Cristian **Pira**

innovate for Sustainable Accelerating Systems

WP3

Nb_3Sn on Cu films for 4.2K cavity operation

This project has received funding from the European Union's Horizon-INFRA-2023-TECH-01 under GA No 101131435 - iSAS

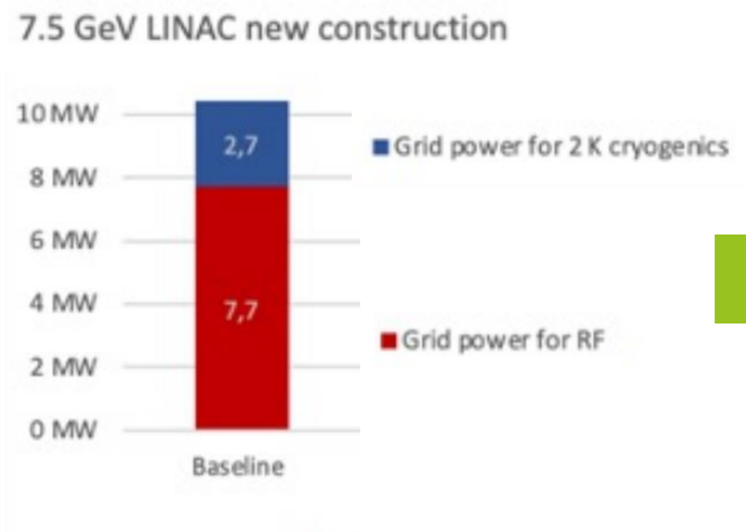
Kick-off meeting

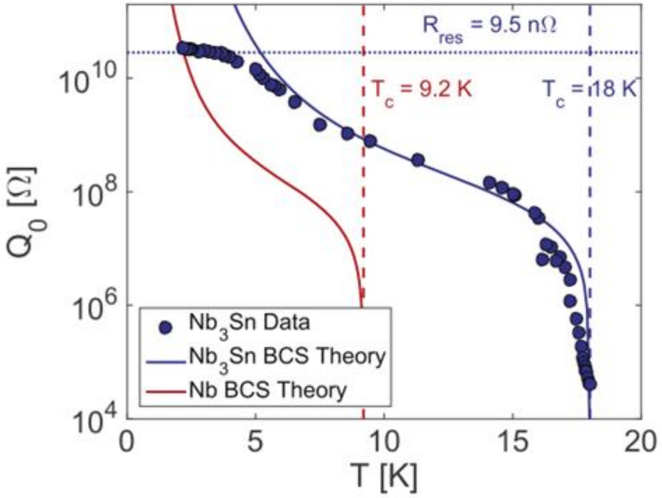
Paris, 15 April 2024

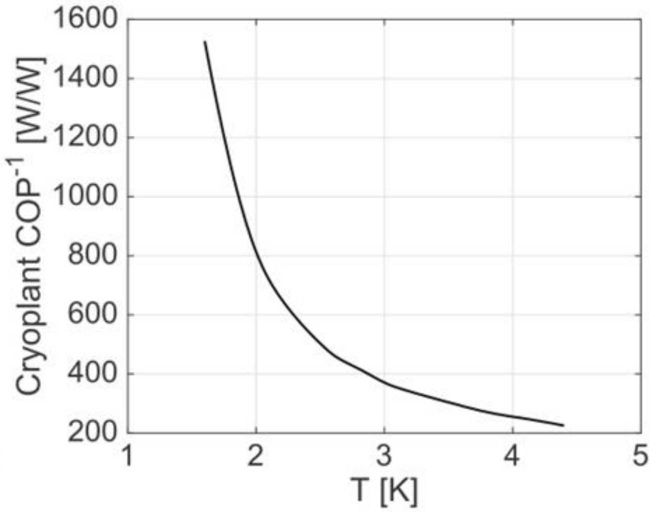
Goal of WP3

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

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







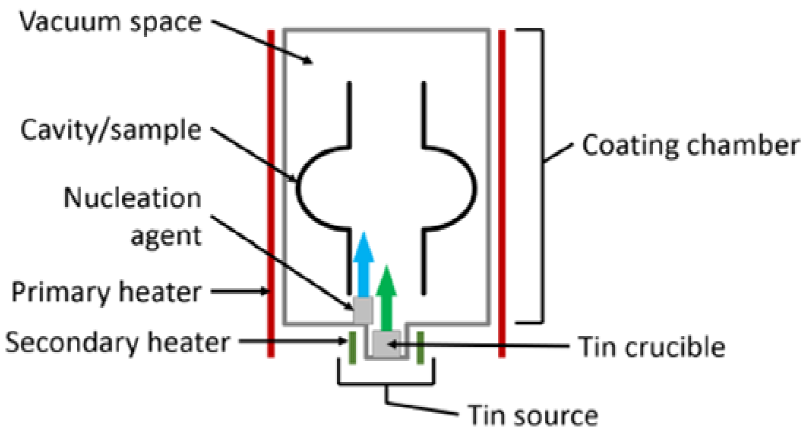
Move from bulk Nb @2K to Nb_3Sn @4.5 K

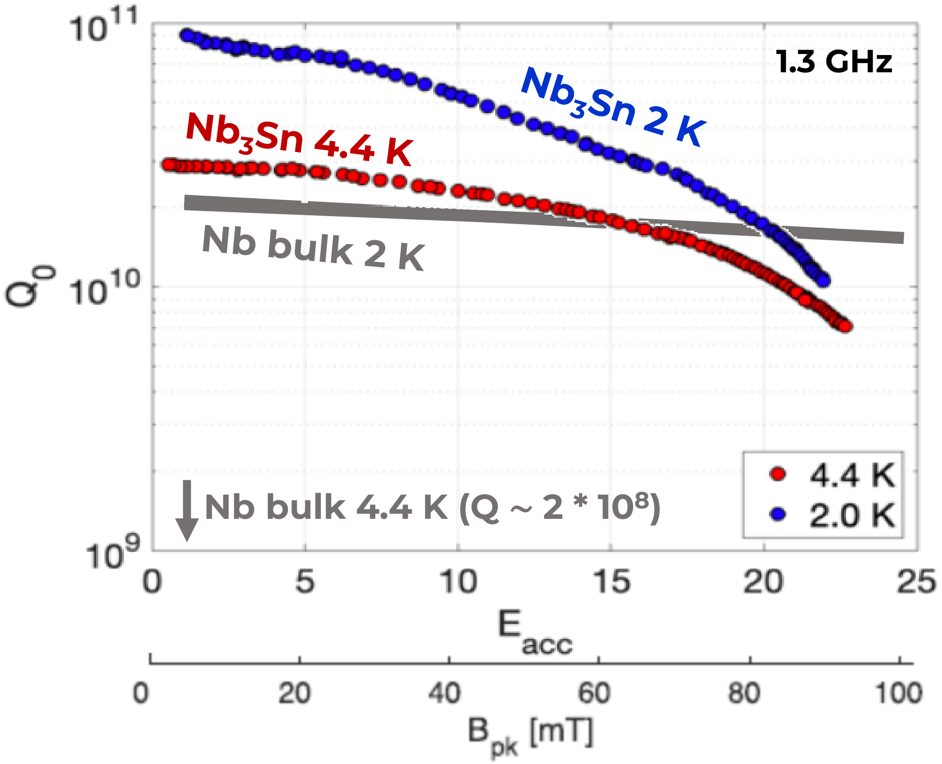
reduces cryogenic power by a factor of 3

Nb_3Sn state of the art

Vapor Tin Diffusion

Cornell, Fermilab, JLab, KEK





S. Posen, SRF 2019 proceedings (elaborated)

Technology limitation:

- **Reproducibility**
- **Substrate cost**

A different approach:
Nb_3Sn on Cu

Cu substrate as several advantages:

- **Cheaper** than Nb
- Higher **thermal conductivity**
- Higher **mechanical stability**
- **PVD technology** (Nb on Cu) already used for
  LEP, LHC, HIE-ISOLDE @ CERN
  ALPI @ INFN LNL
- **Interlayer** can be added to engineering the surface

Nb_3Sn on Cu: Multiple challenges

- A15 are Brittle materials
- Complicate Phase Diagram
- Low melting point substrate
- Substrate preparation
- Interface diffusion
- Target Production
- Coating Parameters
- Trapped Flux
- Tuning

