Roadmap to FCC SRF performance targets

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On behalf of CERN SRF Teams

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4th October 2024

Overview

- Required SRF performance for FCC-ee
- Status, issues, and next steps on the roadmap for Nb/Cu
  - 1.3 GHz R&D program
  - 400 MHz
- Sustainable+ alternatives for 800 MHz: Nb/Cu at 2 K and Nb_3Sn/Cu at 4.5 K

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	$3\ 10^{10}$	$2.7\ 10^{9}$	$2.7\ 10^{9}$	$2.7\ 10^{9}$	$3\ 10^{10}$
E_a(MV/m)	6.2→ 20.1	3.77	10.1	10.6	20.1
R_s (av nΩ)	9.1	89	87	87	9.1
B_{peak}(mT)	87.2	20.2	54	56.4	87.3
E_{peak}(MV/m)	41.2	8.3	20.2	21.2	41.3

NB: 4K and 2K are indicative

- Compared with state of the art for bulk Nb and Nb/Cu,
  - B_{peak} < 100 mT (no HFQS) in all cases (120 mT demonstrated in Nb/Cu)
  - E_{peak} is quite relaxed
- We don't need ultra high fields, except maybe for the booster of the ttb
- Rs is challenging
- 800 MHz with Nb/Cu is not excluded and should be tried
- Challenge staged in time for the collider, booster is pulsed (Q_o may be relaxed?)

Required performance gains in time for series production

Z (2033)

W, H (2038)

ttbar (2041)

400 MHz:

2xLHC gradient @ 35% -50% lower surface resistance: @ $Q=2.7x10^9$

2027?!

Collaborations with JLAB, INFN, KEK, ….

Collaborations with Cornell, FNAL, JLAB, IJCLAB, …

800 MHz:

6.5 MV/m @ $Q=3x10^{10}$ (2 K)

Bulk Nb

21 MV/m @ $Q=3x10^{10}$ (2 K)

Bulk Nb

Nb/Cu?

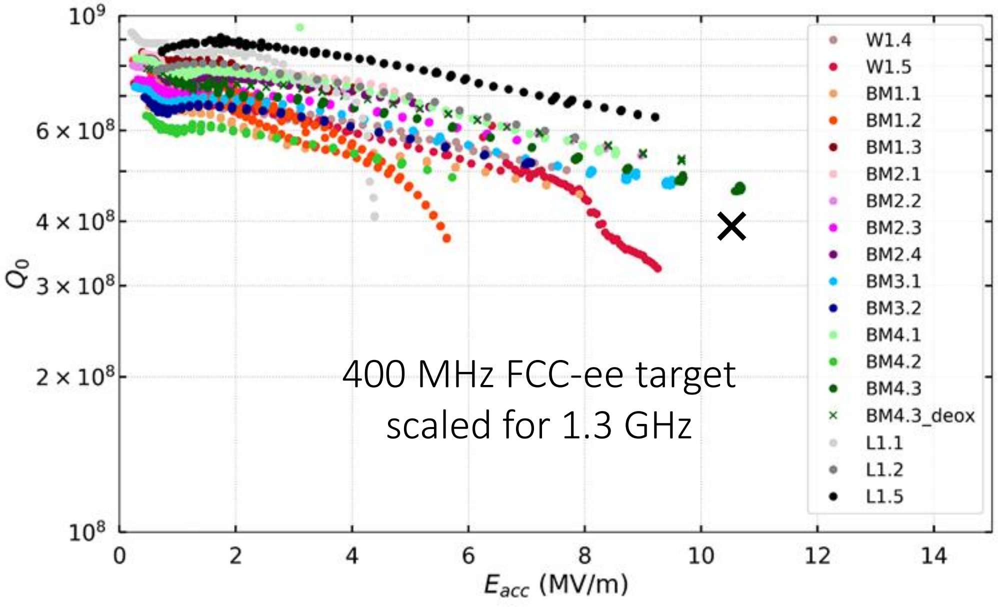
21 MV/m @ $Q=3x10^{10}$ (2 K)

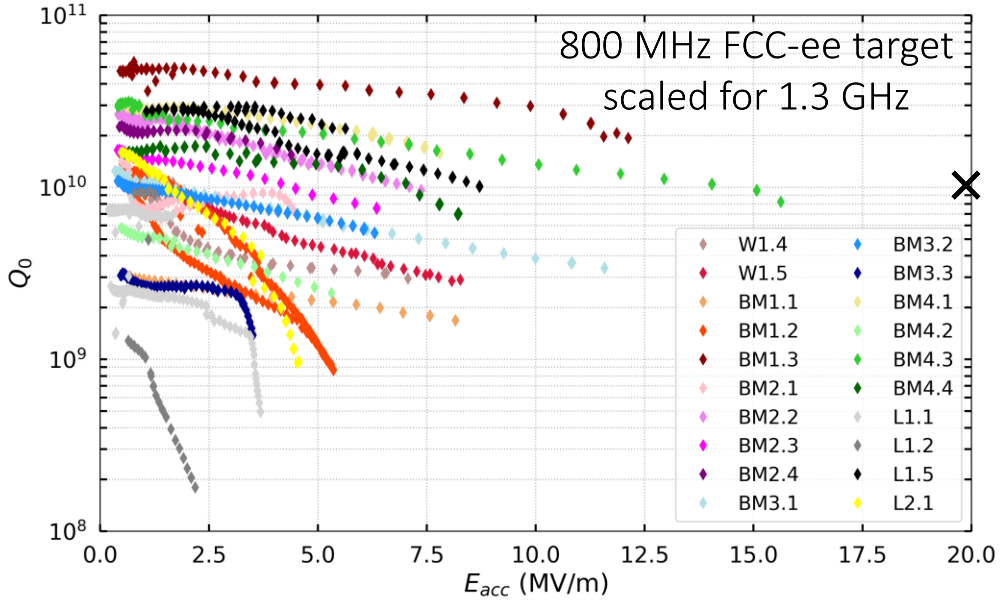
Bulk Nb

Nb/Cu?

A15?

