iFAST

iSAS

SRF cavities
R&D for
FCC-ee

INFN Accelerators European
Strategy Program

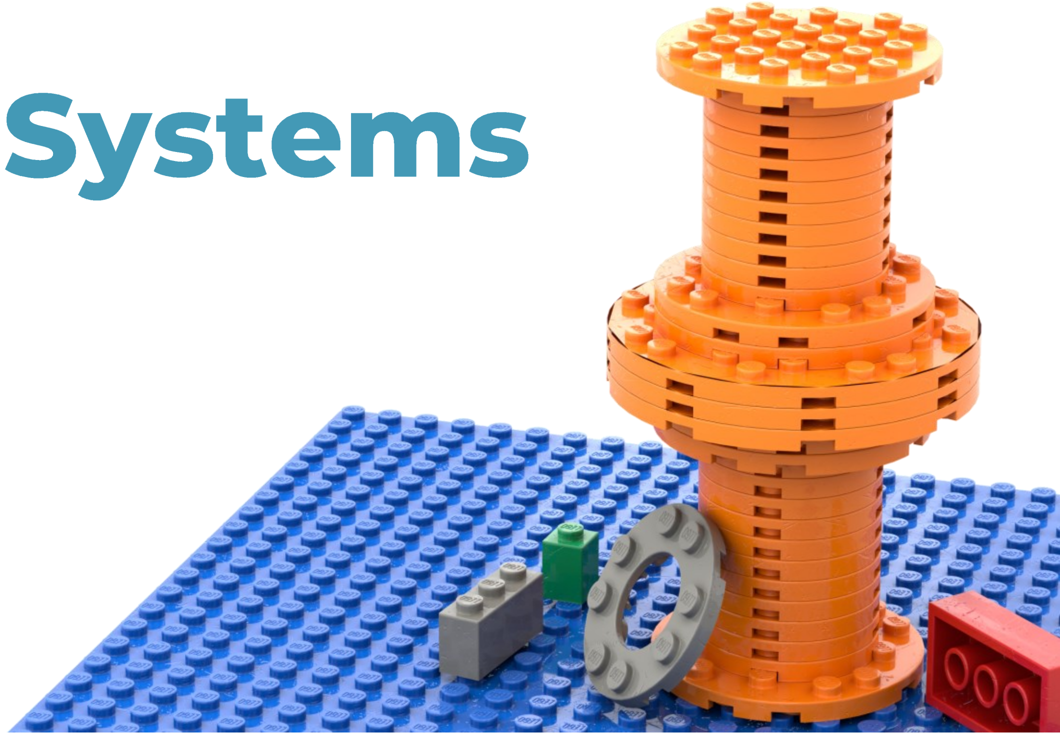
Work supported by INFN CSN5 experiment SAMARA and INFN CSN1 experiments SRF and RD_FCC

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

INFN LNL

Cristian **Pira**

Developments Towards Energy Efficient Superconducting RF Systems



7th Workshop
Energy for Sustainable Science at Research Infrastructures.
September 25th to 27th - Madrid, Spain

Key word: sustainability

European Union United Nations

Save energy

Reduce resources consumption and waste production

Clean and green procedures

Nb_3Sn motivation

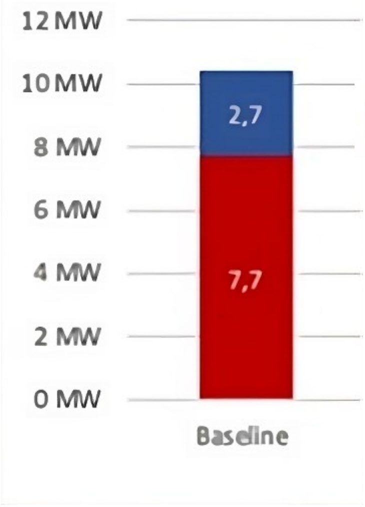
Energy saving** is mandatory for the **next generation accelerators

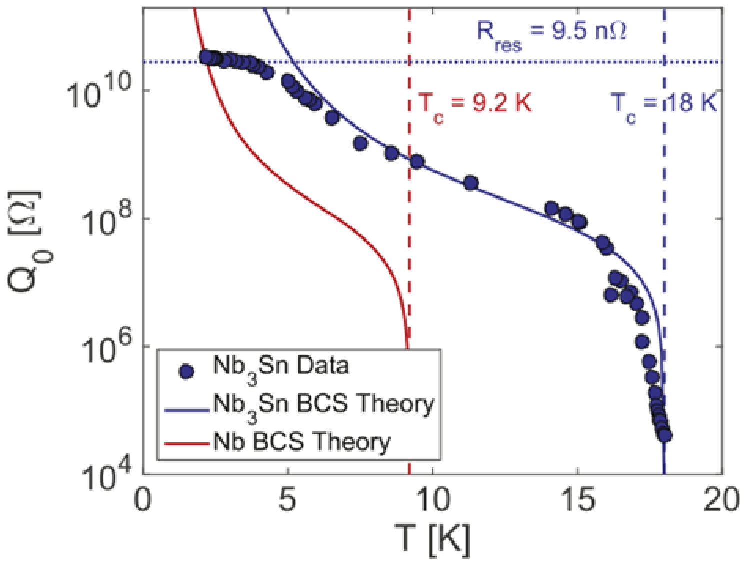
***Cryogenics** is one of the **larger energy cost** in modern SRF accelerators*

