This project has received funding from the European Union's Horizon-INFRA-2023-TECH-01 under GA No 101131435 – iSAS and from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730 – I.FAST

iFAST

iSAS

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

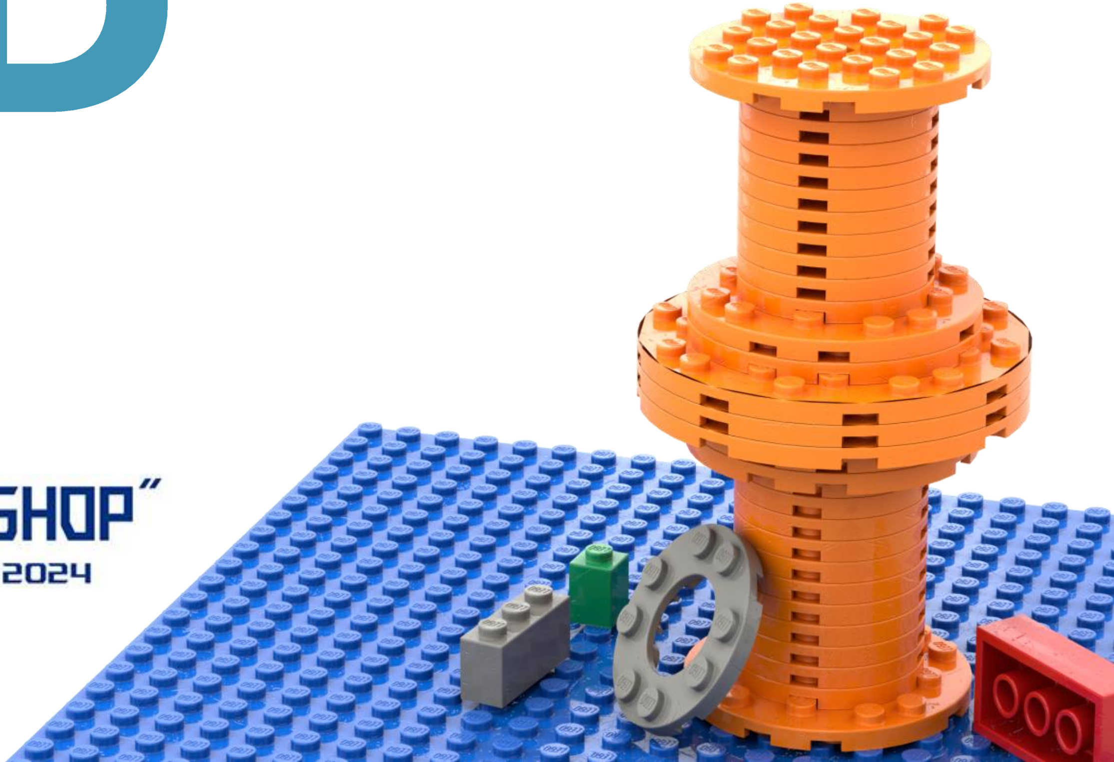
RD_FCC
INFN CSN1 Experiment

SAMARA
INFN CSN5 Experiment

INFN LNL

Cristian **Pira**

SRF R&D



2ND "FCC ITALY & FRANCE WORKSHOP"
VENICE, PALAZZO FRANCHETTI - NOVEMBER 4 - 6, 2024

Collaboration

WP9

WP3

C. Pira, O. Azzolini, R. Caforio, E. Chyhyrynets, D. Fonnesu, D. Ford, V. Garcia, G. Keppel, G. Marconato, A. Salmaso, F. Stivanello (LNL)
M. Bertucci, R. Paparella (LASA)

O.B. Malyshev, R. Valizadeh, C. Benjamin, T. Sian, L. Smith, D. Seal

C.Z. Antoine, S. Berry, Y. Kalboussi, T. Proslier

D. Longuevergne, O. Hryhorenko,

S. Keckert, O. Kugeler, J. Knobloch

S. Prucnal, S. Zhou

X. Jiang, T. Staedler, A. Zubtsovskii

E. Seiler, R. Ries

A. Medvids, A. Mychko, P. Onufrievs

G. Burt, N. Leicester, S. Marks, D. Turner

W. Bradley, S. Simon

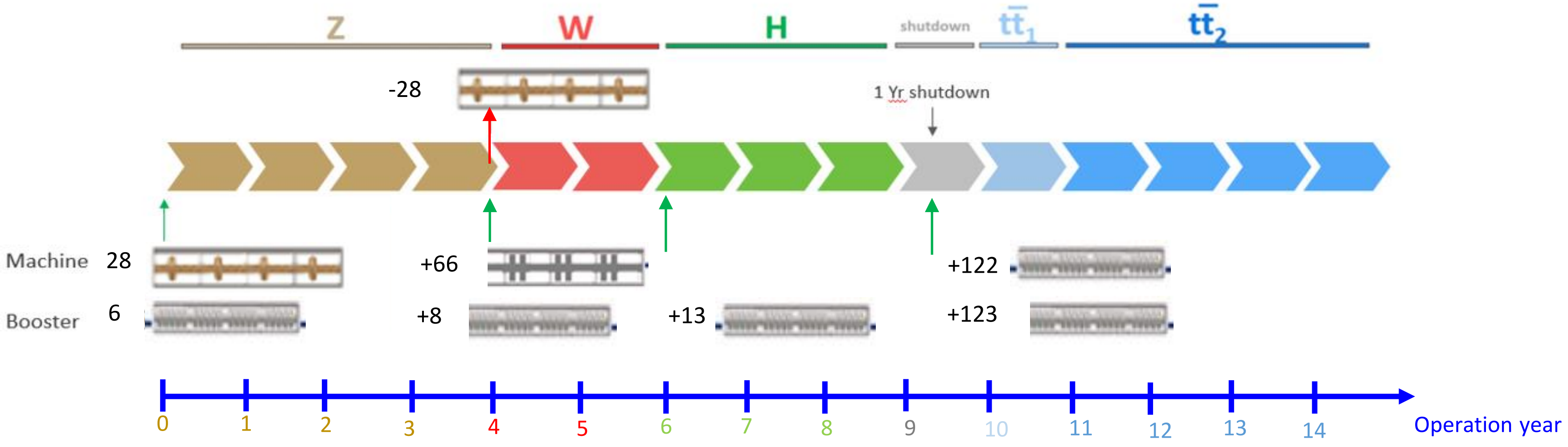
R. Berton, D. Piccoli, F. Piccoli, G. Squizzato, F. Telatin

Associated Partners

Jefferson Lab A. M. Valente Feliciano

Informal Partners

SRF System Baseline for FCC



In total: 366 CM, 1'464 cavities (4 cavities/CM, present assumption):

- **400 MHz single-cell (Nb/Cu): 28 CM, 112 cavities → 4.5 K** *(to be removed after Z)*
- **400 MHz two-cell (Nb/Cu): 66 CM, 264 cavities → 4.5 K**
- 800 MHz five-cell (bulk Nb): 272 CM, 1'088 cavities → 2 K

Collider (ttbar2): 188 CM (264 cavities 400 MHz, 488 cavities 800 MHz)

Booster (ttbar2): 150 CM (600 cavities 800 MHz)

Performance of thin film 400 MHz are one of the main challenges of FCC SRF System

SRF System Baseline from Vittorio Parma, FCC week 2023

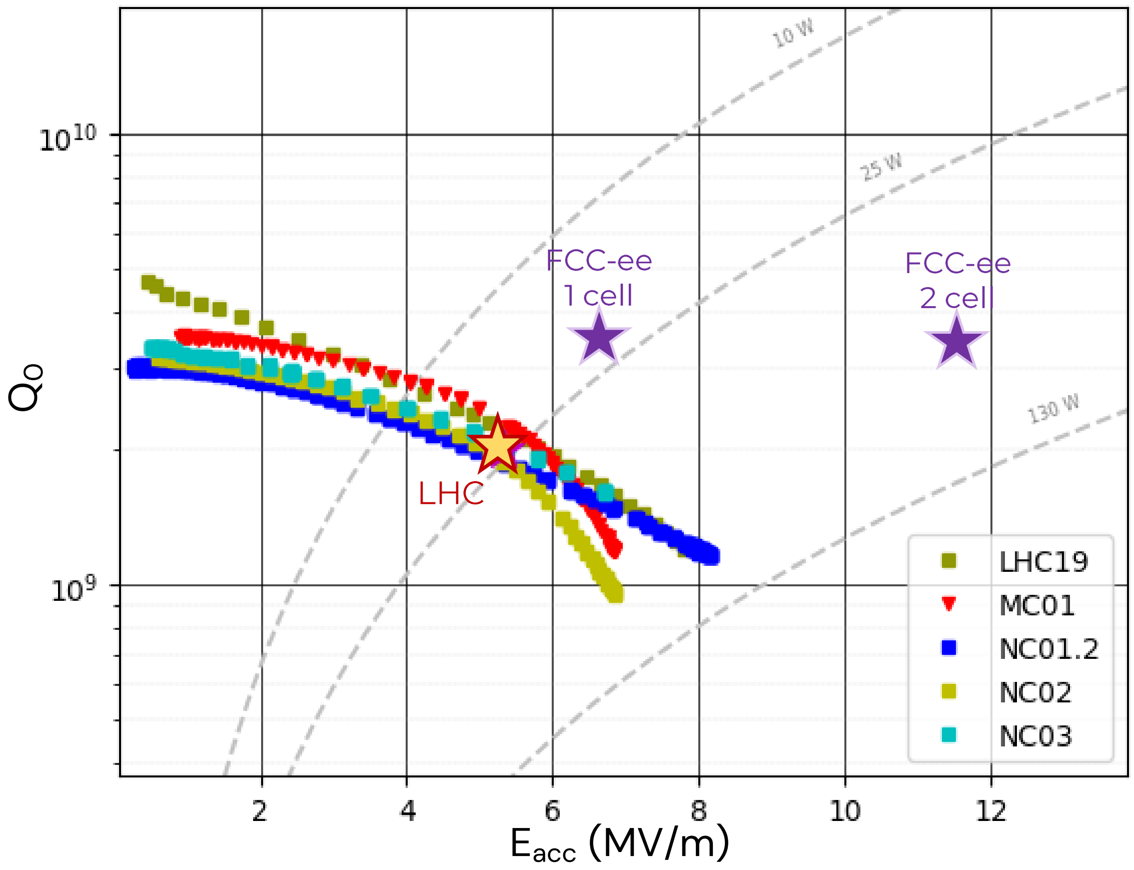
400 MHz requirements

FCC-ee requires
higher cavities performances than LHC

Nb on Cu "baseline", Solid scheme with good margin for reliable operation Clear R&D paths identified (seamless copper cavities, HiPIMS coating, High Q0 bulk Nb cavities)