State of the Nb/Cu 1.3 GHz program



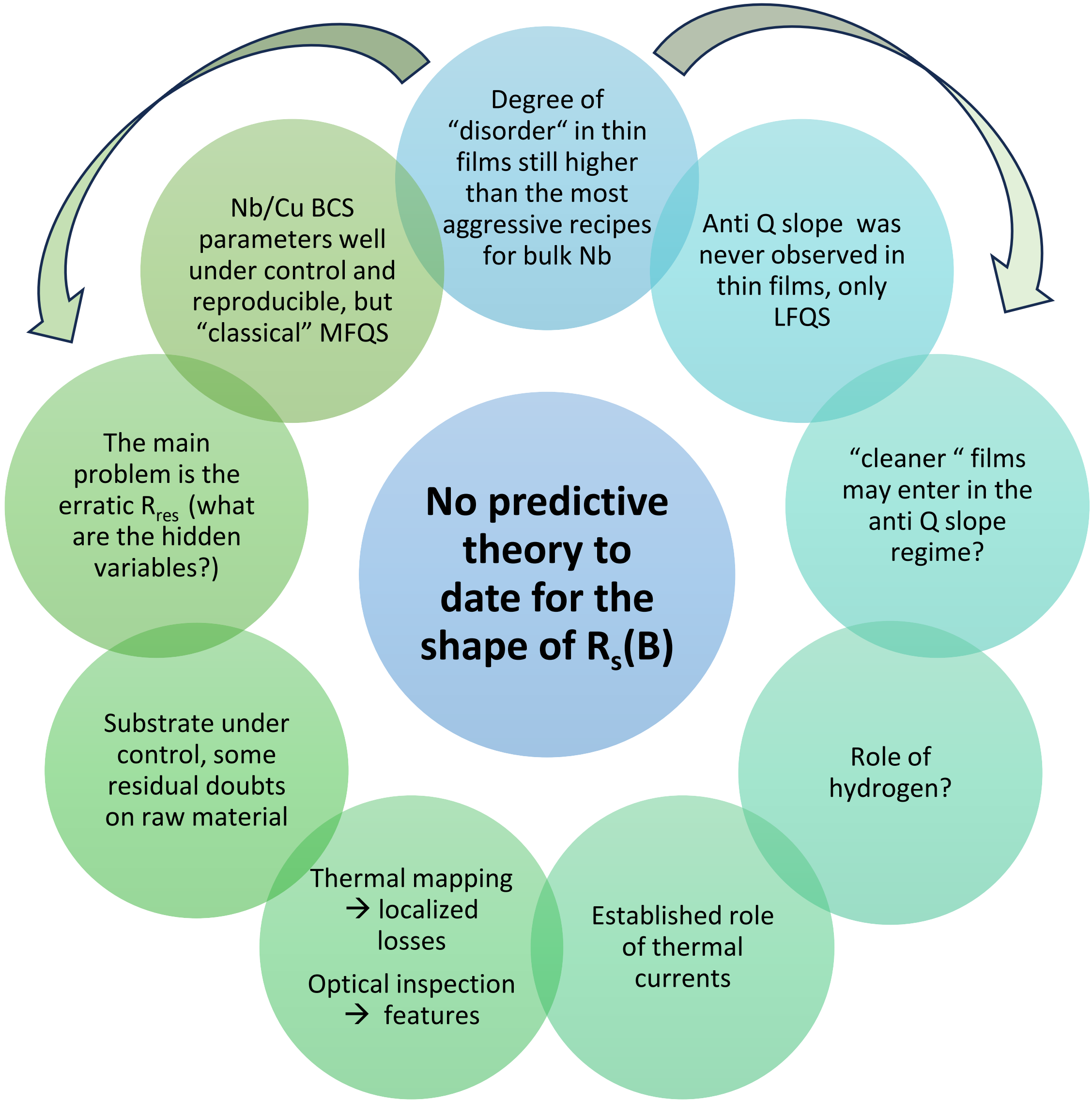


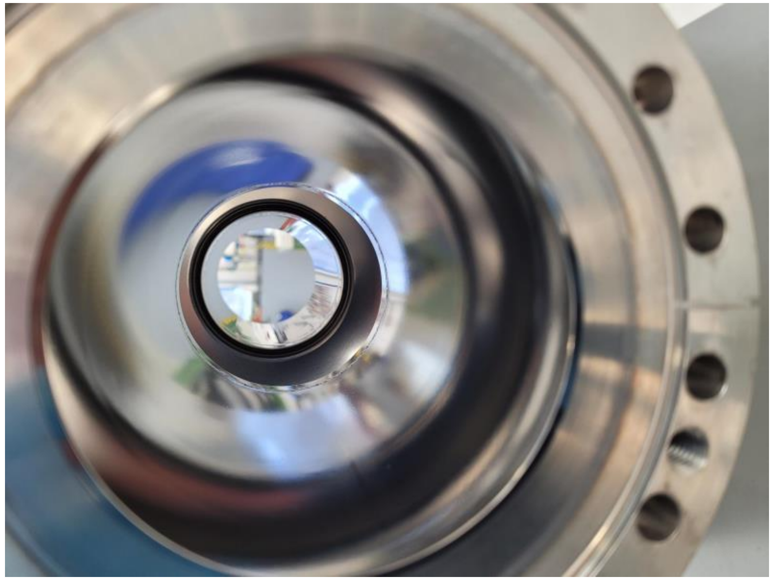
At 4,2 K:
Reproducible BCS parameters
Optimised BCS resistance around 300 nΩ
Scaled FCC ee target already met!