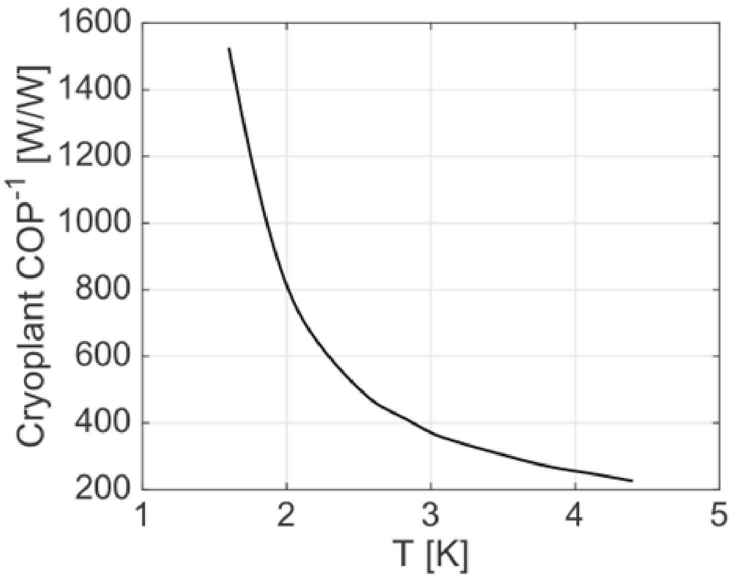
Move from bulk Nb @2K to Nb_3Sn @4.5 K

reduces cryogenic power by a factor of 3

7.5 GeV LINAC new construction





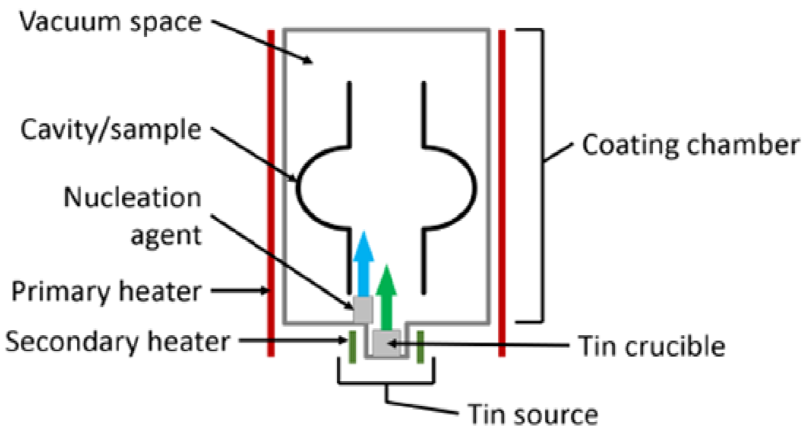


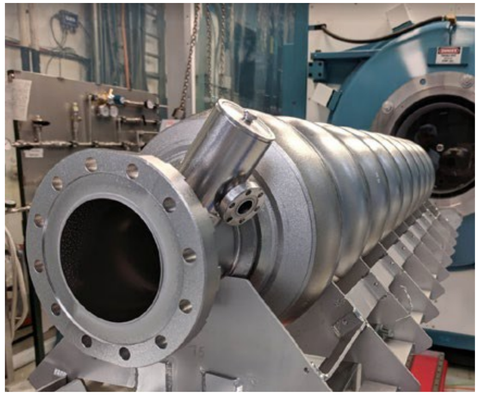
Supercond. Sci. Technol. 30 (2017) 033004