Franck Peauger , FCC week 2023

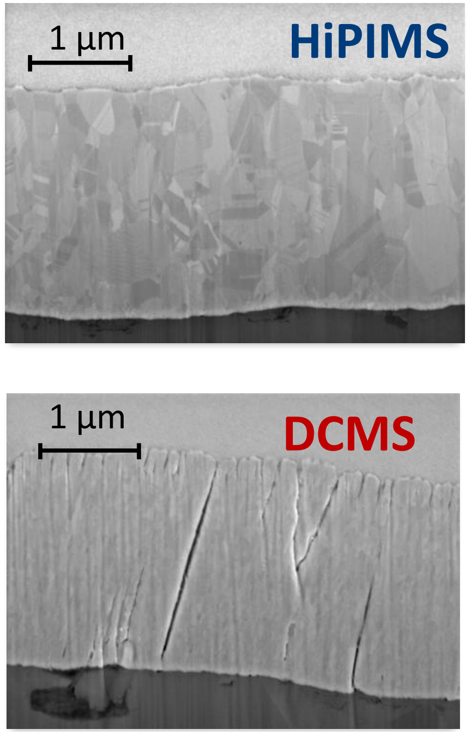
LHC cavities Q vs E_{acc} @4.5 K



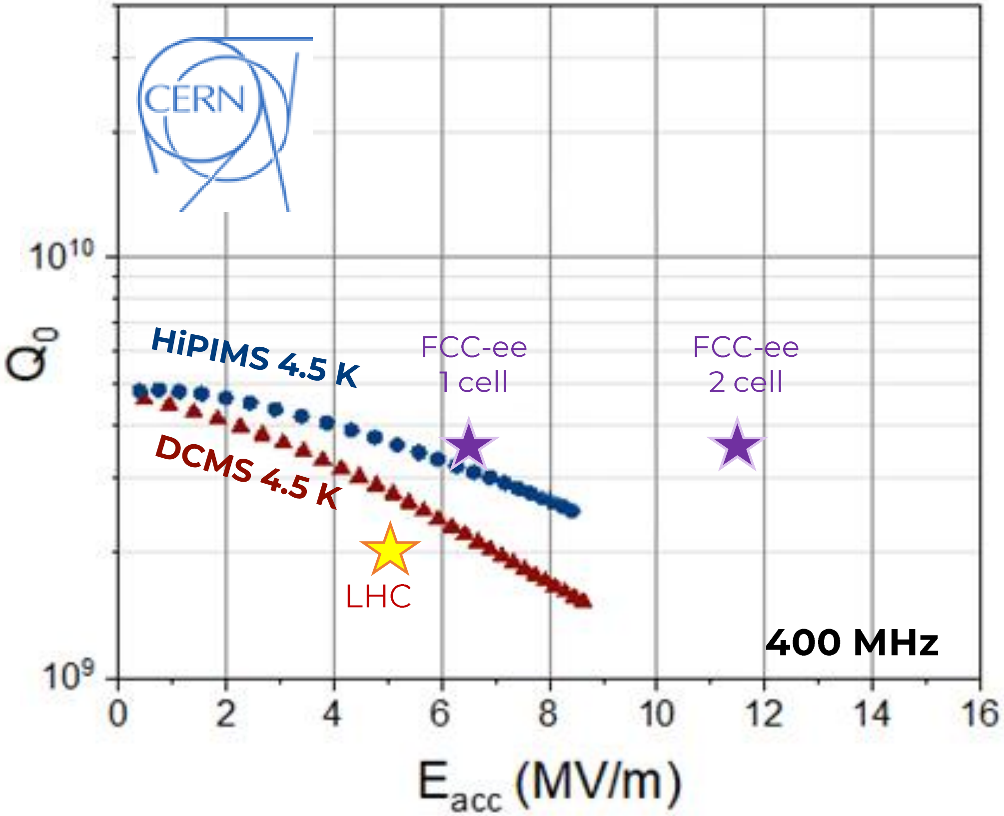
Graph from Carlota Pereira Carlos, FCC week 2023

SRF R&D @CERN for FCC

HiPIMS technology densifies the Nb coating and increases RF performances compared to DCMS

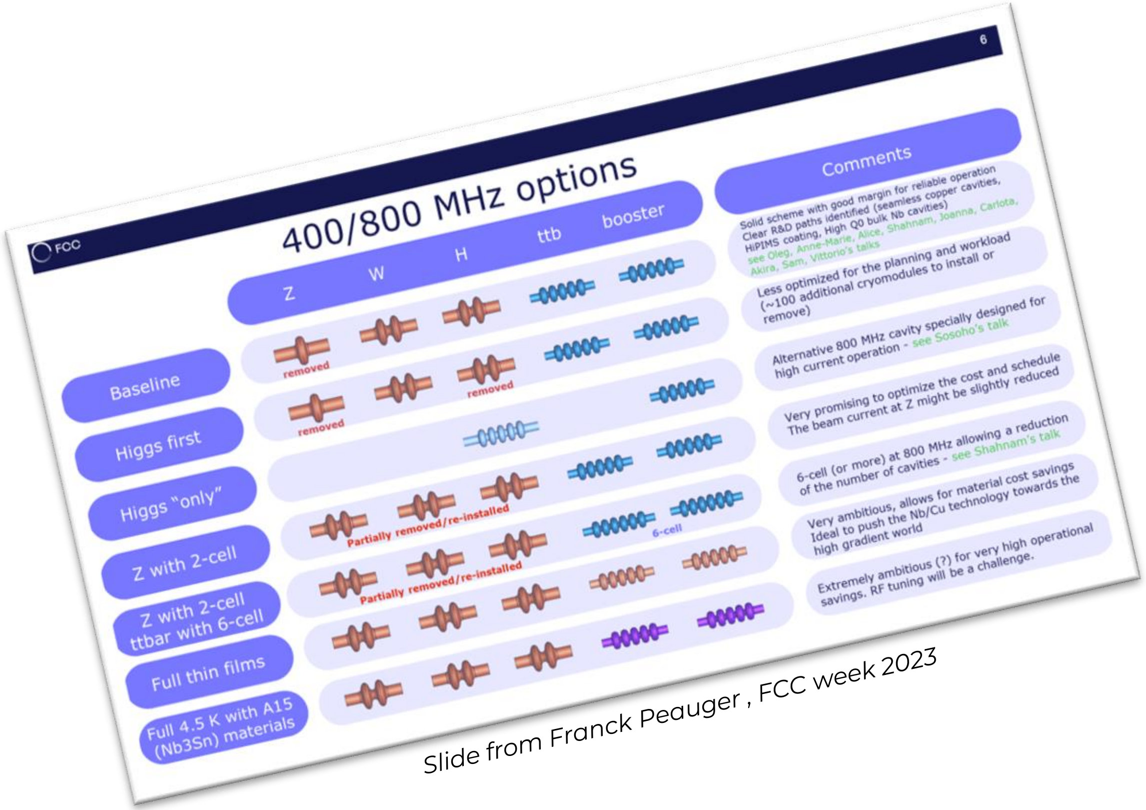


Carlota Pereira Carlos, FCC week 2023 (elaborated)



R&D @CERN also on cavity forming (hydroforming), polishing (EP), Cu oxide layer, Nb_3Sn by HiPIMS

Other Option for FCC SRF System



Slide from Franck Peauger , FCC week 2023

Full 4.5 K with A15 Materials → Nb_3Sn

Extremely ambitious
for very high operational savings

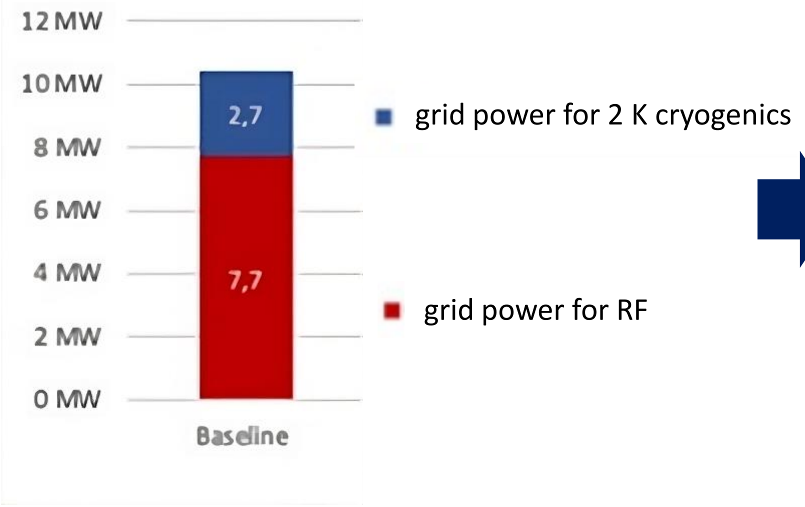
Nb_3Sn motivation

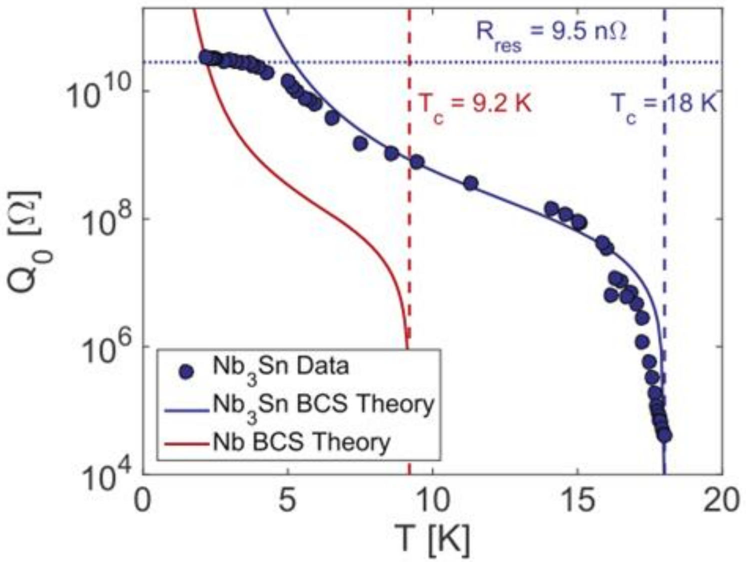
Energy saving *is mandatory for the* ***next generation accelerators***

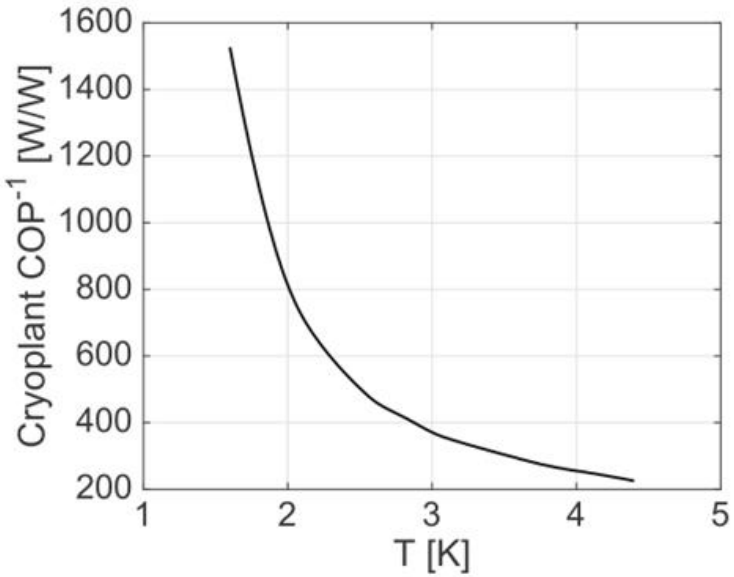
Cryogenics *is one of the* ***larger energy cost*** *in modern SRF accelerators*

