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

SAMARA
INFN CSN5 Experiment

RD_FCC
INFN CSN1 Experiment

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

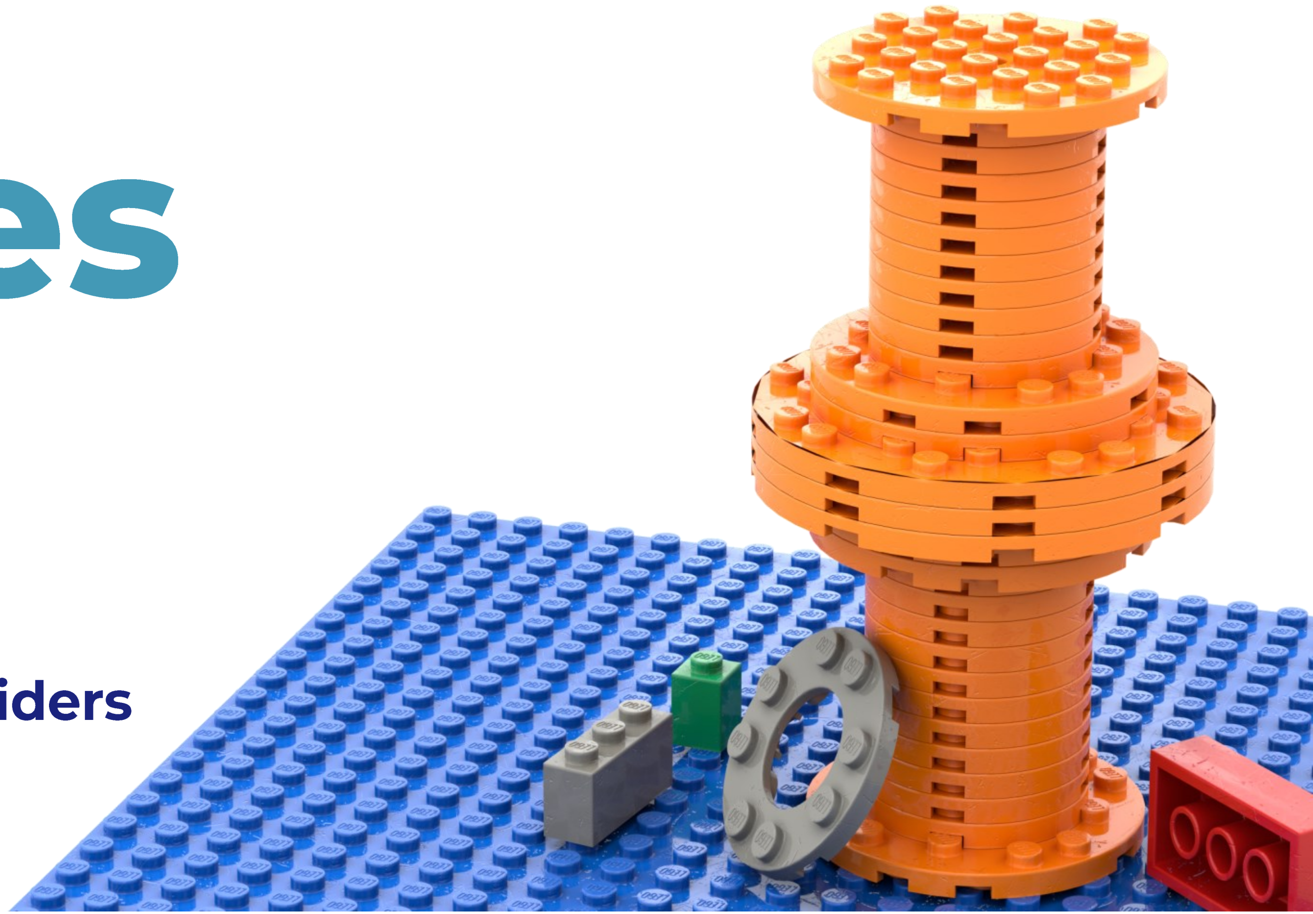
INFN LNL

Cristian **Pira**

Thanks to Walter Venturini and Vittorio Parma

for helping me to understand the new RF layout of FCC-ee.

RF Cavities



Workshop on FCC-ee and Lepton Colliders

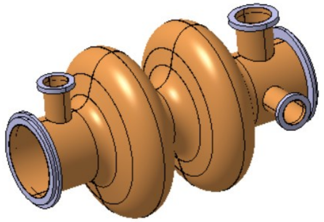
LNF, 22 January 2025

Outline

FCC-ee SRF cavities layout

R&D Bulk Nb 800 MHz

R&D Nb on Cu 400 MHz



INFN LNL present SRF R&D projects focused on FCC-ee

SAMARA
INFN CSN5 Experiment

INFN R&D started to explore PEP and Nb3Sn coatings in a CSN5 experiment

iFAST iSAS

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

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

RD_FCC
INFN CSN1 Experiment

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

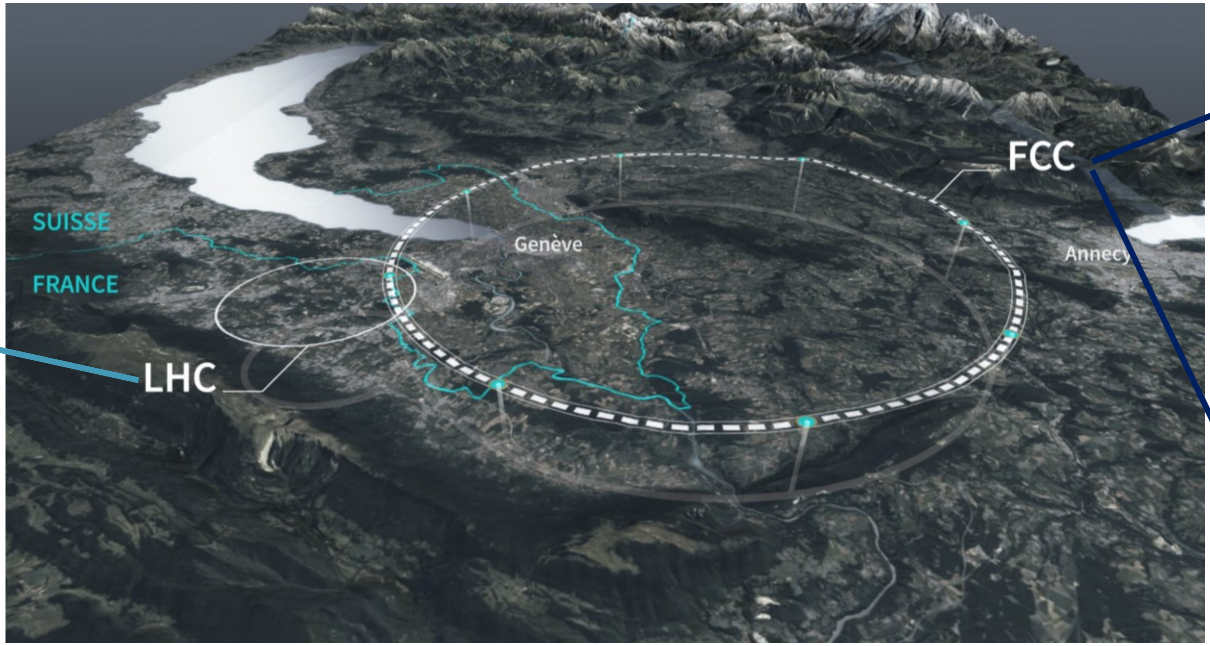
International Partners:

CERN, cea, UKRI Science and Technology Facilities Council, HZB Helmholtz Zentrum Berlin, HZDR Helmholtz Zentrum Dresden Rossendorf, Universität Siegen, IJCLab Irène Joliot-Curie, ELÚ, Rīgas Tehniskā Universitāte, Jefferson Lab, Fermilab, Piccoli

