Status of HiPIMS development at CERN

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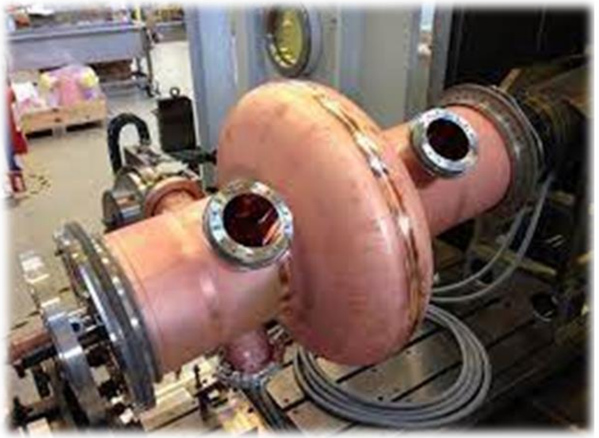
Motivation

Niobium coated copper cavities

- In use at CERN for 20+ years
- LEP, LHC, HIE-ISOLDE
- Advantages
  - Cost, thermal stability,
    less sensitive to flux trapping



LHC

HIE-ISOLDE

Difficulties

- RF performance at medium-high fields is below bulk Nb (Q-slope)
- Bimetallic structure
  - Thermoelectric currents at the Nb - Cu interface

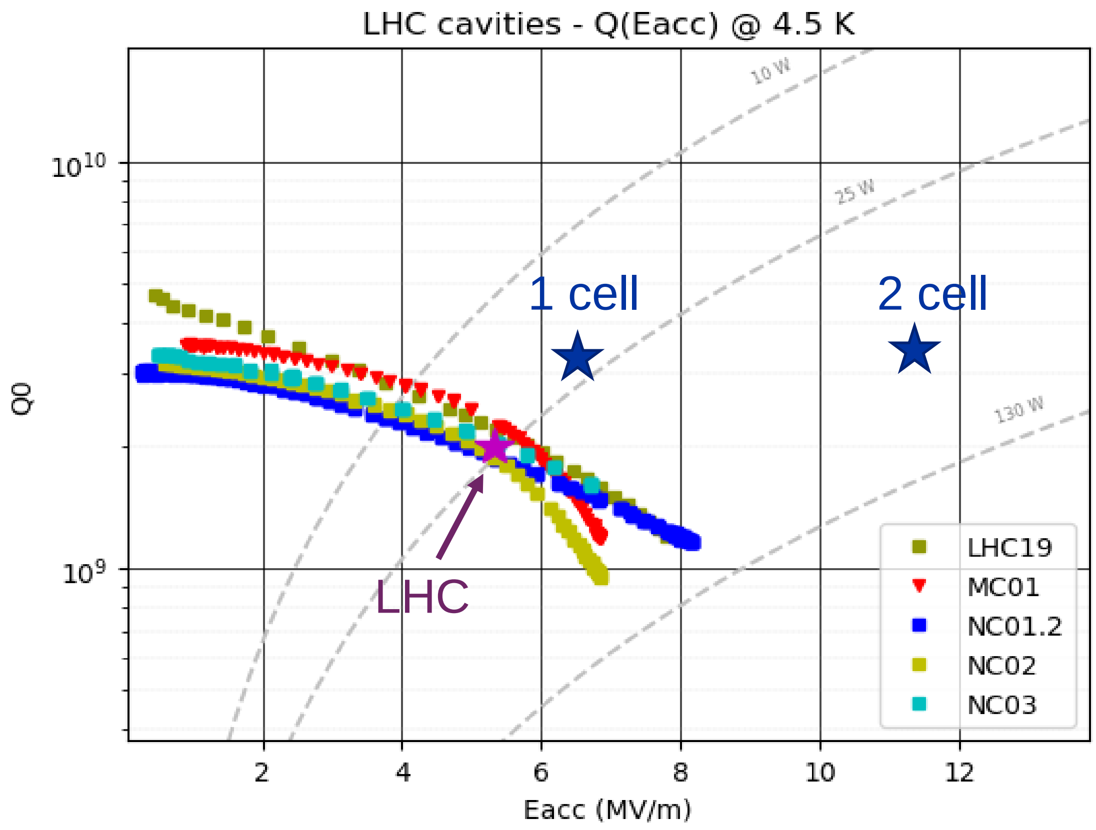
Motivation

Future plans

- Nb-on-Cu is the candidate technology for FCC-ee
- Currently used cavities do not reach the required performance
- Better low field Q and shallower Q-slope is required

Improvement of the film

- Defect density minimization
- Improving the adhesion to the substrate

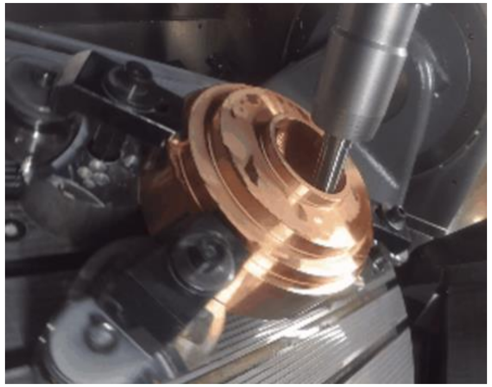


Overview of the 1.3 GHz Nb-on-Cu program of CERN

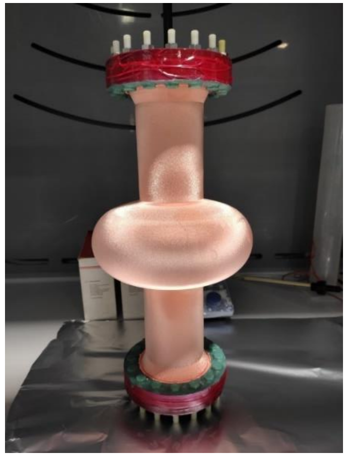
Substrates

- 1.3 GHz (for ease of manufacturing, and testing)
- Seamless, or internally welded cavities

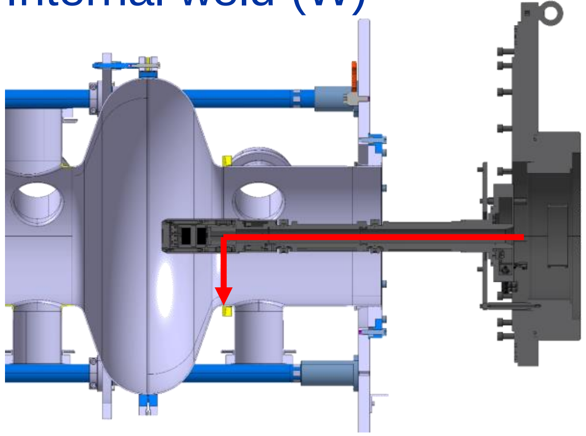
Bulk machined (BM)

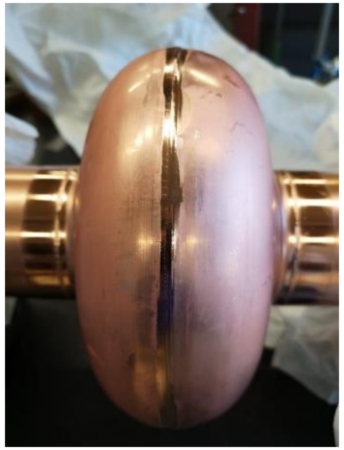


Electroformed (L)

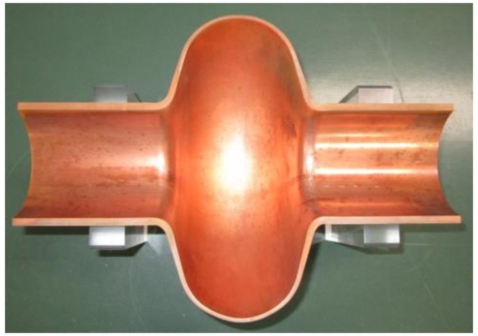


Internal weld (W)





Hydroformed (KEK)