Move from bulk Nb @2K to Nb_3Sn @4.5 K
reduces cryogenic power by a factor of 3

7.5 GeV LINAC new construction







Supercond. Sci. Technol. 30 (2017) 033004

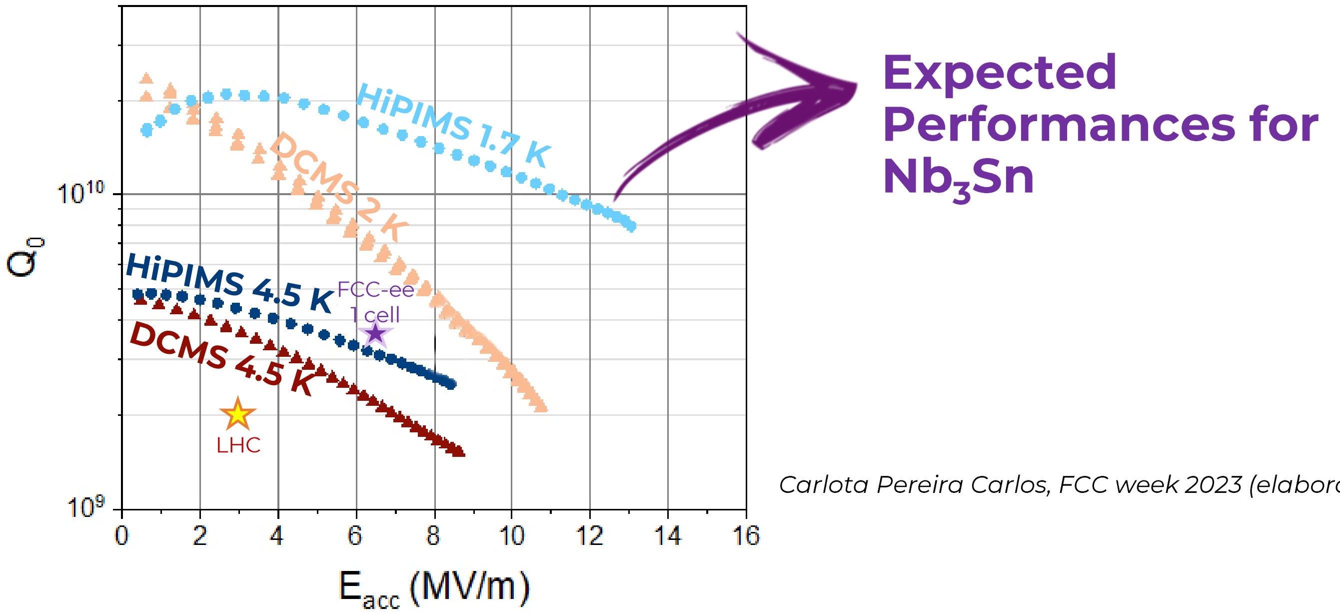
Nb_3Sn motivation

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

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

Move from thin film Nb @4.5 K to Nb_3Sn @4.5 K

Reduce T_{op}/T_c → Suppress R_{BCS} → Increase Q

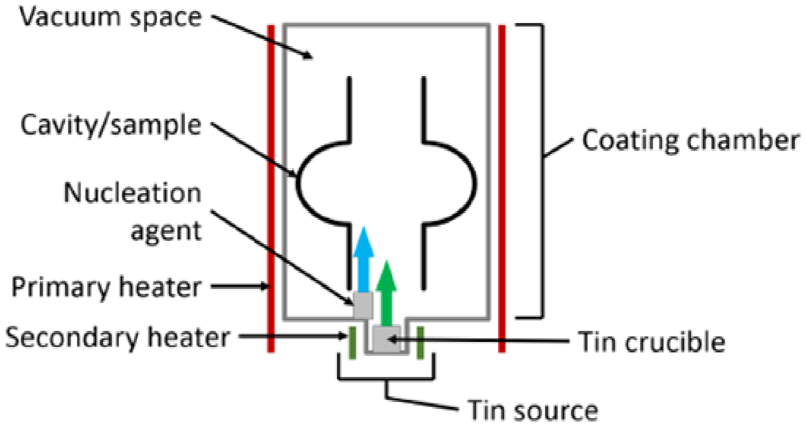


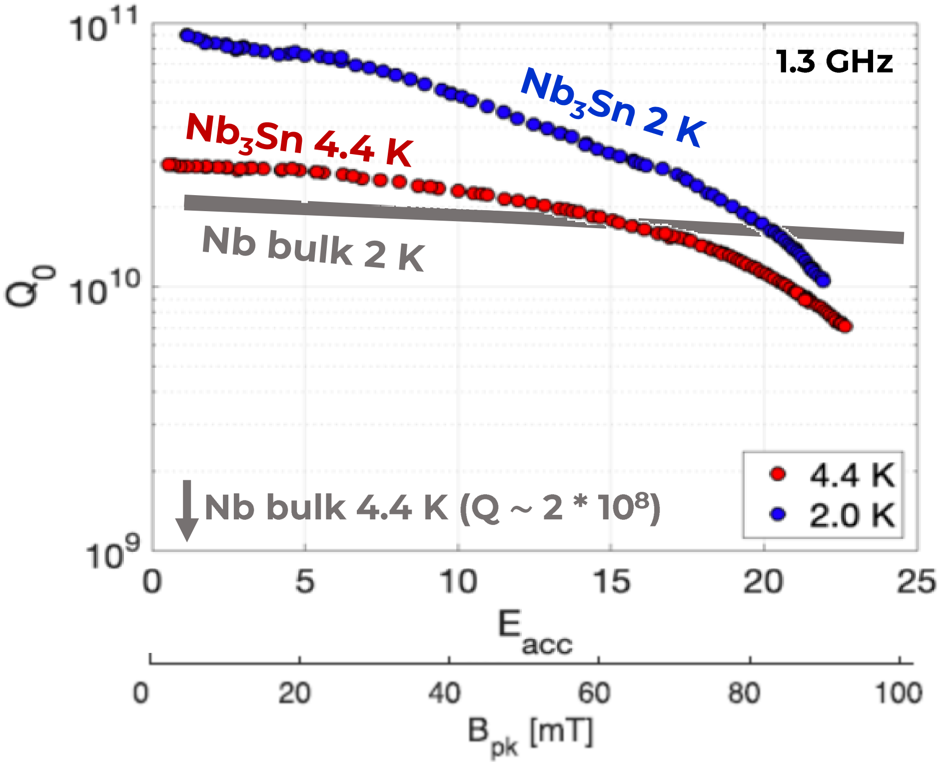
Carlota Pereira Carlos, FCC week 2023 (elaborated)

Nb_3Sn state of the art

Vapor Tin Diffusion

Cornell, Fermilab, JLab, KEK





S. Posen, SRF 2019 proceedings (elaborated)

Technology limitation:

- **Reproducibility**
- **Nb as Substrate** (expensive, chemistry, no interlayer possible)

A different approach:
Nb_3Sn on Cu

Cu substrate as several advantages:

- **Cheaper** than Nb
- Higher **thermal conductivity**
- Higher **mechanical stability**
- Low **carbon footprint**
- **PVD technology** (Nb on Cu) already used for
  LEP, LHC, HIE-ISOLDE @ CERN
  ALPI @ INFN LNL

INFN LNL SRF R&D focused on Nb_3Sn since 2021

The development of **Nb_3Sn on Cu** for SRF accelerating cavities is part of **European Strategy** for Particle Physics Accelerator - **R&D Roadmap**

INFN R&D started in a CSN5 experiment SAMARA
INFN CSN5 Experiment

*INFN LNL has a **leadership role** in the two main **European Projects** on Thin Film SRF R&D:* IFAST iSAS

*A **dedicated Project on R&D of interest of FCC** has been **financed by INFN board**:*

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

RD_FCC
INFN CSN1 Experiment

International Partners:

CERN · cea · UKRI Science and Technology Facilities Council · HZB Helmholtz Zentrum Berlin · HZDR Helmholtz Zentrum Dresden Rossendorf · Universität Siegen · IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis · ELÚ · 1862 Rīgas Tehniskā Universitāte · Jefferson Lab · Fermilab · Piccoli srl · Università di Padova

Nb_3Sn on Cu: Multiple challenges

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

Nb_3Sn on Cu: Multiple challenges

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- **Trapped Flux**
- **Tuning**

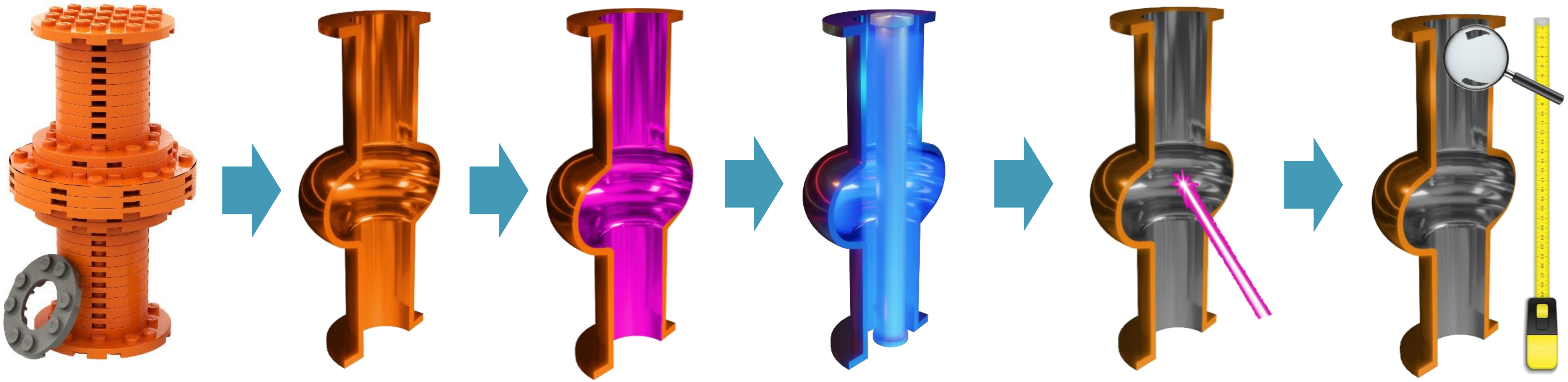
iFAST

SRF cavities R&D for FCC-ee

INFN Accelerators European Strategy Program

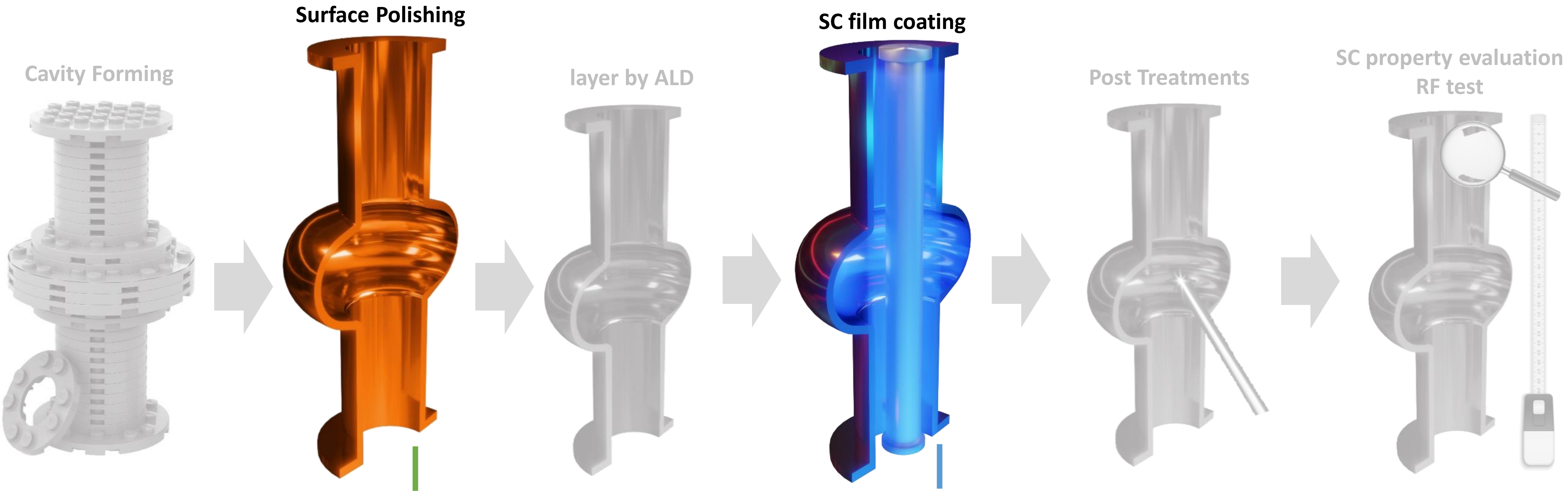
Nb_3Sn on Cu R&D activity covers all cavity production chain