Nb_3Sn on Cu: Multiple challenges

- A15 are Brittle materials
- Complicate Phase Diagram
- Low melting point substrate
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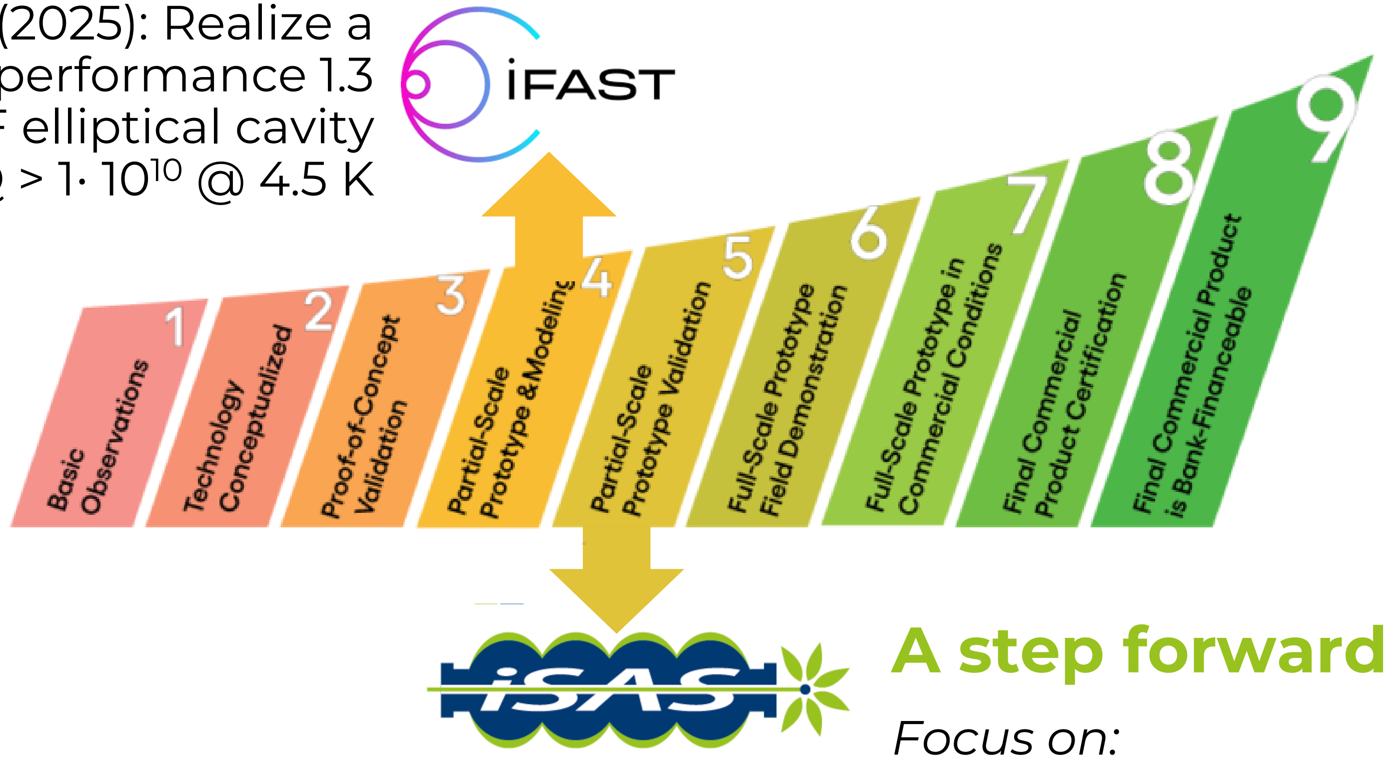
- **Interface diffusion**
- **Target Production**
- **Coating Parameters**
- **Trapped Flux**
- **Tuning**

I.FAST Sinergy

MAIN GOAL (2025): Realize a prototype of high performance 1.3 GHz thin film SRF elliptical cavity $Q > 1 \cdot 10^{10}$ @ 4.5 K



A step forward in TRL

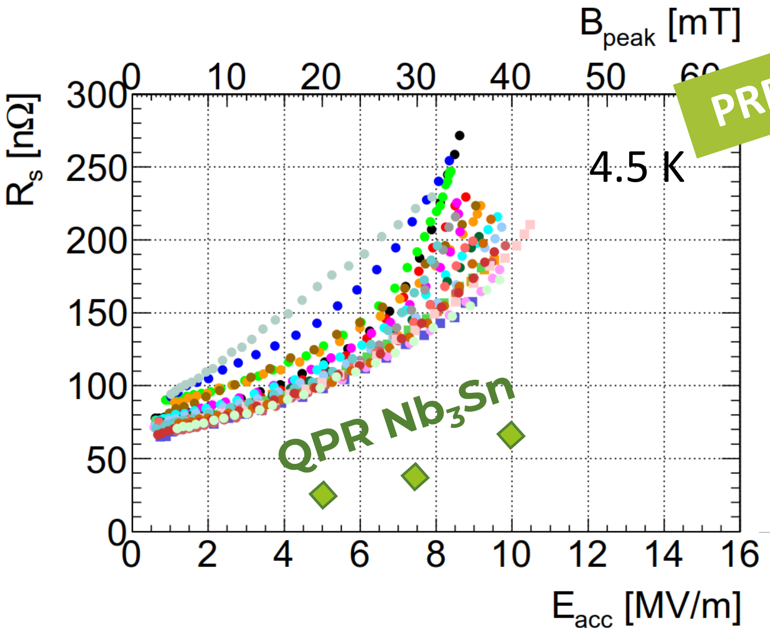
Focus on:

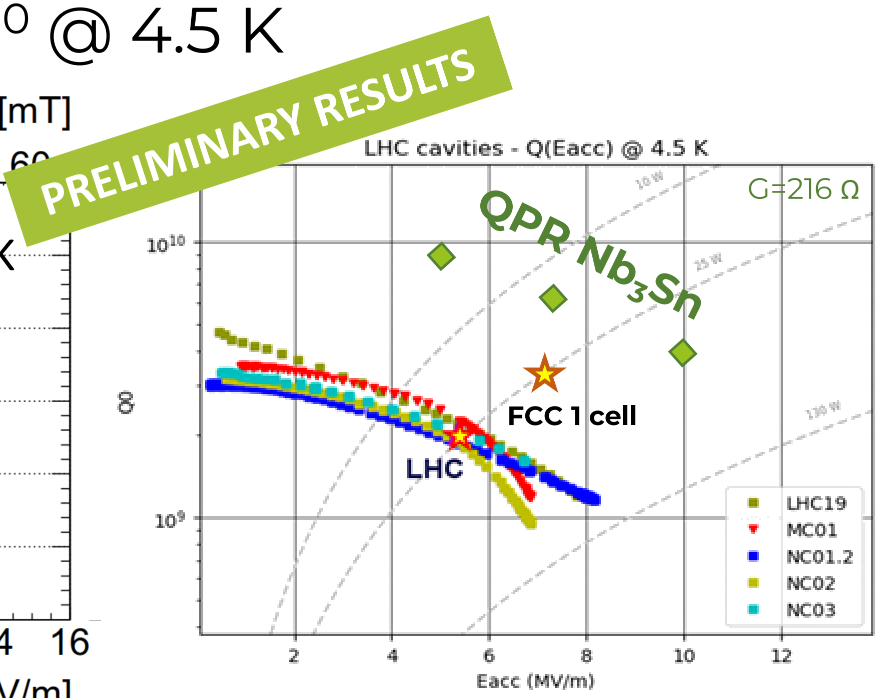
- minimizing **trapped flux**
- increasing coating mechanical strength (to allow **cavity tunability**)

I.FAST Sinergy

MAIN GOAL (2025): Realize a prototype of high performance 1.3 GHz thin film SRF elliptical cavity $Q > 1 \cdot 10^{10}$ @ 4.5 K

Last results (March 2024):





Data of LHC cavities from: W. Venturini, TTC Meeting 2018, Milan (Italy)