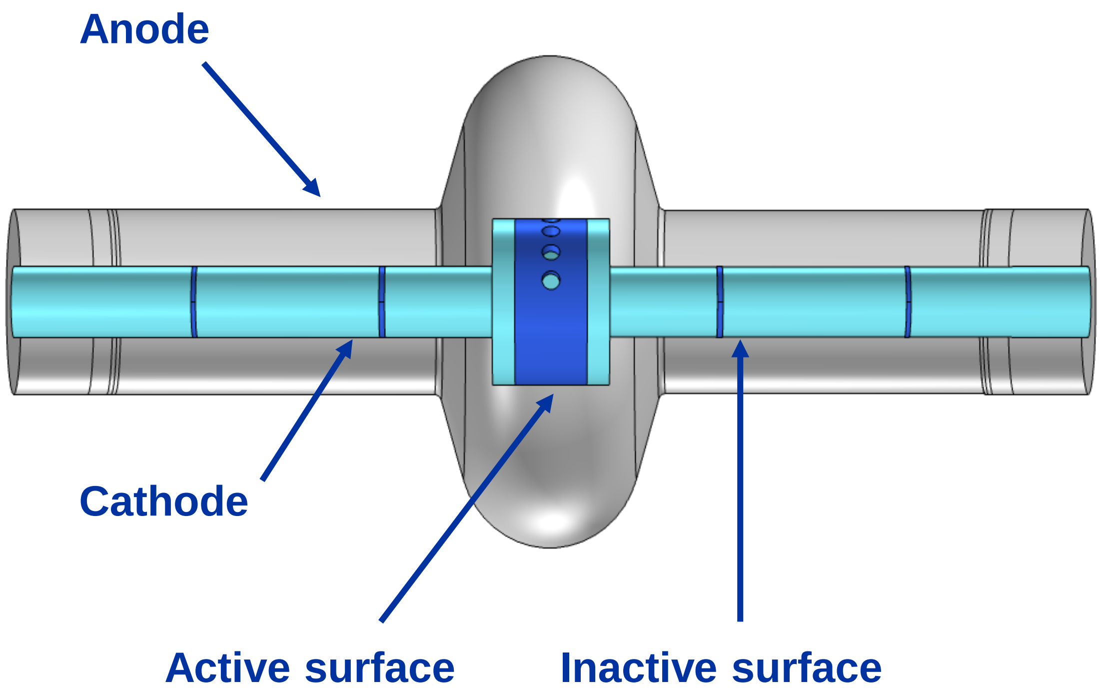
Overview of the 1.3 GHz Nb-on-Cu program of CERN

Substrates

- 1.3 GHz (for ease of manufacturing, and testing)
- Seamless, or internally welded cavities

Preparation

- Electropolishing
- Passivation



Overview of the 1.3 GHz Nb-on-Cu program of CERN

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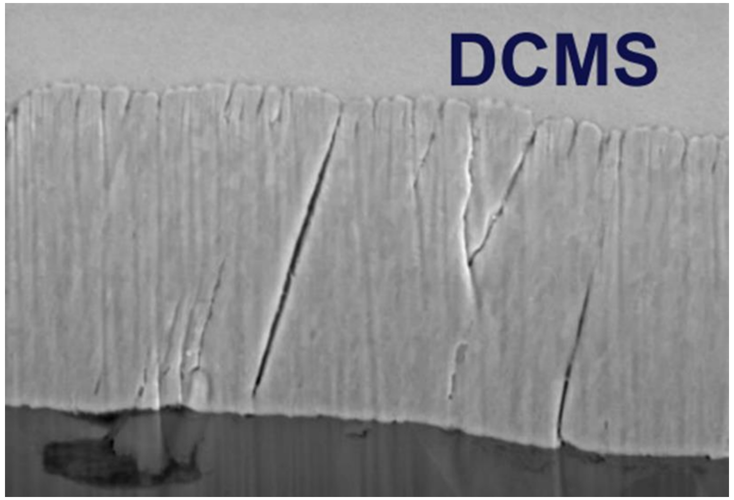
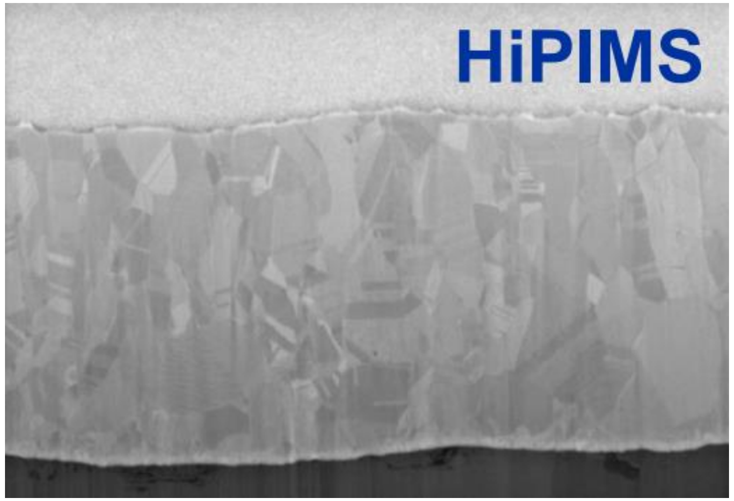
- Passivation

Instead of DCMS, HiPIMS is used

- Dense, void-free layer formation
- Best recipe was found using the quadrupole resonator (**QPR**)
  - **6 µm**
  - **-75 V DC bias**

High Pressure water Rinsing (HPR)





Measurement of the cavities

Mobile coupler

- ~ 6 cm freedom of motion
- Critical coupling 1e8 < Q < 1e11
- Allows 4.2 K and 1.85 K measurement

Phase-locked loop (PLL) based measurement

1 to 2 cooldowns per month

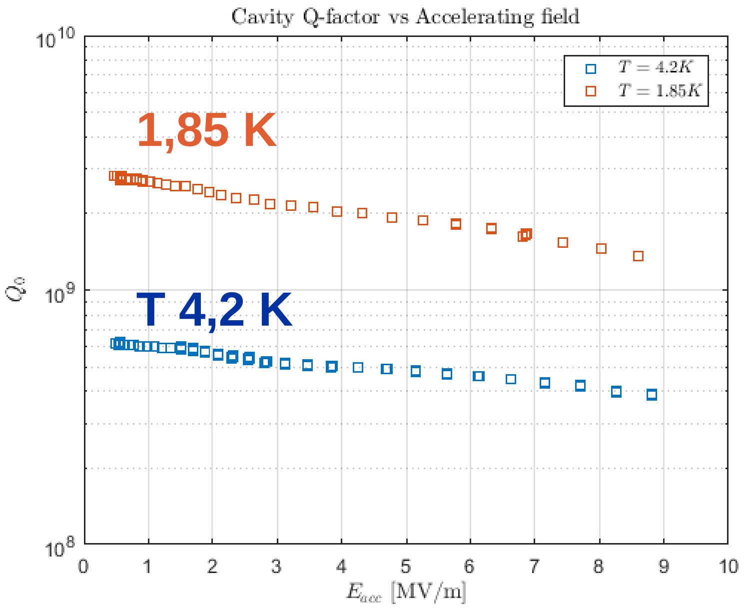
Due to safety limitations, the measurement is stopped at the first sign of radiation

