General Characterization / Surface science, 8 Deposited cavities preparation and RF testing, 9 Theory, 10 Industrialization).

This Report is structured into 4 parts:

- 1) Introduction, where the challenges of the SRF technology are described*
- 2) Detailed Topics, where the context and challenges are described in detail for each of the 10 topics*
- 3) Main recommendations, describing the following details for each topic: (a) an R&D program is detailed by priority order, (b) a global budget and work force are recommended, (c) additional targeted programs and investments are proposed.*
- 4) General conclusion*

By addressing the challenges outlined in this document and fostering a collaborative research environment, the global community can benefit the full potential of this technology for applications from high-energy collisions and high-intensity hadron/neutron sources to light sources, cavity detectors, quantum computing or emerging fields like compact accelerators poised to revolutionize industrial processes and medical diagnostics.

See figure 2 below for a graphic summary.

1 Introduction

SRF systems exhibit a million times lower dissipation than copper systems, and can reach higher duty cycles, but they have several drawbacks:

- The complexity of the cryogenic system;
- The low energy efficiency of the cryogenics at low temperature;
- The cost of production of bulk niobium (Nb) cavities;
- It is not a turnkey technology, for now it is restricted to large instruments;
- The required liquid helium (LHe) inventory is high in large machines.

Over the past five years, helium prices have increased by a factor of 5, electricity costs by a factor of 3, and bulk Nb prices by a factor of 2; therefore, transforming the SRF technology into a more energy- and cost-efficient solution requires significant progress.

Depositing superconducting thin films (TF) capable of operating at higher temperatures on a copper (Cu) substrate is the most effective way to address this trend because:

- Cu cavities have a better thermal stability as Cu is a better thermal conductor than bulk Nb.
- Cu cavities are less expensive than bulk Nb cavities and easier to manipulate (no dangerous acids required).
- Superconductors with a higher critical temperature than the one of Nb are more capable of operating at temperatures above the boiling point of atmospheric liquid helium (4.5 K or higher), even at high frequencies. However, they cannot be economically mass-produced into cavities using bulk materials; therefore, using a thin film deposition technology is essential.

Superconducting thin film technology not only drastically reduces cryogenic costs but also opens the door to simplified alternative cooling schemes with reduced helium inventory. For example, cryocoolers could enable smaller, more compact accelerators capable of competing with industrial and medical applications currently dominated by "hot technology."

Transitioning from laboratory R&D to (quasi-)industrial applications requires the same level of investment that occurred in the 1970s for superconducting magnet development. However, RF cavities operate in a different regime for superconductors; thus, the past success cannot be simply replicated. Continued R&D support is essential. This support should encompass not only deposition processes but also:

- Cu cavity fabrication (in collaboration with industry),
- Cu surface preparation,
- Material science development (collaboration with academic labs and subcontracting),
- Deposition target production (materials and special shapes),
- Development of deposition setups suitable for larger cavities,
- Access to clean rooms and RF testing facilities (including financial aspects and personnel).

Currently, two roadmaps exist that consider thin film alternatives for SRF technology: the HE roadmap from CERN [1] and the Snowmass white papers in USA [2, 3]. Both focus on high-energy physics and include extensive programs in addition to their "small" thin film chapters.

The global TF SRF community, both, in Europe and worldwide, is highly interconnected with intense networking, international bi-annual TF SRF workshop, SRF conference, visits and student exchanges. However, many involved labs and universities do not necessarily have activities in High Energy (HE) physics. While superconducting TF (or TF SRF) technology has applications for colliders (e.g.: ILC, FCC), it also holds potential for application to numerous other fields: light sources (synchrotrons and free-electron lasers), high-intensity hadron sources (nuclear physics, neutron sources, radioisotope production, and accelerator-driven systems such as hybrid nuclear reactors), and compact accelerators (water treatment, surface and material treatment, medical applications, etc.). The superconducting TF technology is a high-risk/high-gain technology that could benefit diverse communities.

Figure 1. Worldwide activities related to superconducting thin films for SRF (updated from [4]).

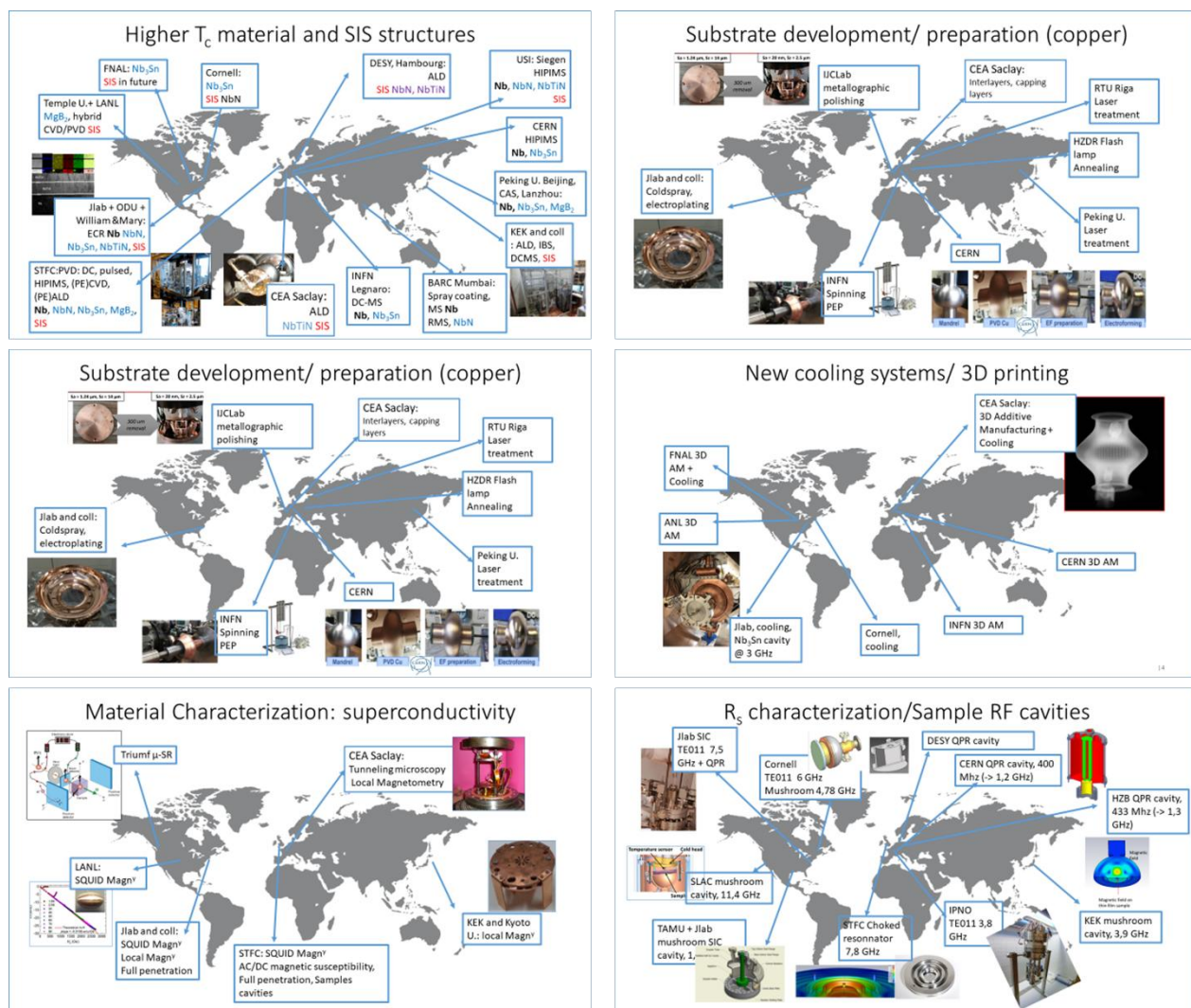


Fig. 1. Worldwide activities related to superconducting thin films for SRF.

The writing of a superconducting TF roadmap is a deliverable from the European H2020 project called IFAST for WP9. This document proposes a comprehensive approach focused on the

expertise and collaborative network that has been built in Europe and in the entire world over the past years, independent of partial or intermittent funding tied to specific projects. The IFAST WP9 team has developed a program aligned with the priorities deemed essential by the TF SRF community for continuous progress in this field. Ten priority topics have been identified (see Table 1). The preparation of this Roadmap took place during the TF-SRF workshop held in Paris-Saclay in September 2024 [5]. 60 participants, worldwide, volunteered to attend the 10 discussion sessions. In addition to the discussions, surveys on each topic pre-sent to the participants (1 answer per lab asked). Depending on the topics, 8 to 10 different labs replied to the surveys. The final version has been finalized during following IFAST WP9 meetings.

This Report is structured into 4 parts:

1. Introduction
2. Detailed Topics, where the context and challenges are described in detail for each of the 10 topics from Table 1
3. Main recommendations
4. General conclusions

Table 1. List of topics discussed during the Roadmap session at TFSRF2024.

Thin films development	Enabling key activities
① Niobium on copper	⑥ Cu cavity production and surface preparation
② Nb ₃ Sn on Cu and Nb	⑦ General Characterization / Surface science
③ Other superconductors (other A15, MgB ₂ , other) on Cu and Nb substrate	⑧ Deposited cavities preparation and RF testing
④ Multilayers (SIS structures)	⑨ Theory
⑤ Surface functionalization	⑩ Industrialization

Figure 2 summarizes the 10-year vision of the TF SRF roadmap that is detailed in Chapters 2 and 3.