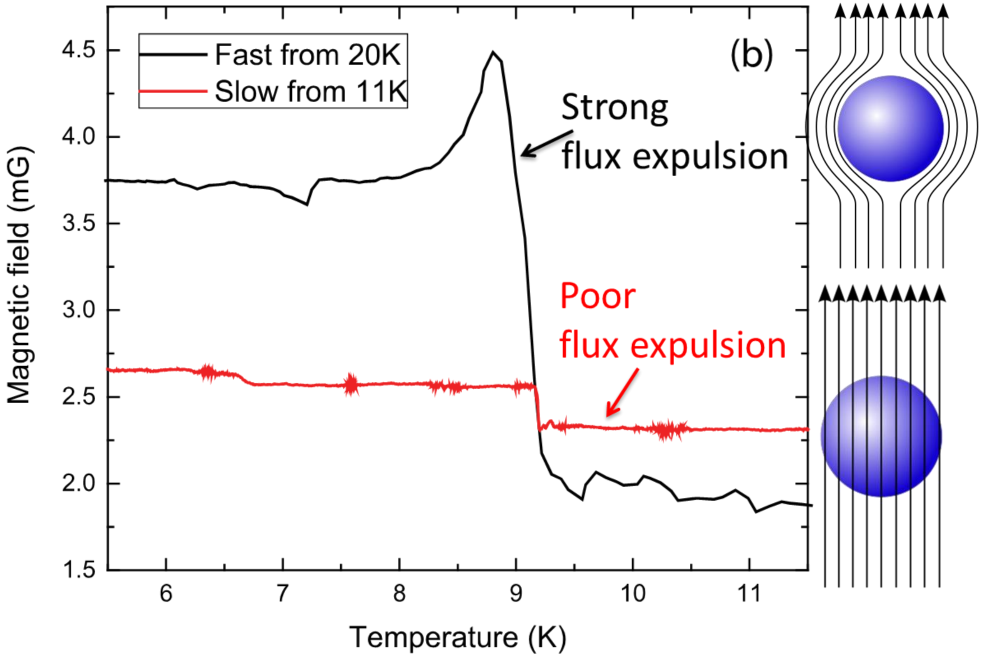
Rs of 23 nΩ @ 20 mT @ 4.5 K
Quench >70 mT @ 4.5 K

Equivalent to a Q of $9*10^9$ @5 MV/m @4.5 K
1 order of magnitude better than LHC!!!
Room for improvement

Trapped Flux

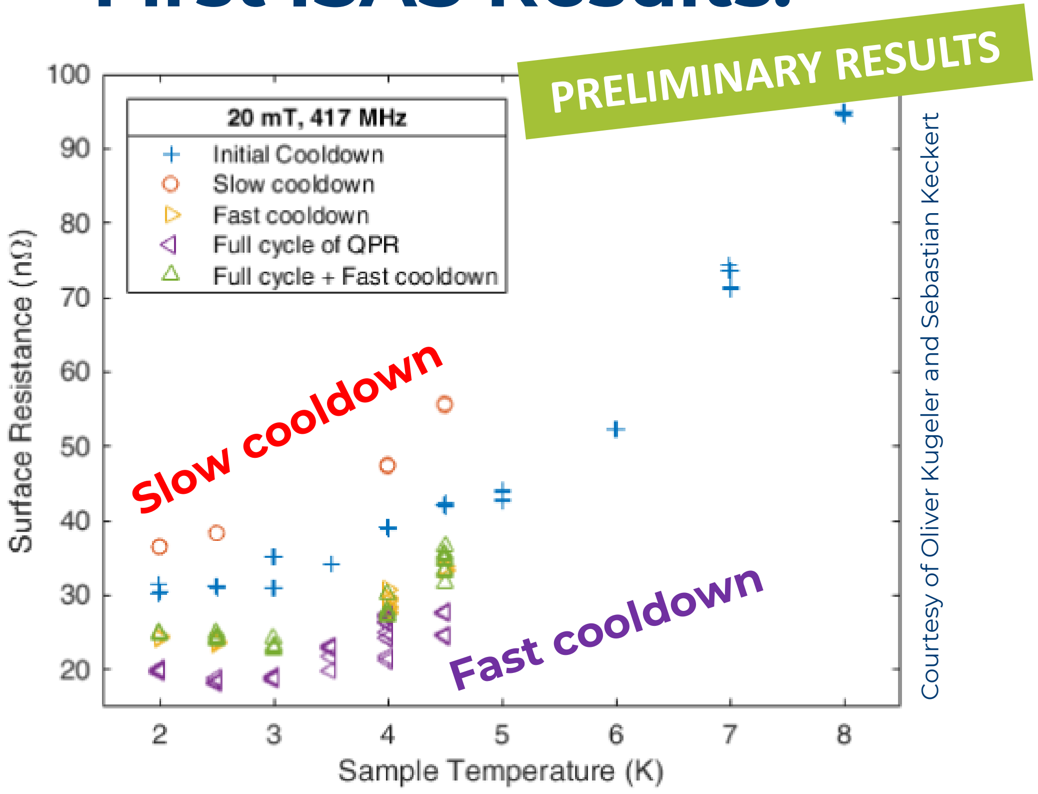
$$Q_0 \propto \frac{1}{R_{BCS} + R_{res} + \eta\, S\, B}$$

Fraction of Trapped Flux — Sensitivity



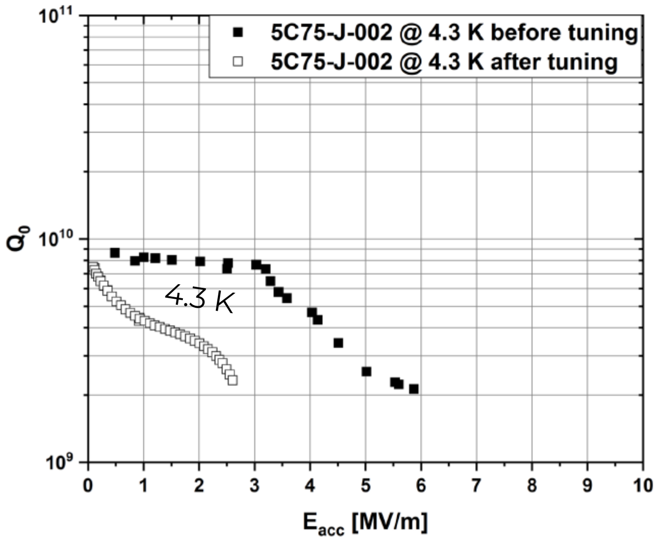
A. Romanenko, A. Grassellino, O. Melnychuk, D. A. Sergatskov, J. Appl. Phys. 115, 184903 (2014)

First ISAS Results:

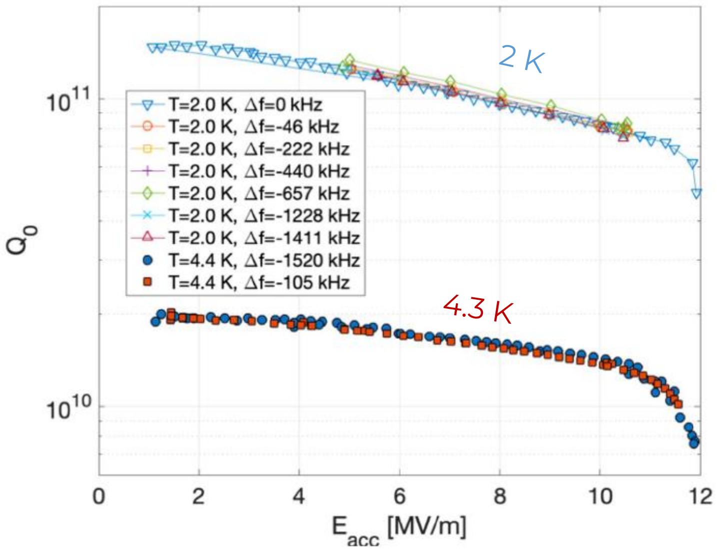


- **Nb_3Sn coating suffer flux trapping**
- **Cooldown procedure influence Rs**

Cavity Tunability



Strong performance degradation after **room temperature** tuning for 200 kHz



Little change in the coated cavity performance after tuning up to 1400 kHz at **cryogenic temperatures**

Nb_3Sn is extremally brittle

Eremeev, G. (2023). Tunability/robustness of Nb3Sn (No. FERMILAB-SLIDES-23-402-TD). Fermi National Accelerator Laboratory (FNAL), Batavia, IL (United States).