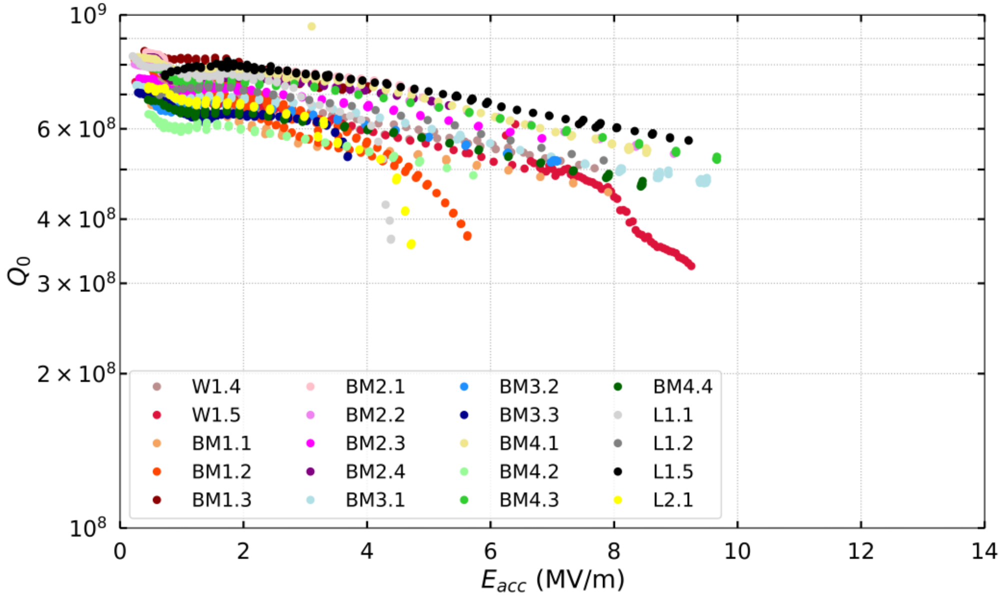
At 2 K:
BCS resistance is suppressed but..
Erratic residual resistance (7-90 nΩ)
Scaled FCC ee target seems possible