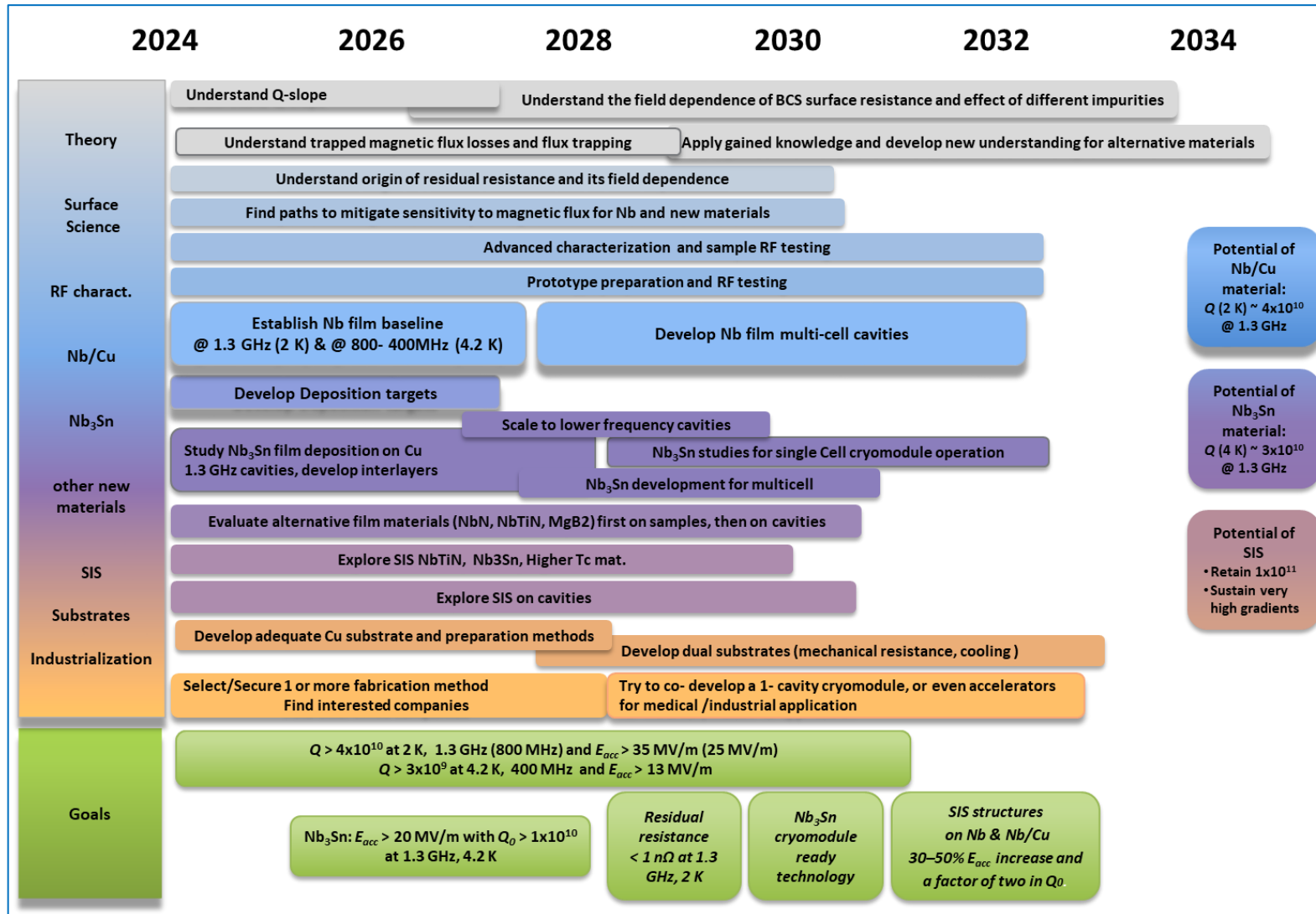


Fig. 2. Main roadmap lines for STF activities in Europe (adapted and updated from Snowmass TF roadmap).

2 Detailed priority topics

2.1 Nb ON Cu

Context

Bulk Nb cavities are used in charges particle accelerators for more than 50 years. However, since 1984 development of superconducting TF technology also takes place [6]. After ~40 years of R&D (where many counterintuitive results were found), it has become a success story for low frequency, f, and low accelerating gradient, Eacc, cavities at $T = 4.5$ K, with a lower cost compared to bulk Nb [7-9].

It is a reliable but not yet industrialized technology. The whole task includes substrate fabrication, surface treatment, superconducting TF deposition... For now, there is no willing industrial partners; usually a company requires minimum 200 pieces (prototype series) to be willing to launch such an activity. Therefore, it is the responsibility for large labs to maintain the know-how on all steps in-between.

Labs with activities in that domain

In Europe: CERN, INFN, LNL, STFC, (CEA if financed)

Outside Europe: JLab, IMP, Peking University, with growing interest in China and India]

Main challenges

Essentials

Facilities for surface treatment of cavities (pickling, passivation, HPR, ..., cleanroom) are absolutely necessary in the same lab where deposition is performed (see Topic 8).

Substrates: Cu

The fabrication of copper substrate is an important step to obtain successful deposition of Nb/Cu.

- See Topic 6 for fabrication and surface treatment prior deposition.
- See Topic 7 surface characterization is required to assess the quality of the preparation.

Flux trapping

Flux trapping behaviour vs deposition “recipe” needs to be studied [10-12].

Thermocurrent

Thermocurrent appears when two metals are in contact within a temperature gradient [13-15].

Role of hydrogen

Needs to be clarified [16].

Conclusion/recommendations

- Mastering this technology is a first steps to go to other technologies (interlayers, SIS structures):

- Technology already mastered at CERN, but improvements still needed for achieving an improved RF performance [9].
- In Europe, several labs have also developed this technique [17-21] (and during Aries program [22]), but it needs to be assessed on cavities.
- Several points need to be studied on samples, then 1.3 GHz prototypes:
 1. Role of interlayers (thermo-current, lattice adaptation, diffusion barrier), Topics 5, 7 and 9.
 2. Ongoing optimization of deposition parameters. For project like FCC one need $Q = 10^{10}$ @ $T = 2$ K, $E_{acc} = 20$ MV/m to be pushed to 25 MV/m @ $f = 1.3$ GHz, Topic 6.
 3. Q -slope mitigation with bulk-like RF performance as a goal, Topics 7 and 9.
 4. Substrate.
- Going to lower frequencies is important in terms of possible applicationsⁱ, moreover the technology for deposition is less complex. Several labs are not equipped yet.
 1. Investment for larger deposition set-ups,
 2. Environment, Topics 6 and 8.

2.2 Nb₃Sn ON CU AND NB

Context

This technology is assessed on bulk Nb cavities by thermal diffusion (several compact cryomodules/accelerators being built in USA and China) [23-25]. The European goal is to go for thick film on copper with a possible interlayer to reduce production costs [26]. Deposition on a bulk Nb cavity could be an interesting first step for comparison with the thermal route performances, allowing taking away the influence of substrate material. It should demonstrate $Q = 8 \cdot 10^9 - 10^{10}$ @ $T = 4$ K.

- For project like FCC one need $Q = 10^{10}$ @ $T = 2$ K, $E_{acc} = 20$ MV/m to be pushed to 25 MV/m @ $f = 800$ MHz [27].
- For compact accelerator one needs $Q = 10^{10}$ @ $T = 4.5$ K, E_{acc} up to 20 MV/m [23].

TF of Nb₃Sn could also be interesting for SIS structures (promising results on samples), see section 2.3.

The resistive losses in RF cavity are related to surface resistance R_s which is the sum of two components: R_{BCS} and R_{res} . The BCS resistance, R_{BCS} , is predicted by the BCS theory and is exponentially decreasing with temperatures, while the residual resistance, R_{res} , gathers unexplained losses; it does not depend on temperature.

A calculated performance comparison of Nb₃Sn to bulk Nb cavities is illustrated in Figs. 3 and 4.

Figure 3 shows that even with a high residual resistance, R_{res} , Nb₃Sn performs at 4 K as good as Nb at 2 K at $f = 1.3$ GHz, which can bring a large simplification of the cryogenic installation and operation cost divided by a factor 3 [4]. If one could reduce further the residual resistance of Nb₃Sn, from $R_{BCS}^{Nb_3Sn}(4.2K) = 30$ to 5 nΩ, the gain in power would be another factor 3 [28-31].

ⁱ Several of the non-HE applications are concerned

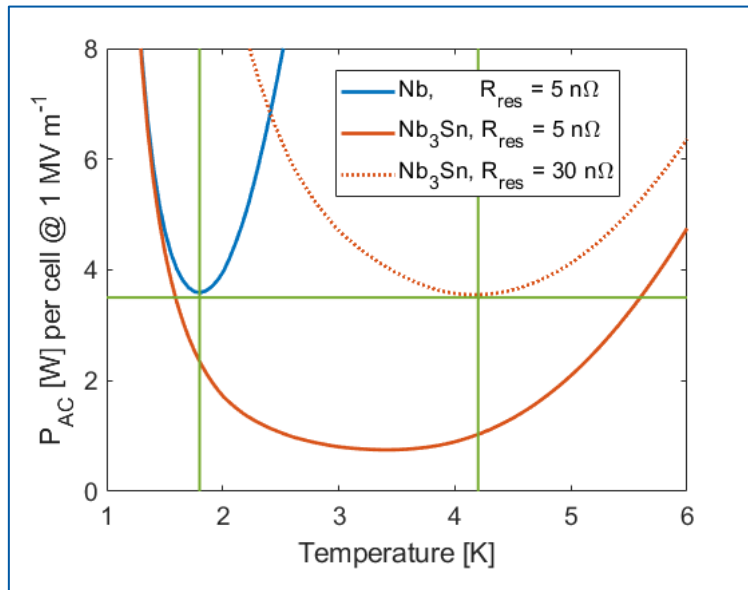


Fig. 3. Calculated AC power dissipation of Nb and Nb₃Sn cavity cells at cryogenic temperatures at 1.3 GHz. A Nb₃Sn cavity operated at 4.2 K outperforms a Nb cavity at 1.8 K - even when allowing for elevated residual resistance values. (courtesy of Sebastian Keckert from HZB).

Figure 4 shows two components of the surface resistance, R_{BCS} and R_{res} , of Nb and Nb₃Sn as a function of RF frequency. For calculating the BCS parameters for Nb₃Sn, the parameters were taken from Ref. [6]). The BCS surface resistance of Nb₃Sn is much lower than the one of Nb at $T = 2$ and 4 K. Presently, the performance of Nb₃Sn is limited by its residual resistance, R_{res} . Thus, Nb₃Sn at $T = 4$ K outperforms both: Nb at $T = 4$ K at any frequency and Nb at $T = 2$ K for $f > 1.3$ GHz. This demonstrates that all projects shown with stars in the graph would benefit in their RF performance in case of Nb₃Sn instead of Nb at 4.2 K.