- **Vapor Tin Diffusion Nb_3Sn on Nb cavities can be tuned only at cryogenic T**
- **An interlayer in Nb_3Sn on Cu coatings can be added to enhance film mechanical stability and tunability**

WP3
Structure and facilities

WP3 Structure

Task 3.1: Coordination of R&D on SC cavities

Task 3.2: Flux trapping

Task 3.3: RF Tunability

Task 3.4: Adaptative layers

Task 3.5: Working Cavity @4.2 K

WP3 Tasks 3.1

Coordination of R&D on SC cavities – *M1-M48*

(**INFN**, CEA, HZB, UKRI) – *Cristian Pira*

Status:

***WP3 Meeting 01* - Task leaders Pre-Kick-Off remote meeting** on 21/02/2024
https://agenda.infn.it/event/40107/

***WP3 Meeting 02* - Kick-Off meeting in presence** (in synergy with I.FAST WP9) on 16/04/2024
https://indico.cern.ch/event/1357302/sessions/528505/#20240416

WP3 Tasks 3.2

Flux Trapping – *M1-M32*

(INFN, CEA, HZB, **UKRI**) – *Oleg Malyshev*

Objectives

- Explore new coating parameters for planar samples and small resonators to minimize flux trapping in SC A15 films.
- Upgrade the STFC choke cavity and the HZB QPR to support detailed flux trapping analyses of coated superconducting films.
- Characterize trapped flux, flux viscosity and the interaction with the RF field with SC A15 films in small resonators and samples with the upgraded systems.

Deliverable 3.2 Flux trapping Report on flux dynamics study in Nb3Sn on Cu samples - *HZB - Report M30*

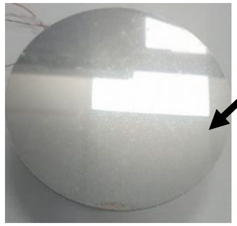
Milestone 3.1 Modification of choke cavity for flux trapping study - *Engineering report M12*

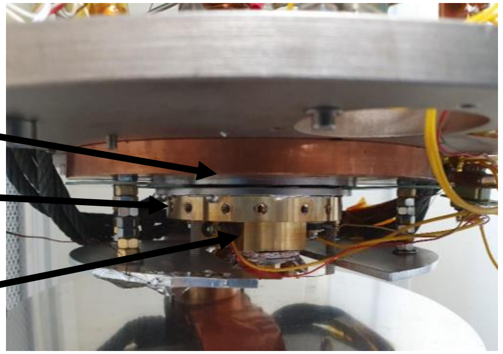
Courtesy of Oleg Malyshev

Facilities for Task 3.2

Choke Cavity Facility

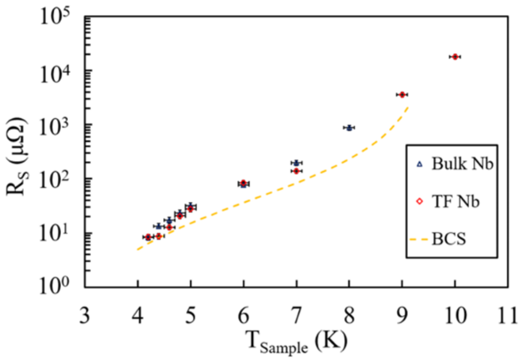
RS measurements with 7.8 GHz cavity

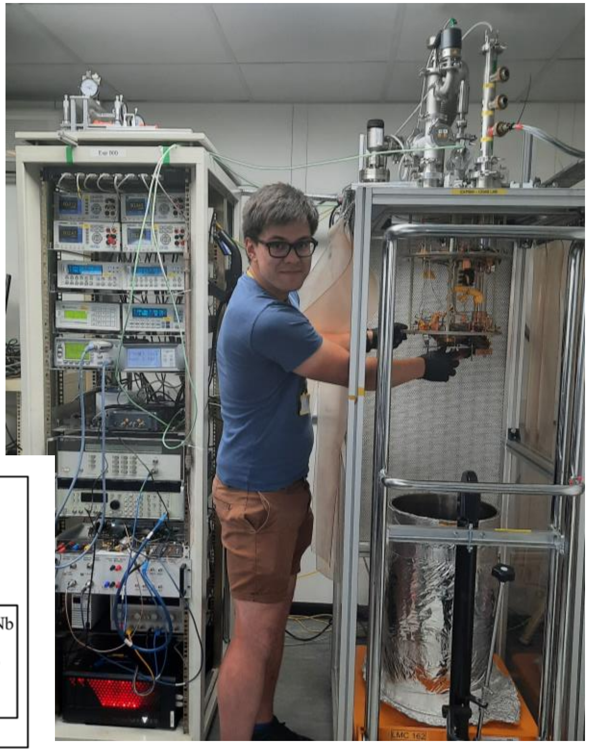


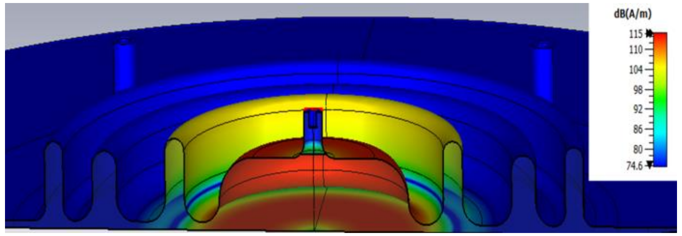


1 sample test $R_s(T)$ in 2 days

- **Two-part test cavity in LHe-free cryostat:**
  - Bulk Nb choke cavity
  - Planar disk - **90 - 130 mm** diameter, **1 – 10 mm** thickness
- **RF-DC compensation** → $R_S(T, B)$
- **VNA measurements** → Δf → $\Delta\lambda$
- **Parameters:**
  - f_0 = 7.8 GHz
  - $T_{Sample} \geq 4$ K
  - RF power up to 1 W
  - $B_{sample,\ pk} \leq 2.5$ mT







2 Hall probes will be added to measure residual magnetisation:

- **In a sample holder**
- **On the chocked cavity**

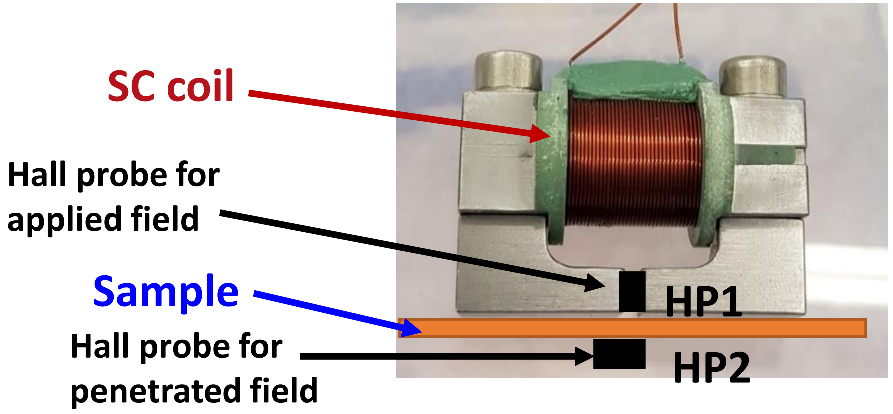
A possibility to add a coil for DC magnetic field (TBD)

Courtesy of Oleg Malyshev

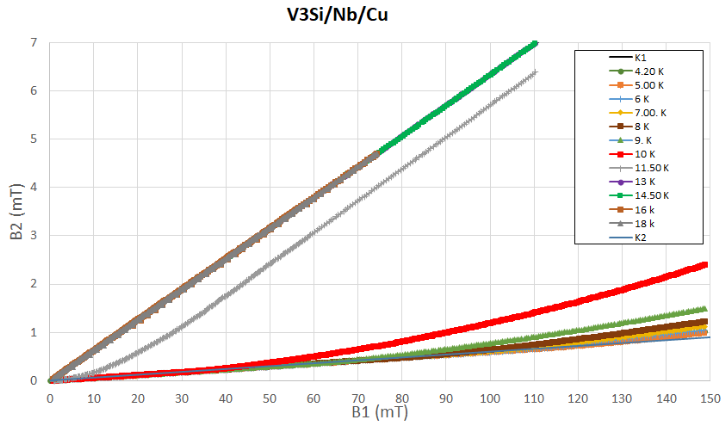
Science and Technology Facilities Council

Facilities for Task 3.2

Field Penetration Test



1 sample test for $B_{fp}(T)$ and T_c in 2 days



- DC magnetic field
  - parallel to the surface
  - B ≤ 600 mT

An operation software modified to test a
residual sample magnetisation
as a function of