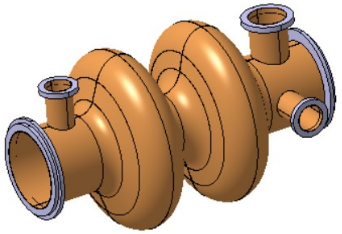
SRF CAVITIES: LHC VS FCC-ee

16 x

Nb on Cu
400 MHz
1-cell



256 x



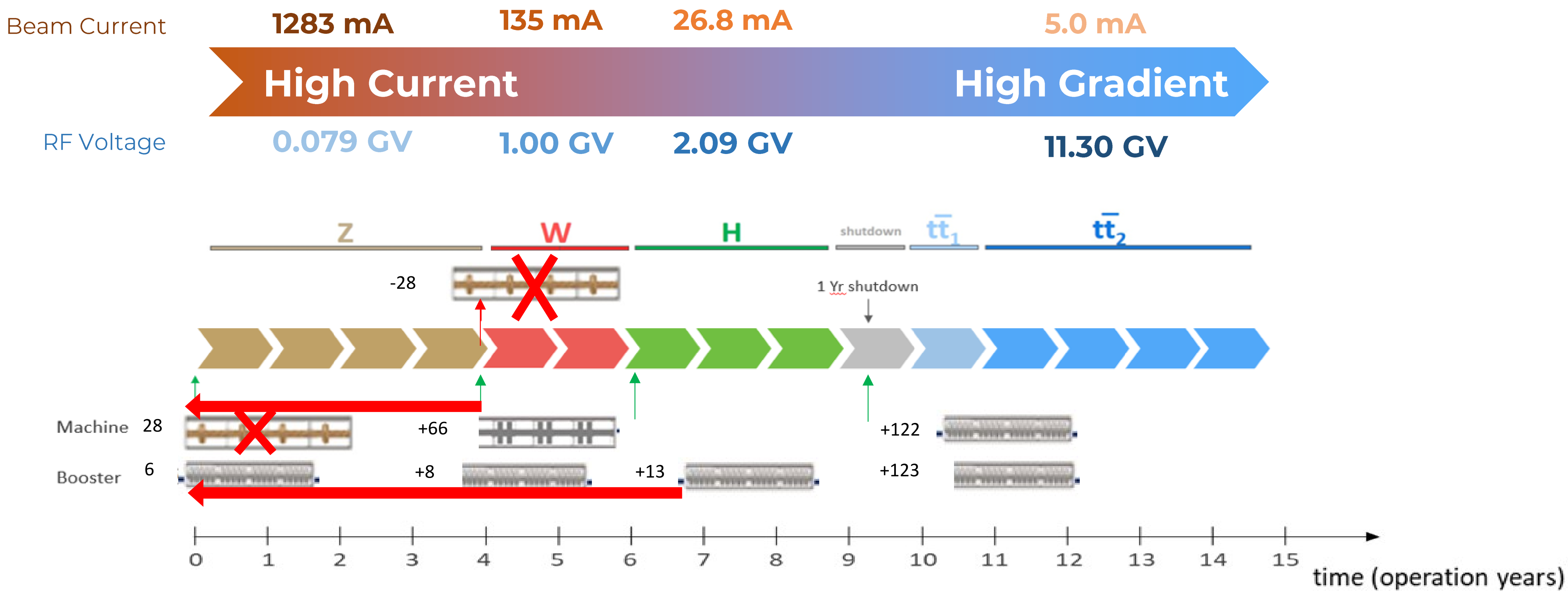
Nb on Cu
400 MHz
2-cell

868 x

Nb bulk
800 MHz
6-cell

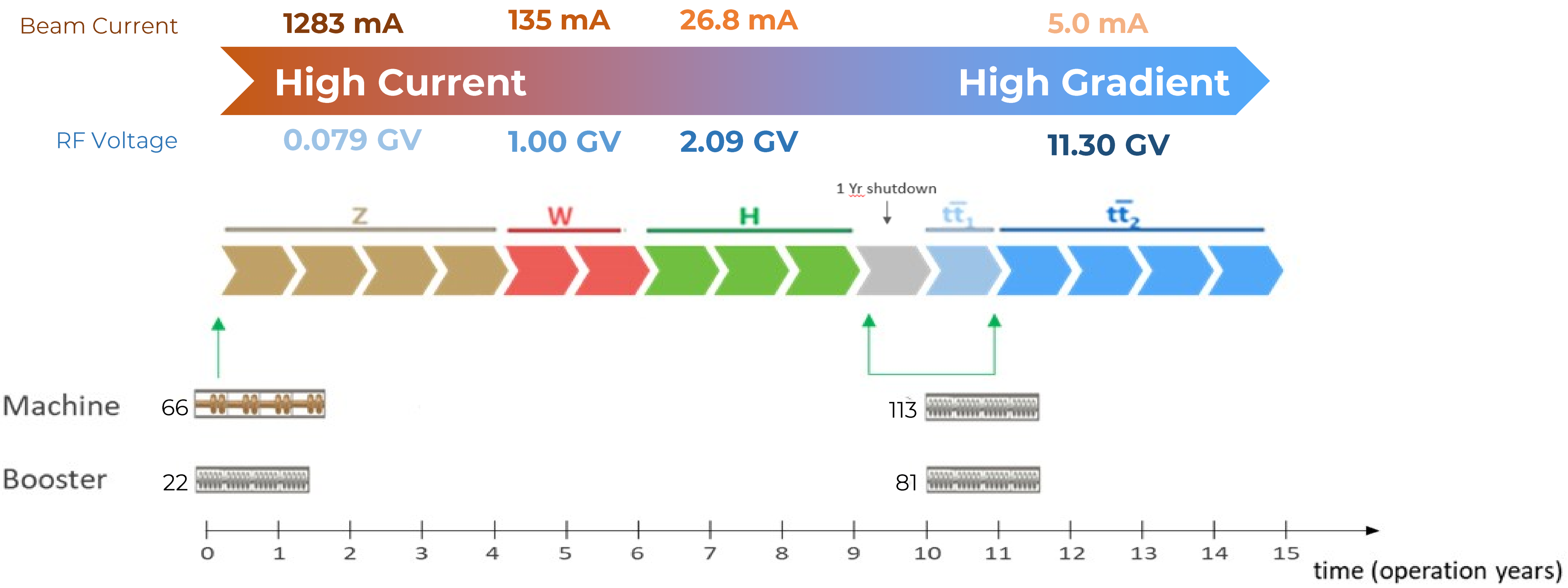
SRF is critical for the success of the FCC-ee machine

Installation Sequence



New simplified baseline adopted in late 2024

New Installation **Sequence**



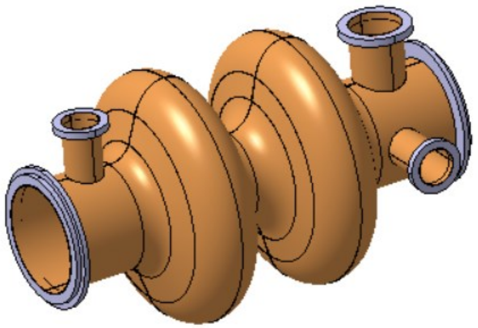
New simplified baseline adopted in late 2024:

- reducing the type of cavities from 3 to 2
- 20% reduction of total installed cryomodules: 351 → 283
- installation of all Z, W, H cavities at t=0 → *possibility of switching between set-ups without hardware changes*

2 Different Type of Cavities

Z, W, H

400 MHz 2-cell cavity
Niobium thin film on Copper



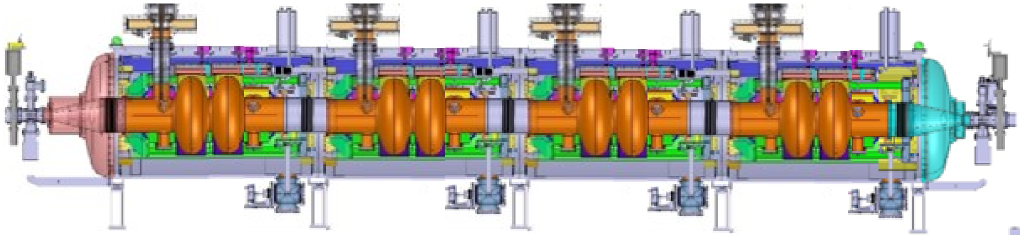
X 264

Operation at 4.5 Kelvin

Max. Accelerating gradient E_{acc} = 10.6 MV/m

Quality factor $Q_0 = 2.7 \times 10^9$

X 66



400 MHz cryomodule, ~12 m. long

ttb, booster

800 MHz 6-cell cavity
Bulk Niobium

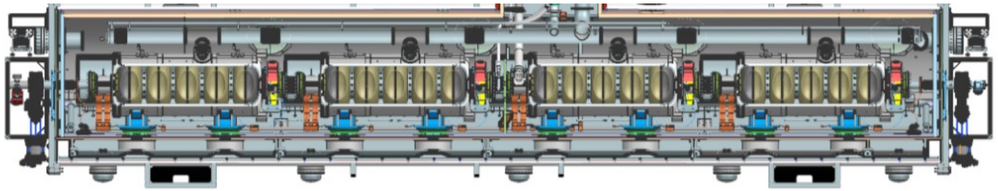
X 868

Operation at 2 Kelvin

Max. Accelerating gradient E_{acc} = 19.9 MV/m

Quality factor $Q_0 = 3.0 \times 10^{10}$

X 217 (114 collider + 103 booster)



800 MHz cryomodule, ~10 m. long

Courtesy of Walter Venturini (CERN)

FCC machine specs (surface resistance and peak fields)

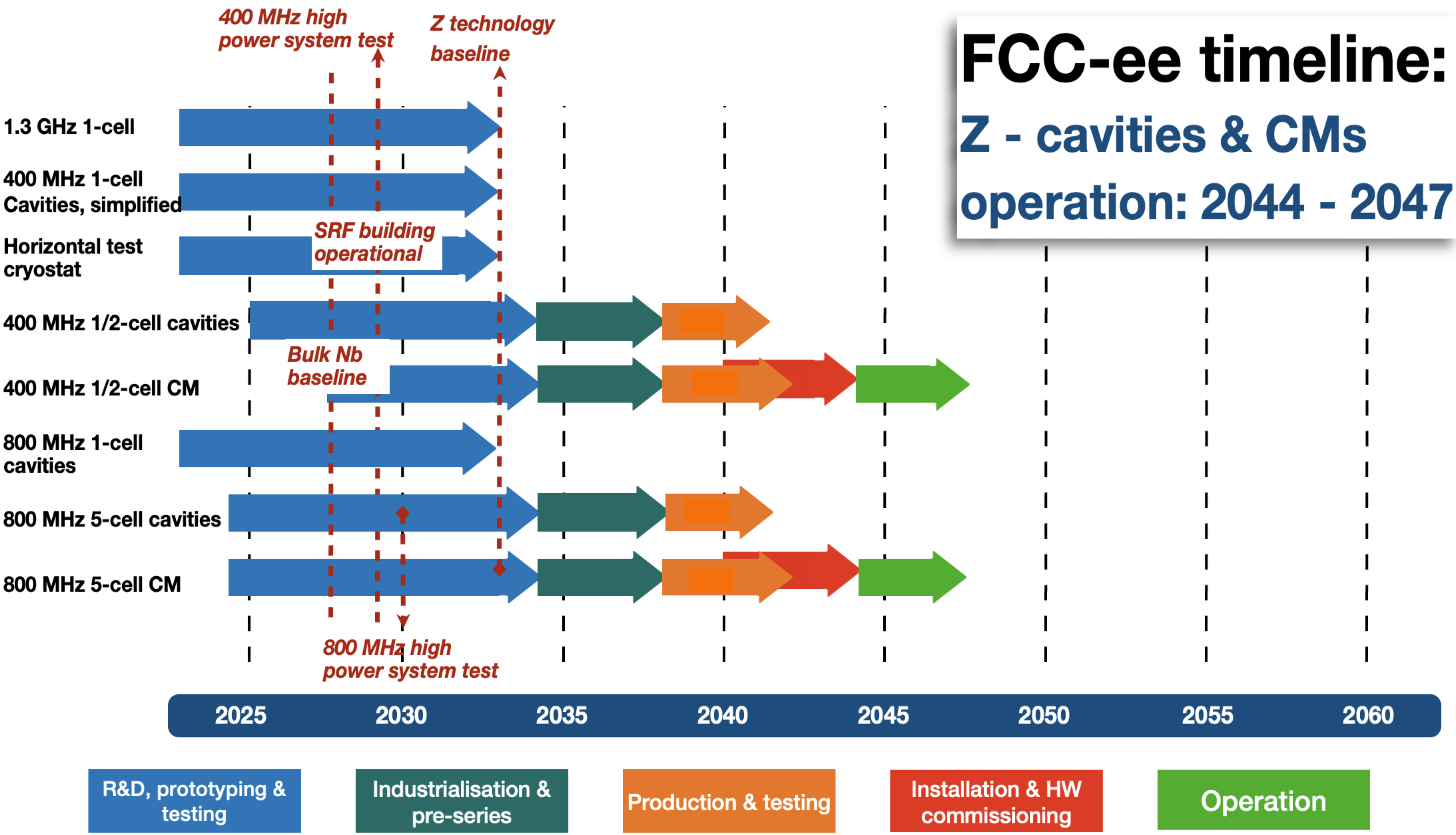
Quantity	Booster (800 MHz)	Z (400 MHz, 4K)	W(400 MHz, 4K)	H(400 MHz, 4K)	ttb (800 MHz, 2K)
Q_o	$3{\cdot}10^{10}$	$2.7{\cdot}10^{9}$	$2.7{\cdot}10^{9}$	$2.7{\cdot}10^{9}$	$3{\cdot}10^{10}$
E_a(MV/m)	6.2→ 20.1	3.8	10.6	10.6	20.1
R_s (av nΩ)	**9.1**	**89**	**87**	**87**	**9.1**
B_{peak}(mT)	87.2	20.4	56.6	56.6	87.2
E_{peak}(MV/m)	41.2	8.4	21.2	21.2	41.2

NB: 4K and 2K are indicative

- Compared with state of the art for bulk Nb and Nb/Cu:
  - B_{peak} < 100 mT (no High Field Q-Slope) in all cases (120 mT demonstrated in Nb/Cu)
  - E_{peak} is quite relaxed
- Fields are limited by RF power: we don't need ultra high fields (x 2 margin to state of the art)
- **But Rs is challenging** (in particular for Nb on Cu)
- Is 800 MHz with Nb/Cu a possibility? Harder but not so crazy seen the longer time scale

Courtesy of Walter Venturini (CERN)

FCC-ee timeline:
Z - cavities & CMs operation: 2044 - 2047



Courtesy of Walter Venturini (CERN)

800 MHz 6-cell cavity Bulk Niobium

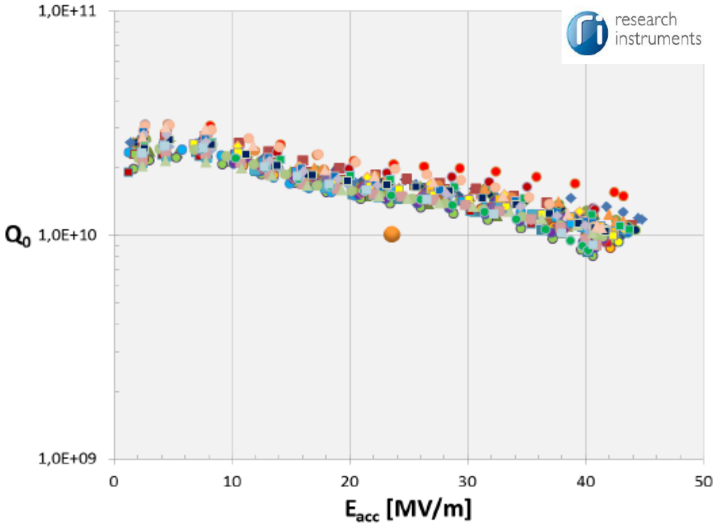
Nb bulk state of the art

European XFEL

768 Nb bulk TESLA type elliptical 1.3 GHz cavity

Accelerating Gradient up to 40 MV/m

(closer to Nb theoretical limits)