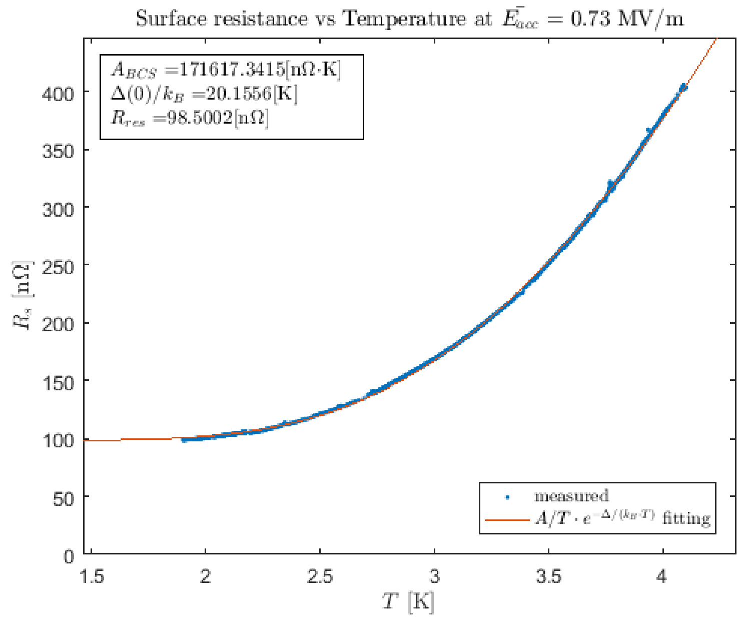
Sweeps performed

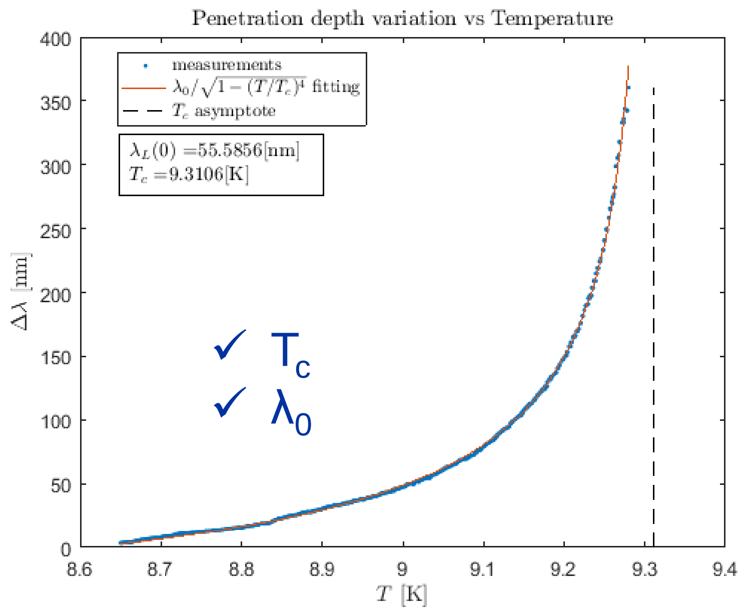
Q vs Temperature ↓ Rs vs Temperature

Frequency vs Temperature ↓ Pen. depth vs Temperature

Q vs E_{acc}@ 4.2 K and 1.85 K







T↓ From 4,2 K to 1,85 K

T↑ Above T_c

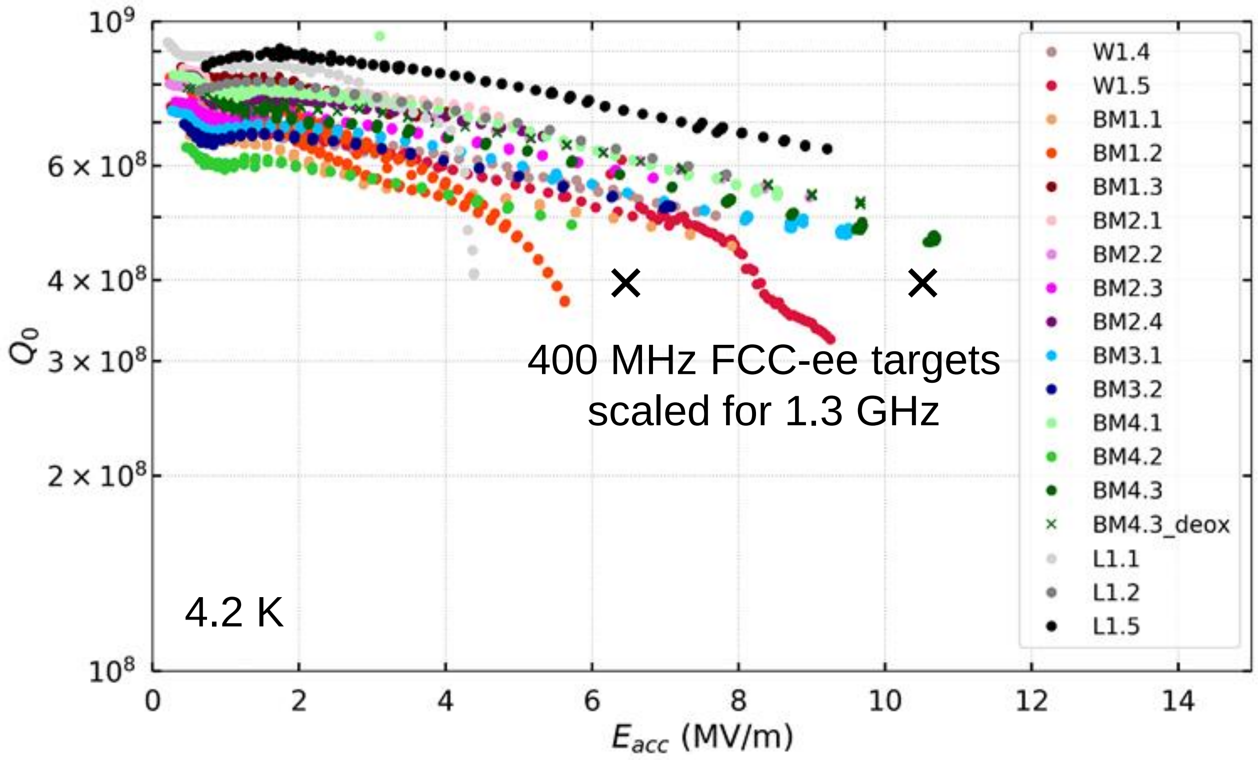
Results of the measurements

The low field Q was improved significantly

The Q-slope was also reduced

At 4.2 K the FCC-ee requirements were achieved (at 1.3 GHz)

- On 400 MHz cavity only a few tests were performed
- The early results are promising



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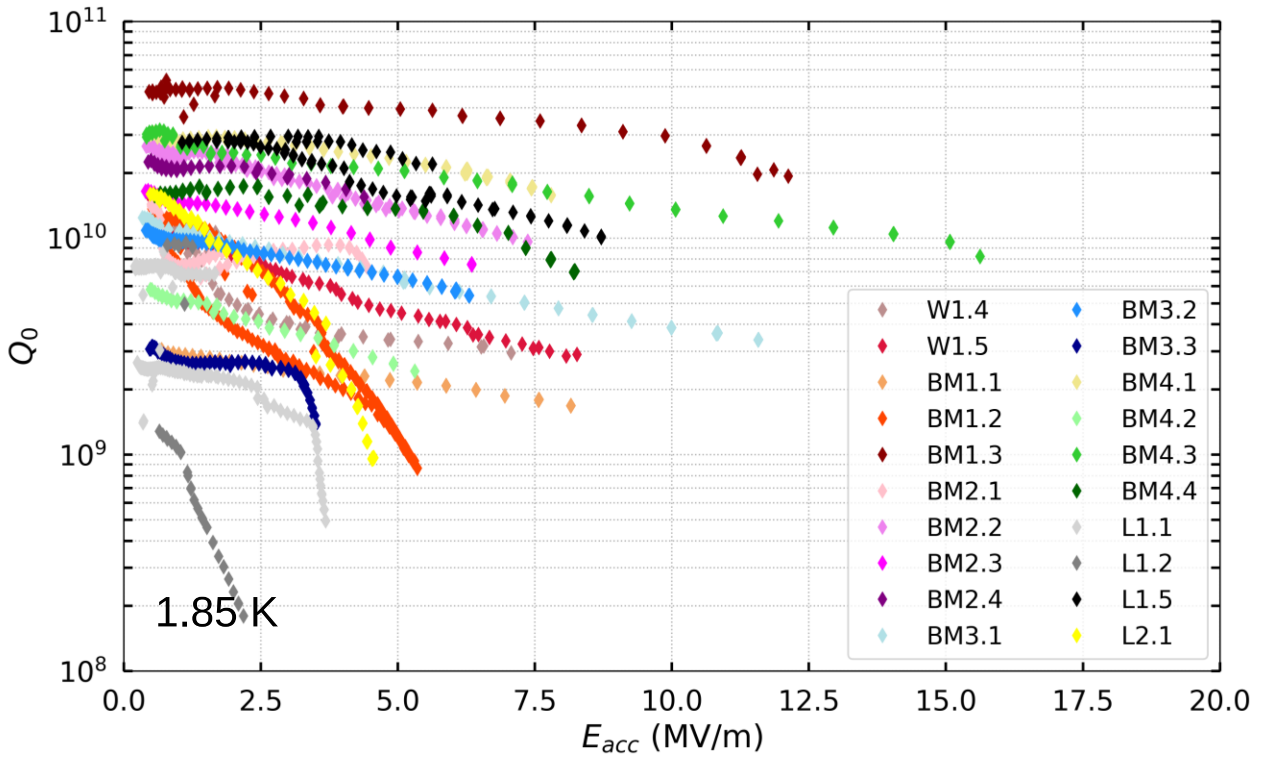