- **operation temperature**
- **applied magnetic field (TBD)**

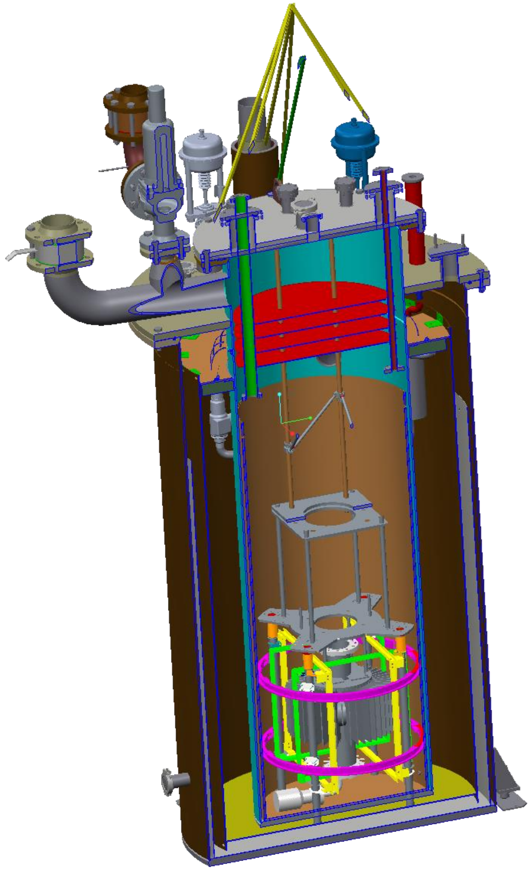
Courtesy of Oliver Kugeler

HZB Helmholtz Zentrum Berlin

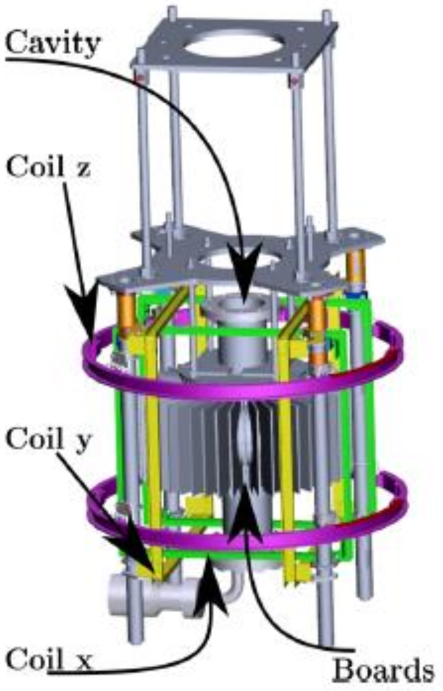
Facilities for Task 3.2

1.3 GHz and QPR RF test

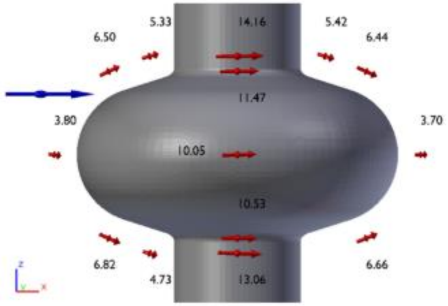
Bath cryostat for vertical cavity testing

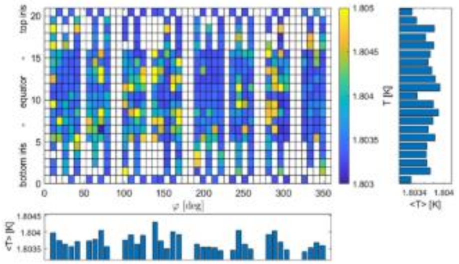


Integration of Helmholtz coils for DC magnetic investigations



Thermal and magnetic mapping of cavities using Allen-Bradley resistors and AMR sensors





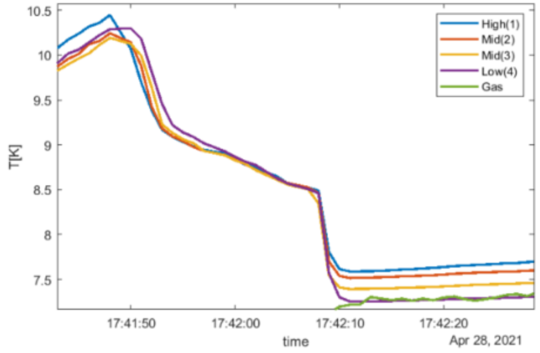
Courtesy of Oliver Kugeler

HZB Helmholtz Zentrum Berlin

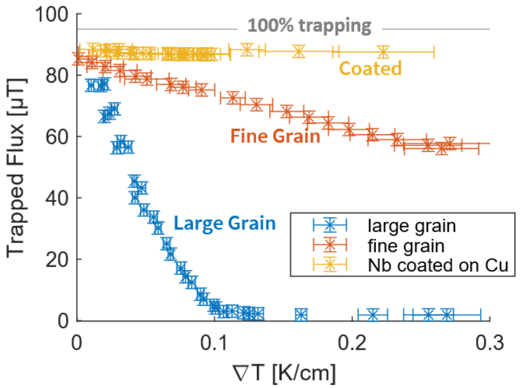
Facilities for Task 3.2

Magnetic diagnost

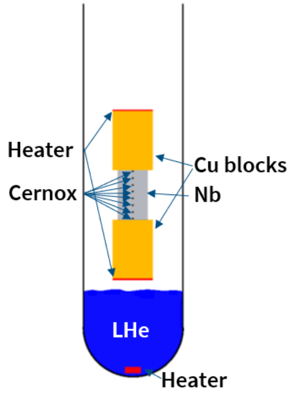
Flux dynamics in Nb_3Sn much different from Nb
Use TraMaFlu facility to measure flux dynamics in samples

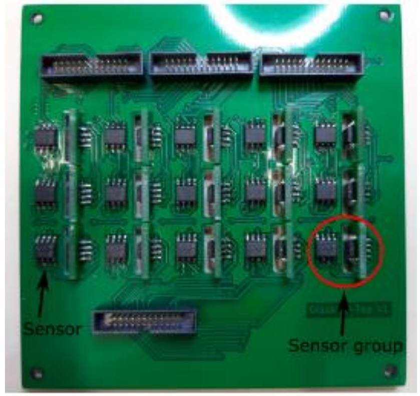


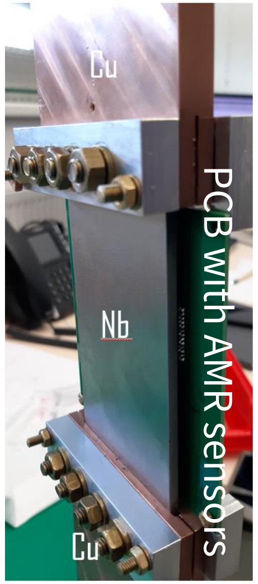
Typical progression of magnetic field deformation due to propagating sc/nc interface

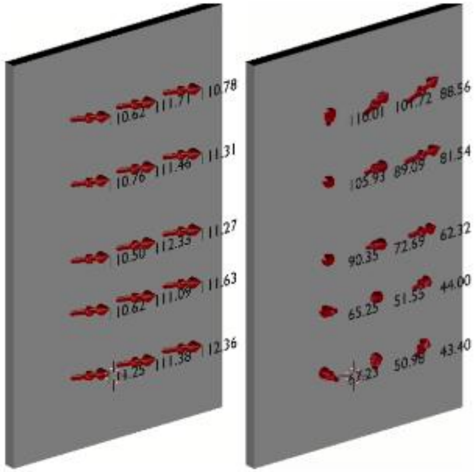


Results obtained for temperatur- gradient driven expulsion behavior of different Nb samples