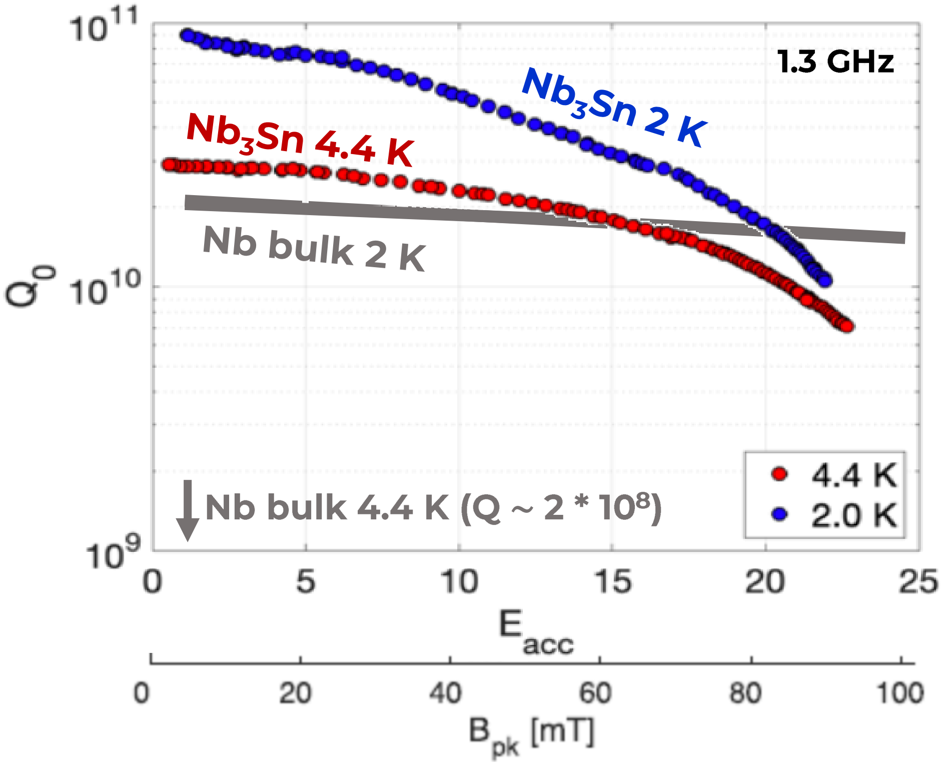
Nb_3Sn state of the art

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

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

SRF cavities R&D for FCC-ee

INFN Accelerators European Strategy Program

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- **Substrate preparation**
- **Target Production/Magnetron Design**
- **Trapped Flux**
- **Tuning**