Cavity Forming | Surface Polishing | layer by ALD | SC film coating | Post Treatments | SC property evaluation RF test



Cavity Forming	Surface Polishing	layer by ALD	SC film coating	Post Treatments	SC property evaluation RF test
Seamless Spinning *Additive Manufacturing*	*Plasma Electrolytic Polishing*	*Atomic Layer Deposition*	*Nb_3Sn on Cu*	*Laser Annealing* *Millisecond Flash Annealing*	

2 Technologies in focus for FCC

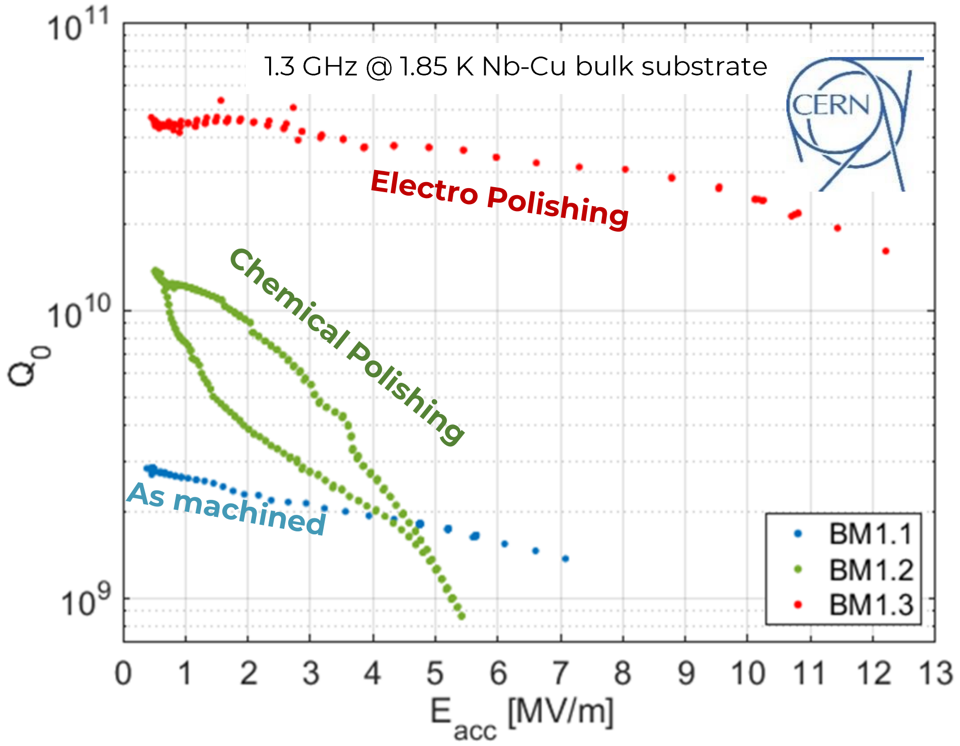


Plasma Electrolytic Polishing

Nb_3Sn on Cu Coatings

Surface Polishing
PEP

Surface Polishing



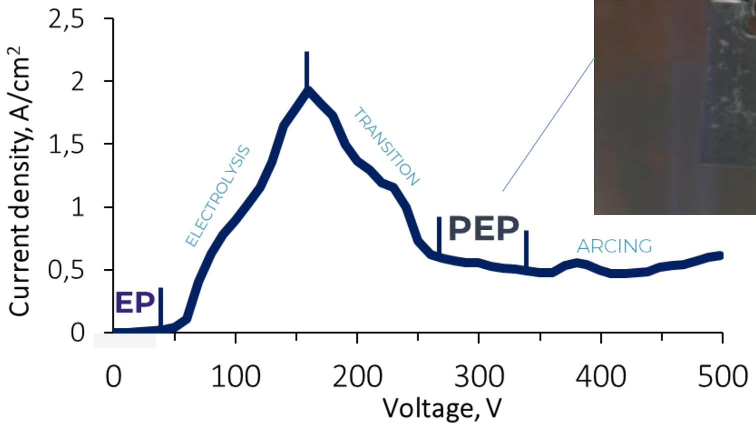
L. Vega Cid, TTC meeting 2022 (elaborated)

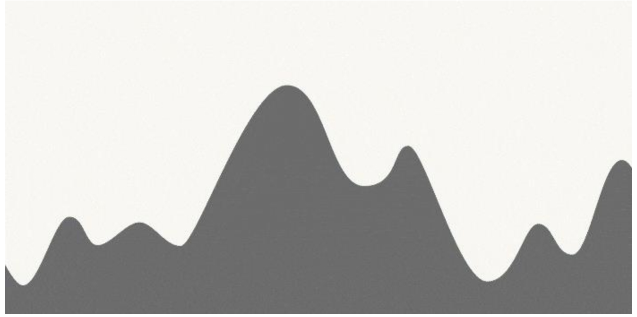
Cu substrate plays a fundamental role in SRF performances

Roughness and defects reduction by **surface treatments are mandatory** for a good and uniform SRF coating

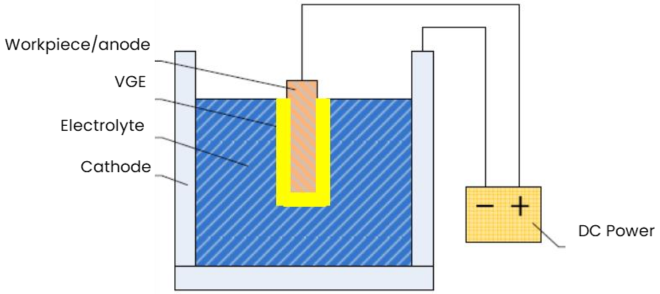
Cavity polishing requires **large amount of acids**. In particular **Nb** requires **HF** (extremely dangerous and poisoning process)

Plasma Electrolytic Polishing PEP
Mechanism





Same EP set-up
Different regime



J. Wang et al., AMR, 2012

Advantages

Plasma Electrolytic Polishing

Green
Diluted water solutions, enviromentally friendly

Fast
The fastest non-destructive polishing

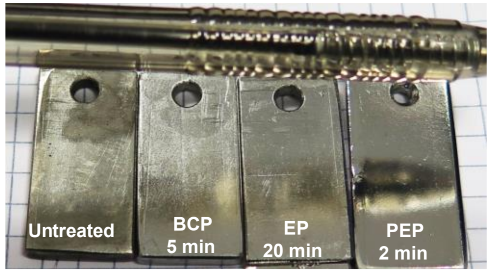
Efficiency
Equal thickness removal yield lowest roughness among competitors

Versatility
Less sensitive to the cathode shape! AM compatible

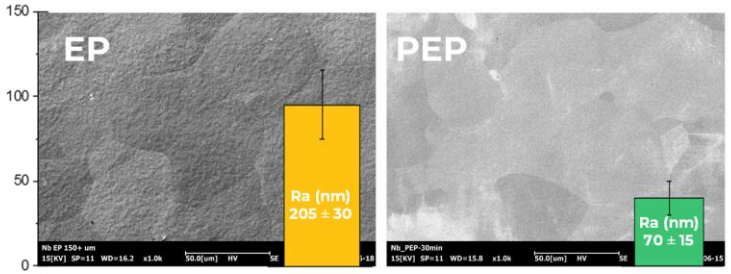
Plasma Electrolytic Polishing PEP Results

1x Nb 3x Cu
Solution Patents by INFN

Planar samples



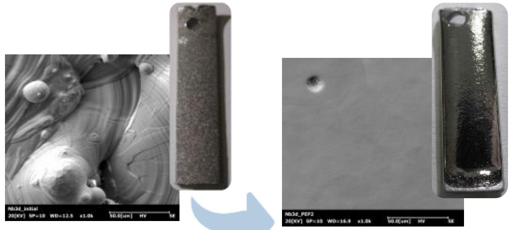
6.5 µm removed



150 µm removed in ~ 5 h

150 µm removed in ~ 40 min

Additive Manufacturing



Initial
Ra= 13 µm

PEP 30 min
Ra= 1.5 µm

QPR Samples

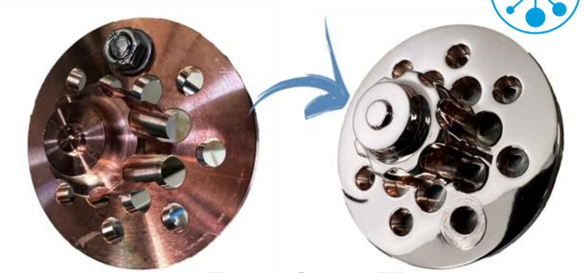
Nb QPR polishing optimizaztion on-going

Full Cu QPR ready for coating

HZB Helmholtz Zentrum Berlin

Cu Photocatodes

DESY.



Ra ~ 8 nm!!!

6 GHz Cu cavity

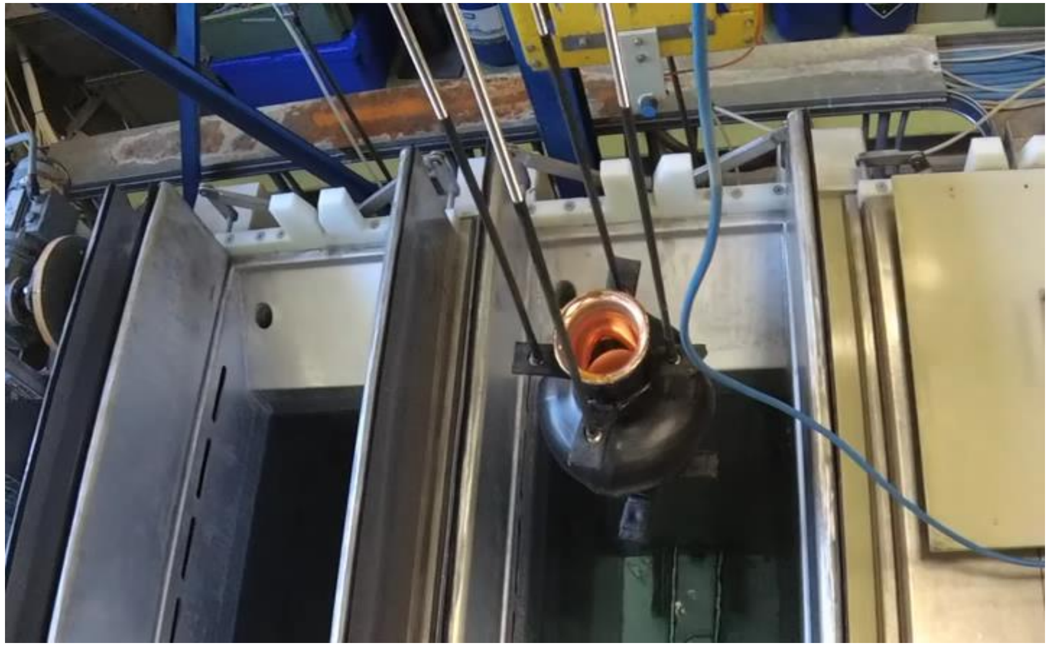
Courtesy of E. Chyhyrynets

No internal cathode!