Collaboration EN-MME/SY-RF/TE-VSC

Our challenge:
understand and control $R_s(H)$: Nb thin films

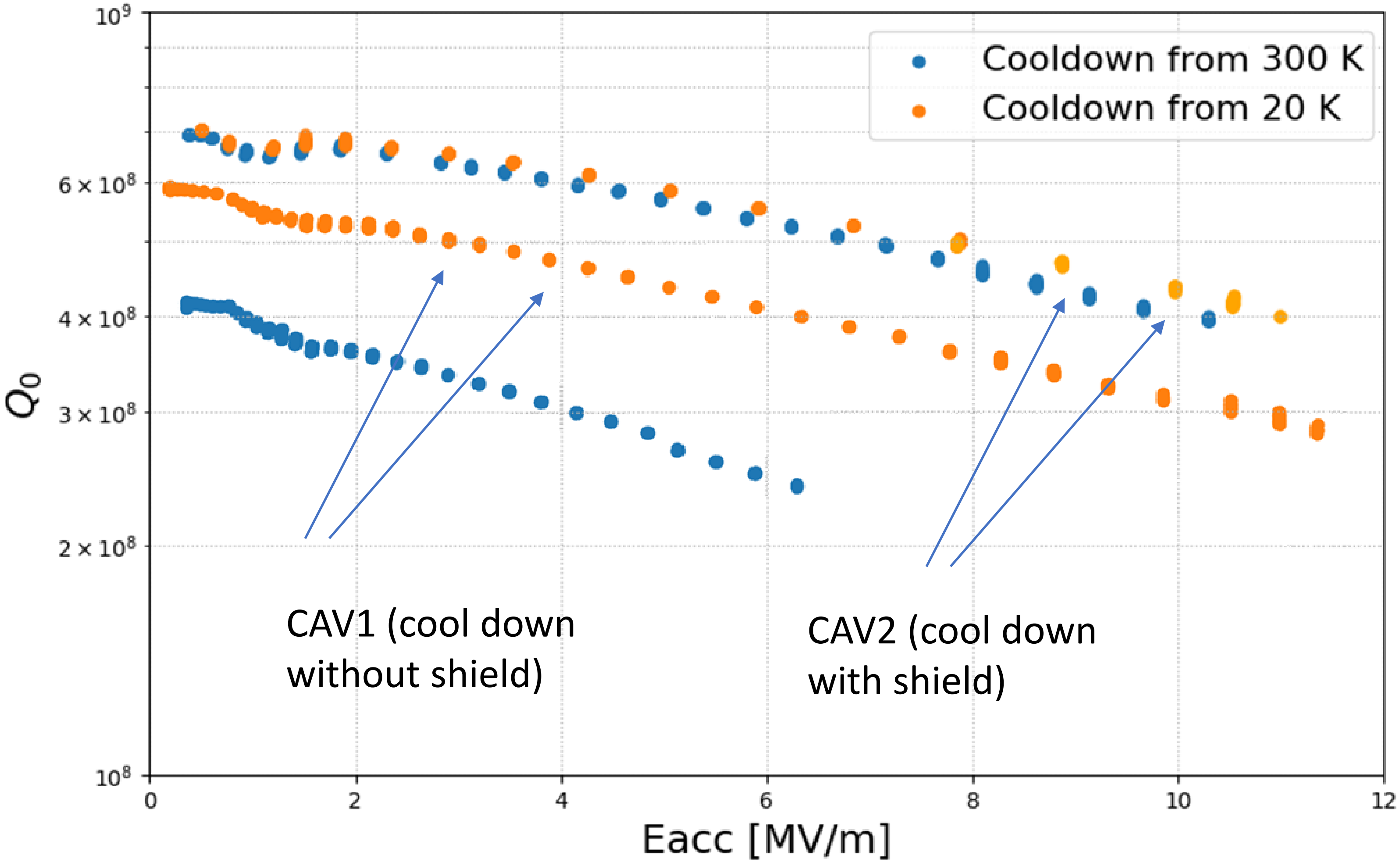






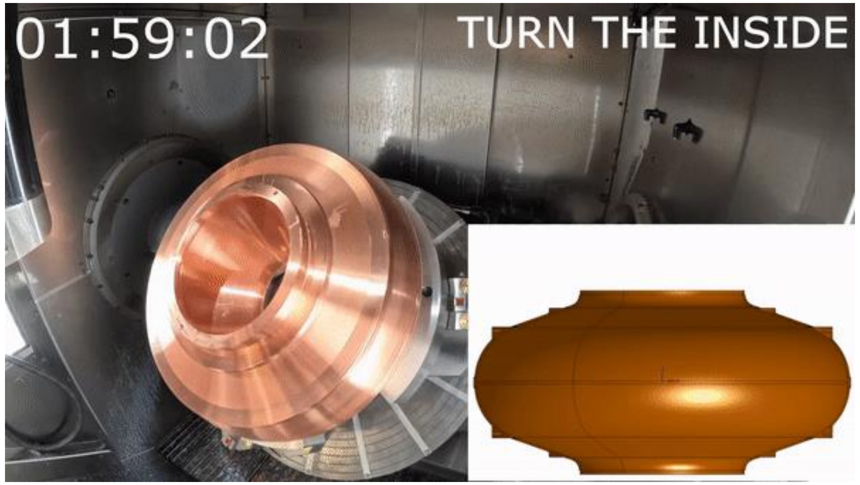
Progress on control of thermal currents

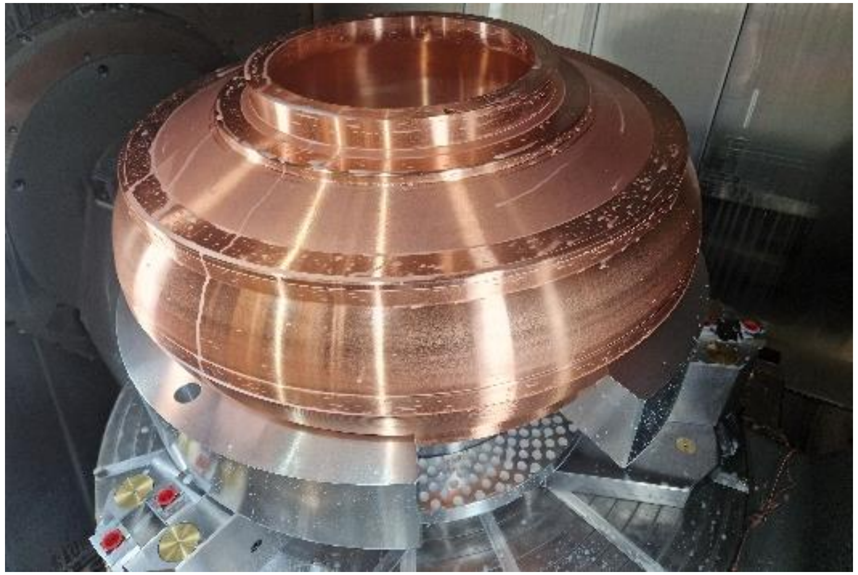
Comparing our measurement data, we noticed KEK is able to reach much better thermal gradients across Tc….