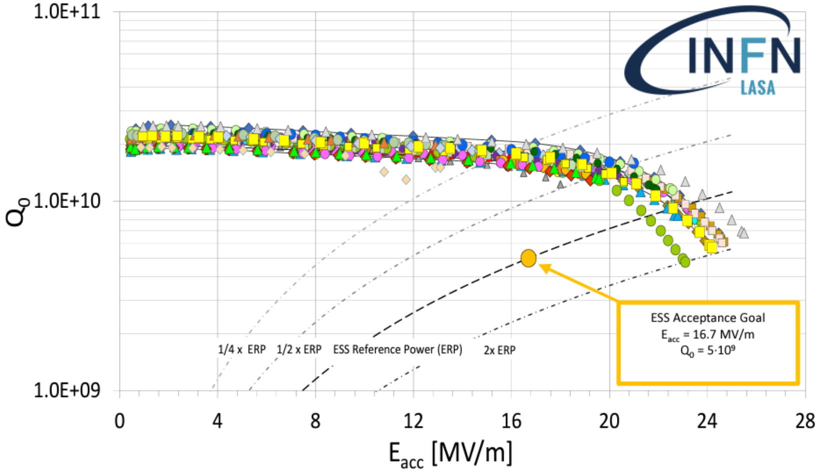


EUROPEAN SPALLATION SOURCE

Technology already transferred at lower frequency (704.4 MHZ)

FCC-ee 800 MHz specs: $Q=3 \cdot 10^{10}$ @ 20 MV/m

Performances not far from FCC requirement



Courtesy of L. Monaco (INFN LASA)

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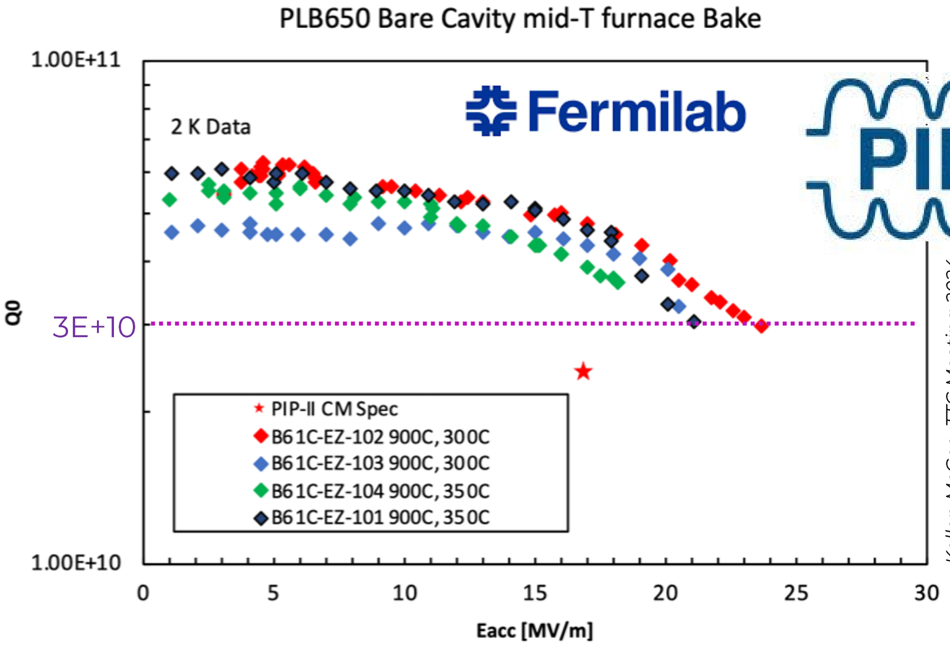
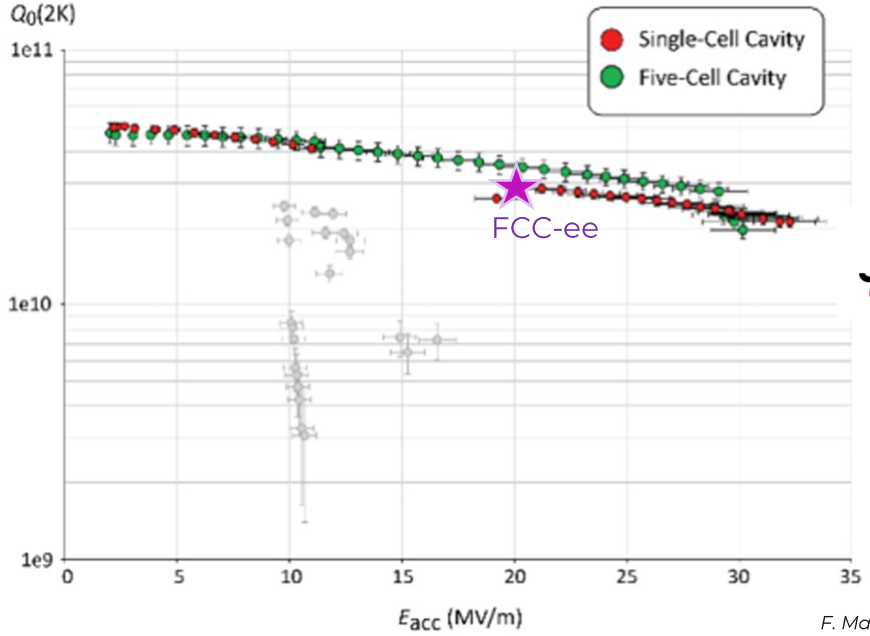
Nb bulk current R&D for FCC

Thermal Treatments studies ongoing @Fermilab on PIP-2 650 MHz cavities

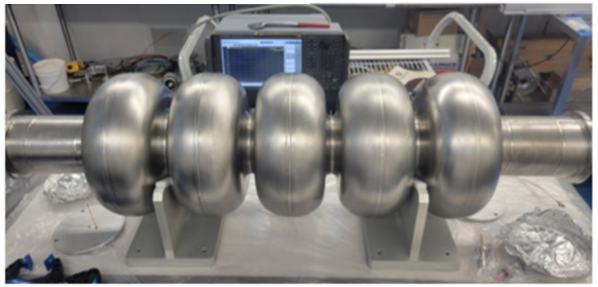


Kellen McGee, TTC Meeting 2024



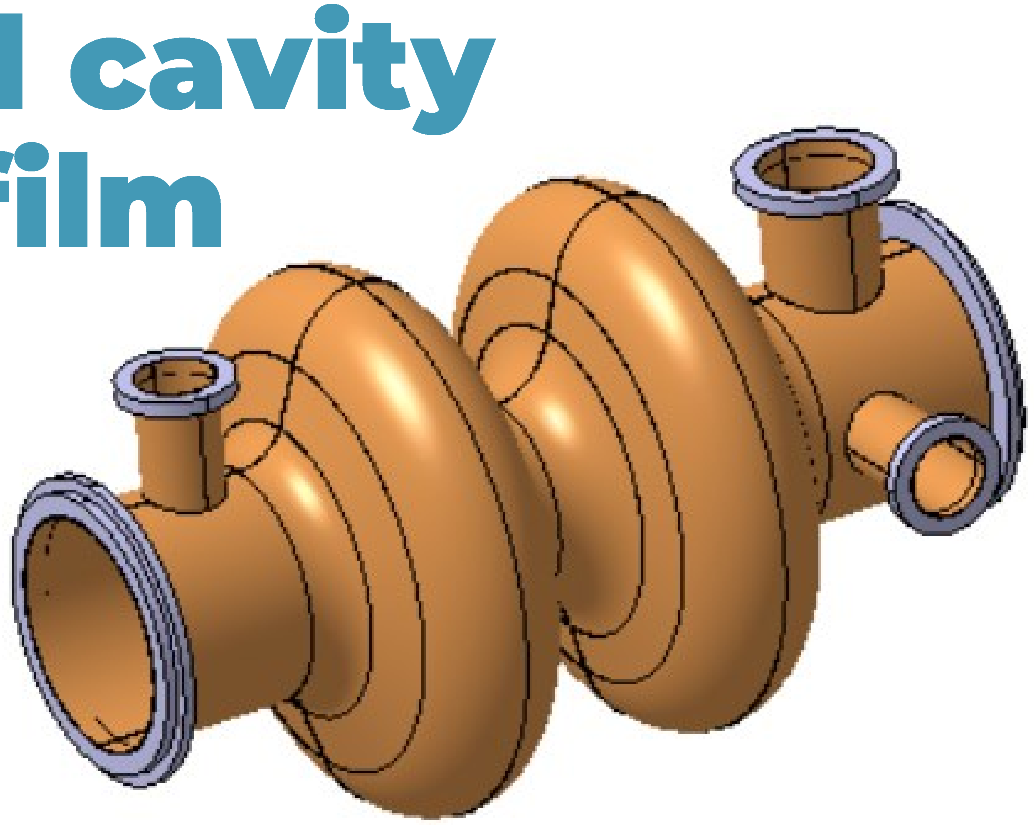
F. Marhauser, IPAC 2018

Jefferson Lab



First 5-cell 800 MHz Prototype produced @Jlab already meets FCC specifications

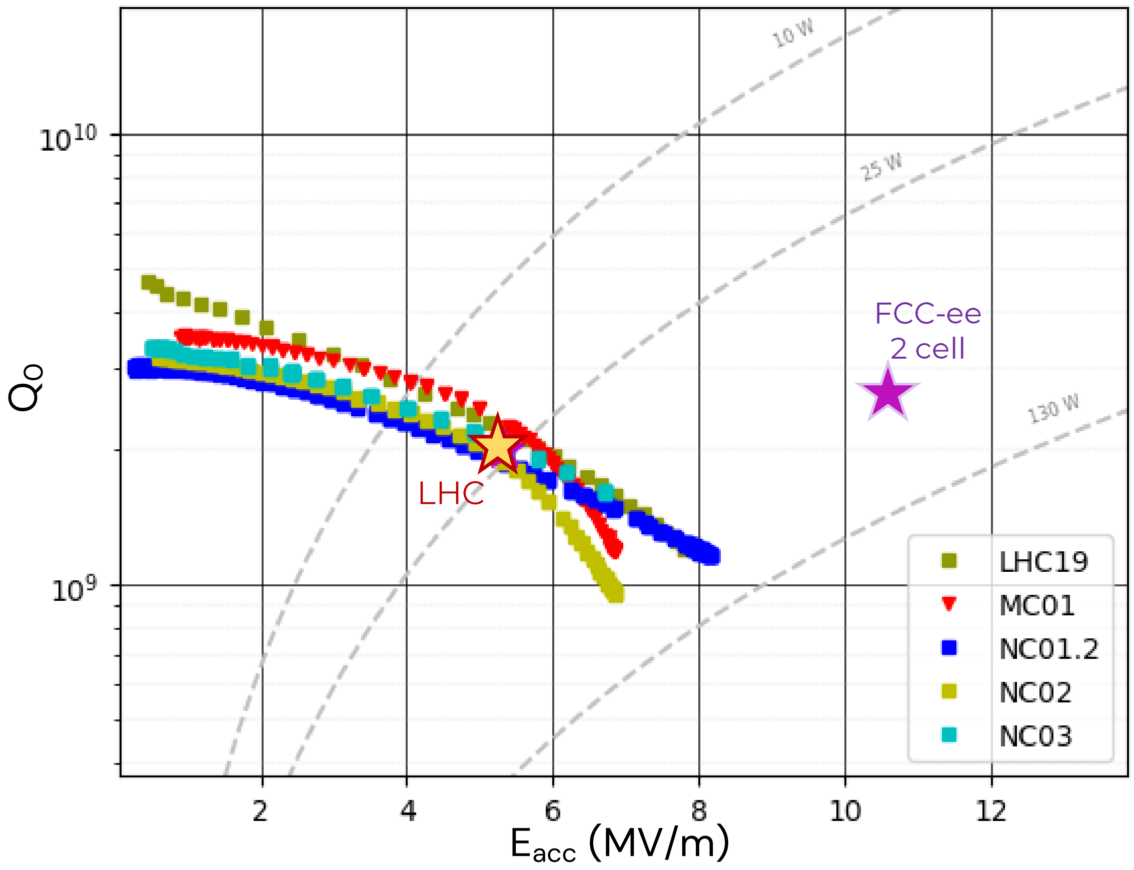
400 MHz 2-cell cavity Niobium thin film on Copper