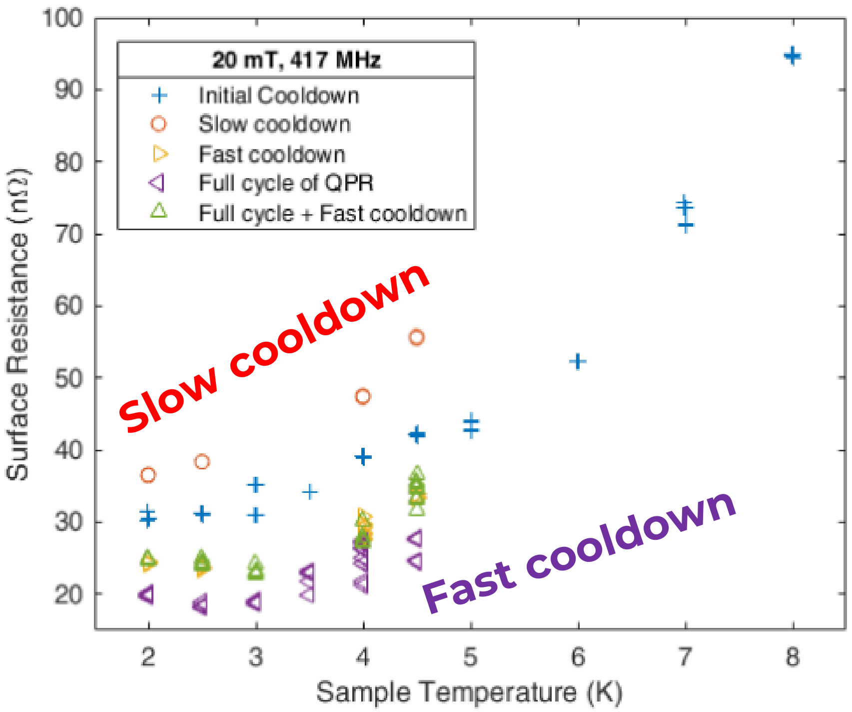




Time resolved field mapping during the sc transition in external field

First Results for Task 3.2

- QPR Nb_3Sn on Nb measured with different cooling rate
- Flux trapping dependence on cooling procedure proved
- High quality coating → low Rs value



Courtesy of Oliver Kugeler and Sebastian Keckert

WP3 Tasks 3.3

RF Tunability – *M1-M32*

(INFN, CEA, **HZB**, UKRI) – *Oliver Kugeler*

Objectives

- Explore new coating parameters on planar samples and small resonators to enhance the mechanical strength in SC A15 films.
- Mechanical film-stability tests with planar samples.
- Build cavity tuning system and perform vertical cryo-tests of coated cavities to explore RF performance limits and acceptable tuning without incurring film damage.
- Devise cavity tuning schemes for Nb_3Sn cavities fulfilling the required tuning parameters while taking into account the constraints of Nb_3Sn. The implementation of FE-FRT to assist will be considered.

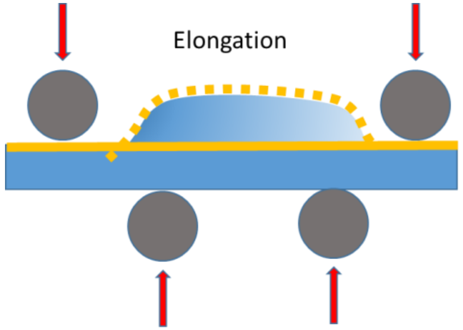
Deliverable 3.1 Cavity tuning Report on implementation of cavity Q vs F tuning tool - *HZB - Report M24*

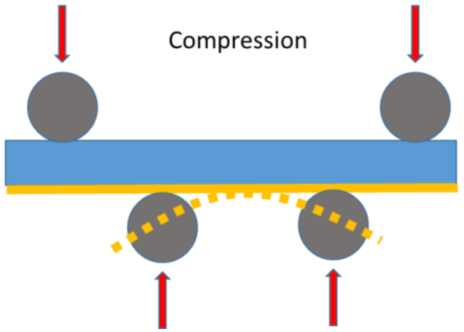
Milestone 3.3 Report on mechanical strength test of SC coatings - *Test report M30*

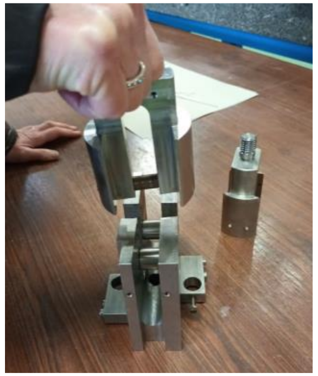
Facilities for Task 3.3

Flexture Tests

- Mechanical tests at room temperature or cryogenic temperature: 77 K (liquid nitrogen) and 4.2 K (liquid helium).
- Among those tests, flexture tests are well adapted to study thin film behavior
  - An Instron electromechanical machine can be fitted with a cryostat with a traction and flexion capacity of 45 kN,
  - 2 kinds of experiments are foreseen
    - *Complete deformation to evaluate adhesion and mechanical resistance of the films*
    - *Progressive small deformations comparable to tuning deformation amplitudes to predict tunability limits*







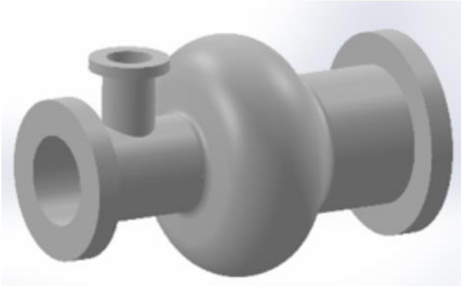
Courtesy of Oiver Kugeler

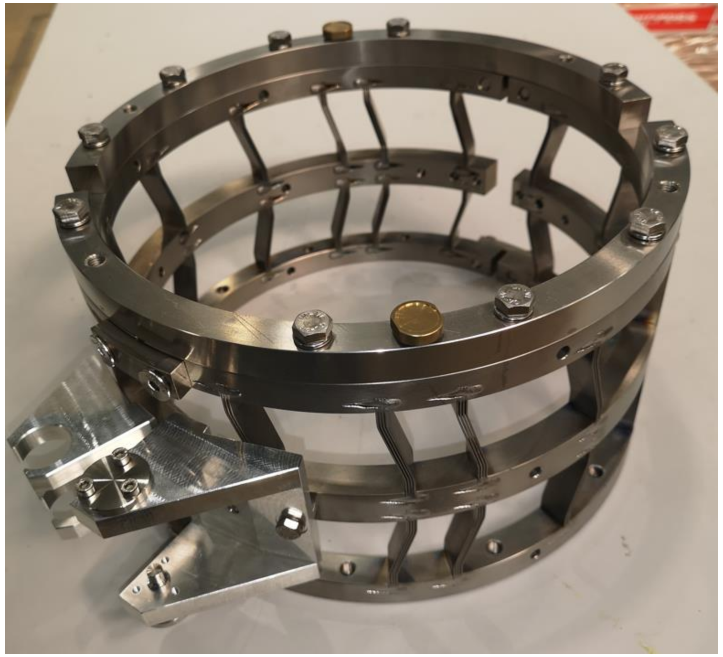
HZB Helmholtz Zentrum Berlin

Facilities for Task 3.3

Cold tuner for vertical tests

- Nb_3Sn poses new challenges to RF performance due to its poor ductility
- Need to evaluate tunability of coated cavities prior to welding them in a tank
- **Intended implementation: Adapt existing blade tuner developed for TESLA cavities (by INFN Milano) to fit arbitrary cavity geometry.**
  - **1 MHz · m motor tuning capability per cavity length**
  - **1 kHz · m piezo tuning capability**
- Perform life-monitoring of RF-performance degradation due to tuning
- Perform long term stress tests of film under cryo-conditions





Status of Task 3.3

- CEA: Preparing protocol for mechanical properties test on Nb3Sn coatings
- UKRI and INFN: Coating systems ready for first planar samples deposition
- HZB: Design Cavity Tuner System in progress

WP3 Tasks 3.4

Adaptive Layers – *M1-M40*

(INFN, **CEA**, HZB, UKRI) – *Thomas Proslier*

Objectives

- Develop adaptative layers by atomic layer deposition on Cu that are stable up to 650 ° C.
- Compare performance Nb3Sn on Cu with and without adaptive layers on planar samples and QPR.