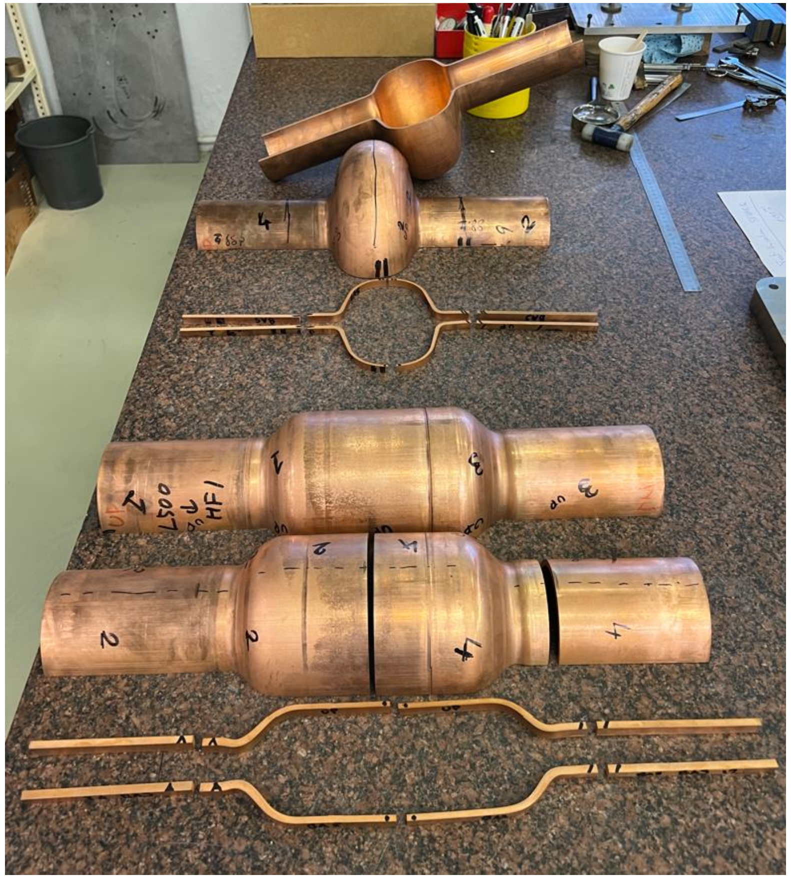
Cavity manufacturing highlights

400 MHz Monoblock prototype



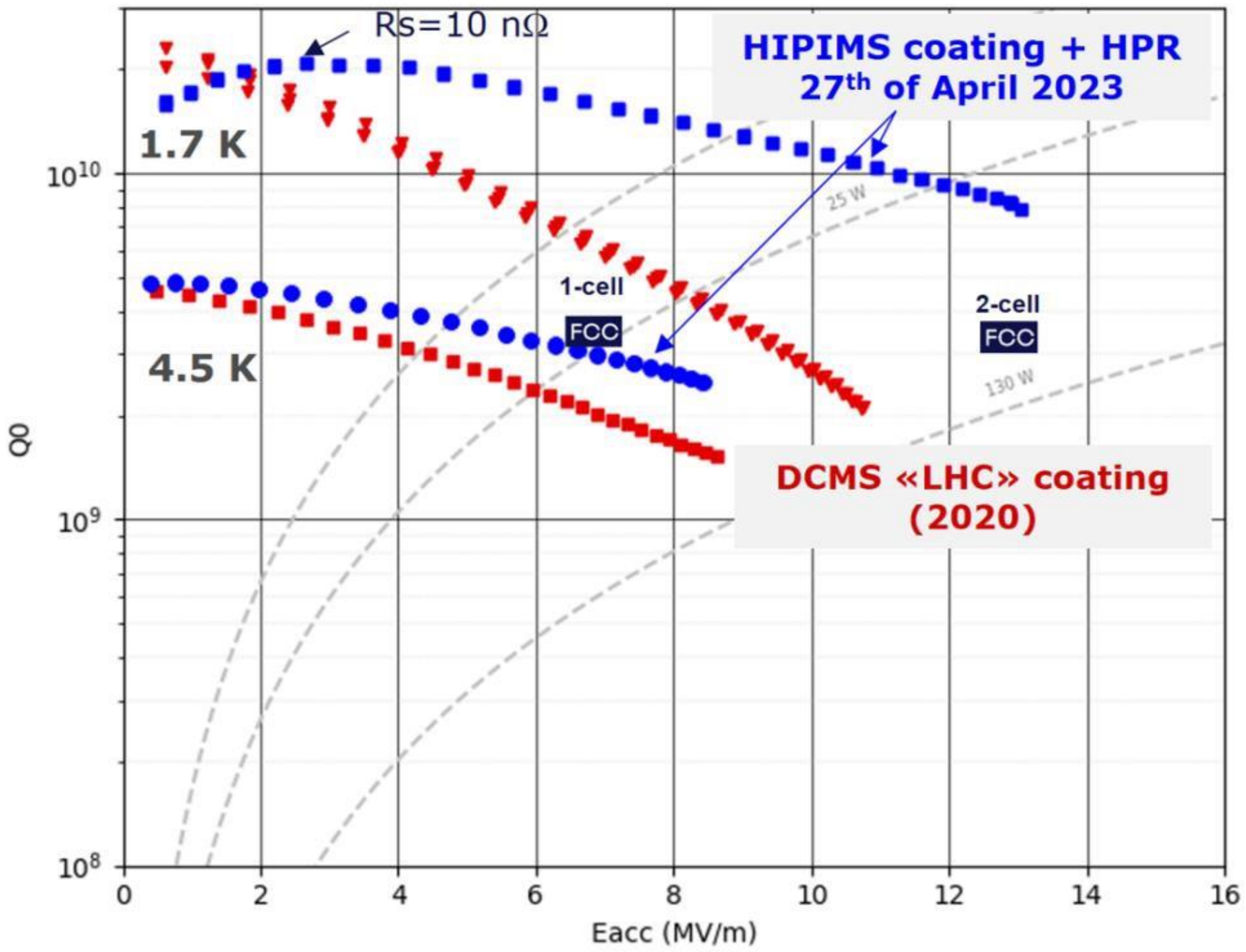


Successful **1.3 GHz hydroforming** (KEK Collaboration)



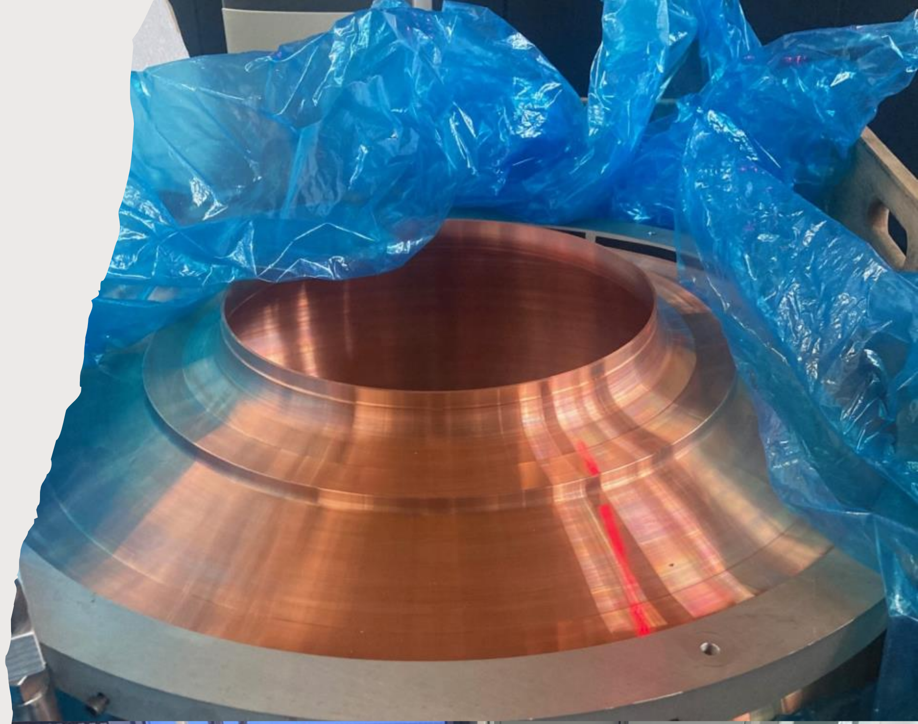
M .Garlasche

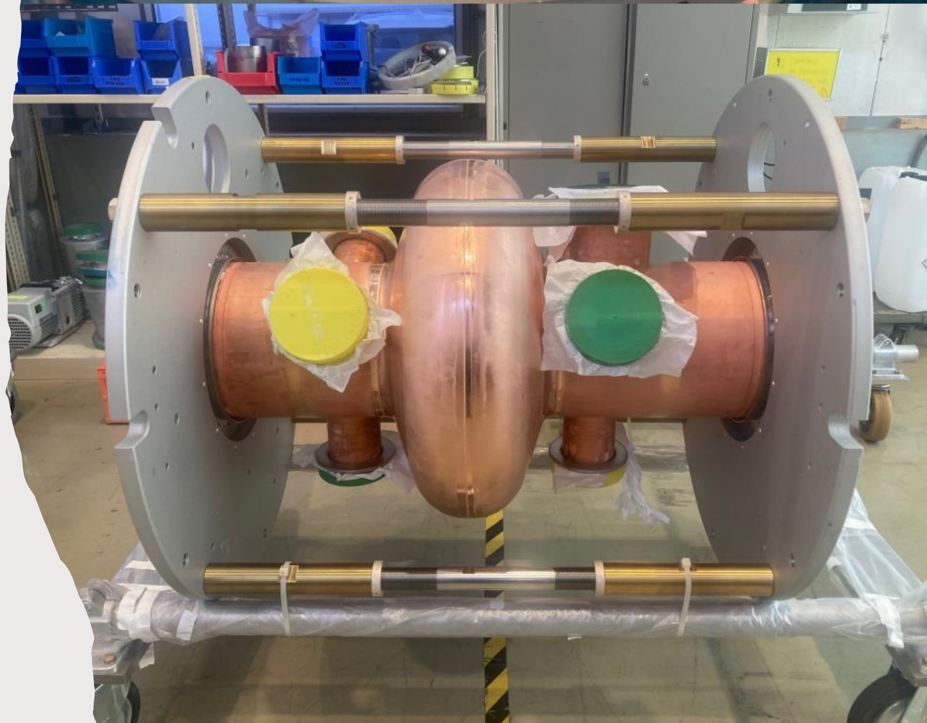
State of the art: 400 MHz (LHC geometry)