400 MHz state of the art

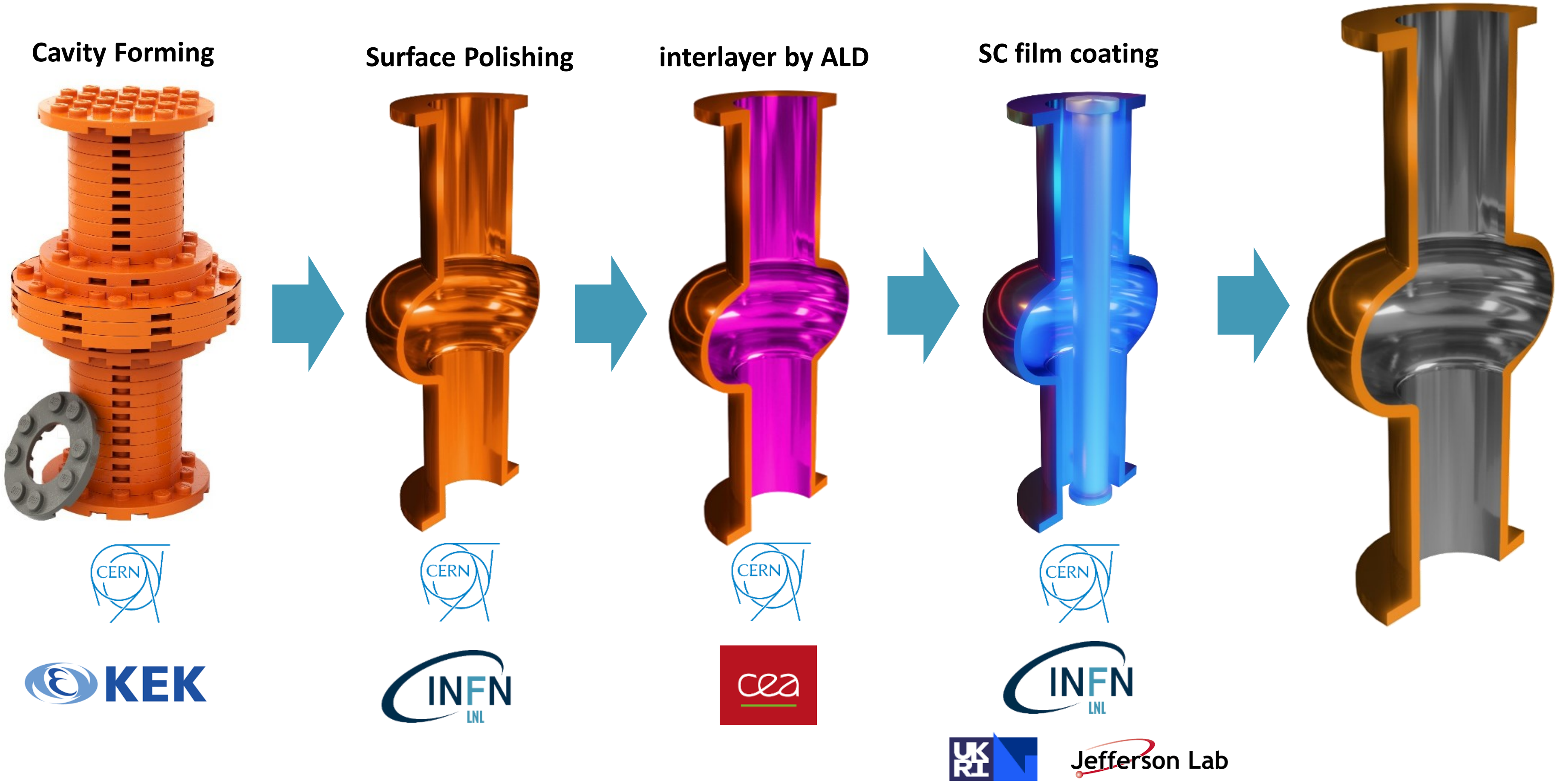
FCC-ee requires
higher cavities performances than LHC

LHC cavities Q vs E_{acc} @4.5 K

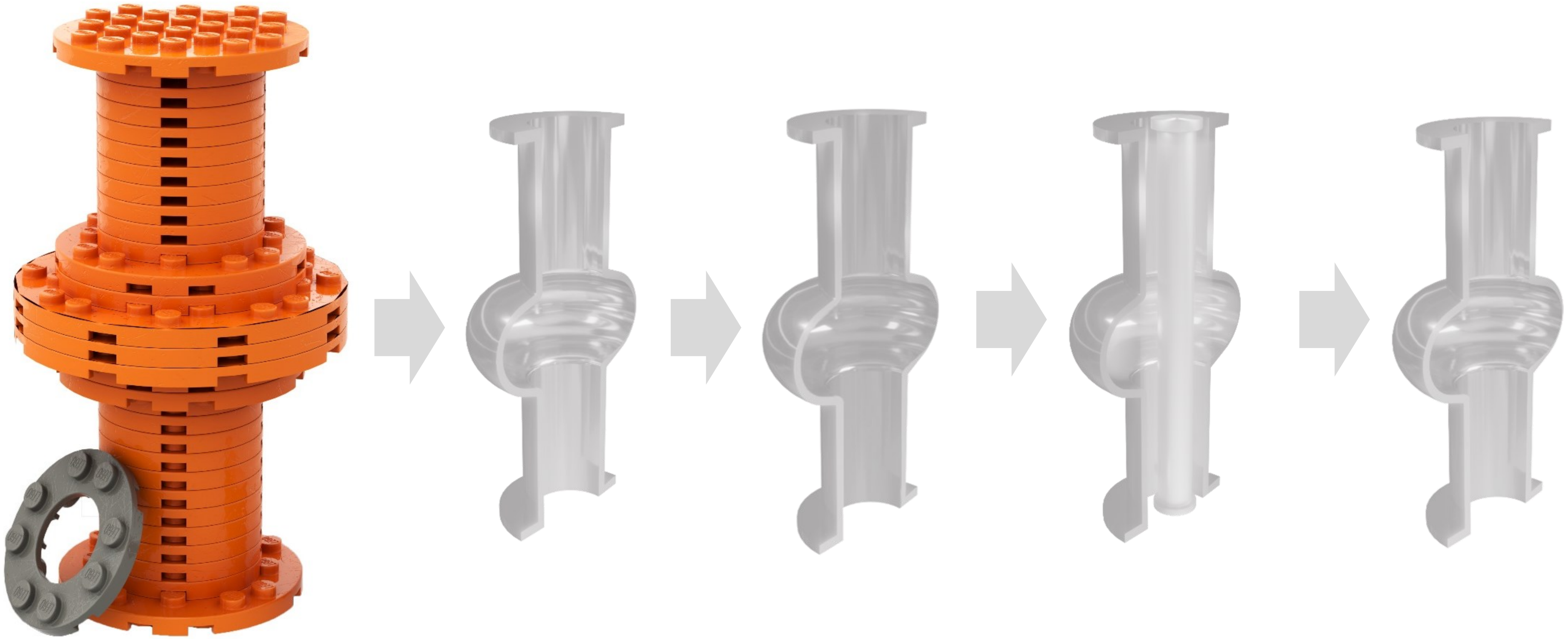


Graph from Carlota Pereira Carlos, FCC week 2023

R&D activity covers
all cavity production chain



Cavity Forming



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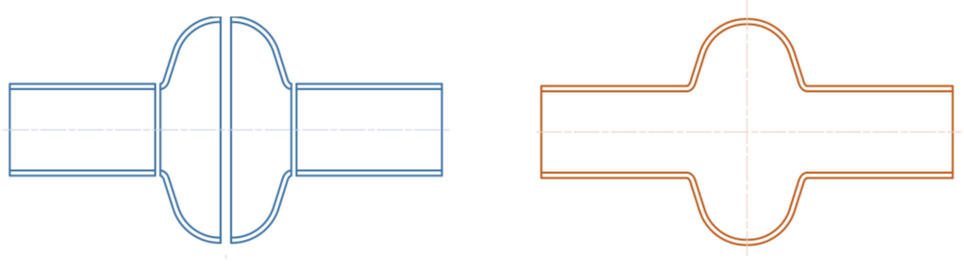
Seamless is better

Different forming techniques available:

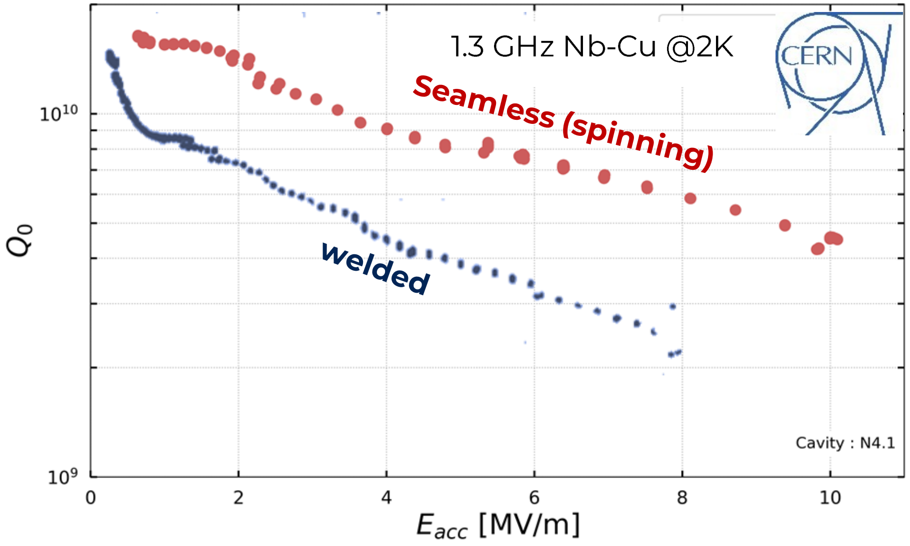
Welding/seamless

Spinning, hydroforming, electroforming, bulk machining…



Different proofs of **seamless** RF performances **superiority**

(Hie-ISOLDE, ALPI-INFN, CERN studies, …)