70 µm removed in 10 minutes

30 A (100 cm2 → 1.3 GHz ~ 300 A)

Scale up to 1.3 GHz cavity successfully done! (Aug 2024)



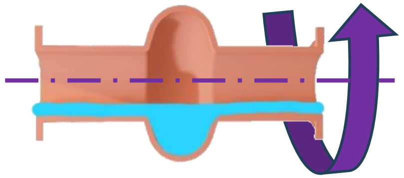
Process Parameters
>150 um removed
30 minutes! (EP→>12 hours)
Voltage 300 V
Current 90-190 A (0,06 – 0,13 A/cm^2)
Surface area 1400 cm^2

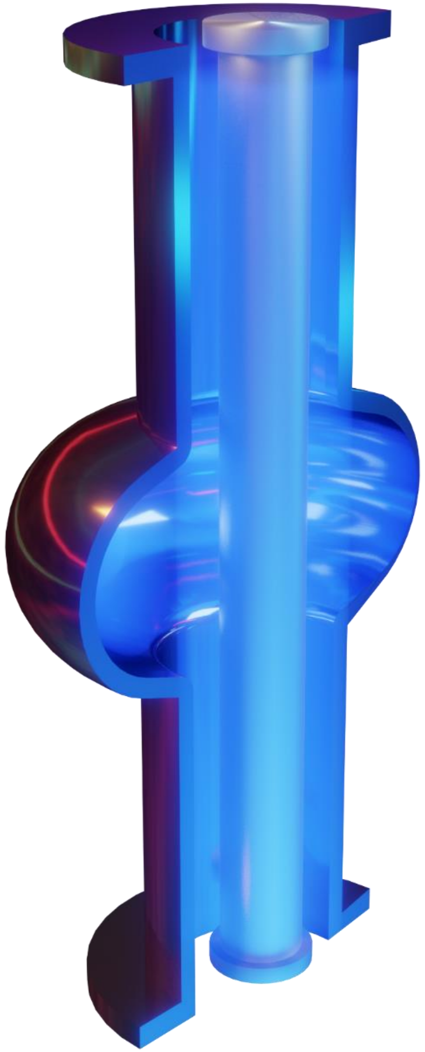
Next Steps:

- Test **reproducibility**
- Validate with **RF Test** *(Nb coating @CERN)* → Feb 2025

Explore alternative set-up to reduce Process Power

- *Reduce Treated Area (rotating cavity)*
- *Optimizing Process Parameters (Temperature, Voltage, …)*

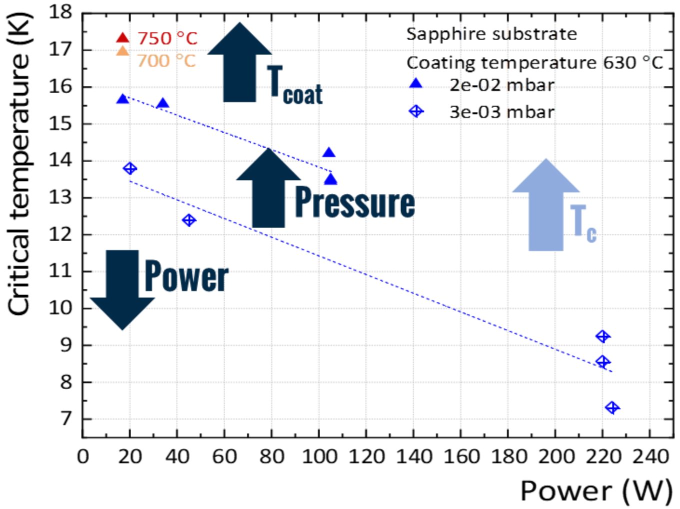


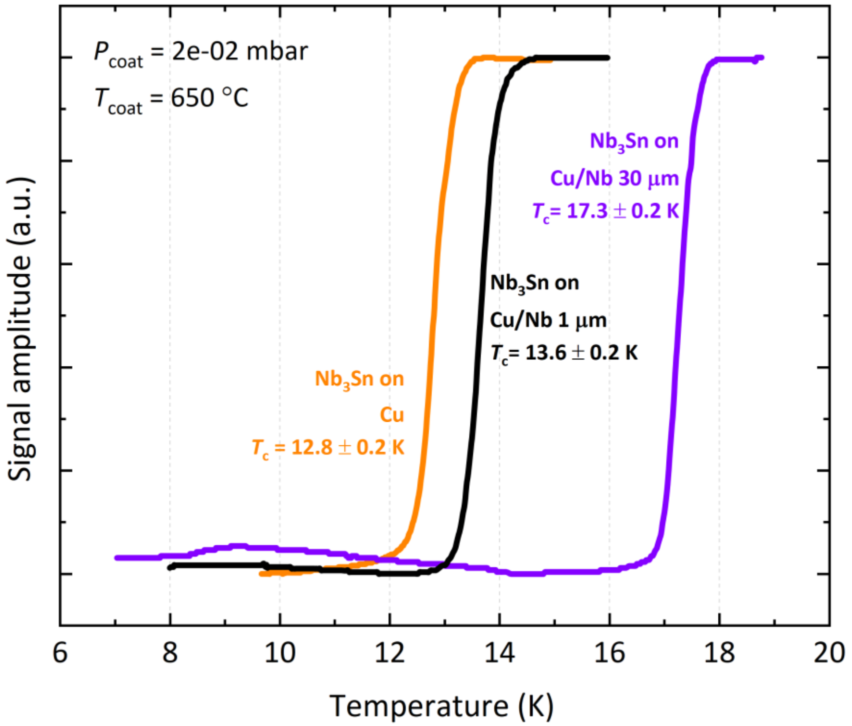


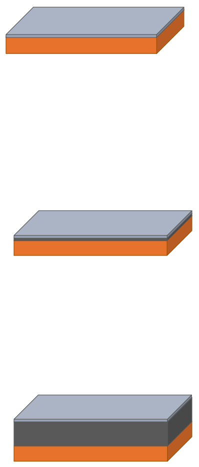
Nb_3Sn on Cu Coatings

Nb_3Sn Coatings

Long R&D phase on PVD Parameter Optimization







Optimized Coating Recipe

- Coating Parameters:
  - Pressure = $2*10^{-2}$ mbar
  - Power = 16 W
  - T substrate ≥ 600 C
- **Nb Thick Barrier Layer > 30 um**

A thick Nb buffer layer accommodates the Nb_3Sn coating

Nb substrate can be used to validate Nb_3Sn Coating Performances

First Nb_3Sn RF Results

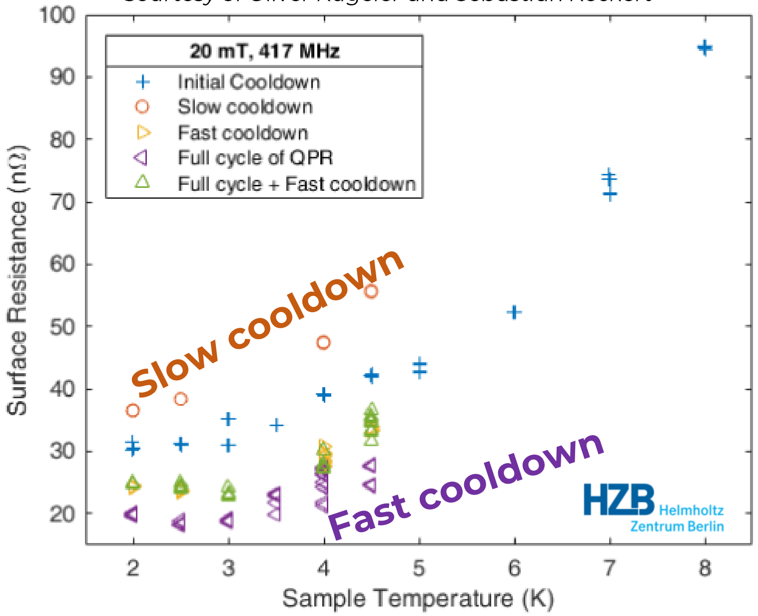
(on a small Nb planar resonator)

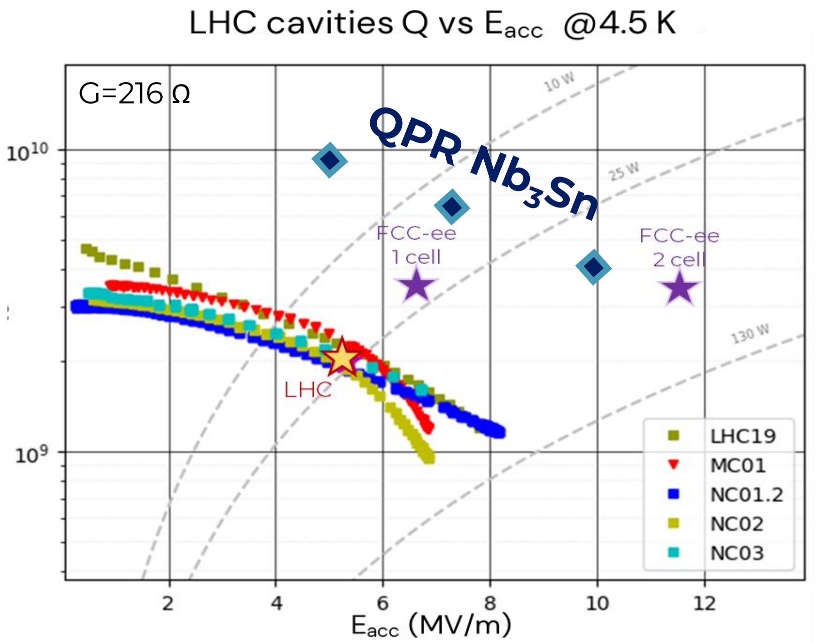
Rs of 23 nΩ
@ 4.5 K, 20 mT

Quench >70 mT
@ 4.5 K

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

Courtesy of Oliver Kugeler and Sebastian Keckert



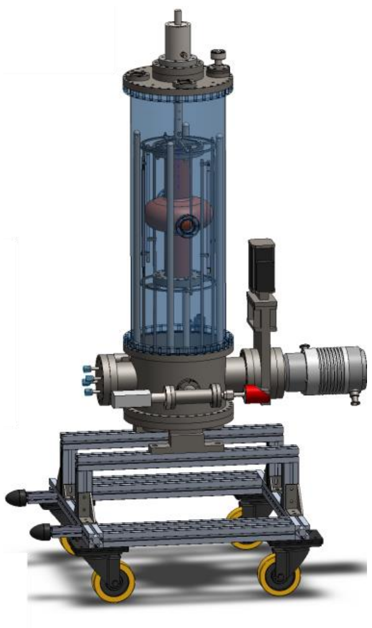


Equivalent to a Q of $9{\cdot}10^9$ @5 MV/m @4.5 K

5 times better than LHC → FCC-ee compatible

Room for improvement

Nb_3Sn Path to Final Prototype

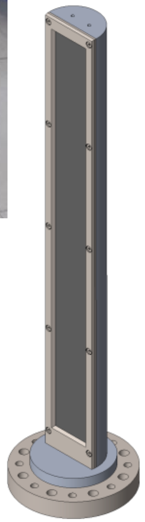


Nb_3Sn on bulk Nb
to validate coating performances
on 1.3 GHz Elliptical Cavities (2025)

Develop Nb thick barrier/accommodation layer
on 1.3 GHz Elliptical Cavities (2025)
(proof of concept on 6 GHz cavities already done)

Nb_3Sn on Cu with thick Nb coating
on 1.3 GHz Elliptical Cavities (2026-2028)