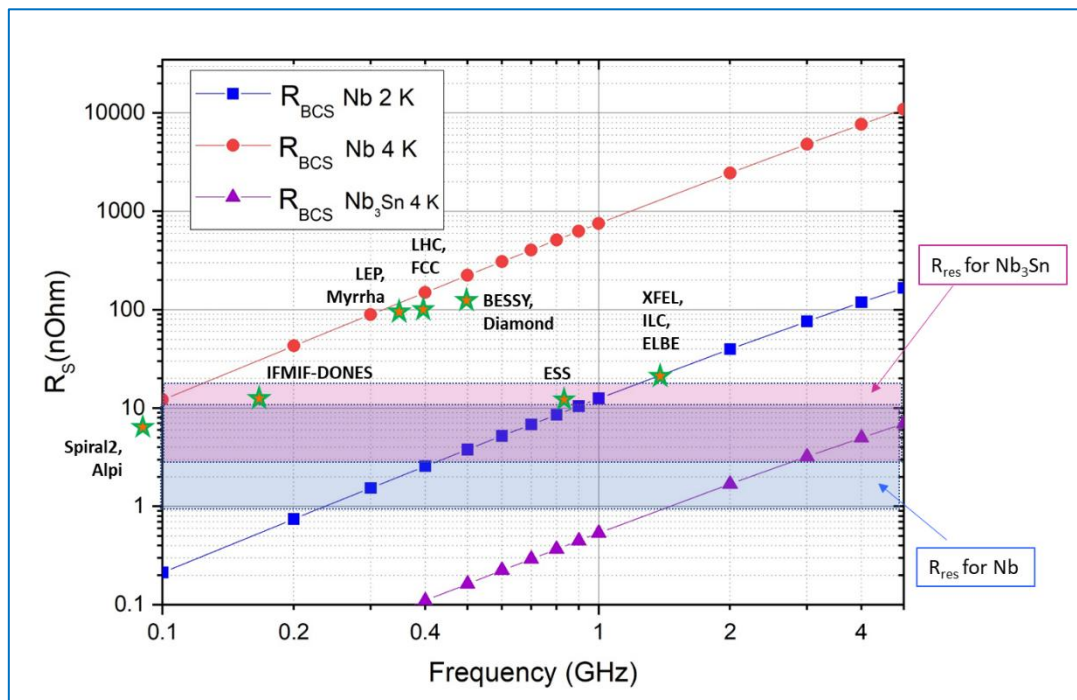


Fig. 4. Calculated components of surface resistance (R_s) for Nb and Nb₃Sn at cryogenic temperatures of 2 and 4.2 K. (courtesy of C. Antoine from CEA and D. Seal from STFC). With present Surface resistance,

Labs with activities in that domain

In Europe: CERN, INFN-LNL, HUH/DESY, STFC/CI, USI, CEA in near future

Outside Europe: USA (JLAB, Fermi Lab and Cornell), Japan (KEK), China (IHEP)

Main challenges

Final target:

- To reach a performance of Nb₃Sn on Cu substrate at **T=4.2 K** similar to performance of bulk Nb at $T = 2 \text{ K}$: i.e. $Q = 10^{10}$ @ $T = 4.2 \text{ K}$, $E_{\text{acc}} = 20 \text{ MV/m}$ @ $f = 1.3 \text{ GHz}$.

Elaboration of Nb₃Sn at $T < T_{\text{diffusion}} (< 1000^\circ\text{C})$

What is the optimum recipe, deposition technique? At this stage, several recipes have been demonstrated on flat sample (PVD, mostly magnetron) [20, 29-31]. The difficulty is to transpose them inside a cavity.

Deposition targets for PVD

- No deposition target commercially available for cylindrical deposition set-ups
 - They need to be perfectly stoichiometric
 - They are issues with brittleness, electrical charge
- Development is done at INFN, STFC, ... [20, 31, 32]
- Alternatives:
 - deposition on split cavities with planar magnetrons,
 - deposition inside lower frequency cavities with planar magnetrons
 - ...

Cu diffusion

- Cu is prone to diffuse from the substrate toward the surface of the Nb₃Sn layer [34].
- It is not observed in every lab, but the risk of a localized defect promoting this phenomenon increases with deposition surface area
- Interlayers
 - INFN has demonstrated that the TF thickness of 30 $\mu\text{m}/\text{nm}$ allows getting the proper structure with no Cu diffusion [35].
 - STFC/DL demonstrated that Nb₃Sn without under layer is possible, and the copper diffusion results to a rich copper surface up to 2-3% which can be removed post deposition [36]
 - The copper diffusion seems to be associated with oxygen profile through the film.
 - CERN on the other hand showed that surface resistance of Nb₃Sn even with copper diffusion is still satisfactory [37].
 - Metallic interlayers do not solve the thermocurrent problem

Thermal current

Thermal current can be generated at the interface of two different metals if there exists a temperature gradient. This current cause magnetic field:

- Interlayer (dielectric) are also explored

- Cooling procedures.

Other concerns

- Cu softening at deposition temperature (need for structural reinforcement)
- Evaporation of tin from the target at high temperature (stoichiometry not kept)
- Brittleness of targets (dust)
- Brittleness of films (tunability)
- Sensitivity to flux trapping

These potential problems will be addressed in an ongoing Horizon Europe project ISAS within WP3.

Conclusion/recommendations

- This technology opens the route to industrial and medical applications (compact accelerators) working at higher temperature
- It's the most developed among superconductors different than Nb, so the most liable to achieve success
 - Thermal diffusion on bulk Nb already mastered in several labs
 - Europe is aiming at films on copper substrates
 - Work is assessed on samples, prototyping within the next years (IFAST + ISAS)
- Recommendations
 1. Ongoing optimization of deposition parameters. For project like FCC one need $Q = 10^{10}$ @ $T = 2$ K, $E_{acc} = 20$ MV/m to be pushed to $E_{acc} = 25$ MV/m @ $f = 1.3$ GHz.
 2. Role of interlayers (thermo-current, lattice adaptation, diffusion barrier) – see Topic **5**
 3. Exploring new structures/ new (pre-)tuning methods to face tunability issues (see Topic **6**: for instance, cold spaying an external structure to counterbalance the softening of the substrate)
 4. Going to lower frequencies:
 - Simplified deposition, prototyping
 - 1st compact prototype with industrial partner becomes possible
 - Need to develop larger deposition set-ups, infrastructures and RF testing

The financing of full compact accelerators would be an opportunity to incorporate industrial actors in this development. A design with one single-cell cavity would not be affected by tunability issues met in longer machines and would constitute an excellent demonstration tool.

2.3 OTHER SUPERCONDUCTORS ON CU AND Nb (A15, MgB₂, OTHERS...)

Context

- As long as Nb₃Sn is not fully assessed, other routes need to be explored [6, 38]:
 - NbN, NbTiN. Less sensitive to stoichiometry deviation, has been employed for decades for SC electronics based on Josephson Junctions. T_c = same order of magnitude than Nb₃Sn, but B_{sh} is expected to be lower [39].

- MgB₂. Less issue to achieve the proper stoichiometry, very cheap. T_c = much higher than Nb₃Sn, but B_{sh} is also expected to be lower [39]. Potential to work at $T = 10$ K with a cryocooler.
- Other A15: potential to find an easier chemistry route (e.g. V₃Si - same structure, but high deposition temperature, not suitable for copper) [38].
- New families: BKBO, Chalcogenides, Pnictides: low TRL but high operation temperature potential, other applications than SRF (e.g. Axion detection)
- Most of these materials are good candidates for SIS structures (see Topic 4)

Labs with activities in that domain

In Europe: STFC (UK), USI (Germany)

Outside Europe: USA (Temple University, JLab, LANL, University of Tennessee), Japan (KEK)

Main challenges

These materials need fundamental full characterization before developing cavities.

Superconductivity

- Exploration must be guided by theory (see Topic 9). Best results if $\Delta/T_{op} > 4^i$ for conventional SC.
- Understanding of the role of normal conductivity, mean free path, penetration depth is needed
- Importance of characterization tools, e.g. cryogenic Point Contact Tunnelling (see Topic 8). Very specific developments made compared to commercial techniques.

Conclusion/recommendations

As Nb₃Sn poses several problems, alternative R&D are alleviating the risks, in case some insurmountable issues appear in this development.

- Compared to Nb₃Sn (or other A15 compounds),
 - NbTiN is plan B: SC parameters are a little less promising, but T_c less sensitive to composition. It has been widely applied to Josephson junction and is well documented. It is considered as an intermediate step in several labs.
 - MgB₂ is plan C: this material is very promising from the cost point of view and operation temperature (possibly 10 K). Unfortunately, no European SRF team has the resources to develop this topic (except for a few samples). It would need a full team full time.
 - Other SC families are plan D: longer-term developments, but promising theoretical predictions for higher temperature operation (liquid nitrogen for pnictides?). It requires a R&D survey.
- Exploration must be guided by theory (see Topic 9).
- Full characterization (see Topic 7), importance of PCT

^{iviii} Δ in Kelvin

- Exploration of the role of normal conductivity, mean free path, penetration depth
- Ongoing optimization of deposition parameters. For project like FCC one need $Q = 10^{10}$ @ $T = 2$ K, $E_{acc} = 20$ MV/m to be pushed to $E_{acc} = 25$ MV/m (@ $f = 1.3$ GHz).
- Role of interlayers (thermo-current, lattice adaptation, diffusion barrier)
- Exploring new structures/ new (pre-)tuning methods to face tunability issues (see Topic 6)
- Going to lower frequencies:
 - Simplified deposition, prototyping
 - 1st compact prototype with industrial partner becomes possible
 - Need to develop deposition set-ups, infrastructures and RF testing

2.4 MULTILAYERS, SIS STRUCTURES

Context

As mentioned in 3, most high T_c superconductors have an interest to be developed in the form of very thin superconducting films such as SIS (superconductor-insulator-superconductor) [40, 41] or metamaterials [42]. They can apply to:

- SRF applications, where higher Q_0 and E_{acc} expected. SIS structures are less sensitive to premature entrance of vortices, see Fig. 5 [43]. It could be the only way to overcome the limitation in accelerating gradient of SC like Nb_3Sn [44].
- Detector cavities at low RF field, high magnetic field (e.g. axion detectors) [45]
- Hyperbolic superconductor metamaterials [46, 47]
- Surface functionalization (see Topic 5)
- NbTiN and NbN have been the most explored (less complex to produce than Nb_3Sn)
- Very promising results on SIS Nb_3Sn samples (ARIES, see Fig. 6) [48].
- First cavities prototypes are being deposited (NbTiN, Nb_3Sn close) [49].
- Others SC (MgB_2 [50], $FeSe_2$ [51], pnictides [52]): only prospective R&D
- Difficulties encountered in Topic 2 and 3 also apply: tunability, interface quality...
- Nonetheless, deposition techniques like ALD are now better adapted to sub-micron films deposition [49, 53].