L. Vega Cid, TTC meeting 2022 (elaborated)

Cu substrate plays a fundamental role in SRF performances

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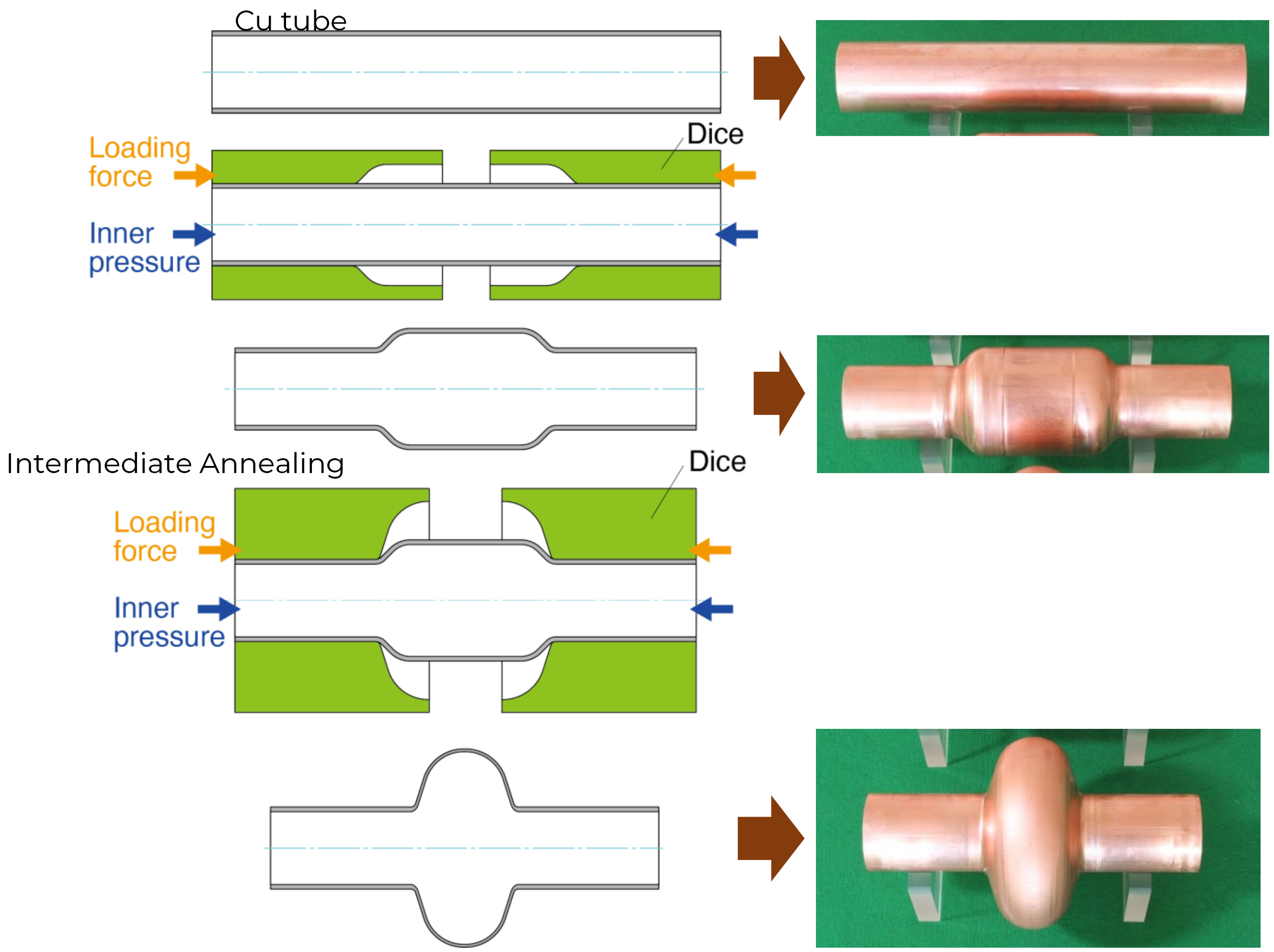
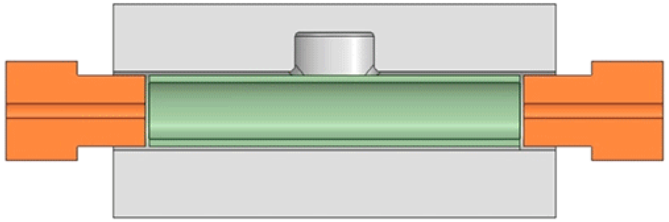
Hydroforming



Principle of hydroforming



https://www.tube-forming.co.jp/bulge.html

Hydroforming machine

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Hydroforming **Results**

2 hydroformed 1.3 GHz Cu cavities has been coated at CERN with Nb film

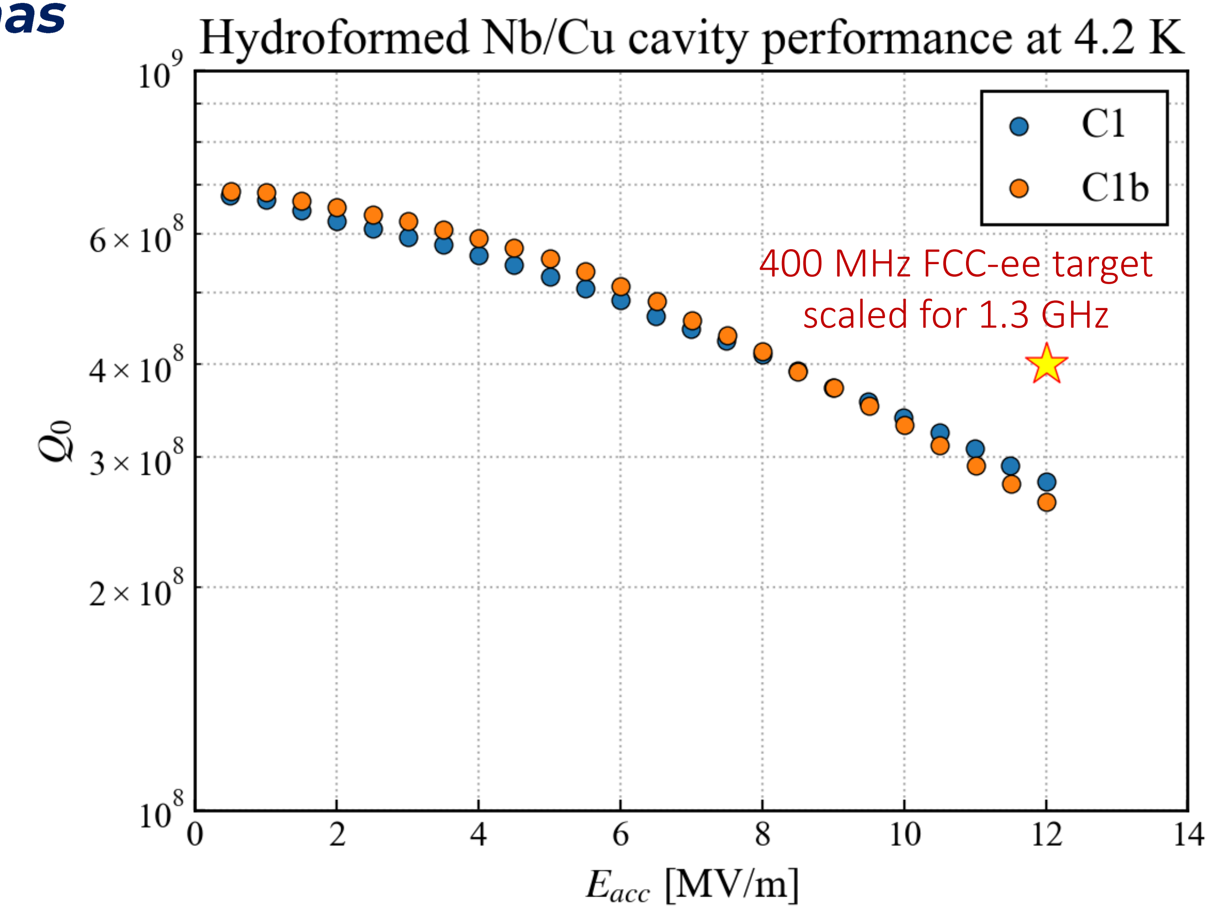
Target:

Q > 4 × 10⁸ at 12 MV/m on 1.3 GHz

Equivalent with Q > 3 × 10^9 at 4.5 K, 400 MHz (FCC)

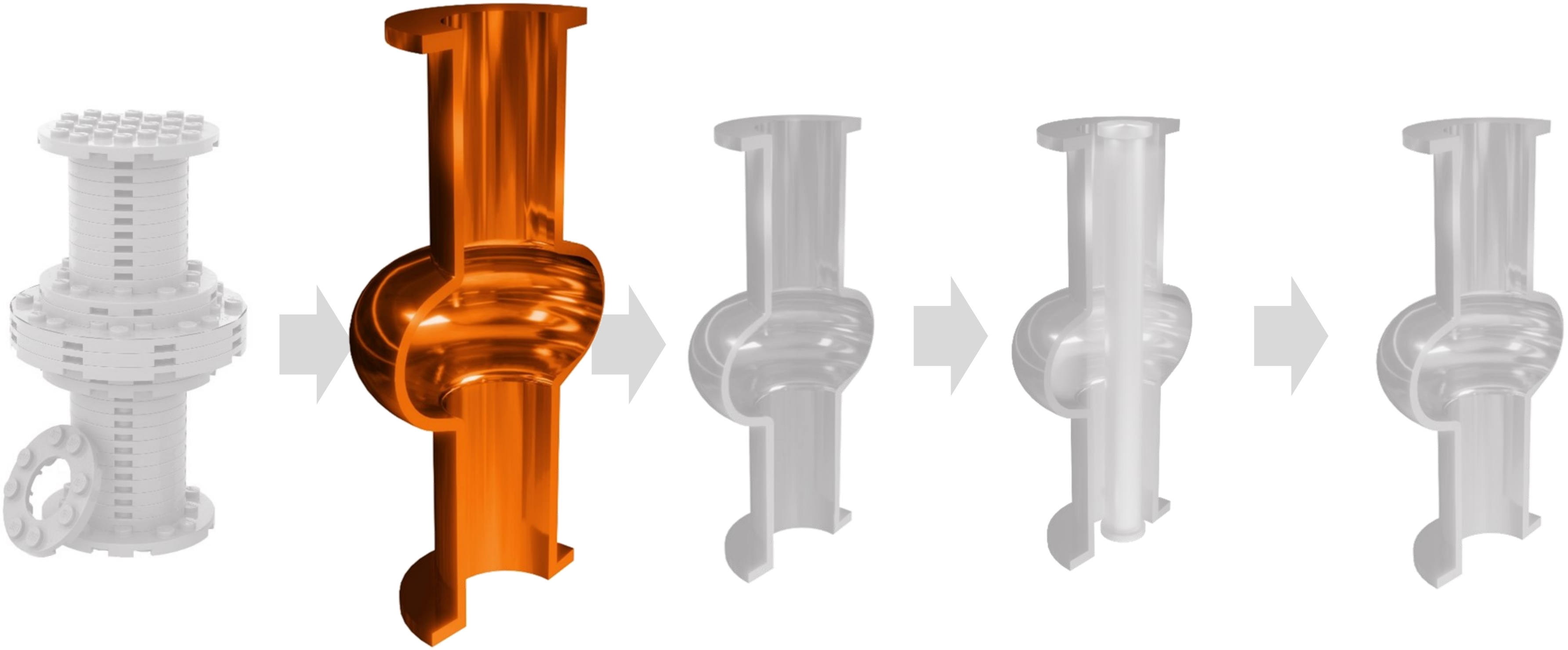
Results:

- Good reproducibility
- Not far from Q requirement
- **Very rough surface → polishing is critical**

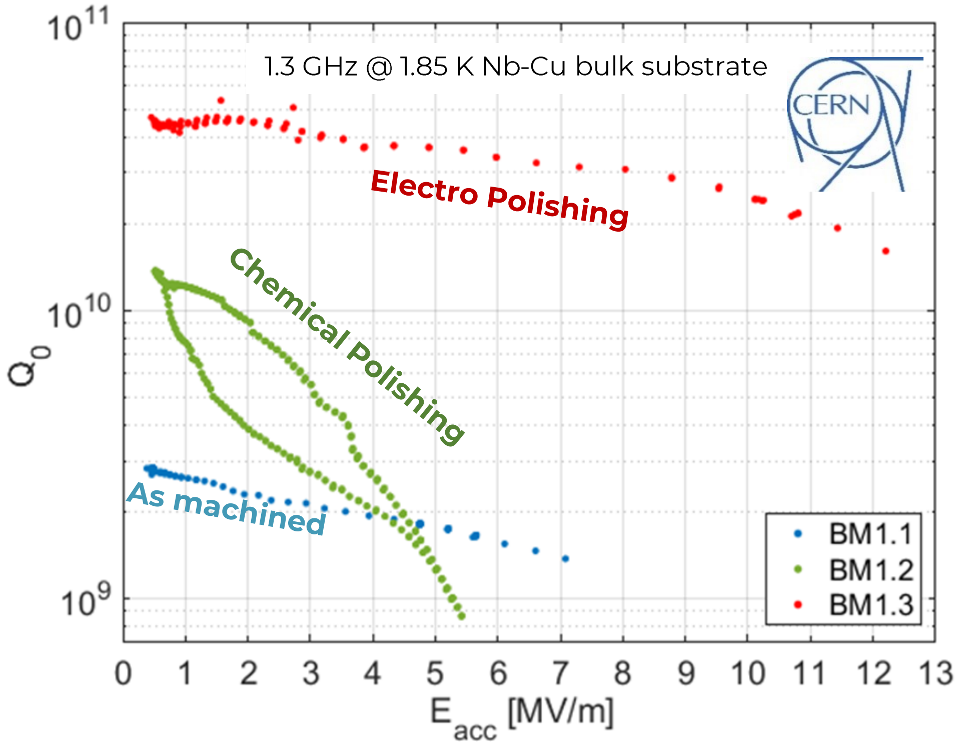


Courtesy of H. Araki (KEK)