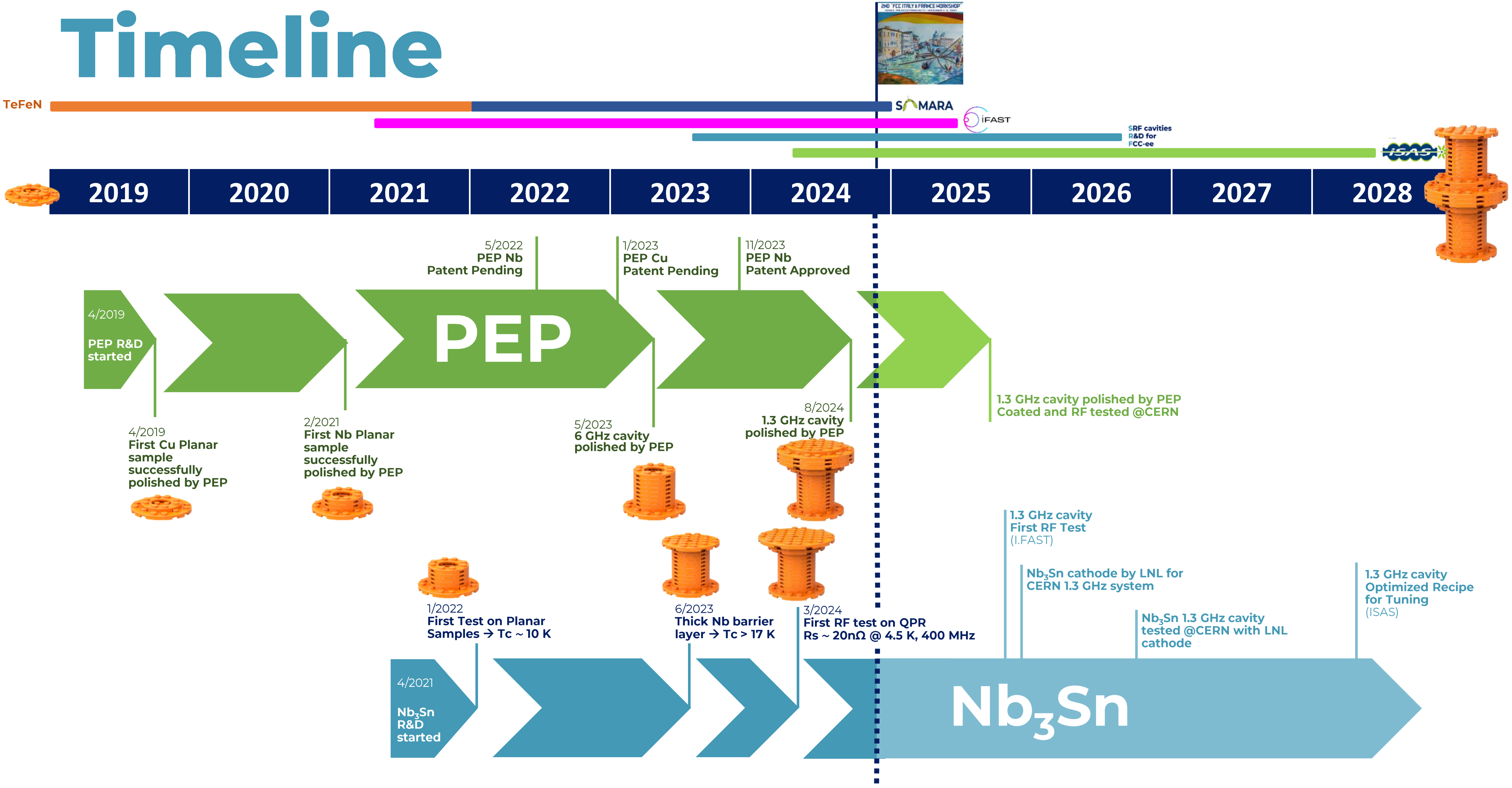
- **1.3 GHz Vacuum system ready**
- **Magnetron source commissioned**



In parallel:

- *Study on alternative buffer layer*
- *Study on flux trapping*

Timeline


TeFeN
SAMARA
iFAST
SRF cavities R&D for FCC-ee
ISAS
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
5/2022 PEP Nb Patent Pending
1/2023 PEP Cu Patent Pending
11/2023 PEP Nb Patent Approved
4/2019 PEP R&D started
PEP
1.3 GHz cavity polished by PEP Coated and RF tested @CERN
4/2019 First Cu Planar sample successfully polished by PEP
2/2021 First Nb Planar sample successfully polished by PEP
5/2023 6 GHz cavity polished by PEP
8/2024 1.3 GHz cavity polished by PEP
1.3 GHz cavity First RF Test (I.FAST)
Nb_3Sn cathode by LNL for CERN 1.3 GHz system
1.3 GHz cavity Optimized Recipe for Tuning (ISAS)
Nb_3Sn 1.3 GHz cavity tested @CERN with LNL cathode
1/2022 First Test on Planar Samples → Tc ~ 10 K
6/2023 Thick Nb barrier layer → Tc > 17 K
3/2024 First RF test on QPR Rs ~ 20nΩ @ 4.5 K, 400 MHz
4/2021 Nb_3Sn R&D started
Nb_3Sn

Conclusion

- **PEP and Nb_3Sn films** are possible **game changer technologies** for SRF accelerating cavities
- **Big steps forward** in the last two years with transition from planar to 3D samples
- **Very promising results from first RF test**
- **Validation with 1.3 GHz cavities is necessary** prior to evaluating the feasibility of implementing these technologies in real accelerators
- **End of 2025** we expect to have the **first tests** available on **1.3 GHz cavities**
- **In 2028 optimized prototypes** are expected

Work supported by INFN CSN5 experiment SAMARA and INFN CSN1 experiments SRF and RD_FCC
This project has received funding from the European Union’s Horizon-INFRA-2023-TECH-01 under GA No 101131435 – iSAS and from the European Union’s Horizon 2020 Research and Innovation programme under GA No 101004730 – I.FAST

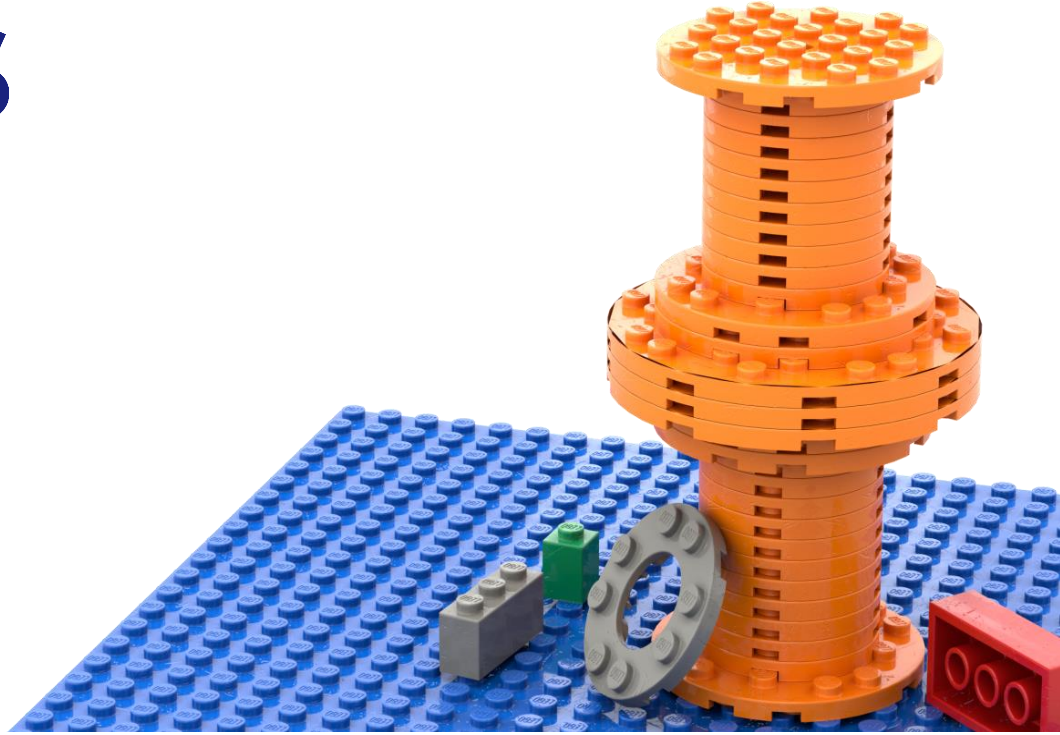
Thank you!

INFN

INFN LNL

Cristian **Pira**

Backup Slides



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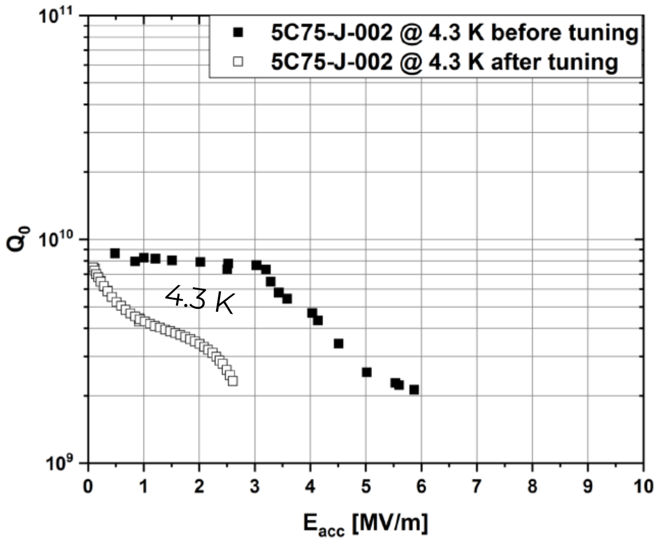
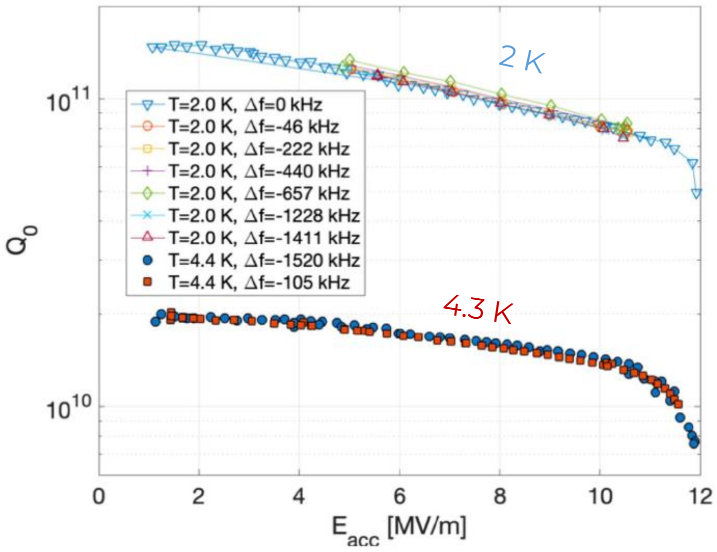
Cavity Tunability



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

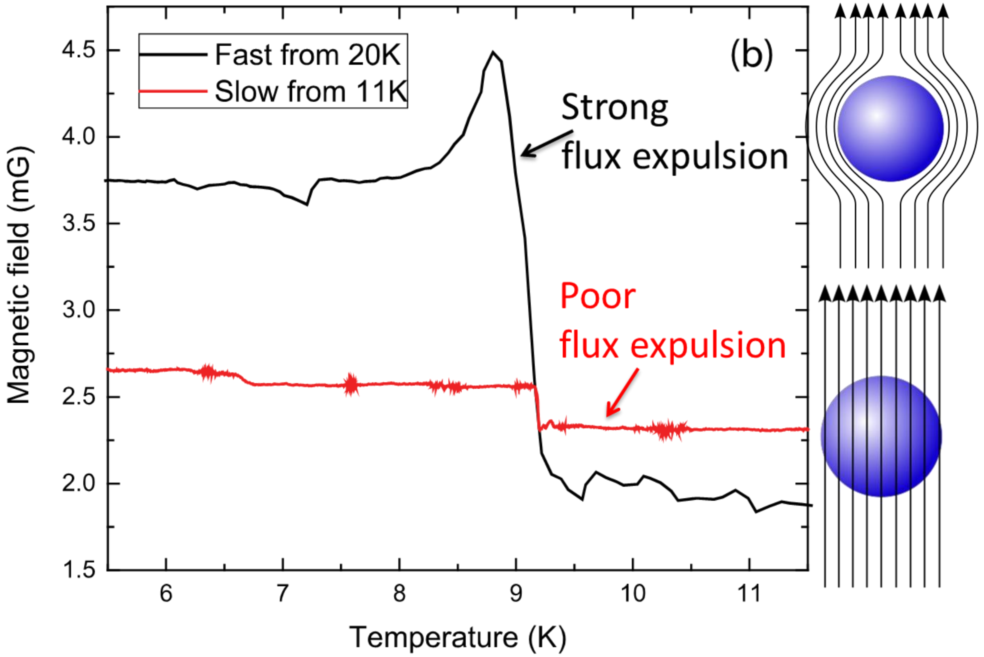
Eremeev, G. (2023). Tunability/robustness of Nb3Sn (No. FERMILAB-SLIDES-23-402-TD). Fermi National Accelerator Laboratory (FNAL), Batavia, IL (United States).