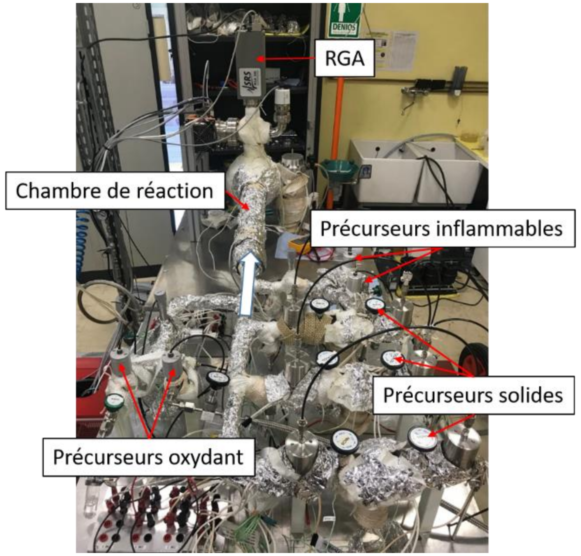
Deliverable 3.3 Adapt. Layer Report on QPR study of Nb3Sn on Cu & adaptive layers - CEA - *Report M38*

Milestone 3.2 Developed ALD adaptive layers on Cu - *Test report M24*

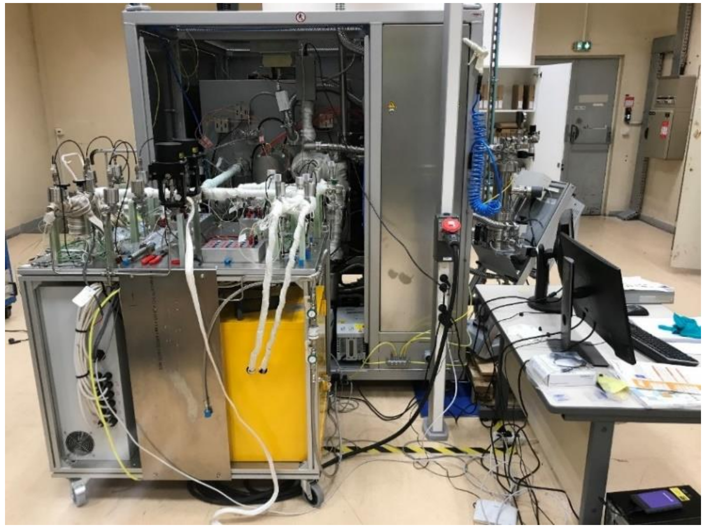
Courtesy of Thomas Proslier

Facilities for Task 3.4

Atomic Layer Deposition (ALD) Reactors



Atomic Layer Deposition Research Scale Reactor

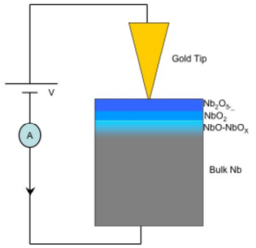


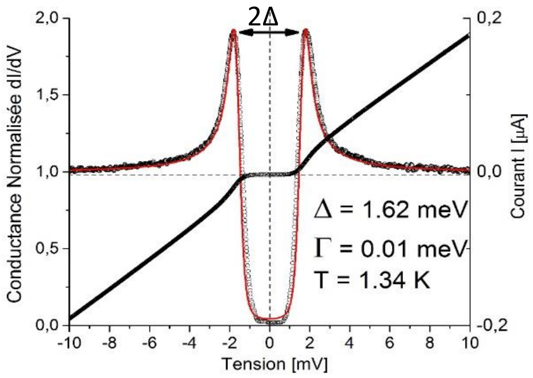
Atomic Layer Deposition Development Scale Reactor

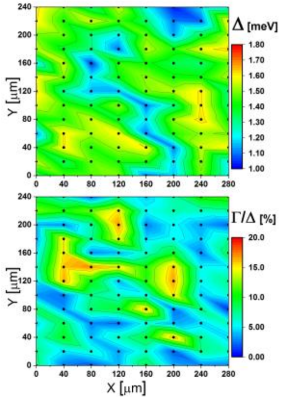
- *High vacuum oven ØxL: 50x110 cm.*
- *Temperature: 30-450°C*
- *8 precursor lines : 4 solids, 2 liquids, 2 gases.*
- *Chamber adaptation (cavités, QPR).*
- *In situ: RGA.*

Other: glove box under N_2, Sorbonne, 4 points measurement at RT, optical microscope, 3 zones tubular oven under gas (Ar, N_2, O_2, N_2-H_2) up to 1100°C.

Measurement of surface electronic properties (DOS)
Measure of fundamental quantities : Δ, Tc, Hc







Tunneling spectrum and Mapping on a Nb sample

Tunneling Spectroscopy

Preliminary Results for Task 3.4

- Layers stable up to 650 C have been developed on Nb, Si, Sapphire substrates
- Layers stable up to 450 C (not tested at higher temperature) on a 1.3 GHz copper cavity
- A 1.3 GHz cavity dedicated ALD apparatus have been built and is operational for this project

WP3 Tasks 3.5

Working Cavity – *M1-M48*

(INFN, CEA, HZB, **UKRI**) – *Reza Valizadeh*

Objectives

- Improve I.FAST 1.3-GHz superconducting coating recipe based on Tasks 3.2-3.4 results.
- Prepare 1.3-GHz thin film cavities with an optimized coating recipe.
- Perform full cavity characterization @4.2 K (Q vs E, Q vs F, and flux trapping in the VTS@SupraLab vertical test stand).

Deliverable 3.4 4.5-K Cavity Report on 4.5-K Cavity performance & tunability tests - INFN - *Report M46*

Milestone 3.4 Characterization of Nb3Sn reference cavity - *Test report M34*

Facilities for Task 3.5

PVD Coating Systems

PVD Coating facilities for planar samples and 1.3 GHz cavities

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

Courtesy of Reza Valizadeh

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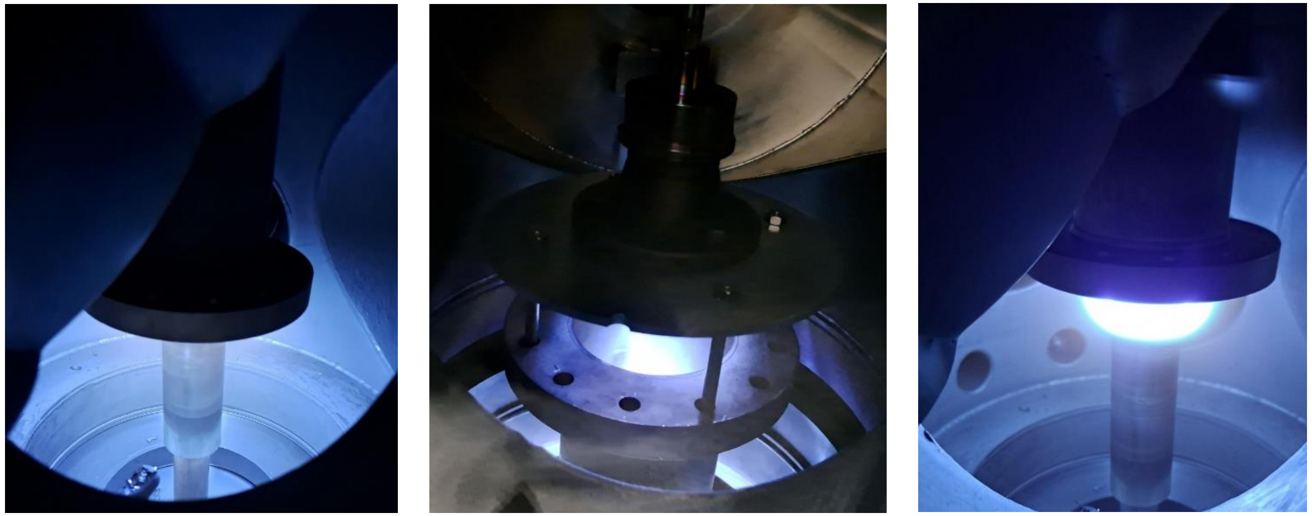
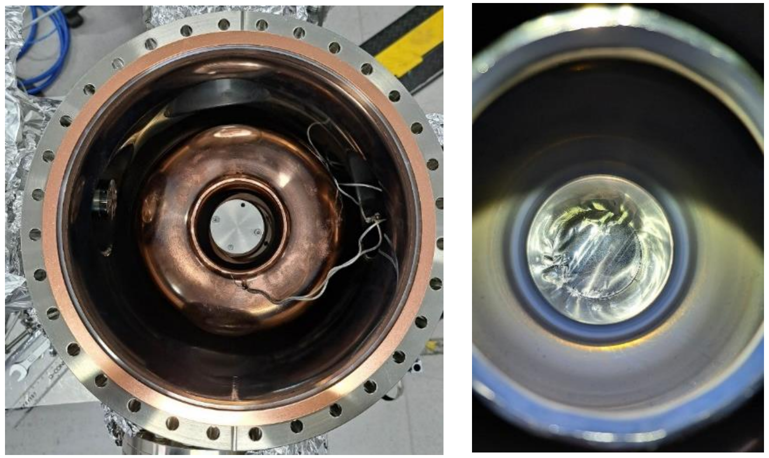
Facilities for Task 3.5