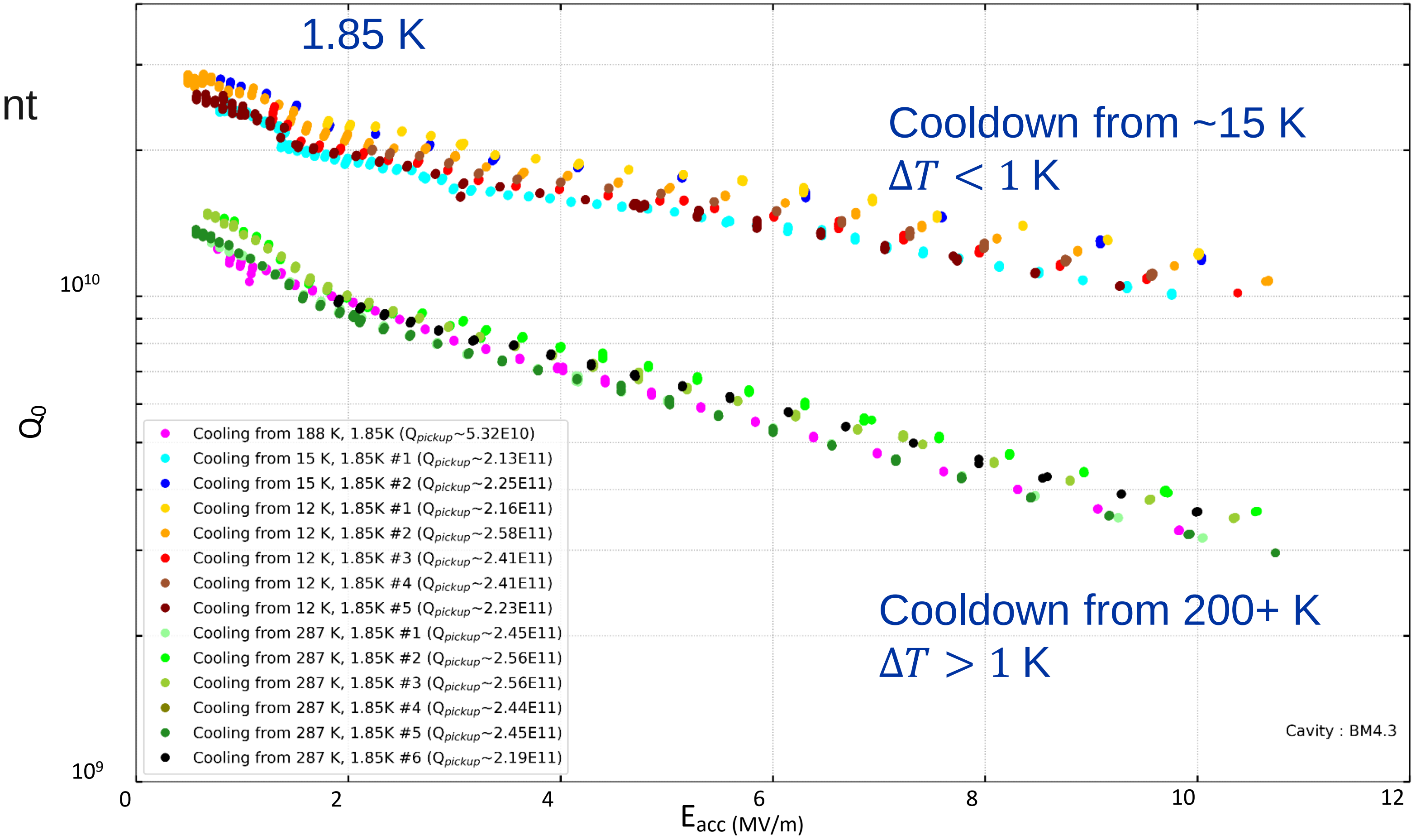
At 1.85 K the results vary much more

- Reproducibility needs to be increased

Thermoelectric currents

Nb – Cu interface

- Q depends on the thermal gradient at the time of the SC transition
- The thermal gradient was not well controlled
- New temperature control system is being implemented



Thermoelectric currents

A copper shield is installed

- The main goal is to shield the cavity from direct cooling

- A heater will be used to control the cooldown
    - Reach equilibrium and pause at 10-15 K
    - Slowly reduce heater power
    - Transition with as low of a thermal gradient as possible

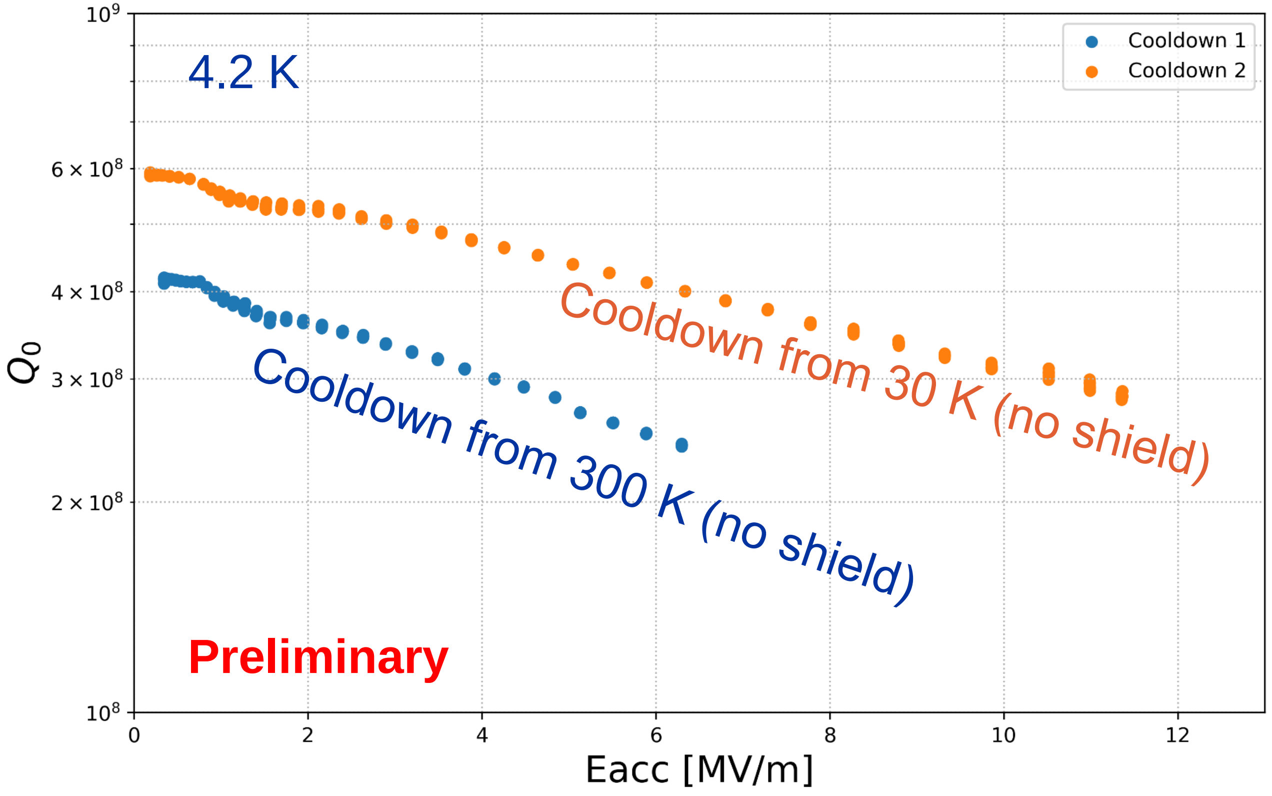
(Procedure developed in collaboration with KEK)

Thermoelectric currents

Tests done using two hydroformed cavities

The cavity preparation will be discussed on Wednesday by Hayato Araki (KEK)

- The first one was measured without the copper shield
  - It showed significant difference between the first and the second cooldown