Status and next steps for 400 MHz Nb/Cu single cell

- The cavity measured in 2023 implemented only one of the lessons learned in the 1.3 GHz program, i.e. HIPIMS. Seamless substrate and EP not yet done.
- Two 400 MHz cells machined from bulk have been produced, cut off welding is planned in October
- Toy cavity with beam ports was completed in May 2024, for EP and HIPIMS tests
- A dedicated cold test facility was commissioned in July and is operational (mitigate clash with HL-LHC). Include magnetic compensation and will integrate control of thermal currents
- In 2024 we have been delayed by EP in bldg. 118. The infrastructure is there but process not yet optimized, crab cavities have taken more slots
- Process optimization still on simplified cavity
- Next cavity test scheduled end of 2024, aiming at (seamless) EP+HIPIMS





Status of the FCC 2-cell

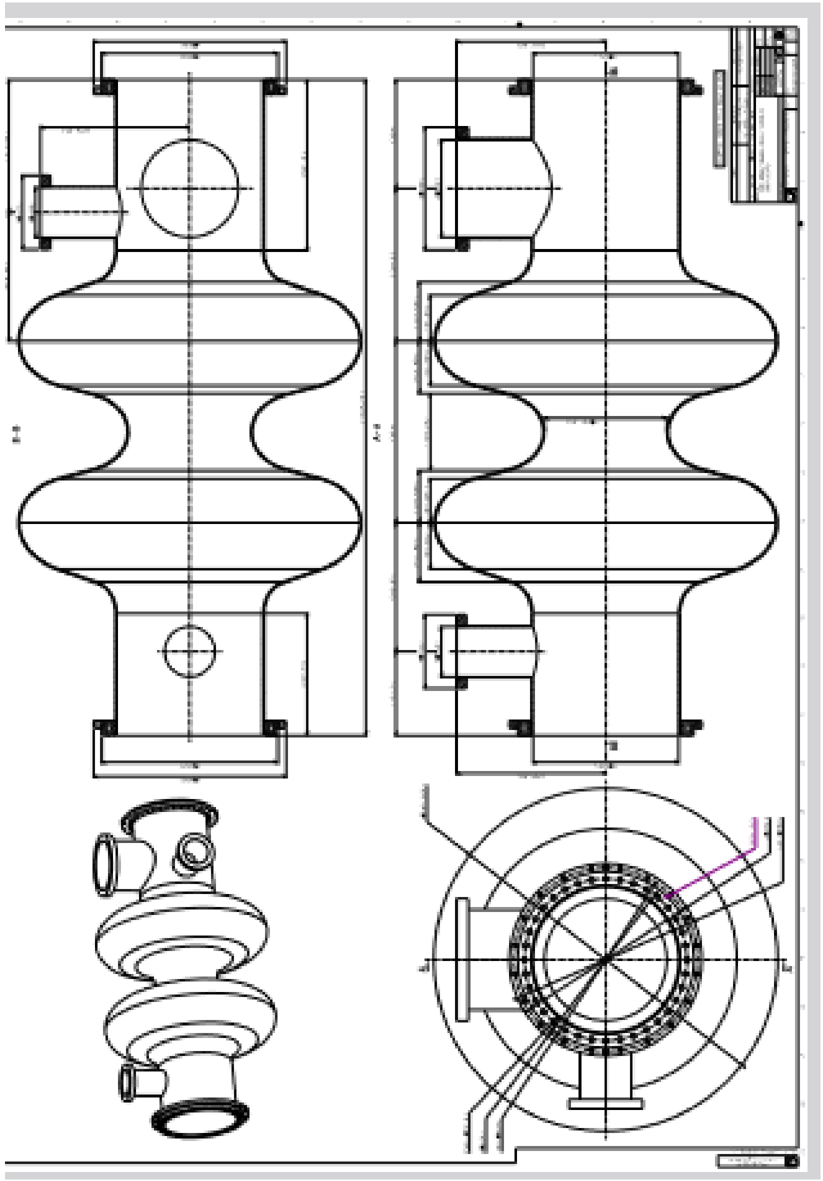
RF design is basically done.
A simplified sketch with key dimensions has been provided to EN-MME and TE-VSC to allow first evaluations on mechanical design, surface treatments and coating systems.

Present issues:

1) Inter cell iris diameter significantly less then cutoff makes hydroforming not trivial. MME looking at possible solutions

2) Unclear if EP is possible with the present infrastructure in bldg. 118, (will be OK in the new SRF building). VSC looking into possible solutions.

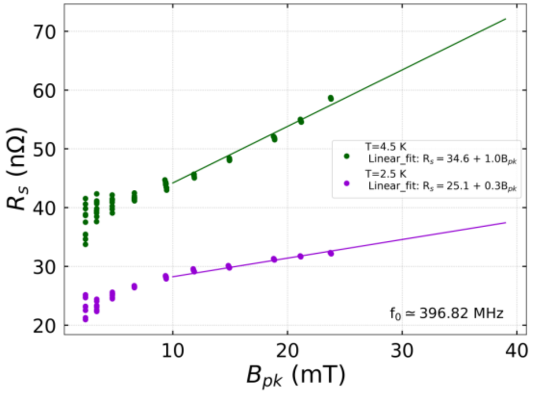
Prototype needed by 2027!