PVD Coating Systems



Static Magnetron With Moving 1.3 GHz cavity

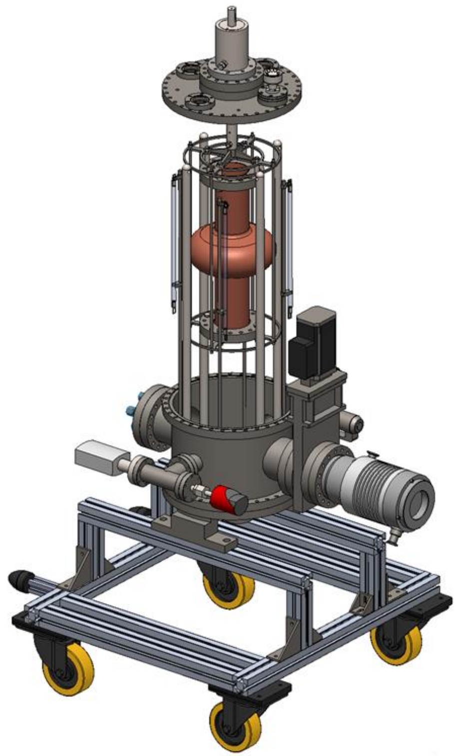


Static Magnetron and Static 1.3 GHz cavity

Coated 1.3 GHz Dummy Cavity

Preliminary Results for Task 3.5

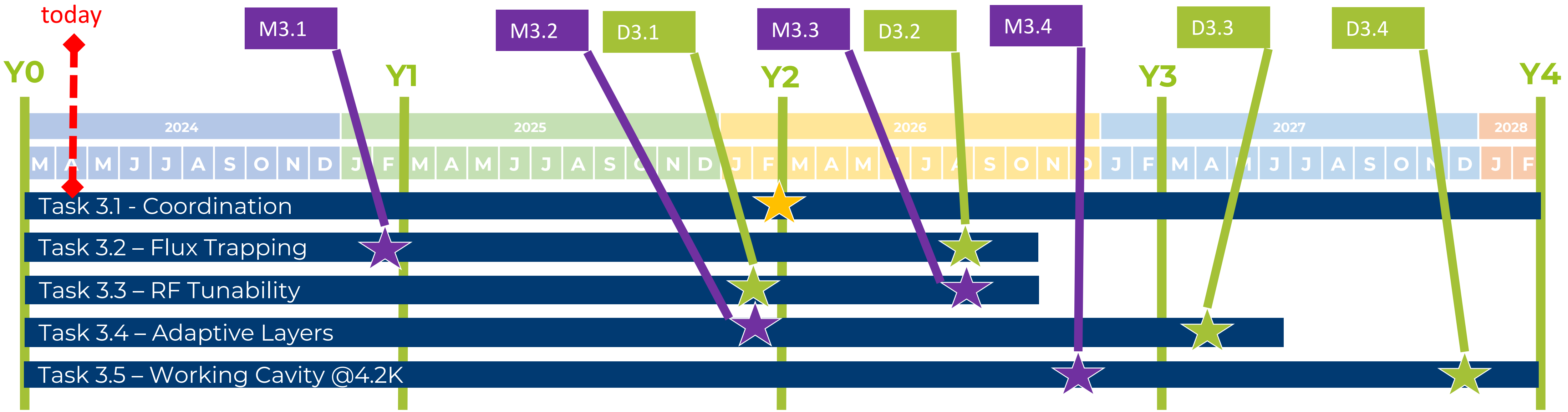
- Coating recipe defined: high performance SC films on planar samples and QPR
- An interlayer is mandatory to get a Tc>17K
  (Best results up to now with Nb thick film)
- 1.3 GHz coating facility ready
- Magnetron source design and test in progress



WP3 Timeline

M3.1 Modification of choke cavity for flux trapping study - *Engineering report M12*
M3.2 Developed ALD adaptive layers on Cu - *Engineering report M24*
M3.3 Report on mechanical strength test of SC coatings - *Test report M30*
M3.4 Characterization of Nb_3Sn reference cavity - *Test report M34*

D3.1 Cavity tuning Report on implementation of cavity Q vs F tuning tool - *Report M24 - HZB*
D3.2 Flux trapping Report on flux dynamics study in Nb3Sn on Cu samples - *Report M30 - HZB*
D3.3 Adapt. Layer Report on QPR study of Nb_3Sn on Cu & adaptive layers - *Report M38 - CEA*
D3.4 4.5-K Cavity Report on 4.5-K Cavity performance & tunability tests - *Report M46 - INFN*



Conclusions

- All the partners already start to work on the project
- First results on QPR are encouraging
- No back stoppers at the moment

Success of ISAS WP3 will be a breakthrough in SRF

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Thank You!

This project has received funding from the European Union's Horizon-INFRA-2023-TECH-01 under GA No 101131435 - iSAS

WP3 Tasks 3.2

Flux Trapping – *M1-M32*

(INFN, CEA, HZB, **UKRI**) – *Oleg Malyshev*

Description of work

This task aims to study how trapped magnetic flux may affect the superconducting properties of the thin film and its RF surface resistance. Initially, copper samples coated with A15 superconductors by PVD techniques will be provided by the INFN and UKRI. Three facilities will be used to characterize the samples: the choke cavity test facility at UKRI and the HZB QPR@SupraLab as well as the magnetometric mapping system at HZB. The facility at UKRI will be upgraded with a magnetic shield and Hall probes, allowing it to study magnetic flux trapping in 100-mm planar samples. At HZB the impact of flux trapping will first be investigated in the QPR equipped with an excitation coil and a fluxgate probe which allows one to correlate flux trapping with the RF performance of the SC film, as well as the study of flux viscosity. In a later step, the existing magnetometric mapping system for 1.3 GHz cavities at HZB will be used to investigate cavities from Task 3.5. The results will feed back on the cavity coating procedures.

WP3 Tasks 3.3

Tunability – *M1-M32*

(INFN, CEA, **HZB**, UKRI) – *Oliver Kugeler*

Description of work

This task aims to study and improve mechanical properties of SC thin films to assess the impact of future cavity tuning during normal 4.2 K operation. Initially, the study concentrates on small planar strips coated at INFN and UKRI and tested at CEA. Elongation and compression tests will be carried out at room temperature and at cryogenic temperature by applying a deformation typically incurred during cavity tuning. In parallel, HZB will design and build a cavity tuner system for vertical RF tests in SupraLab with coated 1.3-GHz cavities. The device should be capable of reproducing both of slow and fast tuning conditions, as needed for microphonics compensation. Length changes in the µm and sub-µm ranges, equivalent to frequency spans in the MHz and kHz ranges, respectively will be studied. Combined with the findings in Task 1.1 regarding the FE-FRT, a tuning scheme for Nb3Sn cavities will be devised.

WP3 Tasks 3.4

Adaptive Layers – *M1-M40*

(INFN, **CEA**, HZB, UKRI) – *Thomas Proslier*

Description of work

This task aims at developing suitable adaptative layers synthesized by ALD on Cu for subsequent Nb_3Sn deposition by PVD to reduce the detrimental effect of mechanical deformation on the superconducting properties of Nb_3Sn. In addition, these layers can also be used as diffusion barriers for Sn diffusion into Cu. The first step will be to find the layer composition and structure to make them stable on Cu up 650 ° C. The second step will be to ensure no detrimental cross contamination between the layers and the Nb_3Sn occurs. Initially, we will conduct experiments on flat Cu coupons to optimize the first two steps prior to scaling up to QPR samples. A comparative study of Nb_3Sn on Cu with and without adaptive layers will be carried out systematically. The results of this task will be then applied for coating a 1.3 GHz cavity for Task 3.5.

WP3 Tasks 3.5

Working Cavity – *M1-M48*

(INFN, CEA, HZB, **UKRI**) – *Reza Valizadeh*

Description of work

This task comprises the main deliverable of the WP3: optimize the SC coating procedure of 1.3 GHz cavities and demonstrate suitability for 4.2 K operation. Substrate preparation will be done at INFN on Cu cavities originally produced for I.FAST. CEA will grow an adaptive layer via ALD according to the results obtained in Task 3.4. SC coating R&D and cavity deposition will be carried out in different PVD facilities at INFN and UKRI in order to test multiple deposition parameters, employing experience and knowledge from Tasks 3.2-3.4. Coated cavities will be shipped to HZB for a full characterization at 4.2 K (Q vs E, Q vs tuning, and flux trapping) on the new vertical stand system developed in Task 3.3. A complete characterization of the prototype cavity coated in I.FAST will be performed for reference.