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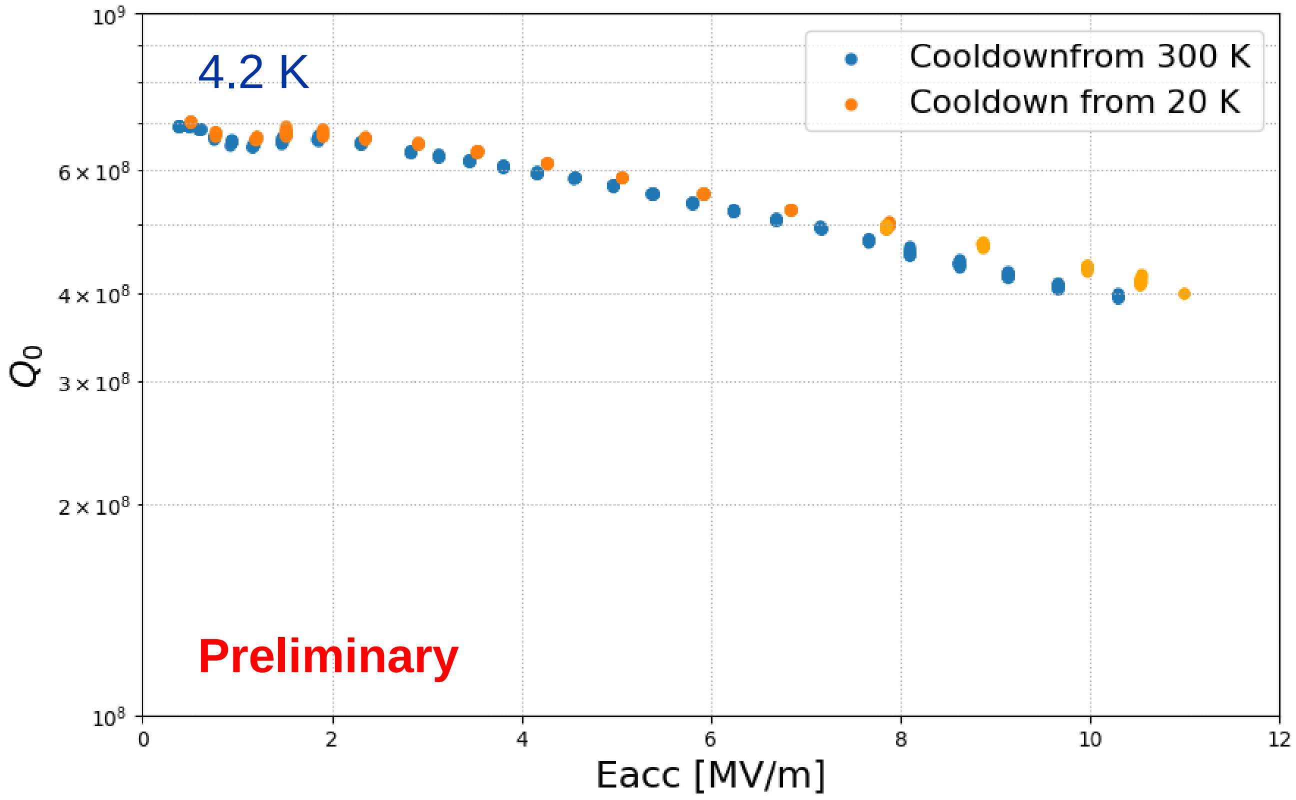
- The second one used the copper shield
  - Increased Q
  - Almost no difference between cooldowns



Thermoelectric currents

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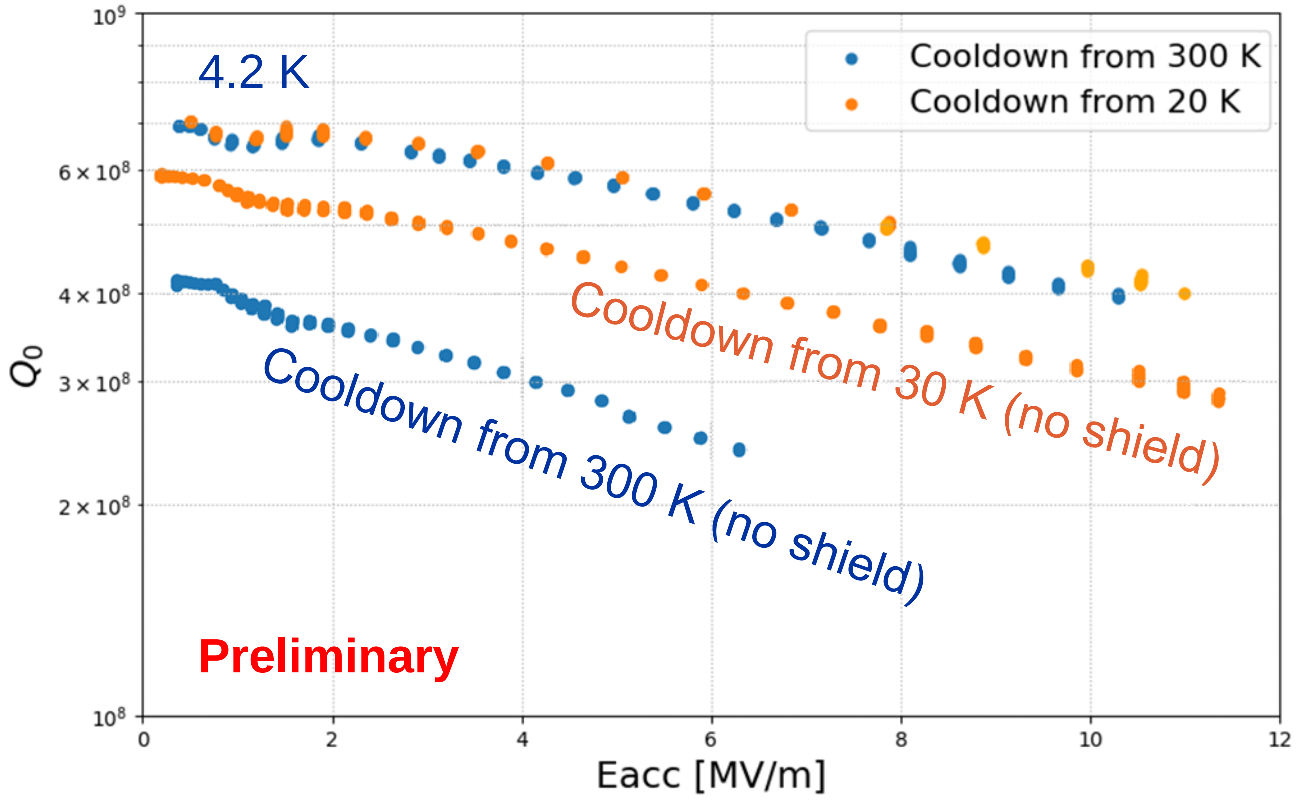
- The first one was measured without the copper shield
  - It showed significant difference between the first and the second cooldown
- The second one used the copper shield
  - Increased Q
  - Almost no difference between cooldowns
- Further tests are planned to perfect the cooldown

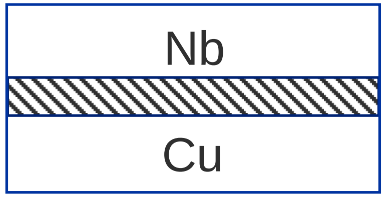


Thermoelectric currents

Eliminating the bimetallic interface would eliminate the thermoelectric currents

Interfacial insulating layer

- Approach 1
  - In-situ oxidization of the Cu
  - Simple, can be done on the same setup as the coating itself
- Approach 2
  - ALD of an insulating layer on the Cu
  - Needs dedicated equipment



e.g. Cu_2O/Al_2O_3

Nb film on bulk Nb cavity

Objective:

- Cross check HiPIMS coating process for Nb-on-Cu without substrate influences
- A case study in reviving RF surface/mitigate surface defects
- Preparation of surface for multilayer Investigations

  (See talk from L. Preece: Characterisation of PEALD Coated Thin Films for SRF Cavity Research)

Ongoing Activity:

- Application of CERN standard HiPIMS coating to a generic (well-worn) 1.3 GHz Nb cavity
  - Measurement/recovery of RF performance at 1.85 K
  - Step-by step evaluation of RF performance of a SIS multilayer coating sequence