Surface Polishing



Surface Polishing



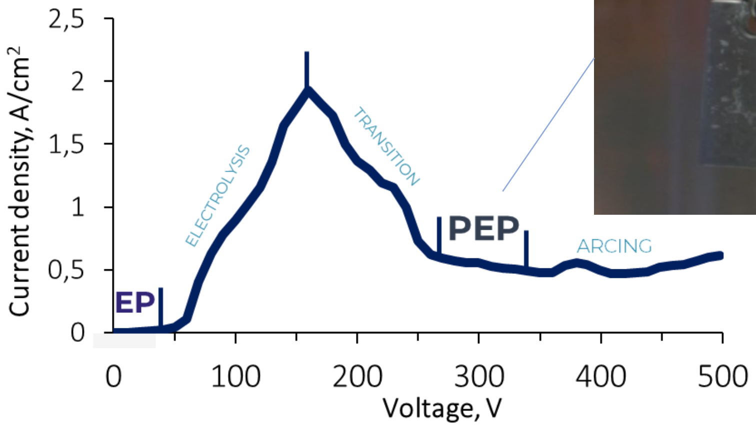
L. Vega Cid, TTC meeting 2022 (elaborated)

Cu substrate plays a fundamental role in SRF performances

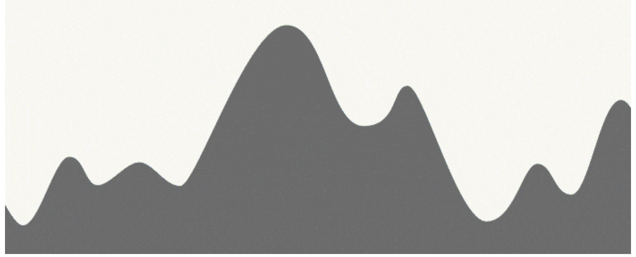
Roughness and defects reduction by **surface treatments are mandatory** for a good and uniform SRF coating

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

Plasma Electrolytic Polishing
Mechanism

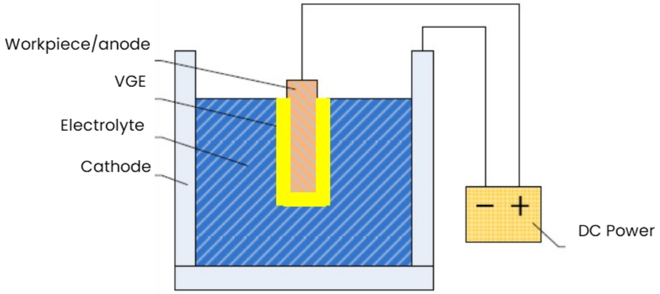


Electrochemistry + Plasma



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

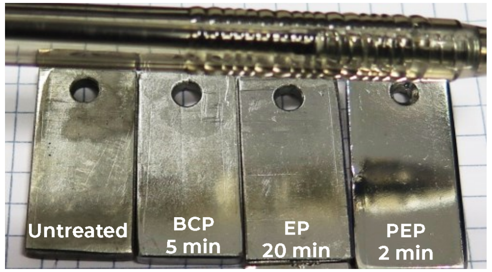
Plasma Electrolytic Polishing

Results

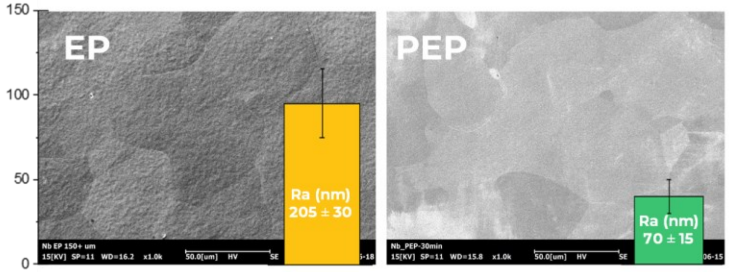
1x Nb 3x Cu

Solution Patents by INFN

Planar samples



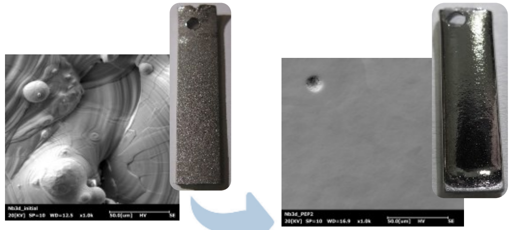
6.5 μm removed



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

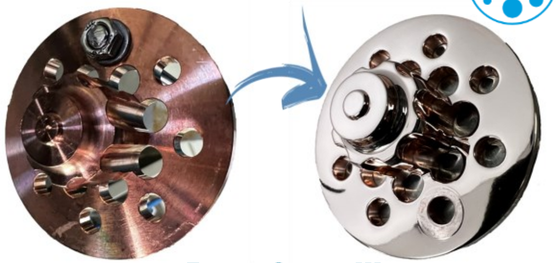
Nb QPR polishing optimizaztion on-going

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)

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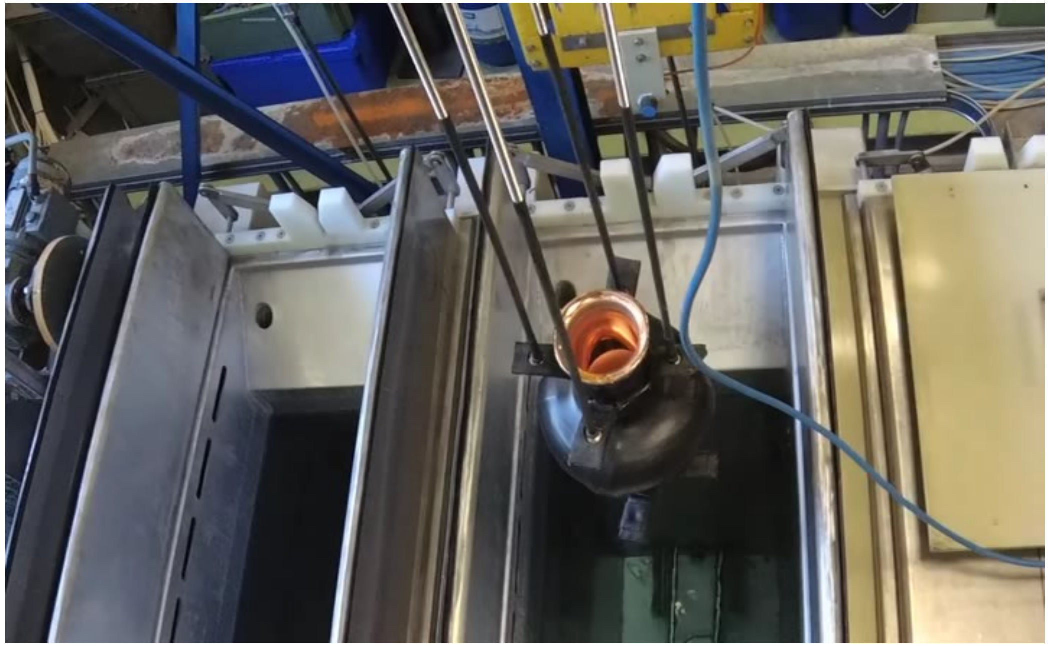
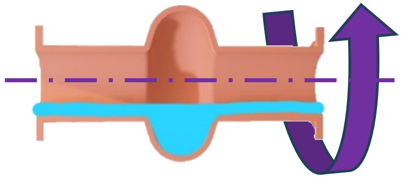
PEP scale up to 1.3 GHz successfully done! (Aug 2024)



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, …)*



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Next Steps:
RF test validation on 1.3 GHz

Possible Timeline:

- Hydroformed cavity production KEK
  (November 2024)
- PEP treatment INFN LNL
  (March-April 2025)
- Coating Nb CERN
  (May-June 2025)
- RF Test KEK
  (July-August 2025)

If we succeed...

Scaling to 400 MHz Cavities

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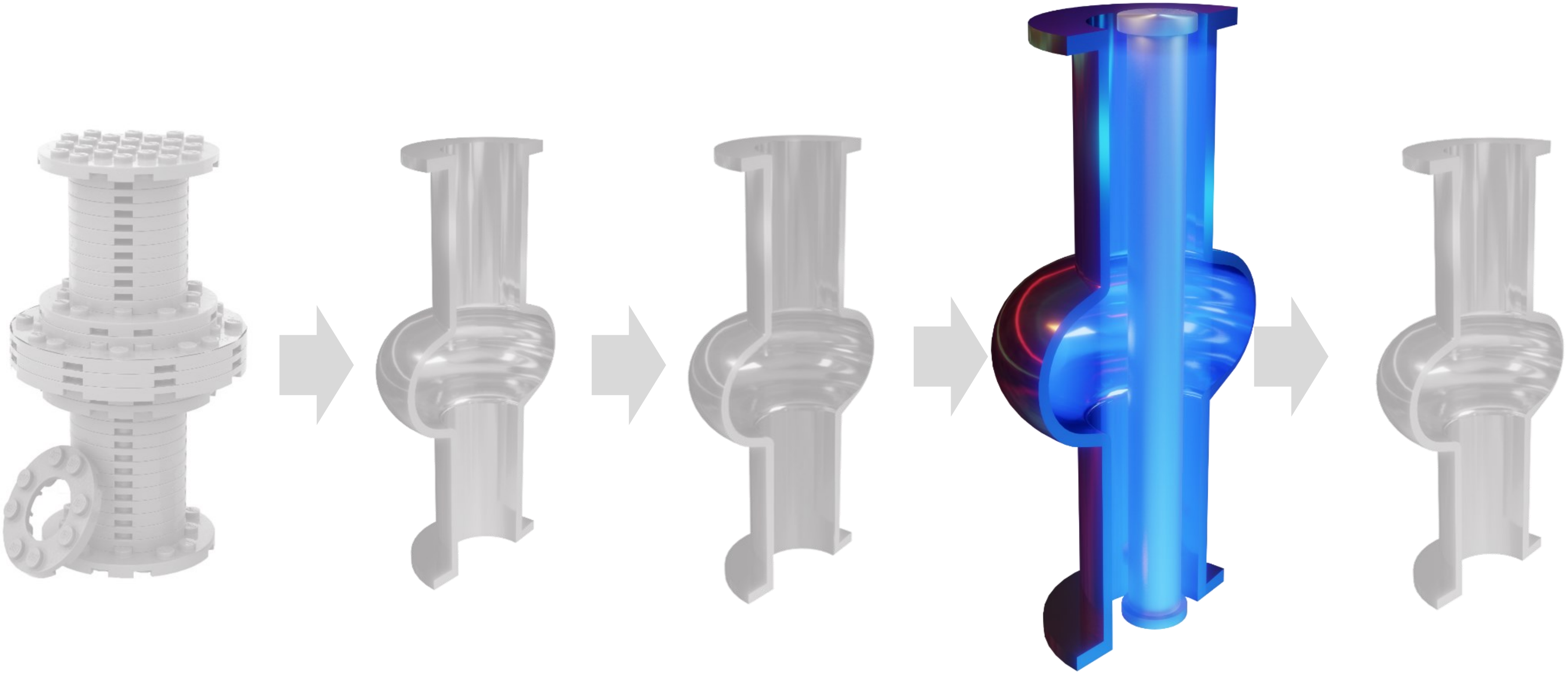
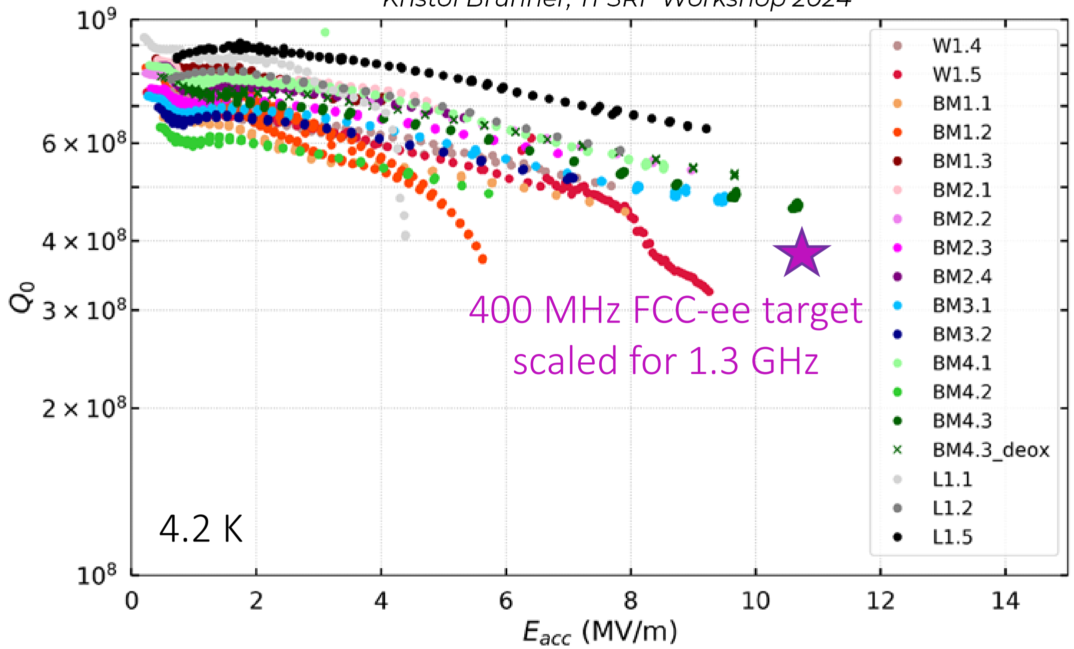
SC film coating