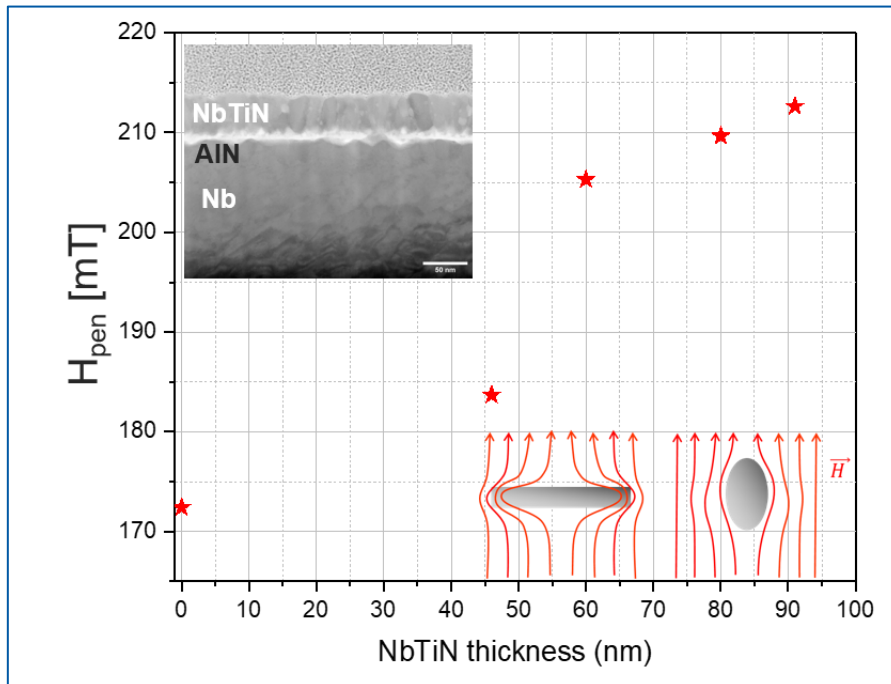


Fig. 5. Enhancement of the penetration field of an SIS samples (bulk Nb/AlN/NbTiN) vs the thickness of the NbTiN top layer (courtesy of T. Proslir, CEA).

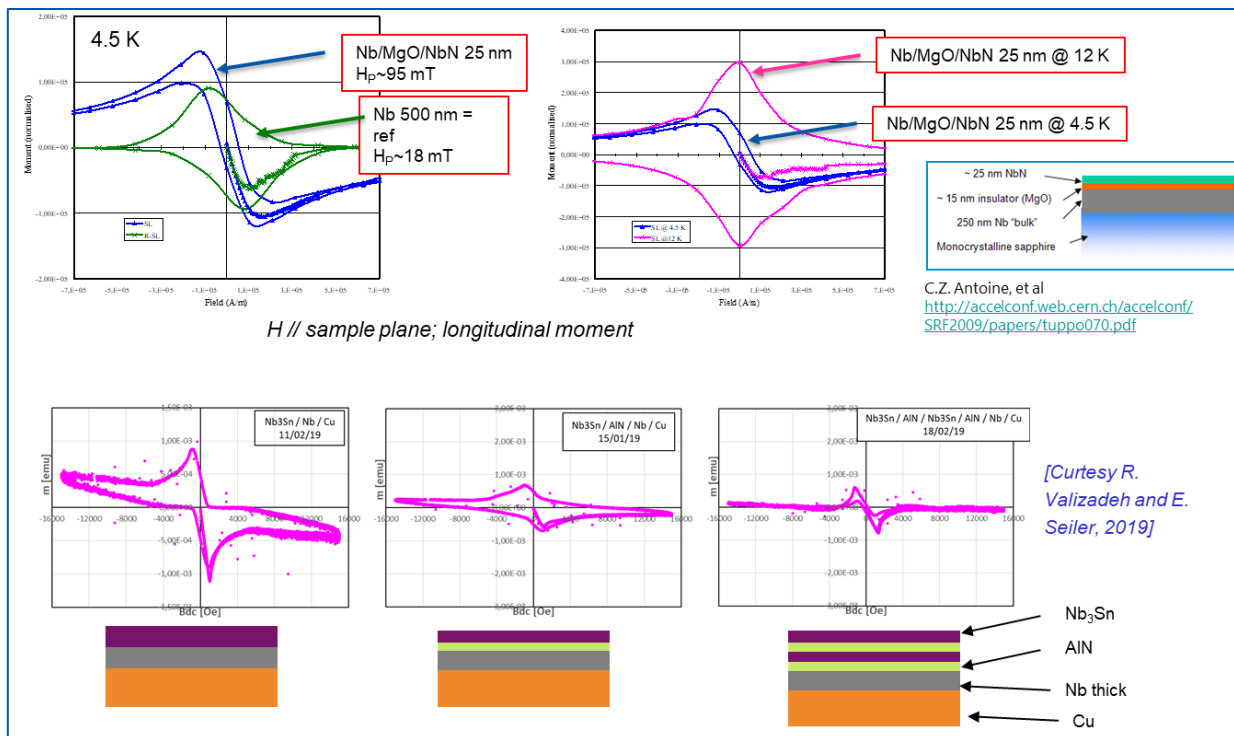


Fig. 6. Examples of DC magnetometry of SIS multilayers based on NbN (top) and Nb₃Sn (bottom). The drastic reduction of the hysteresis surface in multilayers reflects the appearance of a surface barrier that prevents early penetration of vortex. The defects are still present in the individual layers (green and pink curve in the top panel); but their combination in SIS structure is less sensitive to defects (blue curve, top panel or right-hand side curves in the bottom panel).

Labs with activities in that domain

In Europe:

- 1.3 GHz prototypes: CEA, DESY (Hamburg U.).
- Prospective, samples: STFC (UK), USI (Germany)

Outside Europe:

- JLab, KEK.
- Prospective: CAS, FNAL

Main challenges

Target performance: 20-30% field enhancement of the vortex first penetration field compared to thicker materials (B_{C1} or B_{fp}) and $R_s = R_s^{Nb}/2$ @ $T = 4.5$ K, first on QPR, next on a Nb bulk cavity. At longer term, 100% field enhancement.

Importance of the Insulating (I) layer

- Insulating layer main role is to block avalanche penetration of vortices.
- Because of lattice mismatch, it induces strain on the superconducting layers; this strain can affect the superconducting properties of the layer.
- Several dielectric materials are possible and need to be chosen regarding the superconductor lattice parameter: MgO, AlN, Al₂O₃, ZrO, amorphous vs polycrystalline...
- It must be compatible with the temperature synthesis of the SC overlayers.

Delamination

- Delamination is observed on complete cavities when treated the same way as successful done for samples (including curved surfaces).
- Vacuum quality is suspected for now, but this problem must be fully studied to find a solution

Other aspects to be explored yet

- Thermal stress
- Tunability
- Sensitivity to radiation during accelerator operation

Conclusion/recommendations

- “Dirty Nb” layer + dielectric layer on clean bulk Nb cavity could be an interesting demonstration step, simpler to achieve.
- First demonstration of SIS structures needs to be done on Nb cavities. Test on SIS deposited on Nb/Cu cavities can start once the interface issues on copper are solved in Topics ① and ②
- Access to a characterization tools network exist. Manpower and financial resources is needed.

2.5 SURFACE FUNCTIONALIZATION

Context

New treatments are appearing to change the surface properties without affecting underlying materials. Note that doping, LT and MT baking, are already a form of surface functionalization where one improves the surface superconductivity without modifying the bulk thermal conduction properties of Nb.

Applications

- Q -slope management (doping) (all SRF labs), can also be done by ALD.
- Interlayers for Topics ①, ② and ③ [17, 20].
 - Eliminating thermo-current
 - Increasing thermal stability/chemical stability
- Capping/diffusion barrier/protection
- Multipacting mitigation, SEY tailoring, on cavities, but also other high field systems
- Surface thermal engineering (e.g. ITCF films for thermal conduction [54], flash (FLA) [3, 28] or laser annealing) [55, 56].

Labs with activities in that domain

In Europe: HZDR, RTU, CEA, DESY, IJClab

Outside Europe: Japan (KEK), China

Main challenges

- What material, what thickness?
- Temperature and chemical stability
- Sensitivity to radiation
 - During deposition
 - During accelerator operation

Conclusion/recommendations

Multiple other possible applications (Qbits, high voltage devices, detector...) High risk of spread activities in detriment to SRF for accelerators

Already can be applied on bulk layers

2.6 COPPER CAVITIES PRODUCTION

Context

At European level, the priority is to develop deposition processes on copper cavities (even if some other substrate material could be also explored). All film development activities (Topics ① to ⑤) cannot be assessed if the development teams have no substrates for the deposition of the 1st prototypes. Due to post-covid reorganization, the procurement of the required OFE copper has become difficult, putting all the process at delay.

There must be no weld under the RF surface as it degrades an RF performance of a superconducting TF coated cavity. Therefore, producing seamless cavities is the priority as a preferable substrate for superconducting TF coatings. Two aspects need to be mastered:

- Cavity fabrication with asserted or innovating technologies (see Table 2 and Fig. 5)
- Copper surface treatments to provide deposition ready surfaces (see Table 3) [55, 56].