Collaboration

iFAST WP9

iSAS WP3

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Associated Partners

Jefferson Lab A. M. Valente Feliciano

Informal Partners

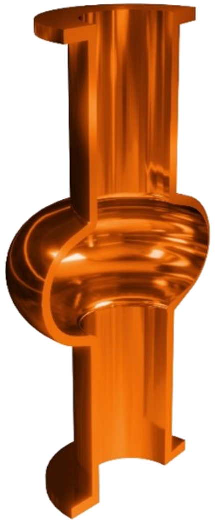
CERN DESY

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

Cavity Forming

Seamless Spinning
Additive Manufacturing

Surface Polishing

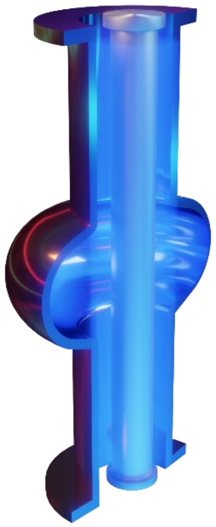


Plasma Electrolytic Polishing

layer by ALD

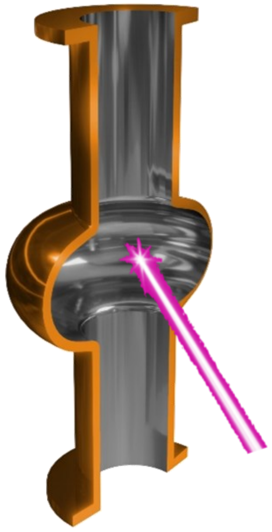
Atomic Layer Deposition

SC film coating



Nb_3Sn on Cu

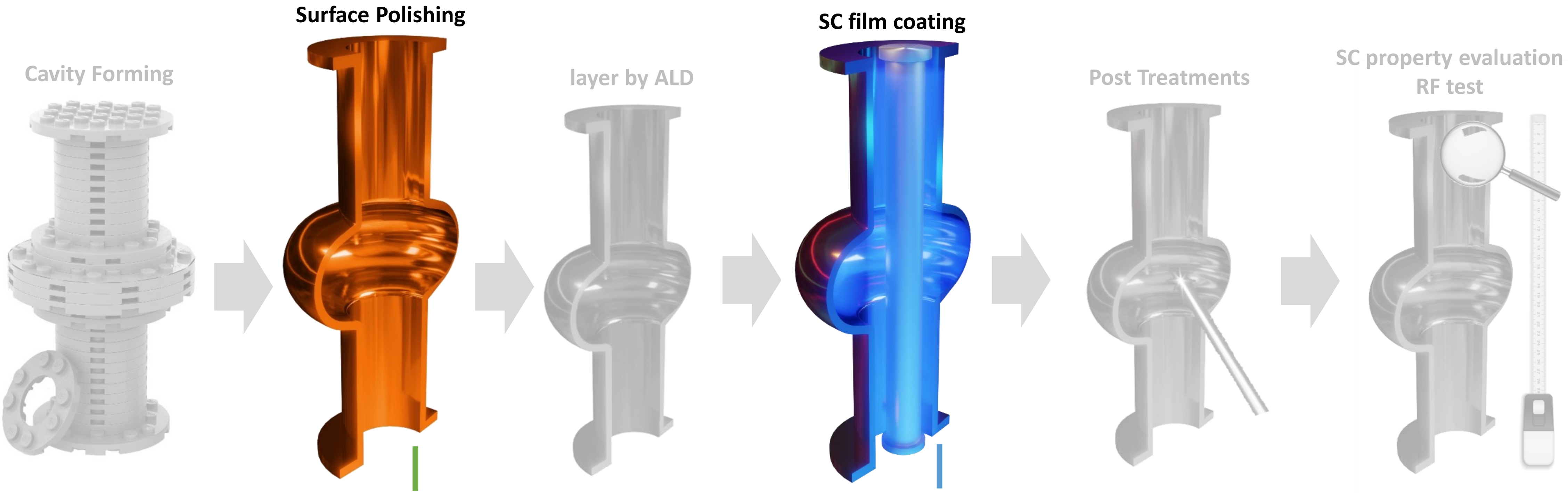
Post Treatments



Laser Annealing
Millisecond Flash Annealing

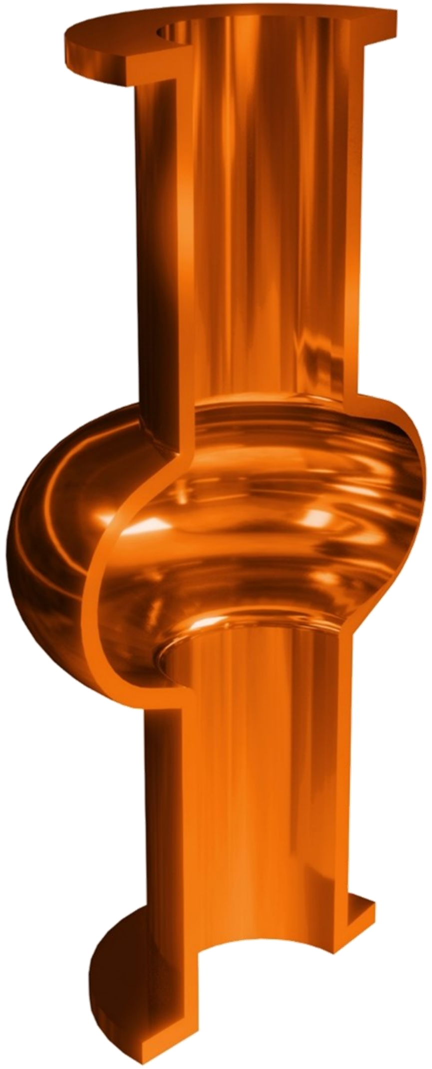
SC property evaluation
RF test

2 Technologies in focus



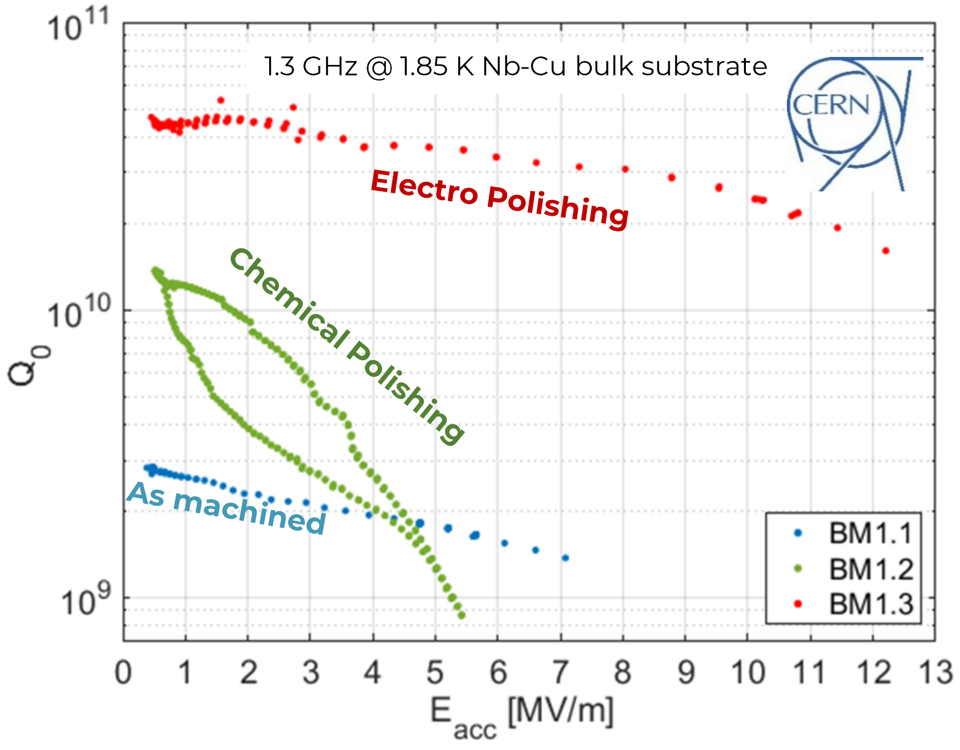
Plasma
Electrolytic
Polishing

Nb_3Sn on Cu
Coatings



Surface Polishing
PEP

Surface Polishing



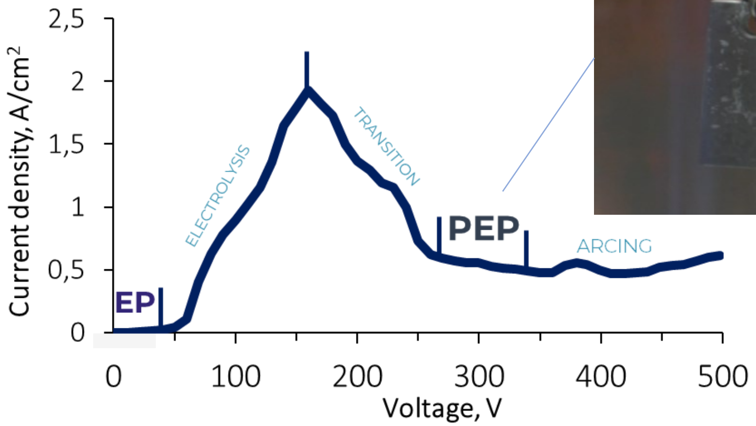
L. Vega Cid, TTC meeting 2022 (elaborated)