Foreseen next steps

- Apply an SIS deposition to new/ dedicated 1.3 GHz bulk Nb cavities:
  - Assess reproducibility and performance
    - Cavities under fabrication: Delivery in Q1 of 2025
- Couple SIS deposition with enhanced magnetic flux expulsion (flux ratcheting)

Nb-on-Nb: HiPIMS Coating

Nb Substrate: Well tested standard 1.3 GHz cavity: numerous prior surface preparations

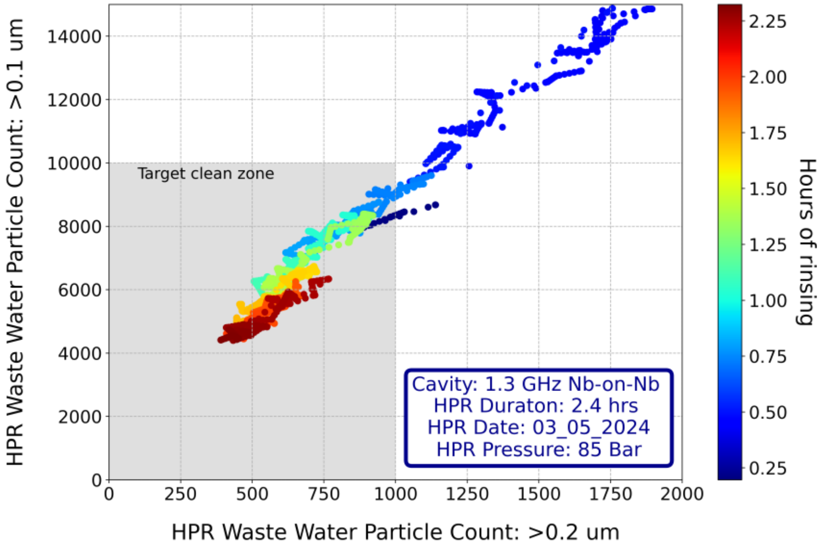
Nb film: (Standard CERN HiPIMS coating)

- Pulse duration: 200 μs, Repetition rate 100 Hz, Av power 1.2 kW, Sputtering gas: Krypton (Kr)
- Coating Duration: 6 hours => deposited layer thickness ~ 6 μm
- Deposition only in cavity cell

HiPIMS coating setup

Coated Cell

Particulate counting: HPR outflow

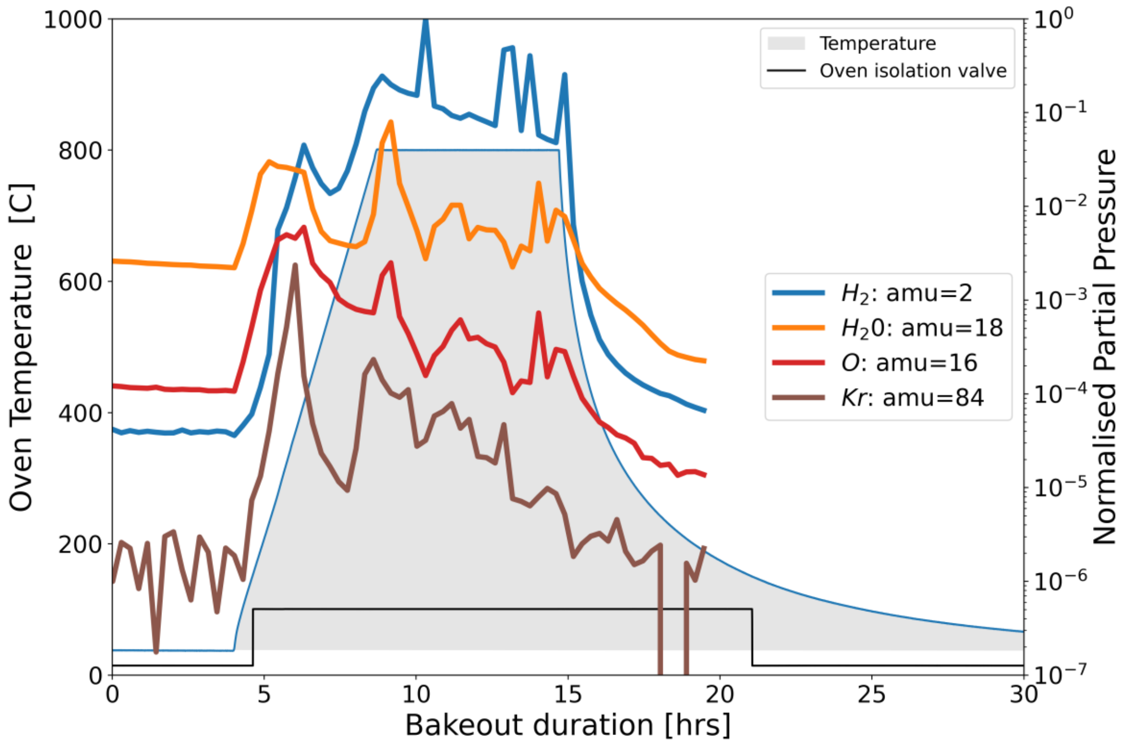


Post-coating HPR: no sign of peel off

Nb-on-Nb: Post-coating Heat treatment

1st Heat treatment: 800 ºC for 6hrs

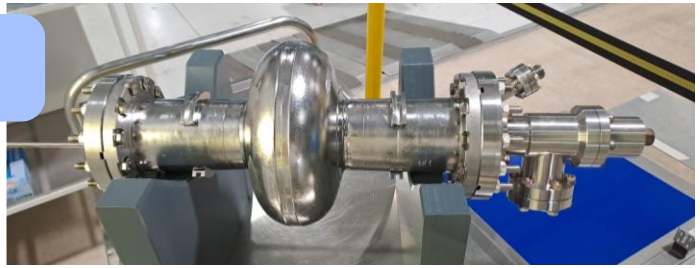
- DESY vacuum furnace monitoring of partial pressures



Courtesy M. Wenskat: Uni Hamburg/ DESY

Before

After



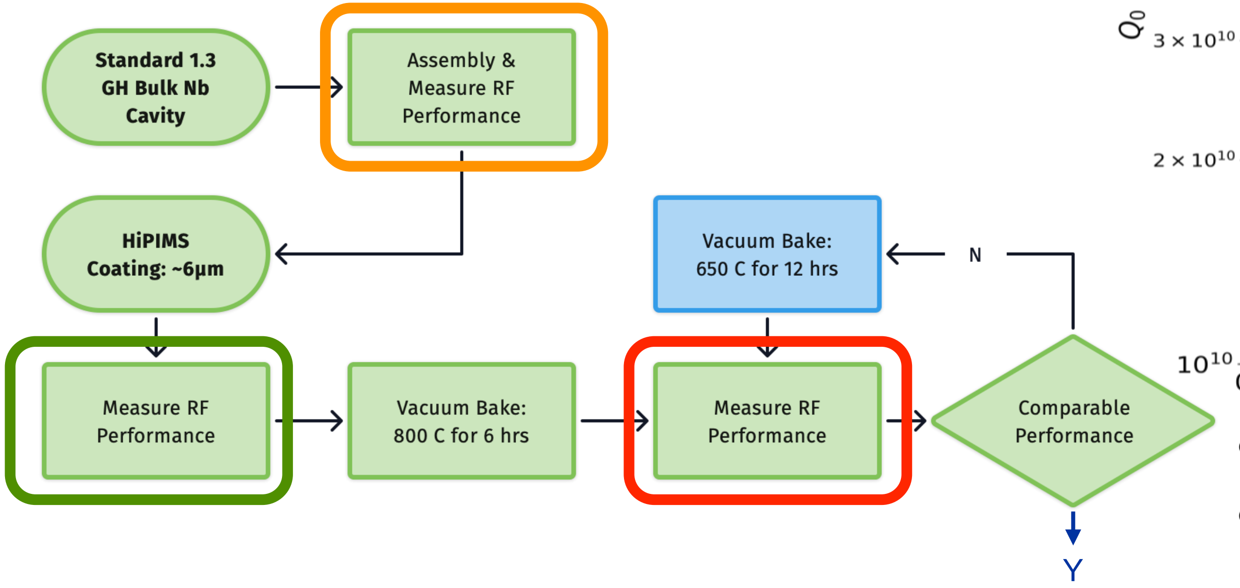
Pressure spikes at plateau
- from vacuum line heating& valve