Table 2. List of fabrication techniques for seamless cavities.

Technique	TRL	pro	con	Labs
Spinning [57]	7	cheap, fast	non uniform thickness, non-optimal surface finishing	INFN*
Hydroforming [58]	6	fast, uniform thickness	expensive set-up, non-optimal surface finishing	KEK**
Bulk machining, Diamond turning [59]	6	Optimal surface finishing, Uniform thickness	Very expensive	CERN***
Electroforming	6	Good surface finishing, cheap	Coating peel-off to solve, non-uniform thickness	CERN
Additive Manufacturing	4-5	Innovative cooling system possible, less geometrical constrain	Very poor surface finishing, no RF test yet	CEA, INFN
Split cavities geometry	4	Simpler machining, easy to coat	RF performance not validated yet	CERN, STFC/DL

* Has been used for the production of LEP and LHC cavities

** Had also been developed at CERN in the 80s, CEA and DESY in the 90s

*** Has been used for the production of HIE-ISOLDE cavities

Labs with activities in that domain

In Europe: CERN, INFN-LNL, IJCLab, STFC/DL

Outside Europe: KEK

Main challenges

Production chain is missing up to now.

Table 3. List of copper surface treatment.

Technique	TRL	pro	con	Labs
Chemical Polishing (SUBU5)	9	Fast, simpler set-up	Crystallographic orientation dependent, pitting	CERN, INFN
Electropolishing (EP)	9	Best RF performance so far on Nb on Cu, Crystallographic orientation independent	Slow, cathode-anode distance/geometry important, challenging in complex 3D shapes	CERN, INFN
Plasma Electrolytic	5	Faster Technique, best surface finishing so far, Crystallographic	High peak power required, higher power consumption than EP	INFN

Polishing (PEP) [60]		orientation independent, diluted chemical solution, cathode geometry less important than EP		
Metallographic Polishing	5	No chemical solution, mechanical treatment, Crystallographic orientation independent	Possible only on Cu sheets before cavity forming	IJCLab

Flanges

- Electron beam (EB) welding of flanges is another bottleneck to get ready to test cavities: collaborators from Belarus are not available anymore, and the industrial price was not included initially.
- NB: Electra is developing a laser welding

Surface treatment

- SUBU is well mastered but show some pitting. It is foreseen to go to EP or PEP (@INFN)
- Treatments need to be adapted to “real” cavities with complex shapes, e.g. with HOM ports
- Necessity to be able to do passivation/ aging soon before deposition: ad hoc installations needed (see Topic 8)
- The exact impact of surface roughness /porosities must be determined

Mechanical properties

- If the deposition temperature is high, copper becomes too soft for mechanical stability
 - Explore reinforcing structures, or lattices, of external layers (see Fig. 7)
 - Other nature of Cu (lower grade, alloys, nanocrystalline Cu ?), how does it play
 - Explore other substrates, e.g. Mo

Conclusion/recommendations

- Industrialization: completely transfer high TRL techniques to industry
 - spinning, hydroforming
 - Rather small companies
 - Including flange completion process
 - No surface treatment at first stage
- Copper selection: do we need OFE Cu ?
 - Lower grade, alloys, nanocrystalline material
- Surface treatment
 - It is better to have surface treatment close to deposition facilities (at the end everything should end up to a company)
 - Even SUBU and EP (high TRL) need to achieve better surface quality for film deposition
 - Bring PEP and metallographic polishing to higher TRL

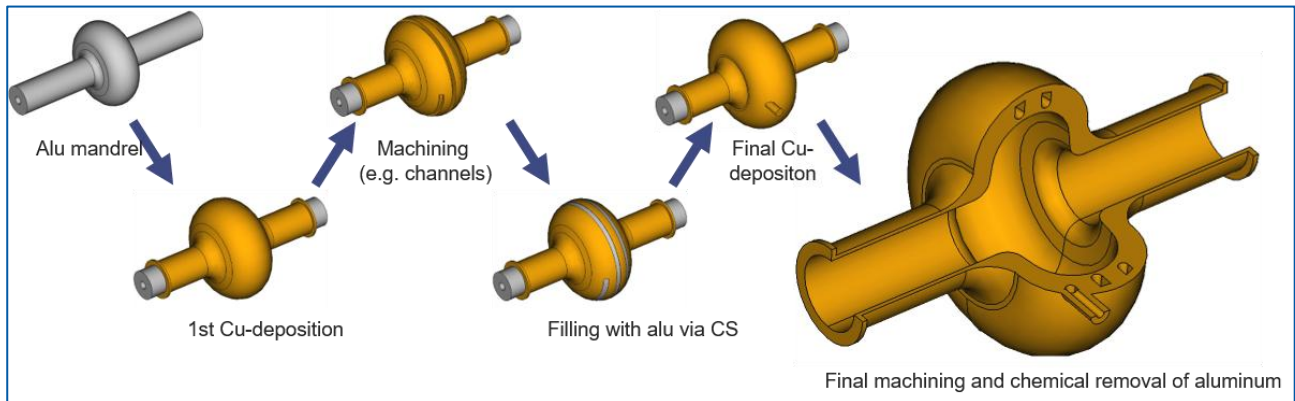


Fig. 7. Example of seamless cavity fabrication including cooling channels (Courtesy of T. Prosliev).

2.7 CHARACTERIZATION / SURFACE SCIENCE

Context

The development of new materials requires thorough **classical material characterization techniques**, (a) before deposition, to characterize the substrate condition; and (b) after deposition to assess the film quality, in particular, its crystalline structure and composition and impurities/defects levels:

- Surface and film characterisation:
 - Surface composition and chemical bonding by an X-ray photon spectroscopy (XPS).
 - Film compositions can be examined by Rutherford Back Scattering (RBS), Energy Dispersion X-ray Spectroscopy (EDX) or Secondary-Ion Mass Spectrometry (SIMS).
 - Film morphology will be examined by Scanning Electron Microscopy (SEM), Focused Ion Beam (FIB), and Atomic Force microscopy (AFM).
 - Grain size, crystal structure and phase will be examined by Transmission Electron Microscopy (TEM), Grazing angle X-ray Diffraction (GXR) and Electron Backscatter Diffraction (EBSD).
 - Scratch test for film adhesion
 - Surface roughness and nucleation with AFM
- Current Superconducting properties:
 - Superconductor critical temperature (T_c) and a width of transition (ΔT_c),
 - Residual resistance ratio (RRR),
 - Superconductor critical current density (J_c),
 - DC magnetometry: lower and higher critical magnetic field (B_{c1} and B_{c2})

Besides these current techniques, they are also **advanced solid-state techniques**, those results provide invaluable information, but need to be conducted on large instruments (accelerators most of the time). Except in very few cases, this needs to be outsourced to an external team with enough expertise (and an outsourcing budget needs to be foreseen)

- Particle-induced X-ray emission or proton-induced X-ray emission (PIXE), nuclear reaction analysis (NRA) and elastic recoil detection analysis (ERDA) are used for the depth profiled composition with resolution of 10s nm, contamination at ppm level
- Positron annihilation: (vacancy, vacancy clusters) point defects with depth resolution
- μ -SR, β -NMR : implantation of μ or β particles, detailed information about magnetic and electronic properties with depth resolution.
- Near-field microwave microscopy: measure local defects

Locally developed specific tools. Such tools have been and will need to be developed when on-shelf solutions do not exist for required operation conditions...

- Point contact tunnelling (PCT) Scanning: cartography of electronic densities of states (DOS) of strongly disordered superconducting thin films (Δ, \dots)
- Magnetic field penetration, DC/AC magnetic susceptibility and 3rd harmonic techniques (best case measurement of a sample)
- Quadrupole Resonator (QPR): Macroscopic measurement of superconducting properties such as surface resistance R_s vs applied magnetic field B , R_s vs temperature T , critical temperature T_c , superheating field B_{sh} , London penetration depth λ , (worst case measurement of a sample)
- Flux lens: measurement of expelled ambient field of donut shaped superconductor sample
- Cryocooler-based analysis of flux-trapping (CRAFT): Magnetic field mapping of superconducting transition in arbitrary temperature gradients (see Fig. 8)

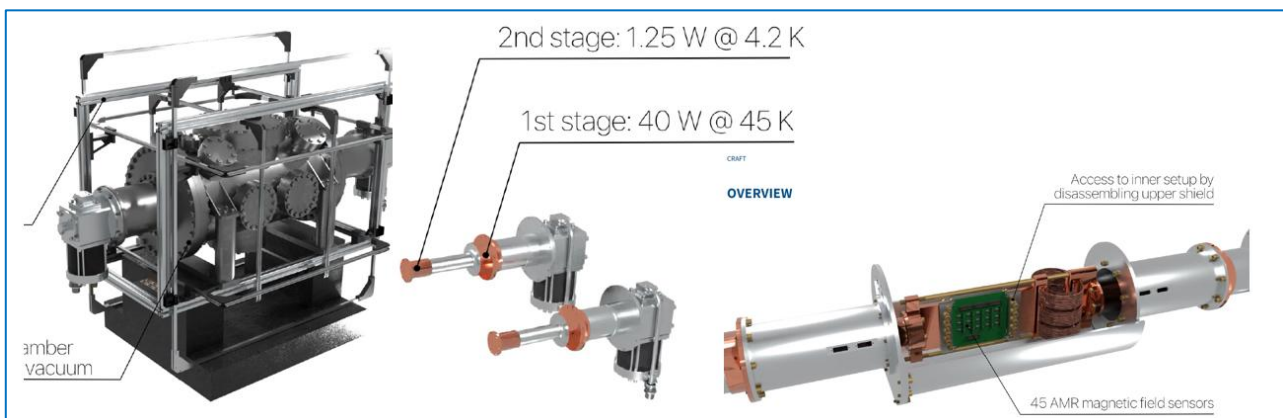


Fig. 8: CRAFT at HZB.