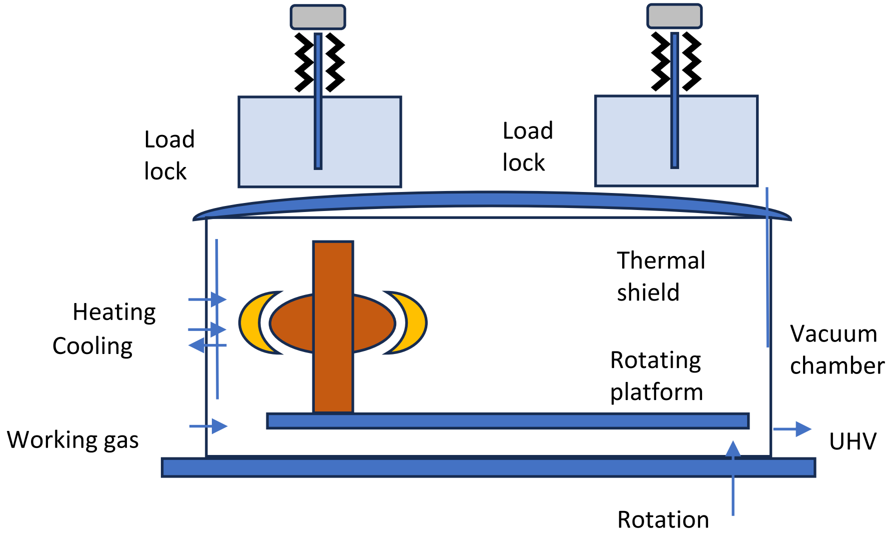
Nb_3Sn on copper

- Motivation
  - Operation at 4 K saving capital cost
  - Breakeven Q_0 for plug power: 7.5 10^9 at 4K (~ 3 10^{10} at 2 K)
  - Potential to drastically reduce plug power
- Good progress with flat samples, huge challenge: scale the process to a real cavity!
- Clear decision at 2024 CERN SRF workshop to focus on 800 MHz.
- Issues:
  - High temperature (700°C) coating system avoiding cavity collapse
  - Multiple cathodes
  - Mechanical design of the cavity
  - Conduction cooling for 4.5 K operation
- Ongoing definition of milestones
  - Flat sample performance target (4 K/2K breakeven point)
  - Cavity design
  - Coating system design
  - Cold test bench (must have for 800 MHz ayway)

QPR sample



Best Nb3/Cu (HIPIMS)



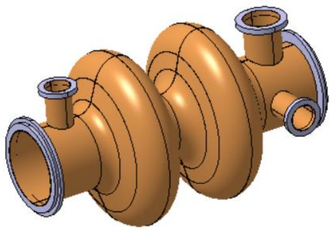
Coating system concept with needed functionalities

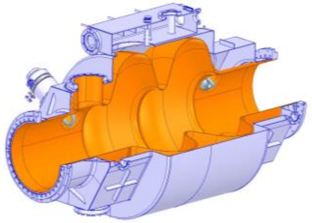
Summary

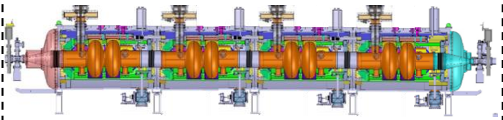
- Change of baseline would bring forward by ~10 years the goal of 2-cell 400 MHz Nb/Cu working at 10 MV/m and Q_0 ~3 10^9.
- So far, we proved that this is possible with Nb/Cu
- 1.3 GHz program takeaways: seamless substrates, EP, HIPIMS coatings, control of thermoelectric currents, magnetic hygiene, cleanliness chain (infrastructure).
- Performance gains at 400 MHz probed on LHC geometry, with slow pace so far.
- Some bottlenecks (substrate, test facility) have been removed and we expect to speed up in 2024-2026.
- New SRF building coming online in 2029
- 2-cells: mechanical design only starting now. Prototype by end 2027 is very very tight. If done, it may not integrate all the improvements we have identified
- 800 MHz baseline with bulk Nb and some of the available “recipes” is relatively straightforward, this part is the subject of collaborations with other labs (FNAL, JLAB, IJLC)
- Alternatives (more sustainable) i.e. Nb/Cu and Nb_3Sn/Cu are so far pursued in the context of the SRF R&D program. Detailed plan and costing under discussion with EN MME and TE VSC.

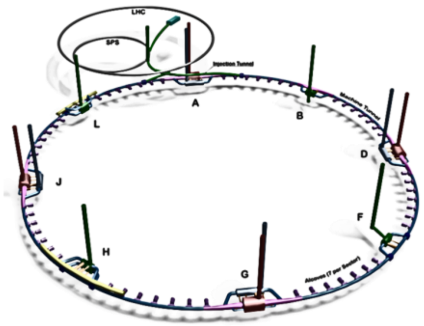
SPARE SLIDES

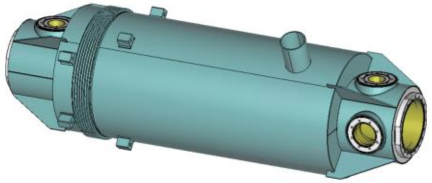
22-Aug-24	**Bare cavity** in vertical test		**Equipped cavity (with HOM couplers)** in vertical test		**Cryomodule (with FPC)** in horizontal test		**Operation in the machine**	
	Eacc (MV/m)	**Q0**	**Eacc (MV/m)**	**Q0**	**Eacc (MV/m)**	**Q0**	**Eacc (MV/m)**	**Q0**
2-cell 400 MHz	**13.0**	**3.3E+09**	**12.4**	**3.15E+09**	**11.8**	**3.0E+09**	**10.6**	**2.7E+09**
6-cell 800 MHz	**24.8**	**3.8E+10**	**23.6**	**3.65E+10**	**22.5**	**3.5E+10**	**20.25**	**3.0E+10**