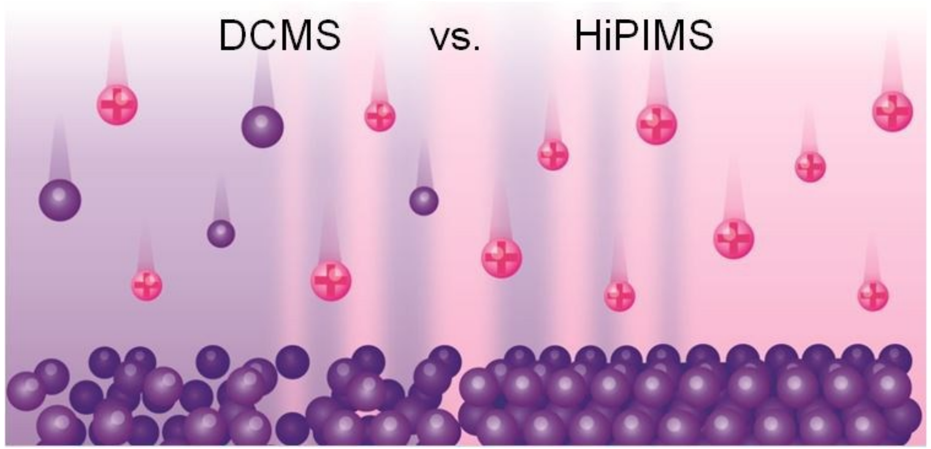
Nb coating densification by HiPIMS

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

Kristòf Brunner, TFSRF Workshop 2024

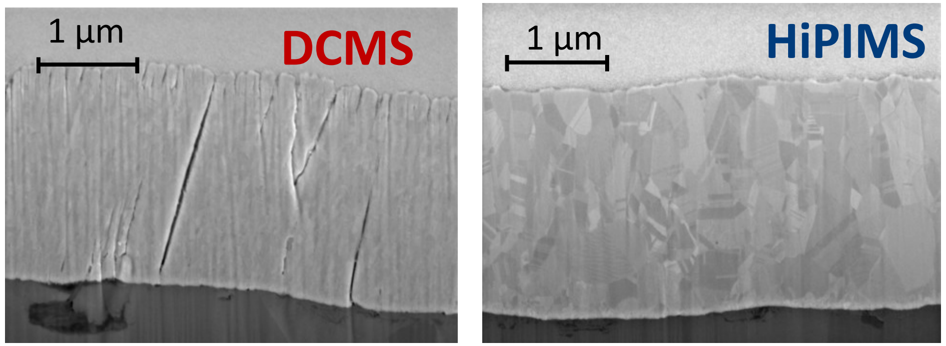


On 1.3 GHz FCC-ee requirements were achieved



HiPIMS provides complete ionization of Nb species

Kristòf Brunner, TFSRF Workshop 2024

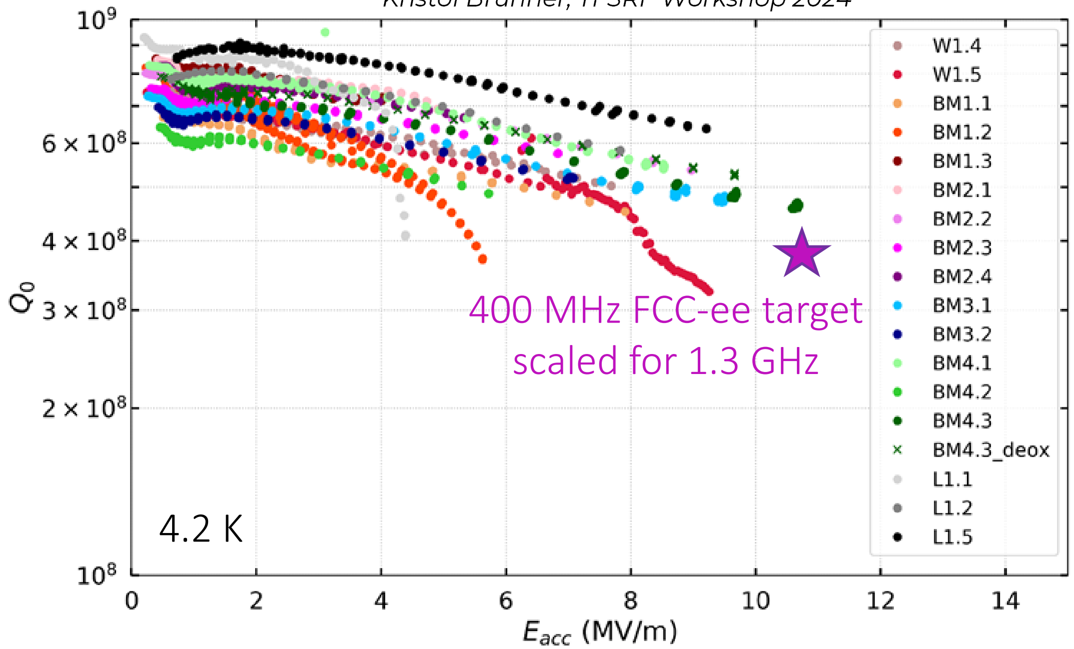


Nb on Cu coatings at CERN by DCMS and HPIMS

Nb coating densification by HiPIMS

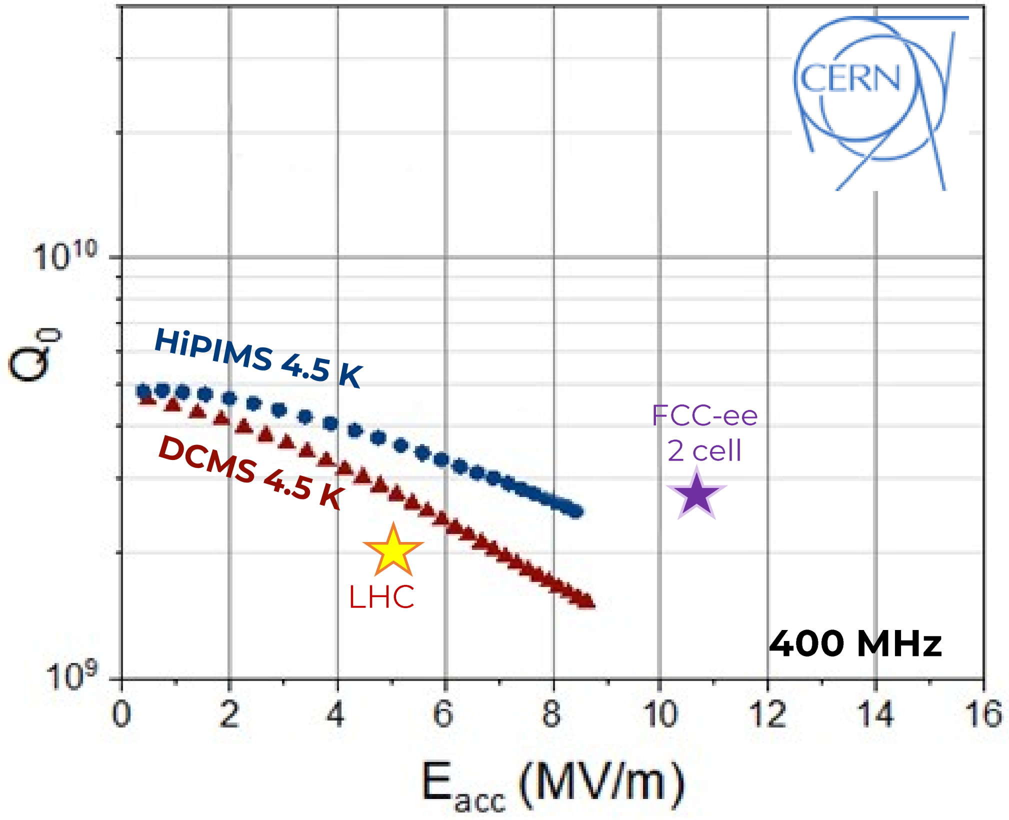
HiPIMS technology densifies the Nb coating and increases RF performances compared to DCMS