Labs with activities in that domain

Table 4. List of labs with characterization activities.

labs	Standard surface characterisation techniques	Advanced surface characterisation techniques	Standard cryogenic facilities	Advanced cryogenic facilities
SRF labs EU	CEA, CERN, Darmstadt TU, DESY, INFN Legnaro, HZB, STFC/DL/CI	HZB, DESY, CERN, STFC/DL/CI, Uni Roma	CEA, CERN, INFN, DESY, STFC/RAL	CEA, CERN, HZB, Hamburg U, STFC/DL/CI
SRF labs outside EU	FNAL, KEK, IHEP, IMPCAS, Triumpf, Peking U	KEK	JLab	
Non SRF EU	IJCLab, HZDR U Wuppertal (SEY, laser polishing, FESEM) Siegen U, RTU, Temple U	HZDR, U Victoria	IEE-SAS (PPMS)	
Non SRF outside EU		FSU; U Maryland	ODU, FSU	

Main challenges

Today, after decades of R&D, it is still impossible to predict the surface resistance R_s of a material (from theory or experimental/operational experience) just by looking at its classical characterization chart. The final proof of achievement is still the RF test of a full RF cavity prototype. Because of the slow turnover, it makes the development of new materials very difficult. Intermediate measurements have been developed to counterbalance this issue.

Limitation in accelerating field

- The limitation in accelerating field is related to the transition from Meissner state to the mixed state. DC magnetization is a fast way to measure it, but in a geometry of very different from the cavity operation. It can be used for fast screening but needs to be comforted with other techniques like 3rd harmonic or full magnetic field penetration set-ups.

Limitation in Quality factor

- The limitation in Q_0 is related to surface resistance $R_s = R_{BCS} + R_0$. R_{BCS} can be predicted by theory but needs to be reassessed for complex structures like multilayers (Topic 9). The residual resistance R_0 cannot be predicted by theory and needs to be experimentally measured. Two tendencies appear for the evaluation of R_s with a fast turnover, before going to full prototype testing:
 - “sample (or testing) cavities”, e.g. QPR (CERN [61], HZB [62, 63], Uni Hamburg [64], Jlab [65]...), choke cavities (STFC/CI) [66], split cavities (STFC/CI) [33], with limited accelerating fields.
 - Very low field 1.3 GHz cavity prototype testing (HZB, STFC).

Managing flux trapping

- Flux trapping contributes to the non-BCS part of the surface resistance and occurs during the phase transition upon cooldown. The amount of trapped flux is dependent on the density of pinning centres, the ambient magnetic field, thermocurrents or the intrinsic viscosity of the flux line compared to the cooldown-speed. In order to balance these factors, a thorough understanding of the expulsion efficiency (a), or even beyond that the expulsion dynamics (b) is desired. Two dedicated devices have been developed and are in operation:
 - Flux lens at CERN
 - CRAFT at HZB (see Fig. 7)

Conclusion/recommendations

Multiple and complementary characterization techniques are mandatory to progress in the superconducting TF developments. During the past European project (EuCard, ARIES...), most of the European labs have started to acquire standard characterization, develop collaborations to access more advanced techniques and develop their own equipment when necessary. In some case, subcontracting to another lab is a way to access expensive techniques.

Such dedicated equipment requires continuous technical support and that the knowledge and expertise is conserved over time. Resources (manpower, funds) need to be englobed in the projects.

2.8 CAVITIES PREPARATION AND RF TESTING

Context

Most SRF labs are engaged in large projects:

- Project have often a priority over the R&D prototype testing
- R&D teams are often not in the same groups as clean room technicians and RF test manpower. Budget for helium and said manpower needs to be foreseen.

Labs with activities in that domain

Table 5. List of labs with RF characterization activities in Europe.

Dedicated R&D SRF Testing	No RF testing	RF testing in competition with other activities
HZB (for samples)	U Siegen	CEA
STFC/DL (samples and cavities at low power)	HZDR	DESY (and U Hamburg) STFC/DL (high power)
CERN (2029)		CERN (before 2029)
INFN		IJCLab
		HZB (for cavities)

A similar situation applies worldwide

Main challenges

- Obtaining enough allotted time to test prototypes with a reasonable time scale to evaluate corrective actions.
- Having enough RF evaluation to correlate classical characterization chart and RF results

Figure 9 show a flowchart for a typical workflow for evaluating the superconducting TF coated RF cavity prototypes.

Thin film cavity test stands

- For CERN, a facility with cleanrooms, chemical surface preparation, deposition, assembly and RF testing, available in 2029
- STFC/DL/CI is building two new facilities dedicated to research cavity testing: a low-power RF test based on a cryocooler in a new CI bunker and a high-power RF tests (both available from early 2025)
- HZB has a facility for both, bulk and TF cavity testing at temperatures down to $T = 1.5$ K, and 80 W cooling power available. It dedicated for R&D, main limitations are LHe cost, manpower and maintenance.
- HZB has set up a cryocooler based sample test stand exclusively dedicated to superconducting TF research. It could possibly be upgraded to cavity testing. It is easy to use, independent of helium infrastructure, fast turn-around, but has power and size limitation.

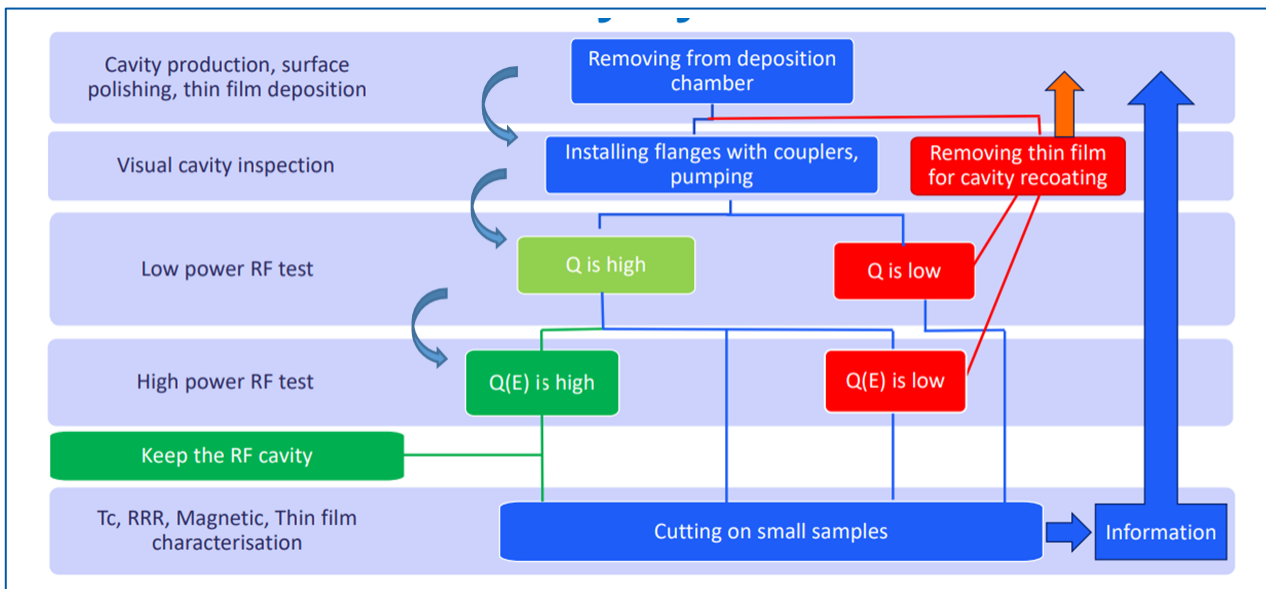


Fig. 9. Typical workflow for evaluating the superconducting TF coated cavity prototypes.

Thin film cavity test program

- Except for CERN and STFC most of the labs do not have the resources to build a new facility.
- Enough budget for clean assembly + RF testing (helium, manpower) must be included in all R&D developments, including subcontracting when necessary.

Conclusion/recommendations

- 1) Go to low-power, cryocooler based test stands specifically dedicated to thin-films research for the screening of prototypes
- 2) Resources for full RF testing in the R&D projects: for allotted time, He, technical manpower in clean room and RF stands must be included in superconducting TF development projects.
- 3) If no R&D testing facilities exist in the R&D group, then....
 - a) Address the RF group if locally available
 - b) Go for subcontracting (other labs, if not locally equipped)
- 4) Possibility of having a shared user facility must be considered/financed

2.9 THEORY

Context

- Only KEK ODU and Cornell have developed dedicated SRF theory activity, in particular, for SIS structures, non-linear BCS resistance and losses due to trapped vortices at high field [40, 41, 67-72].
- Punctually there exist limited collaborations of universities with labs specialized in superconductivity (e.g. Comenius U. (SL) on doping behaviour), or local development (e.g. IJCLab work on pnictides SIS).
- Results are shared in the international community (strong collaborative international network)
- It is not a high priority, but nevertheless very useful.

Labs with activities in that domain

In Europe: Comenius U. (SL), HZB (expulsion of magnetic flux), IJCLab (Pnictides); CERN, INFN, CEA and coll. (Q-slope)

Outside Europe: ODU, KEK, FNAL, Cornell...

Main challenges

For TF SRF it is required to develop theory to explain the behaviour of low to medium T_c superconductors in the Meissner state, and the non-linear surface resistance at high RF field. Most of theoretical development in superconductivity is dedicated to high κ superconductors at high DC field, in the mixed state, aiming at magnet development. These findings are not immediately applicable to superconductors in SRF cavities. Unfortunately, SRF physics has been very incompletely explored.

Theoretical developments needed

- Field dependence of BCS surface resistance, R_{BCS} , at high field (non-linear regime)
- High field non-equilibrium kinetics of quasiparticles

- Influence of magnetic and non-magnetic impurities
- SIS structure optimization, comparison with S-S', S-I-N structures, vortex behaviour at interfaces
- Sensitivity to trapped flux, Flux trapping efficiency
- Mechanisms of flux trapping during SC phase transition, flux expulsion
- Developments on proximity effects and surface nano-structuring
- Q-slope in superconducting TF

DOS Survey of materials

- Helps in the choice of materials
- Understanding how theoretical “identity” values (ξ , λ , κ , Δ) are affected in realistic material
- Electronic densities of states (DOS) are not really known in practical materials. So far, there is only one PCT (point contact tunnelling) microscope worldwide able to map DOS on realistic samples (with their native oxide) and able to correlate superconducting behaviour and observable defects (Topic 7). Theory is needed to explain the observed degradation.