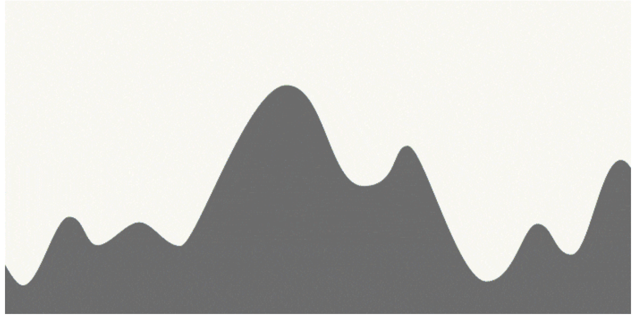
Cu substrate plays a fundamental role in SRF performances

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)

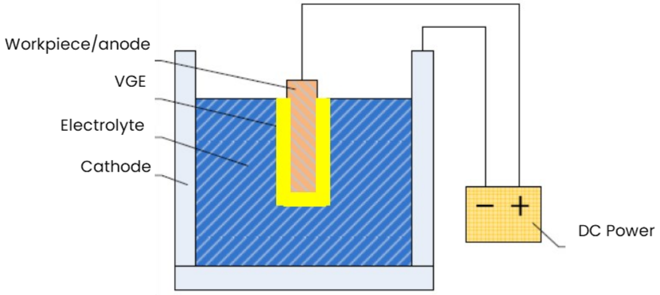
Plasma Electrolytic Polishing PEP Mechanism





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

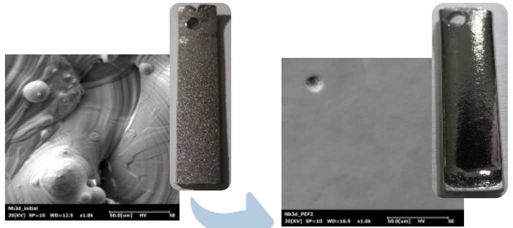
Versatility
Less sensitive to the cathode shape! AM compatible

Plasma Electrolytic Polishing PEP Results

1x Nb 3x Cu

Solution Patents by INFN

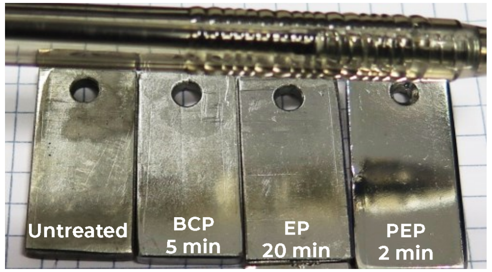
Additive Manufacturing



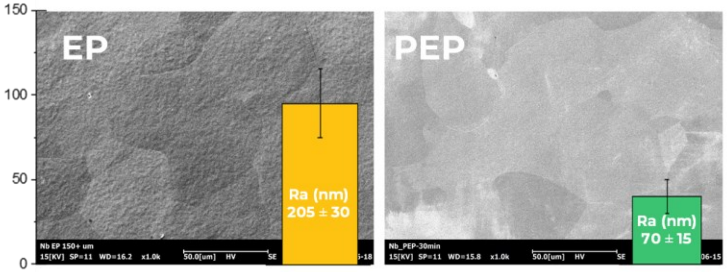
Initial
Ra= 13 µm

PEP 30 min
Ra= 1.5 µm

Planar samples



6.5 µm removed



150 µm removed in ~ 5 h

150 µm removed in ~ 40 min

QPR Samples

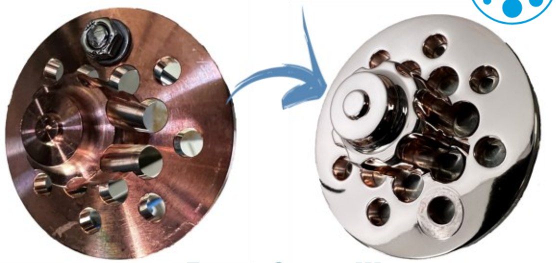
Nb QPR polishing optimizaztion on-going

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

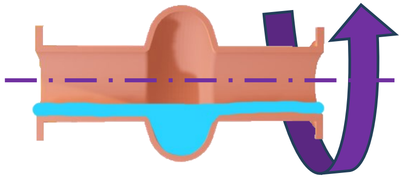
30 A (100 cm2 → 1.3 GHz ~ 300 A)