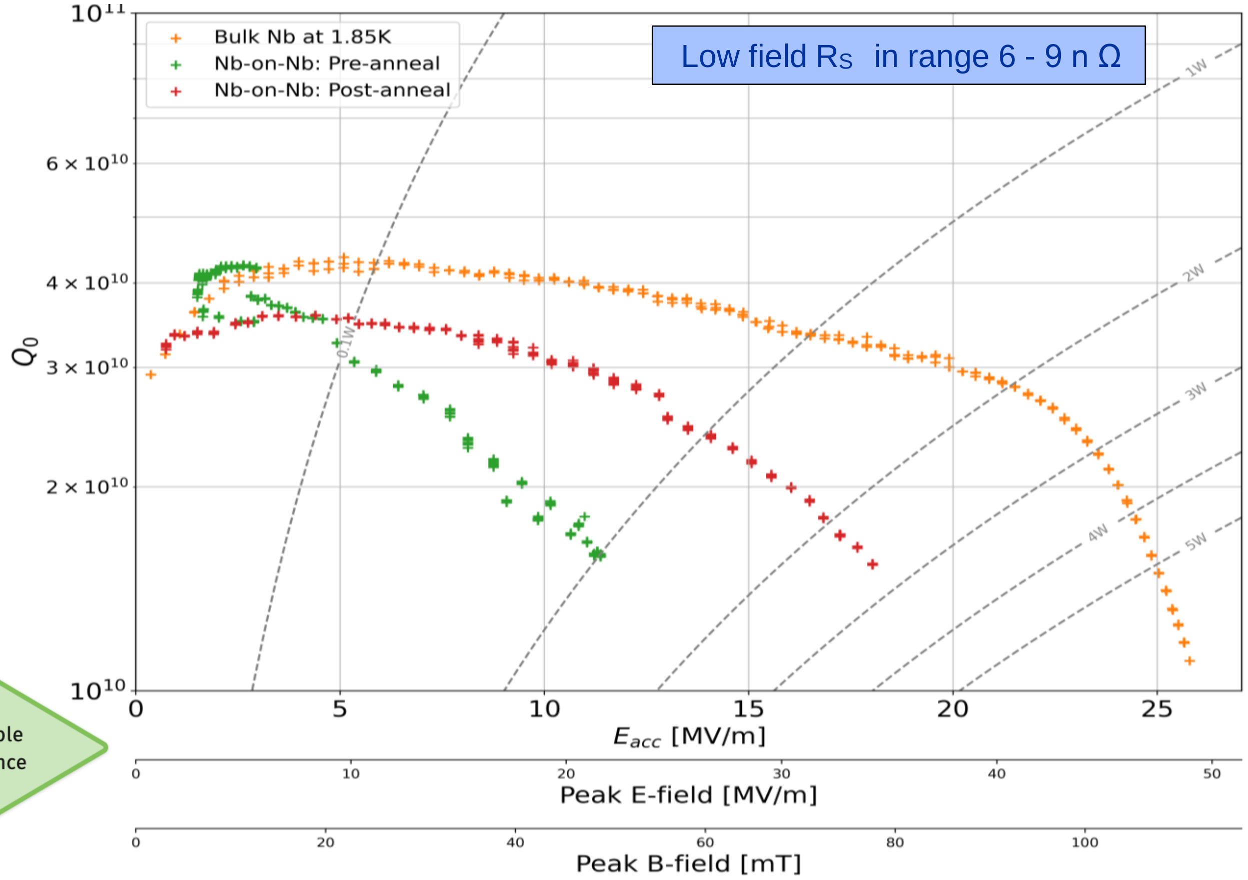
Spike in Krypton signal at T~400ºC
- Krypton is from HiPIMS process
- **Confirms HiPIMS film is present**
- **Indicator of Nb_2O_5 dissociation**

Nb-on-Nb: Measurement results

Pre-coating: (orange)