Conclusion/recommendations

Several theory groups are exploring specific aspects of RF superconductivity. The worldwide community is sufficiently knitted so that superconducting TF development can benefit from their activity through collaborations. These collaborations are an important support for R&D activities and must be sustained / encouraged. (manpower for PhD, post docs).

2.10 INDUSTRIALIZATION

Context

The ultimate aim is to have copper cavities coated with superconducting thin films available commercially. There are the following challenges:

- Very difficult to get an industry involved as long as still in the R&D phase
- So far, in EU only the 1.3 and 6 GHz seamless copper cavity fabrication has been industrialized (but just fabrication, no flange welding).
- The more processes (e.g.: surface polishing, thin film coating, etc.) are included in the cavity production, the fewer companies are available.
- Even procurement in small number of pieces poses a problem: e.g. QPR sample, deposition targets, there two option available:
 - To develop and manufacture parts internally
 - To coordinate and proceed with joint orders when the number of parts required for a few labs is larger and interesting for industry

Labs with activities in that domain

In Europe:

- INFN/Picoli: Seamless spinning;
- INFN: PEP;
- CERN

Outside Europe:

- IHEP
- Jlab, FNAL, Cornell, PKU: compact cryomodule development

Main challenges

Companies are not interested at the moment in Europe. An industrial market has been identified (compact accelerators), but the final product is missing. Industry would be interested in a collaboration development only if externally financed.

Conclusion/recommendations

- 1) For the cavity fabrication (without surface treatment) consider interested small mechanical company (spinning, hydroforming, bulk machining...)
- 2) To achieve the complete production cycle, a financed project like a complete Nb₃Sn cryomodule fabrication, could help to draw the main cavities fabrication company in the loop (Zanon, RI...)
- 3) During the development phase, to prepare joint orders for limited series parts (e.g. QPR samples)

3 Main recommendations

Based on the advances of the past decades, Topics ② to ⑤ are at the eve of depositing the first prototypes (Topic ① has already reach this stage earlier). Today the bottlenecks for superconducting TF development are mainly related to the enabling key activities. All Topics from ⑥ to ⑩ are of high importance and must be carefully accounted when allocating financial and human resources for future projects.

3.1 COMMON ISSUES FOR ALL DEVELOPMENTS

- Today the bottlenecks for superconducting TF development are mostly related to Topics ⑥ (copper/substrate fabrication) and ⑧ (clean room assembly and RF testing).
 - For Topic ⑥, there is no industry that is ready to produce the seamless copper cavities to specifications. There are some uncertainties regarding copper/substrate fabrication. This is partly due to post-covid procurement difficulties and the lack of a fully developed industrial process.
 - For Topic ⑧, the main problem is availability of RF testing facility timeslot for testing novel (Superconducting TF coated) cavity prototypes. This problem exists even for R&D groups that belong to SRF labs, as such tests are in competition with other projects. Allotted time and/or dedicated facilities must be put in place, which means that the external resources for the testing (manpower, clean room access, helium...) must be integrated in the R&D project, and well supported at the laboratory director's level.
- Another critical bottleneck is availability of deposition of targets of SC materials for Topics ② and ③. Targets might be available in planar form and limited size choice (ex: 2'' target), but there are no targets on a market in a form of tubes or roads required for cavity deposition. Thus, a significant effort is required for in-house development of target deposition.

- For IFAST WP9 collaboration, it was agreed to focus on a single cell 1.3 GHz prototype for easiness of handling, and because most SRF labs are equipped for SRF test at this frequency. Moreover, at this frequency, the two components of the surface resistance, R_{BCS} and R_0 , are of the same order of magnitude, so it makes it easier to probe both aspects. Working on cavities with lower frequencies would ease considerably the development of deposition system (for instance, wider space can accommodate standard, commercial deposition target). It would also open to wider application fields, such as in SNS, ESS, FRIB, PIP-II or CSNS, which all operate well below 1.3 GHz. It would present several drawbacks:
 - Necessity to develop larger systems (deposition facilities, but also handling tools), with an enhancement of cost due to volume.
 - Not all labs are equipped with lower frequency testing devices, and they are many different frequencies available. A choice of common frequency(-ies) must be made inside the STF community (see Table 6).
- Interlayers need to be developed for several reasons:
 - Strain of the crystalline lattice heavily influences the superconductor T_c , in particular strain due to lattice mismatch between the superconductor and the Cu substrate. A well-chosen intermediate layer could release the strain.
 - In case of deposition at high temperature, Cu tends to diffuse toward the surface, a well-chosen interlayer could act like a diffusion barrier.
 - Two different metals in contact submitted to a temperature gradient (e.g. during cooling) can generate thermal currents which cause flux trapping during the superconductivity transition. Cool-down procedures need to be developed to minimize this aspect, but here again, interlayers could play a role.
- Continuous funding for student, post-doc and technical support is needed.
- Whatever the type of STF is developed, an intermediate step is to deposit onto bulk Nb cavities, so that one can focus on issues inherently related to the deposition process without being influenced by the copper substrate behaviour.

Strong collaboration exists within the international superconducting TF community on these topics, even when researchers work on different types of superconducting TF; this should be actively pursued. Including key activities in the superconducting TF development budget would increase funding toward a more realistic situation, leading to greater chances of progress.

Most developments have not yet reached a Technology Readiness Level (TRL) that allows industrial companies to project themselves into developments (i.e. TRL-8).

The support of the European community (or the ensemble of concerned lab) for a limited number of targeted projects in addition to the going-on improvement of R&D topics could trigger some industrial and new collaborators participation, for example:

- The construction of a compact accelerator based on a (Nb₃Sn coated) 1-cell cavity could be an interesting target.

- Another example would be to launch a special MgB₂ program. Today this material looks very promising, but none of the IFAST WP9 participant has the resource to pursue this topic without abandoning other higher priorities activities. With enough resources to follow up the project, and open new collaboration with labs specialized in this material, its feasibility could be explored for SRF application.

Table 6. List of institutions involved in TF SRF activities in Europe.

Institution	Frequencies [MHz]	Application field
CEA	88 - 1300 (cavity test), <i>quasi continuous spectrum</i>	HEP (ILC, PIP2, PERLE) also NP(Sarf, ESS, IFMIF) Light Sources (Soleil, XFEL, LCLS2) + generic R&D
CERN	100 (Isolde) 400 (LHC) 800 (FCC) 600 (split cavity) 1300 †	HEP
Hamburg U. + DESY	424, 704, 852, 1300, 3900 QPR†: 400, 800, 1200	Mainly light source + generic R&D
HZB	QPR†: 400, 800, 1200 TM020†: 4800 RaSTA	Mainly light source + generic R&D
HZDR	NA	
INFN LNL	80-160, 1300, 1500, 6000 †	HEP, NP + generic R&D
IEE-SAS	NA	NA
RTU	NA	NA
STFC/CI	1300 and 6000 (cavity test) 1300 and 6000 (split cavity) 7800 (†choke cavity)	Yes (UK-XFEL, ISIS-II, FCC, ILC, etc.)
U Siegen	NA	NA
IJClab	704, 352, 325, 88	HEP, ERL + generic R&D

† Specific for thin film RF measurement

3.2 DETAILED PROGRAMME

The program detailed in Table 6 below has been established after consulting 11 European labs:

- CEA (Commissariat à l'énergie atomique) - France
- CERN (European Organization for Nuclear Research) - Switzerland
- HUH / DESY (Germany)
- HZB (Helmholtz-Zentrum Berlin) - Germany
- HZDR (Helmholtz-Zentrum Dresden-Rossendorf) - Germany
- IEE-SAS (Institute of Electrical Engineering Slovak Academy of Sciences) - Slovakia
- IJCLAB (France)
- INFN-LNL (Istituto Nazionale Fisica Nucleare - Laboratori Nazionali di Legnaro) - Italy
- RTU (Riga Technical University) - Latvia
- STFC / CI (Science and Technology Facilities Council and Cockcroft Institute) - UK
- USI (Universität Siegen) - Germany

The figures have been estimated starting from the full budget established by the labs and distributed in function of their activities. This division is a little artificial, but it was our purpose to better assess the importance of key activities in our developments.

For each topic an R&D program is detailed by priority order, a global budget and manpower are recommended, and additional targeted programs and investments are proposed (**in red** in Table 6).

Table 6. Detailed programme for each topic.

Topic	Manpower per year	Resources per year	Large investments	Comment
<p>1 Nb on Cu</p> <ol style="list-style-type: none"> 1. Substrate issues: see Topic 6 (Cu cavity production) 2. Samples, then 1.3 GHz prototypes <ol style="list-style-type: none"> i. Role of interlayers (thermo-current, lattice adaptation, diffusion barrier) (topics 5 (surface functionalisation5, surface science and characterization7, theory9)) ii. Ongoing optimization of deposition parameters (topics 7, 9) iii. Q-slope mitigation with bulk-like RF performance as a goal (topics 7, 9) 3. RF testing: see Topic 8 (prototype preparation and RF testing) 4. Going to lower frequencies <ol style="list-style-type: none"> i. Investment for larger deposition set-ups ii. Other lab equipment (tooling, testing...see topics 6 and 8) 5. Transfer to industry (see Topic 6 and 10) 	6 FTE + 4 PhD	250 k€	500 k€	Larger deposition set-up for multicells of lower frequency

Topic	Manpower per year	Resources per year	Large investments	Comment
<p>2 Nb₃Sn on Cu and Nb</p> <ol style="list-style-type: none"> 1. Substrate issues: see Topic 6 2. Samples, then 1.3 GHz prototypes <ol style="list-style-type: none"> i. Role of interlayers (thermo-current, lattice adaptation, diffusion barrier) (topics 5, 7, 9) ii. Ongoing optimization of deposition parameters (topics 7, 9). iii. Q-slope mitigation with bulk-like RF performance as a goal. (topics, 7, 9) iv. RF testing (8) 3. Going to lower frequencies <ol style="list-style-type: none"> i. Investment for larger deposition set-ups ii. Other lab equipment (tooling, testing...see topics 6 and 8) 4. Developing deposition targets 5. Going to lower frequencies <ol style="list-style-type: none"> i. Investment for larger deposition set-ups ii. Other lab equipment (tooling, testing...see topics 6 and 8) 6. Developing a 1-cavity cryomodule with industrial partners <ol style="list-style-type: none"> i. Find a full project funding ii. Build an RF team for the design, specifications iii. Find interested companies (they will if it is financed) iv. Deposition done by the “Thin film” teams 	<p>7FTE + 4 PhD</p> <p>10 FTE</p>	<p>210 k€</p> <p>2 M€</p>	<p>500 k€</p> <p>2 M€</p>	<p>Larger deposition set-up for multicells of lower frequency</p>