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

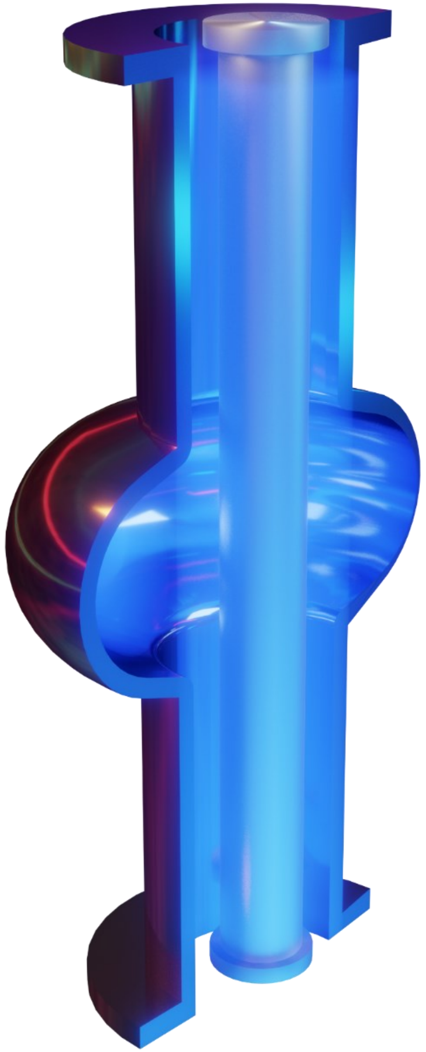
Explore alternative set-up to reduce Process Power

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



Next Steps:

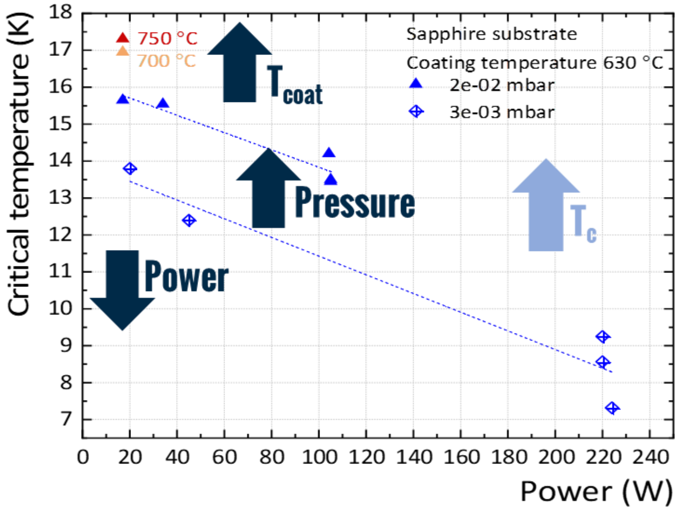
- Test **reproducibility**
- Validate with **RF Test** *(Nb coating @CERN)* → February 2025