- **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**

Trapped Flux

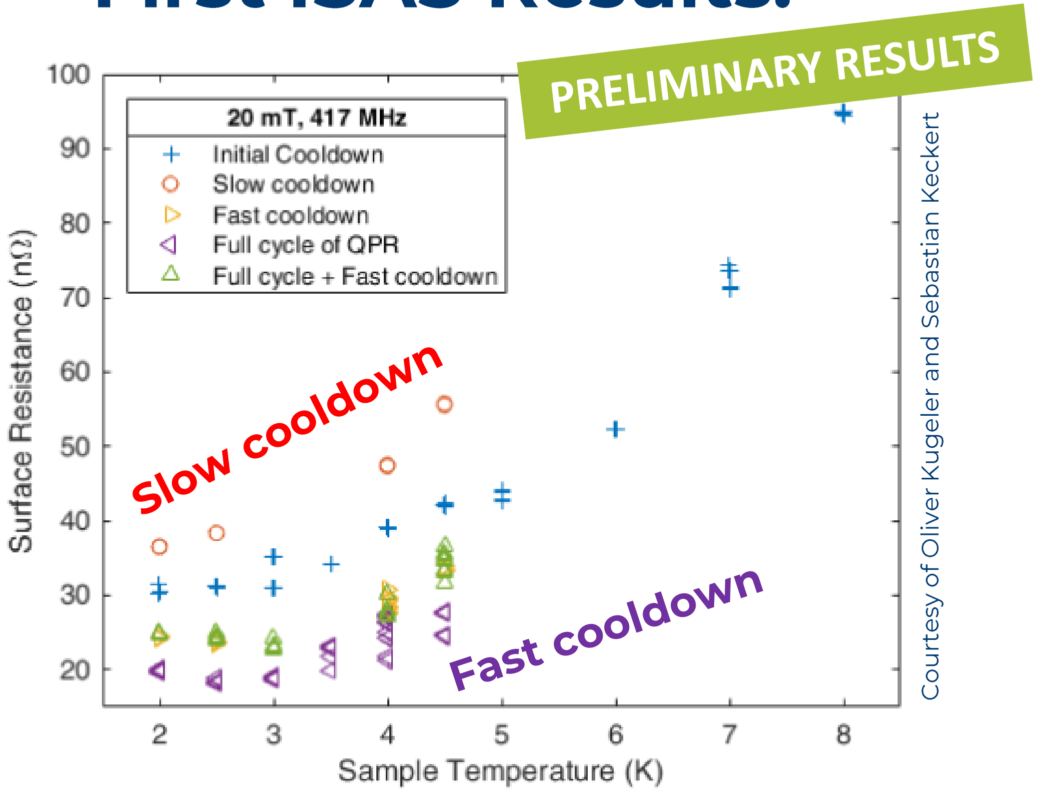
$$Q_0 \propto \frac{1}{R_{BCS} + R_{res} + \eta\, S\, B}$$

Fraction of Trapped Flux — Sensitivity



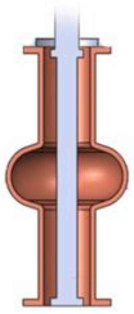
A. Romanenko, A. Grassellino, O. Melnychuk, D. A. Sergatskov, J. Appl. Phys. 115, 184903 (2014)

First ISAS Results:



- Nb_3Sn coating suffer flux trapping
- Cooldown procedure influence Rs

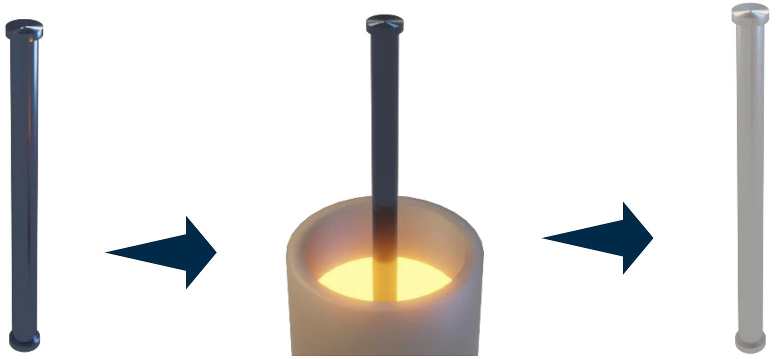
Nb_3Sn coatings: target production



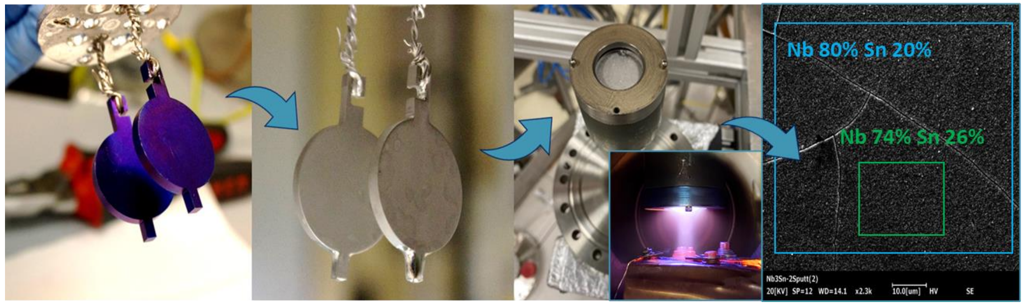
Single target configuration easiest to scale onto elliptical geometry

Nb_3Sn cylindrical targets are not commercially available

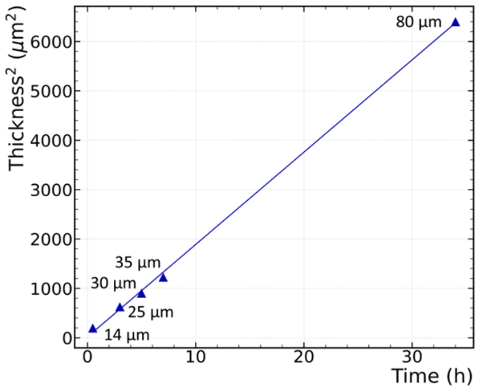
LNL Strategy for Nb_3Sn cylindrical targets production for 6 GHz cavities



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



Proof of concept



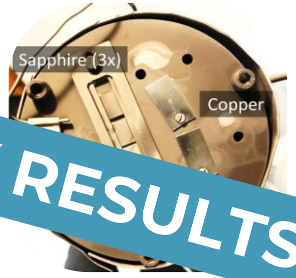
Nb_3Sn **thickness** related to **dipping time**