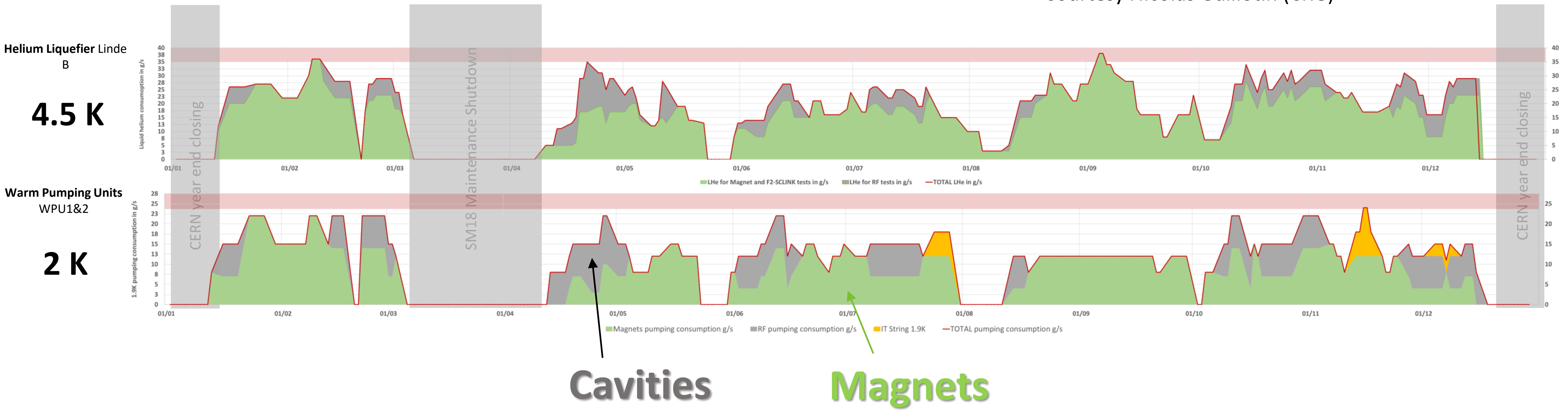
+5%

+5%

-10%

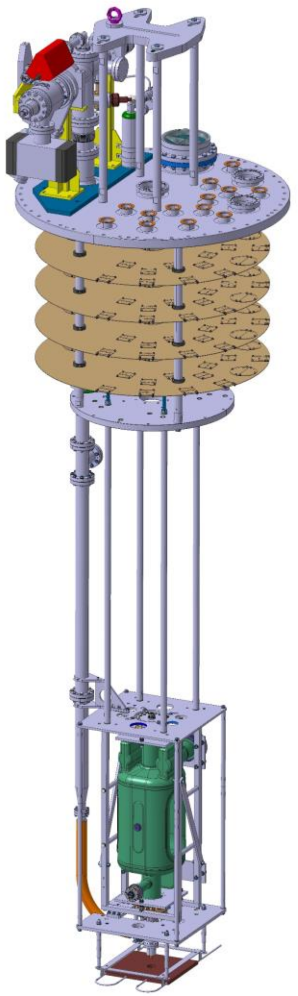
SM18 Cryogenic capabilities – situation in 2023

Courtesy Nicolas Guillotin (CRG)

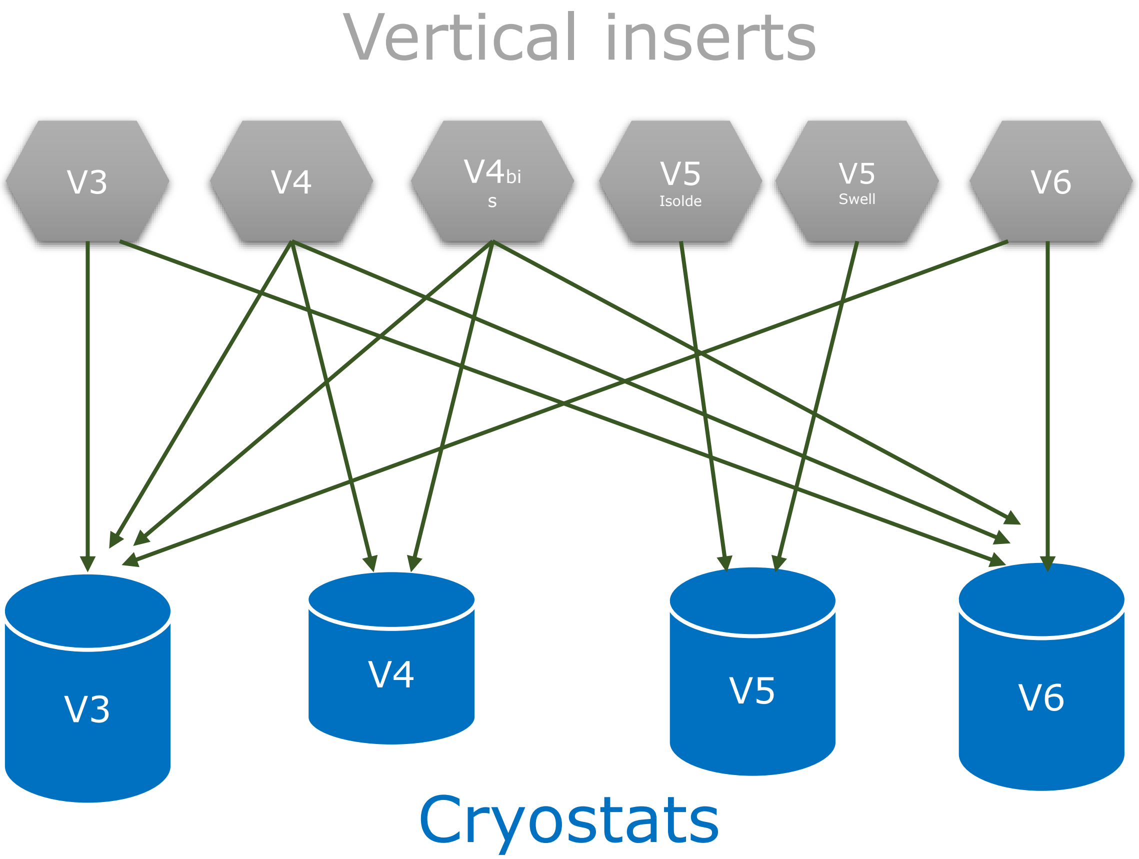


How can we optimize the cryogenic consumption and benefit from available helium in transitory periods ?

Upgrades of RF cold testing facility



V3 / V6 insert with RFD crab bare cavity



⇒ This will allow to have a stock of prepared cavities “ready to be tested”

New V4bis insert and preparation area