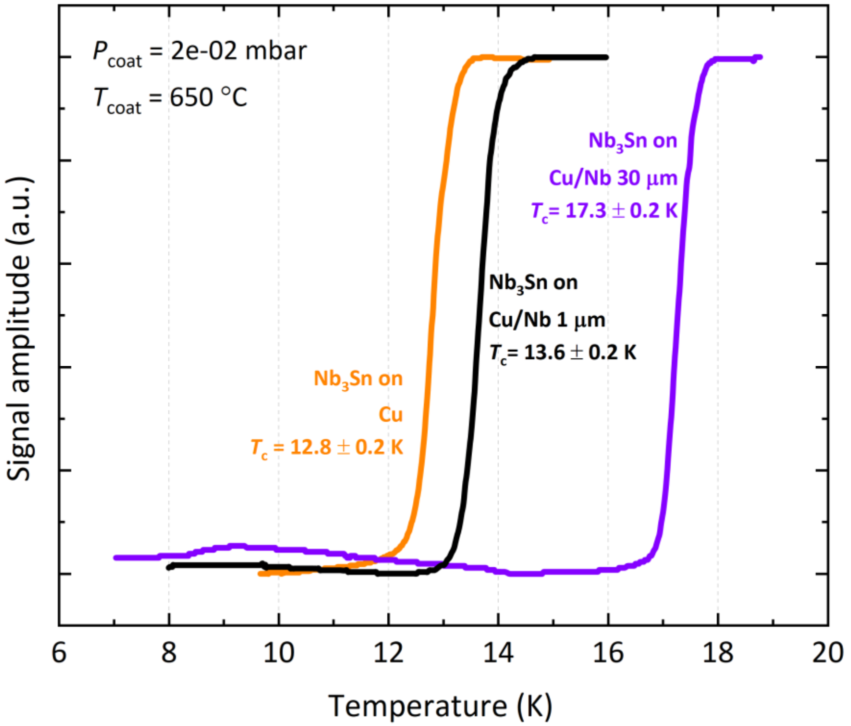


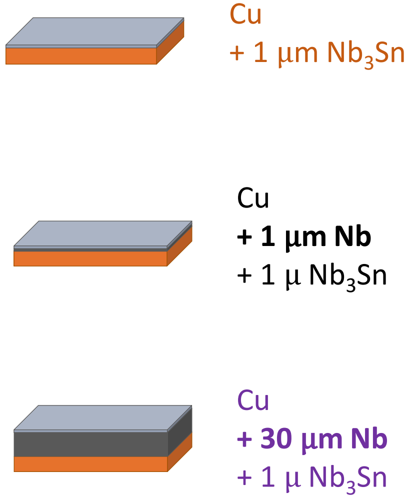
Nb_3Sn on Cu
Coatings

Nb_3Sn Coatings

Long R&D phase on PVD Parameter Optimization







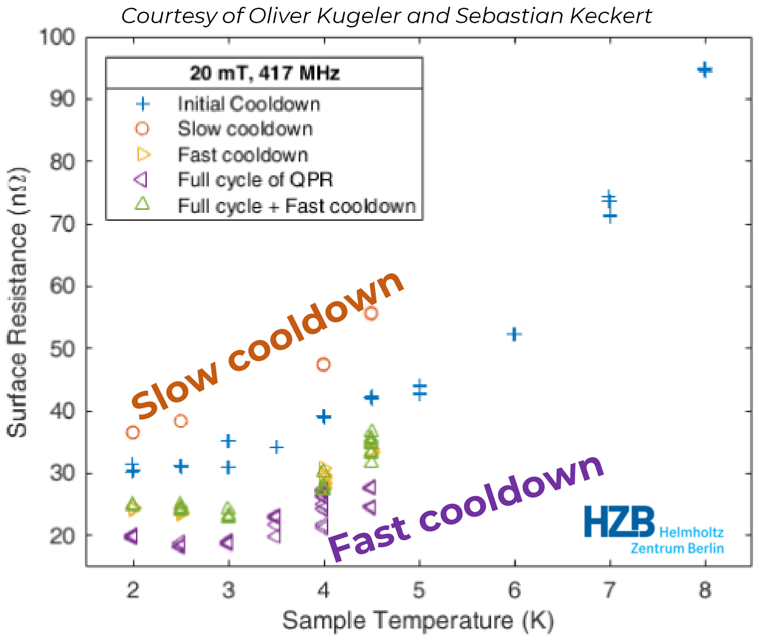
Optimized Coating Recipe

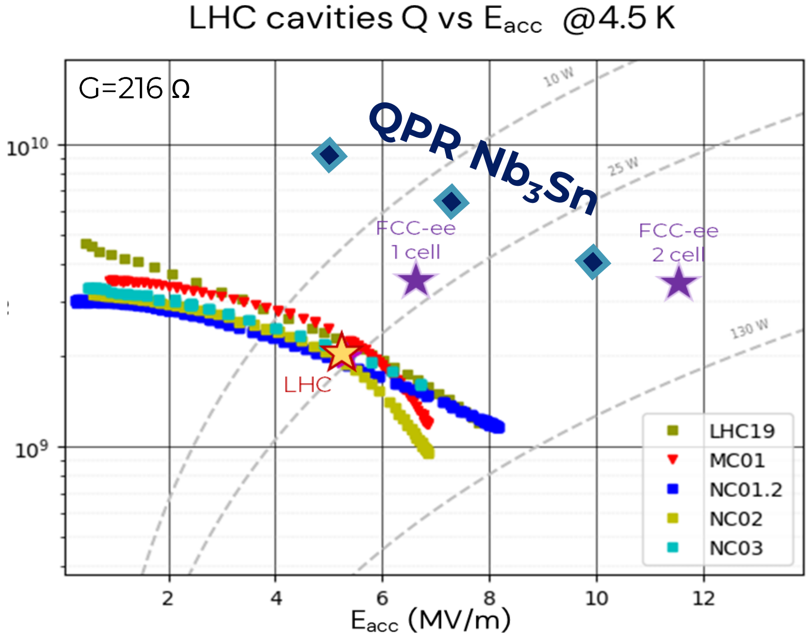
- Coating Parameters:
  - Pressure = $2*10^{-2}$ mbar
  - Power = 16 W
  - T substrate ≥ 600 C
- **Nb Thick Barrier Layer > 30 um**

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

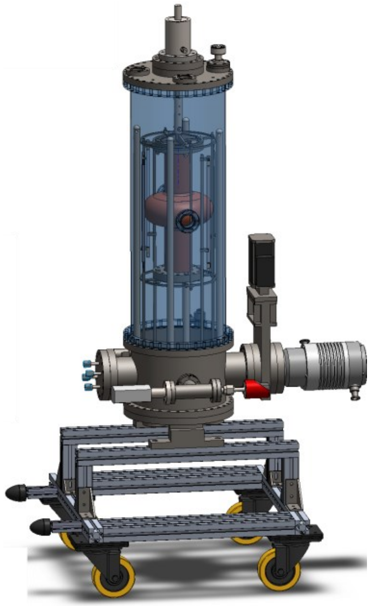
- **Nb_3Sn coating suffer flux trapping**
- **Cooldown procedure influence Rs**