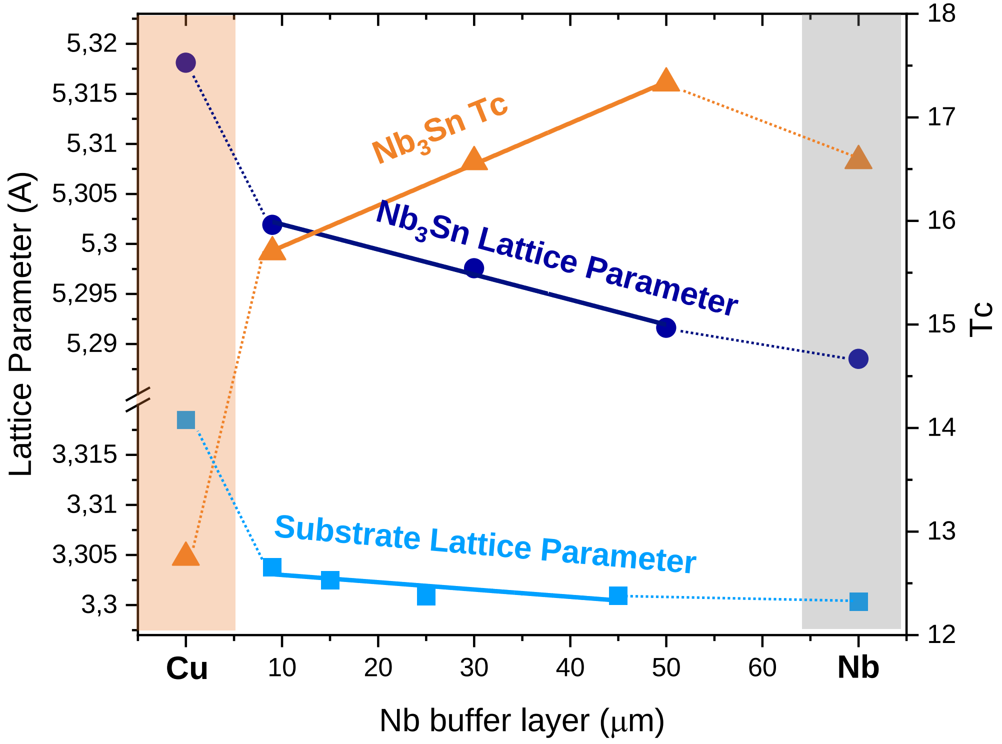
Possible **tin content modulation**

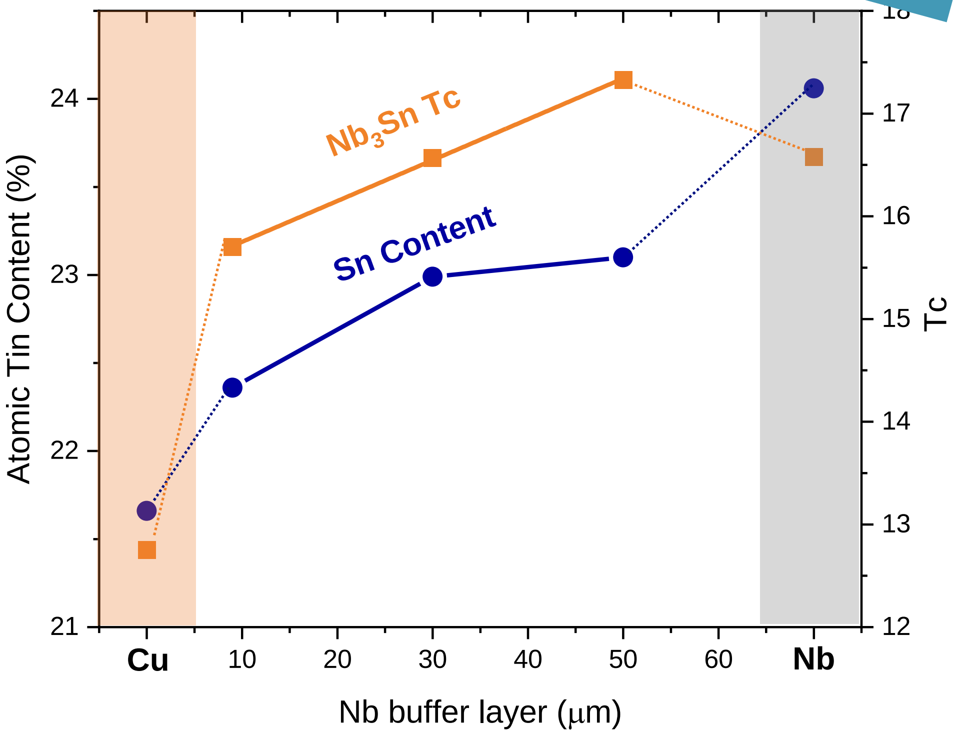
Nb_3Sn coatings

Sputtering parameter optimization

PRELIMINARY RESULTS



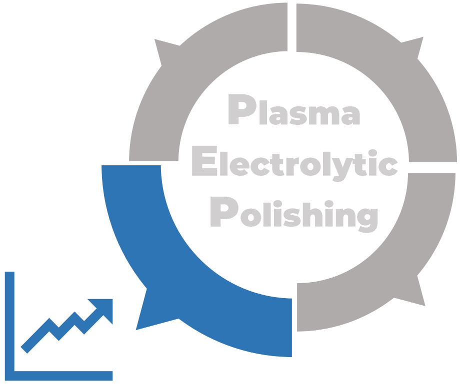




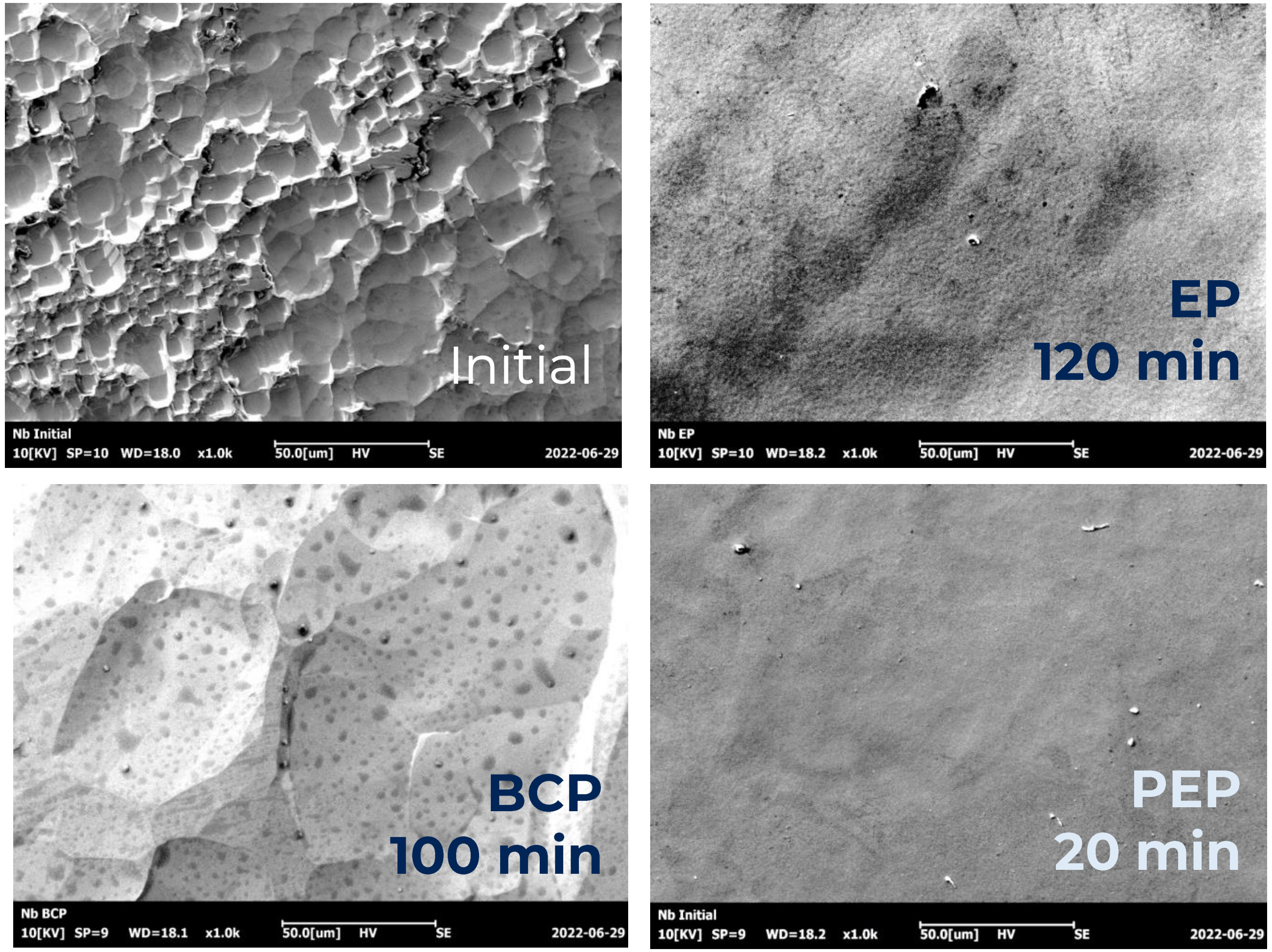
The role of the thick Nb layer is to accommodate the Nb_3Sn lattice parameter

ALD layer could be an alternative to explore

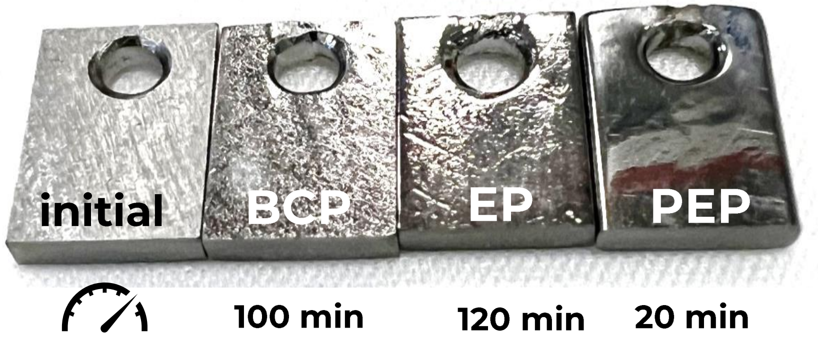
PEP is Efficient



Comparision with EP and BCP



Nb, Magnification **1000x**;
100 μm Removal

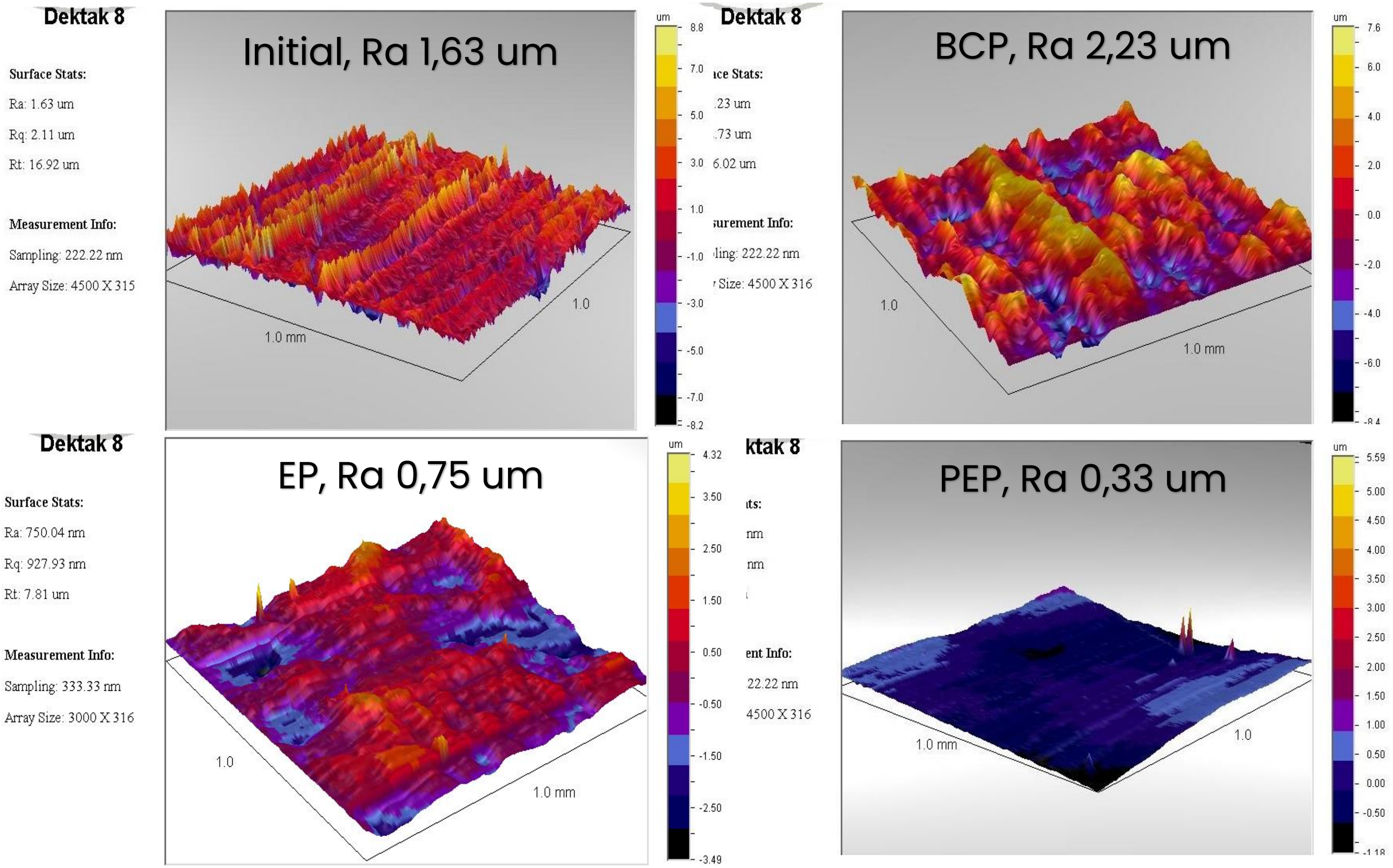


Both micro and macro **roughness is improved significantly**

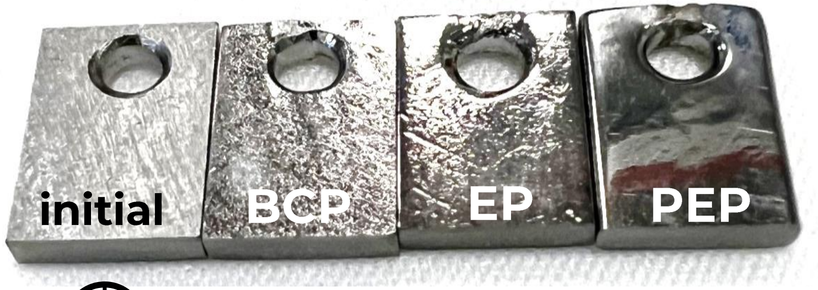
PEP is Efficient

Comparision with EP and BCP

Plasma Electrolytic Polishing



Nb, Magnification **1000x**;
100 µm Removal



	100 min	**120 min**	**20 min**

Both micro and macro **roughness is improved significantly**

Comparison

Copper treatments

Process / parameters	"SUBU5"	EP (3:2)	PEP in "SUBU5"
Solution composition	Sulfamic acid 5 g/l; NH_4-citrate 1 g/l Butanol 50 ml/l; H_2O_2 50 ml/l	85 % H_3PO_4 60 p. 99% n-Butanol 40p.	Sulfamic acid 5 g/l; NH_4-citrate 1 g/l Butanol 50 ml/l; H_2O_2 50 ml/l
Voltage	-	2-6 V	300 V
Current density	-	0,01 – 0,03 A/cm^2	0,25-0,8 A/cm^2
Power draw	-	0,06 – 0,18 W/cm^2	75 – 240 W/cm^2
Removing rate	1,5 µm/min (70±2℃)	0,15-0,5 µm/min (25℃)	20-30 µm/min (80℃)