Topic	Manpower per year	Resources per year	Large investments	Comment
<p>3 Other Superconductors on Cu and Nb</p> <ol style="list-style-type: none"> 1. Substrate issues: see topic 6 2. Alternatives to Nb₃Sn in case of showstopper <ol style="list-style-type: none"> (i) NbTiN : go from samples to cavities (ii) MgB₂: see below (iii) Other SC families: R&D survey (7, 9). 3. Ongoing optimization of deposition parameters 4. Role of interlayers 5. Prototype deposition 1.3 GHz, then lower frequency 6. Develop a European MgB₂ sector <ol style="list-style-type: none"> (i) Complete experimented SRF TF teams for the management of the project (ii) Forge collaborations with teams specialized in this material for other applications (e.g. Josephson Junctions) 	<p>4.5 FTE + 3 PhD</p> <p>5 FTE</p>	<p>235 k€</p>	<p>500 k€</p> <p>300 k€</p>	<p>Larger deposition set-up for multicells of lower frequency</p>
<p>4 Multilayers, SIS structures</p> <ol style="list-style-type: none"> 1. Field enhancement demonstration on a cavity compared to single (thick) layers 2. Access to substrate cavities (Nb and Cu 6) and RF testing 8 3. Manpower and financial resource for R&D <ol style="list-style-type: none"> (i) NbTiN : optimize 1.3 GHz prototypes, 1st on Nb cavities, then on Cu cavities (ii) Dirty Nb /dielectric/bulk Nb as a demonstration (1.3 GHz) (iii) Nb₃Sn, MgB₂: optimization on samples, find precursors for ALD (iv) Other SC families: R&D survey (7, 9). 4. Prototype deposition 1.3 GHz, then lower frequency 5. Upgrade of existing cavities 	<p>4.5 FTE + 3 PhD</p>	<p>235 k€</p>	<p>500 k€</p>	<p>Larger deposition set-up for multicells of lower frequency</p> <p>No large investment needed</p>

Topic	Manpower per year	Resources per year	Large investments	Comment
<p>5 Surface functionalization</p> <p>1- Interlayers for thin films cavities (topics 5, 7, 9)</p> <ul style="list-style-type: none"> (i) thermo-current mitigation, (ii) lattice adaptation, (iii) diffusion barrier, capping barriers (iv) thermal management <p>2-Synergies, application to other fields</p> <ul style="list-style-type: none"> (i) Multipactor (high field devices) (ii) low field Q0 (Qbits) (iii) doping with ALD 	5.5 FTE + 3 PhD	365 k€	500 k€	Large furnace for bigger cavities Would work also for Topic 1 to 4 (e.g. interlayers)
<p>6 Copper cavities production (high priority for 1 to 4)</p> <p>1-Cavity fabrication with asserted or innovating technologies (see table 2, §2.6)</p> <ul style="list-style-type: none"> (i) Industrialization for TRL 7 (see 10) (ii) Improve TRL for other techniques, (iii) Put effort on dual structures (see below) <p>2-Copper surface treatments to provide deposition ready surfaces</p> <ul style="list-style-type: none"> (i) Industrialization for TRL >9 (see 10) (ii) Improve TRL for other techniques <p>3-Dual structures</p> <ul style="list-style-type: none"> (i) External mechanical reinforcement (spray coating, external lattice...) (ii) Integrated cooling circuits. 	4 FTE + 2 PhD 3 FTE	192	300k€	Collaboration with mechanical labs

Topic	Manpower per year	Resources per year	Large investments	Comment
<p>7 Surface science and characterization (high priority for 1 to 6)</p> <ol style="list-style-type: none"> 1. Standard surface characterization <ol style="list-style-type: none"> (i) In House equipment (ii) Subcontracting 2. Advanced Surface characterization <ol style="list-style-type: none"> (i) New Collaborations (ii) Supply (special samples, helium...) 3. Standard Cryogenic characterization <ol style="list-style-type: none"> (i) In House equipment (ii) Subcontracting 4. Advanced cryogenic characterization (specific In house developments) <ol style="list-style-type: none"> (i) New developments (ii) Supply (special samples, helium...) 5. Large investment <ol style="list-style-type: none"> (i) Additional PCT microscope (important for 9 too) (ii) Provision for other characterization tools/experiments 	<p>7 FTE + 5 PhD</p>	<p>350 k€</p>	<p>200-400 k€ 200-400 k€</p>	<p>Only 1 worldwide. <i>Other Tunnel microscopes must remove surface oxide</i></p>

Topic	Manpower per year	Resources per year	Large investments	Comment
<p>8 Cavities preparation and RF testing (high priority for 1 to 5)</p> <ol style="list-style-type: none"> 1. Testing on existing infrastructures <ol style="list-style-type: none"> (i) Reallocating budget for the cleanroom/rf testing group (ii) Subcontracting to another lab 2. Developing dedicated cryostats based on cryocoolers <ol style="list-style-type: none"> (i) Set-ups (ii) Manpower support (Clean room + RF test) 3. Mutualising infrastructures? <ol style="list-style-type: none"> (i) Cf CERN lab SM18 available in 2029 (ii) Duplicate installation, provide access for collaborators? 	<p>5 FTE + 2 PhD</p>	<p>300 k€</p>	<p>400 k€</p>	<p>Developing low power, cryocooler based special thin film testing stands</p>
<p>9 Theory</p> <ol style="list-style-type: none"> 1. Q-slope in superconducting TF 2. Flux trapping <ol style="list-style-type: none"> (i) Sensitivity to trapped flux, Flux trapping efficiency (ii) Mechanisms of flux trapping during SC phase transition, flux expulsion 3. High field behaviour <ol style="list-style-type: none"> (i) Field dependence of BCS surface resistance (non-linear regime) (ii) High field non-equilibrium kinetics of quasiparticles (iii) Influence of magnetic and non-magnetic impurities (iv) SIS structure optimization, comparison with S-S', S-I-N structures, vortex behaviour at interfaces (v) Developments on proximity effects and surface nanostructuring 4. DOS survey of materials <ol style="list-style-type: none"> (i) Material exploration: how (ξ, λ, κ, Δ) are affected in realistic material (see 7) (ii) Help to the choice of materials 	<p>3 FTE + 1 PhD</p>	<p>123 k€</p>		<p>Some internal R&D, Most fundamental done by collaboration with theory groups outside the thin film community</p>

topic	Manpower	Resources	Large investment	Comment
<p>10 Industrialization</p> <ol style="list-style-type: none"> 1. Copper cavities <ol style="list-style-type: none"> (i) Find a company to transfer the technologies with high enough TRL (ii) Try to build a group to integrate fabrication, flange welding, and finally surface treatment 2. “special topic”: whole cryomodule development <ol style="list-style-type: none"> i) RF design ii) Cavity fabrication iii) Film deposition iv) Assembly + testing 	<p>1 FTE</p>	<p>30 k€</p>		<p>So far, only one lab has quantified this activity.</p> <p>See topic 2</p>

4 Future plans / Conclusion / relation to other IFAST work

In Europe, a dedicated research community actively engaged in international collaborations focuses on developing thin film for Superconducting Radio Frequency accelerator technology. This Report provides an overview of present state and future R&D directions for TF SRF developments, based on a consensus reached among the labs involved.

TF SRF technology holds immense promise for revolutionizing particle accelerator science. It has wide-ranging applications, from high-energy colliders and high-intensity hadron/neutron sources to light sources, cavity detectors, and even quantum computing. The advent of 4 K operability and progress in cryocooler technology are now opening doors to compact accelerators with societal benefits like wastewater treatment, food and medical sterilization, or advanced manufacturing.

In recent years, significant effort has been dedicated to optimize TF deposition process on samples. Work on the first prototypes is now underway, but substantial investment is required to bridge the gap between research and practical applications.

By fostering collaborations, encouraging industrial involvement, and providing adequate resources, the global community can unlock the transformative potential of SRF technology and bring its numerous benefits to society.

Future plans.

This Report in a present stage is written by IFAST WP leaders. In the next stage it should be distributed within TF SRF community for comments, suggestions and feedback.

After the completion of second round of consultation, this roadmap will be published to be available to a wider scientific community. Its purpose is to provide indication for the funding of future SRF R&D projects, not only aimed at high energy physics, which was our initial field of application, but also to a larger field of applications.

5 Annexes

Glossary

Acronym	Definition
EB welding	Electron Beam welding
EP	Electro-Polishing
PEP	Plasma Electro-Polishing
TF	Thin Film
SRF	Superconducting Radio Frequency (cavity)
SIS	Superconductor – Insulator – Superconductor multilayer (nm scale)
SNS	Superconductor – Normal metal – Superconductor
SS	Superconductor – Superconductor
SS'	Superconductor – Superconductor (different materials)
SUBU	Chemical polishing recipe for copper
Superconducting parameters	<p>Those parameters constitute the “identity card” of the material. They are affected by its quality.</p> <ul style="list-style-type: none"> • T_c • ξ • λ • κ • Δ
Flux trapping	In a defect less material, flux lines present in the material (e.g. earth magnetic field) are properly expelled from the material when it transits to Meissner state. In realistic material, some of these lines are retained by defects and will trigger losses when exposed to RF field
Type II Superconductors	All application SC are type II, which means they exhibit 2 superconducting states: below the first critical field H_{C1} , they are in the Meissner state, characterized by zero induction inside the material. This is the operational regime required for SRF cavities. Above H_{C1} (below H_{C2}), they transition to the mixed state, where all other SC applications operate.

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