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

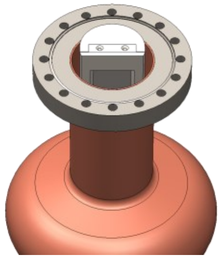
Nb_3Sn Path to Final Prototype



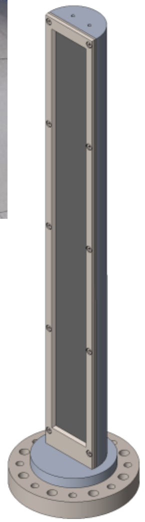
Nb_3Sn on bulk Nb to validate coating performances (2025)
on 1.3 GHz Elliptical Cavities (2025)

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)



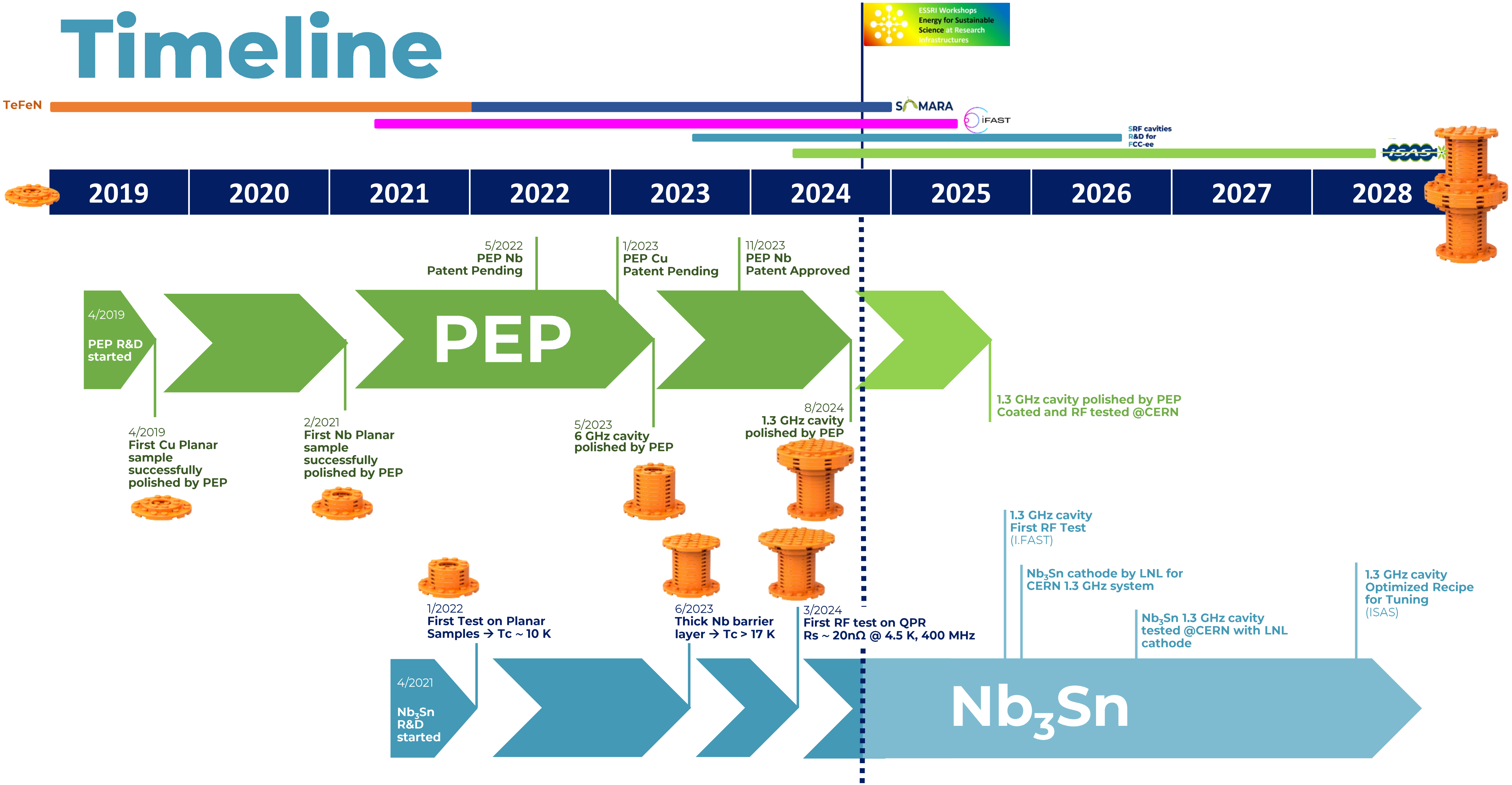
- **1.3 GHz Vacuum system ready**
- **Magnetron source commissioned**



In parallel:

- *Study on alternative buffer layer* (cea)
- *Study on flux trapping* (UKRI Science and Technology Facilities Council; HZB Helmholtz Zentrum Berlin)

Timeline


ESSRI Workshops
Energy for Sustainable Science at Research Infrastructures
TeFeN
SMARA
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

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Thank you!