Kristòf Brunner, TFSRF Workshop 2024



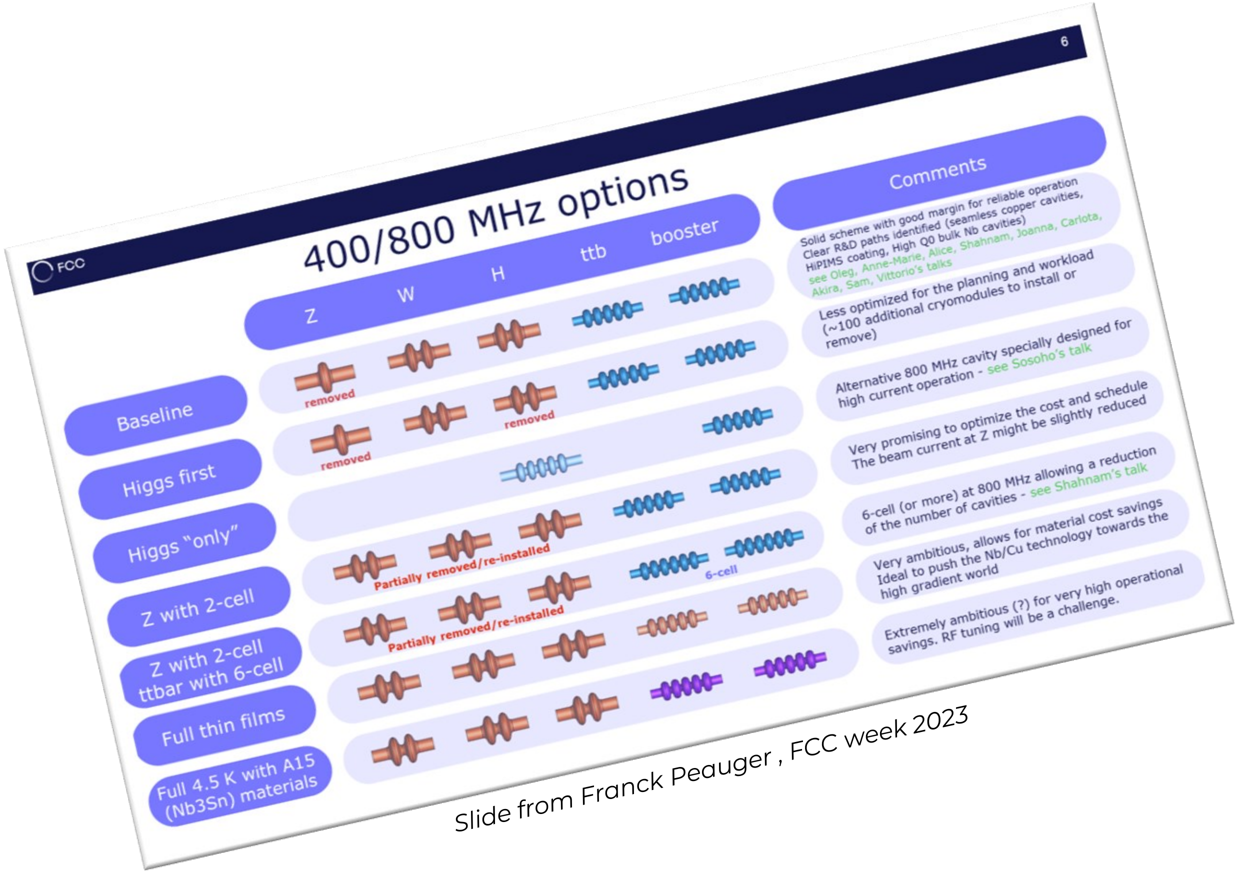
On 1.3 GHz FCC-ee requirements were achieved

Carlota Pereira Carlos, FCC week 2023 (elaborated)



On 400 MHz great improvement, but still some work to do

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

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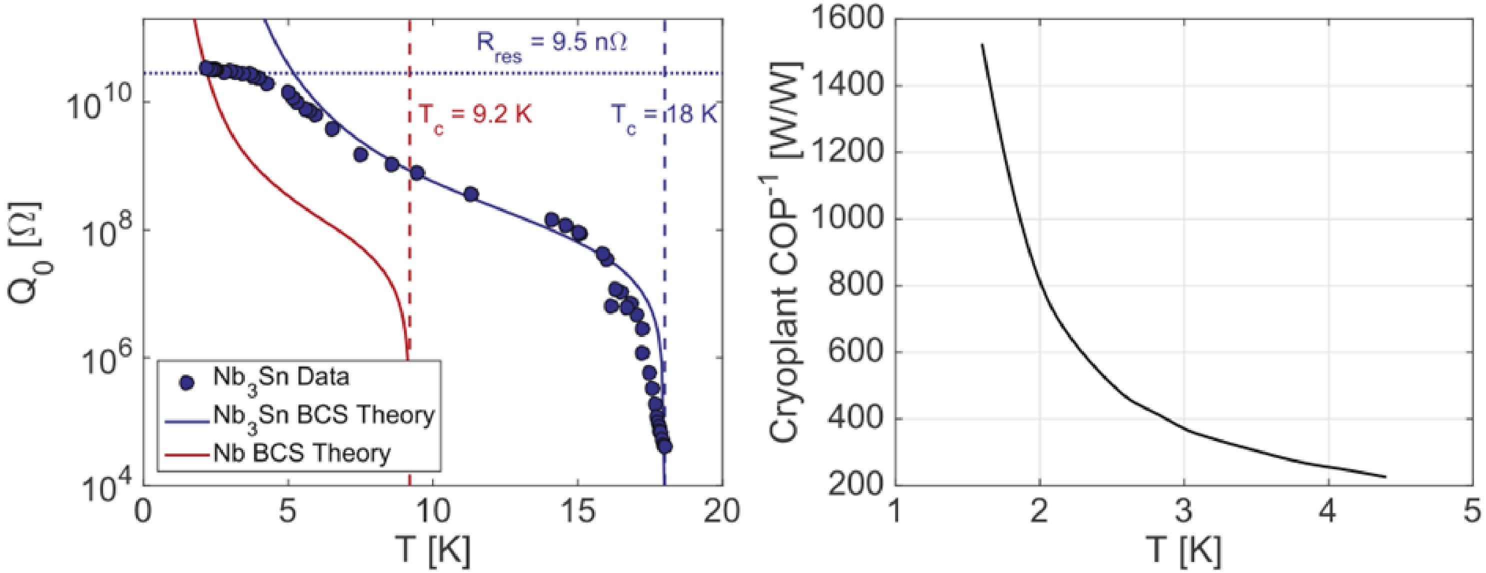
Nb_3Sn motivation (1)

***Energy saving** is mandatory for **FCC-ee** and 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



Supercond. Sci. Technol. 30 (2017) 033004

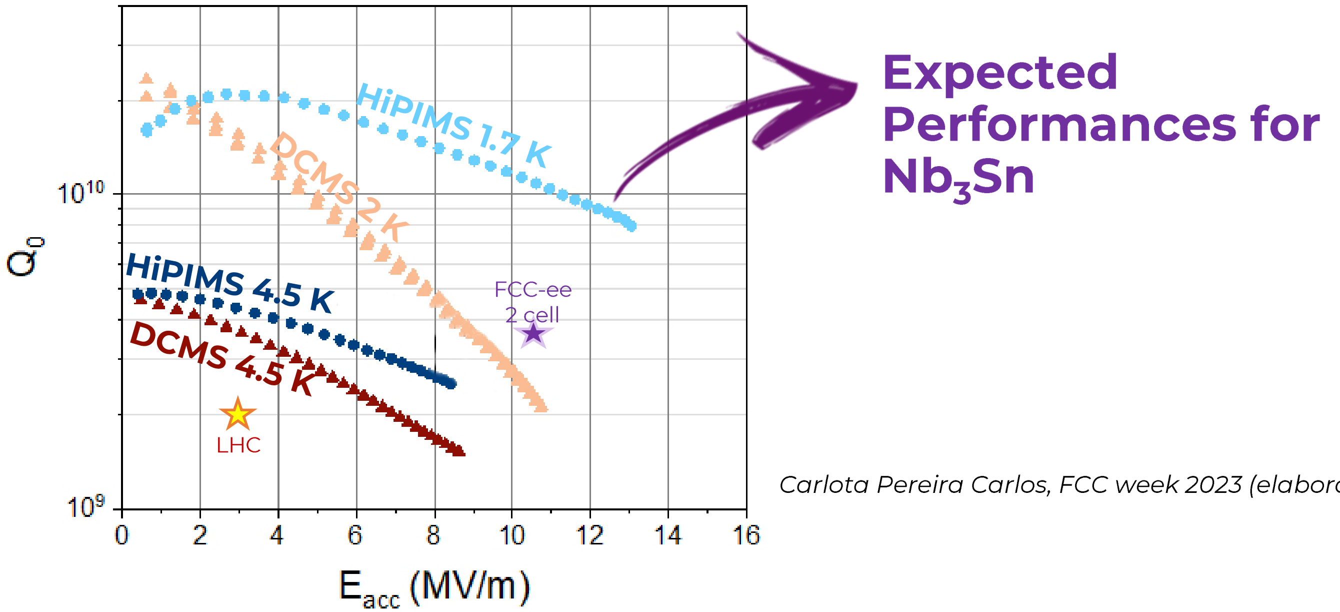
Nb_3Sn motivation (2)

Energy saving *is mandatory for* ***FCC-ee*** *and 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 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

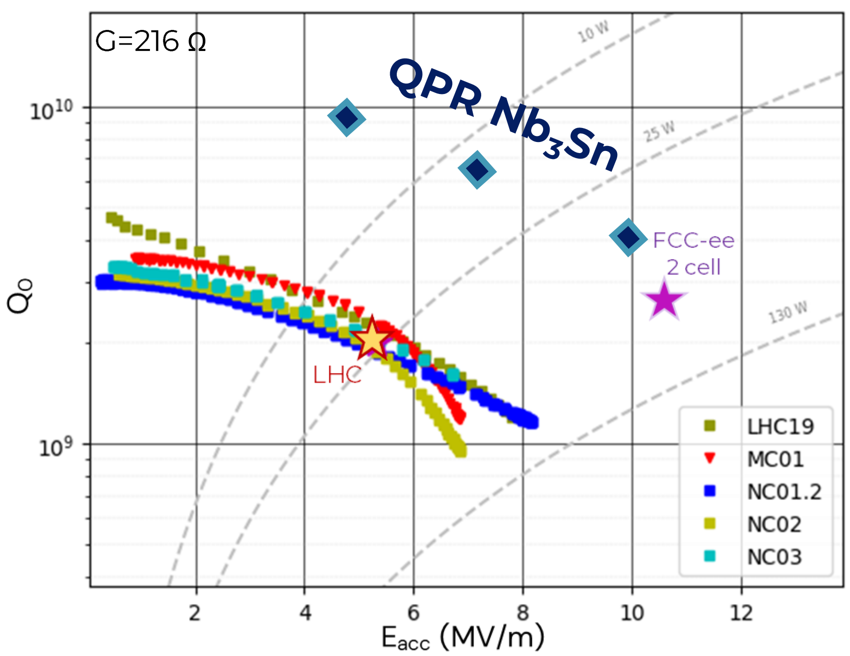
Nb_3Sn results

Nb_3Sn optimized coating recipe

Best RF performance on a QPR @4.2 K

Tc = 17.2 K
Rs of 23 nΩ @ 4.5 K, 20 mT
Quench >70 mT @ 4.5 K

LHC cavities Q vs E_{acc} @4.5 K



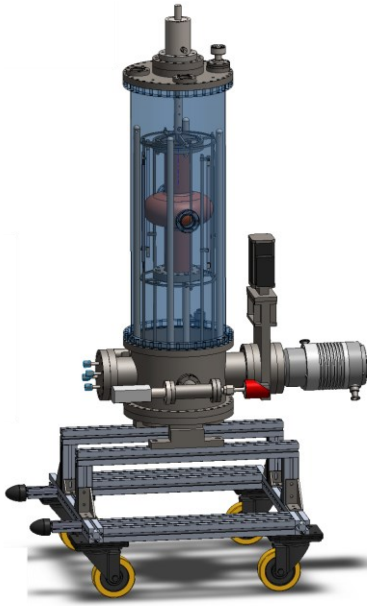
Nb_3Sn QPR RF measurement done at HZB Helmholtz Zentrum Berlin

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

5 times better than LHC

Already meets FCC-ee specifications

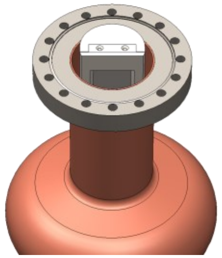
Nb_3Sn Path to Final Prototype



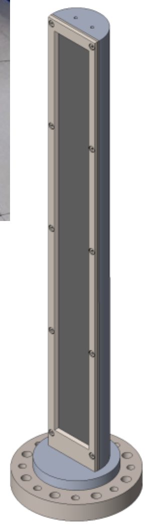
Nb_3Sn on bulk Nb to validate coating performances (2025)
on 1.3 GHz Elliptical Cavities (2025)

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*
- *Study on flux trapping*

Conclusion

- **New SRF baseline** for a smoother installation procedure
- Nb on Cu 400 MHz and Nb bulk 800 MHz **R&D on track**
- **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 of Nb_3Sn** available on **1.3 GHz cavities**
- **In 2028 Nb_3Sn optimized prototypes** are expected

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Thank you!

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