- High Q, no Q-slope up to ~20 MV/m
- Q reduction, and radiation at high field

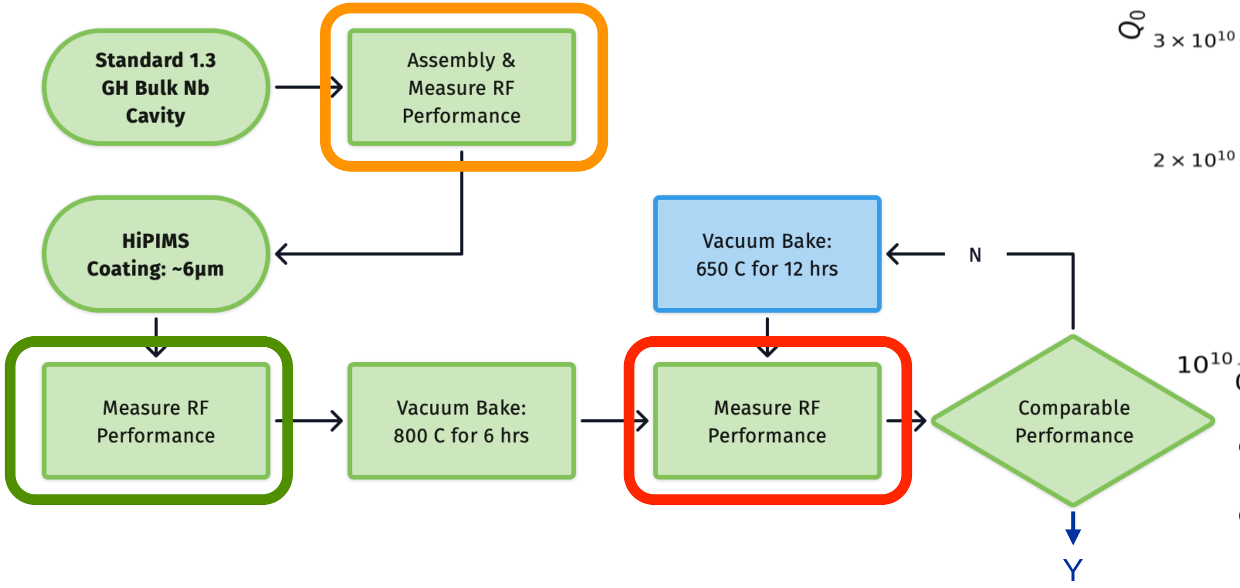


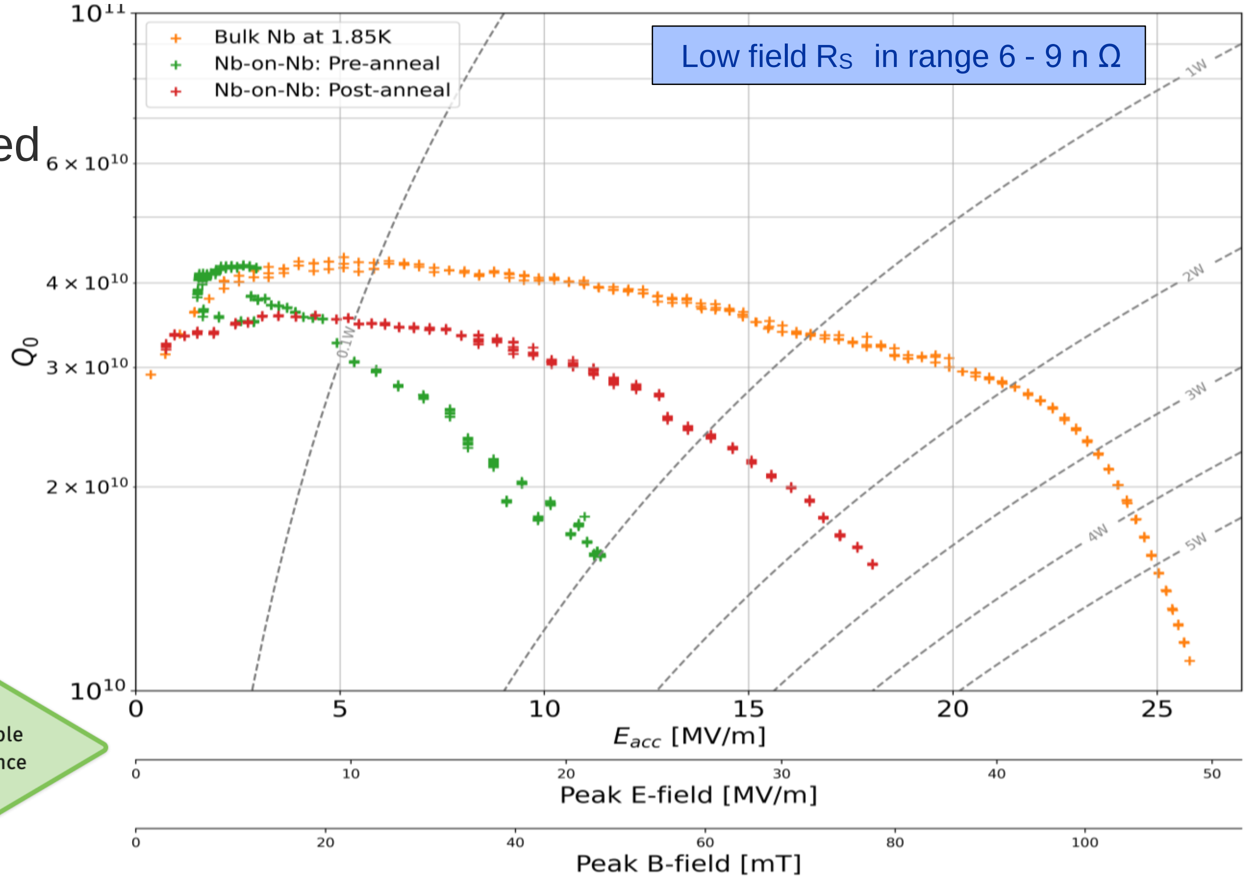


Nb-on-Nb: Measurement results

Pre-annealing: (green)

- Low field Q was maintained
- Several Q switches
- Significant Q-slope: Niobium hydrides suspected
- Quench at ~12 MV/m

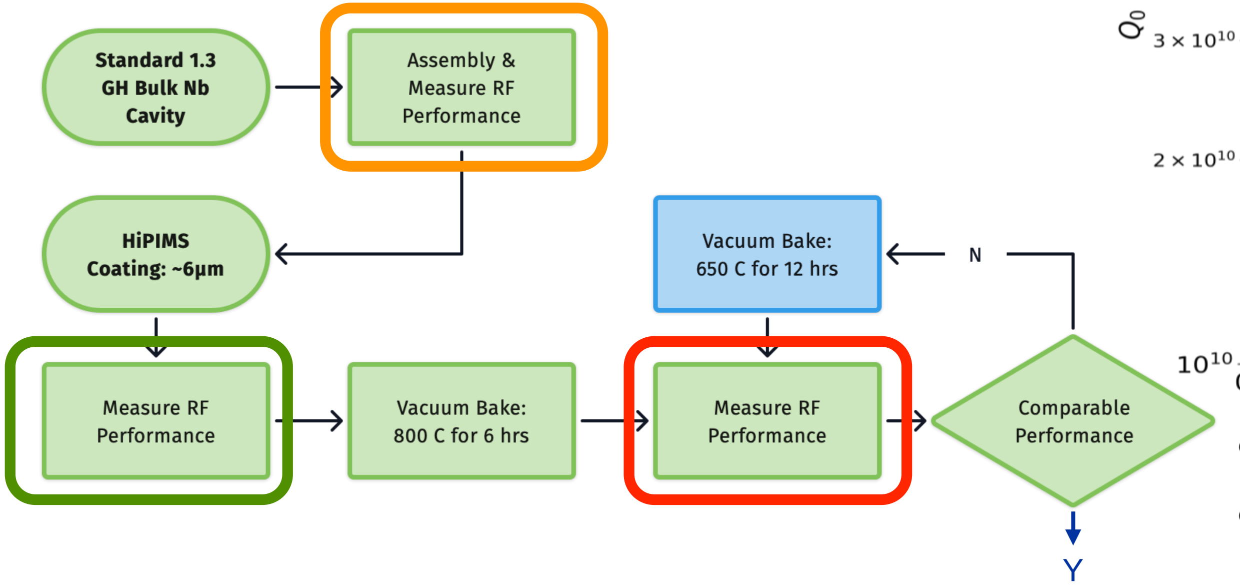


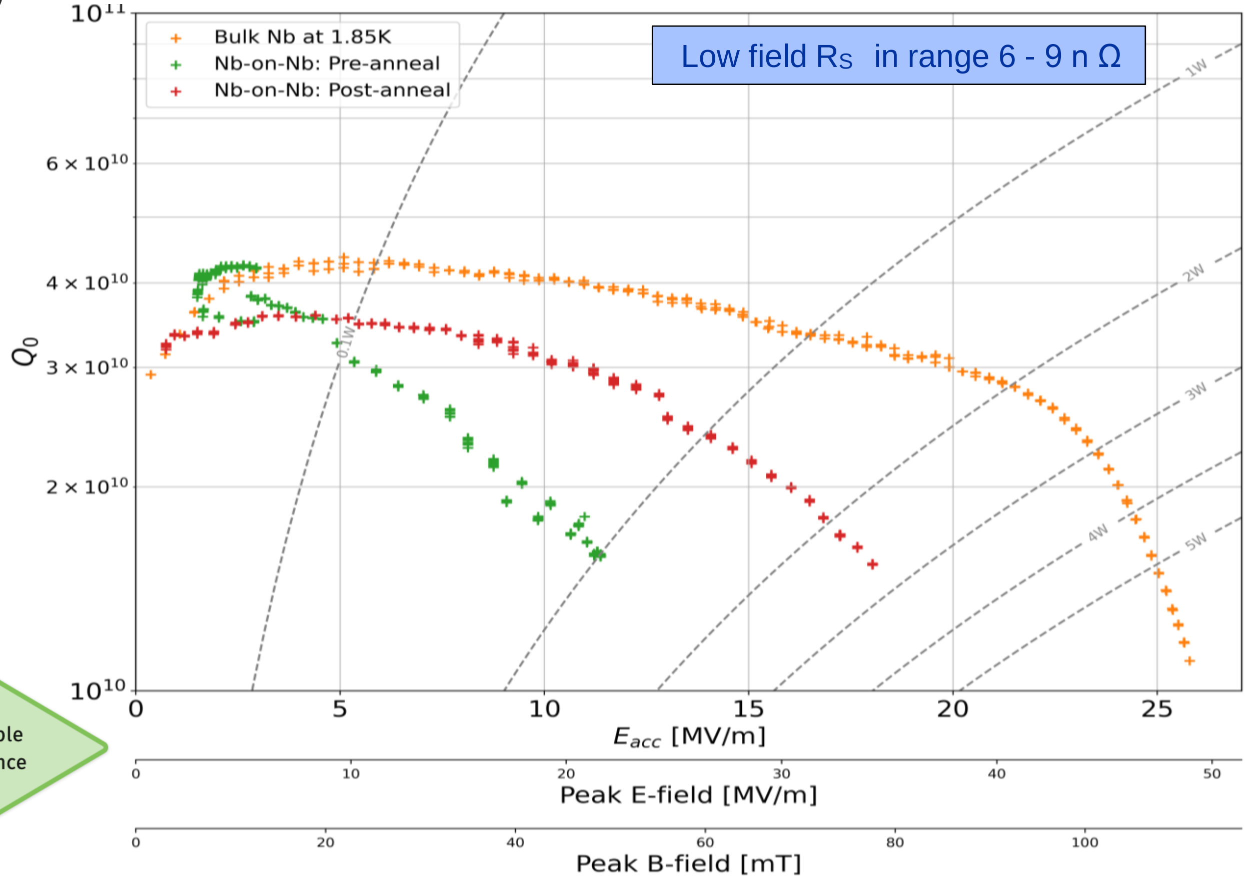


Nb-on-Nb: Measurement results

Post-annealing: (red)

- Partial recovery of field reach but reduced Q(0)
- Mid field Q-switch is more apparent
- Quench at ~18 MV/m
  - **Cavity needs further heat treatment**
  - Now ongoing at DESY: 12 hrs @ 650º C





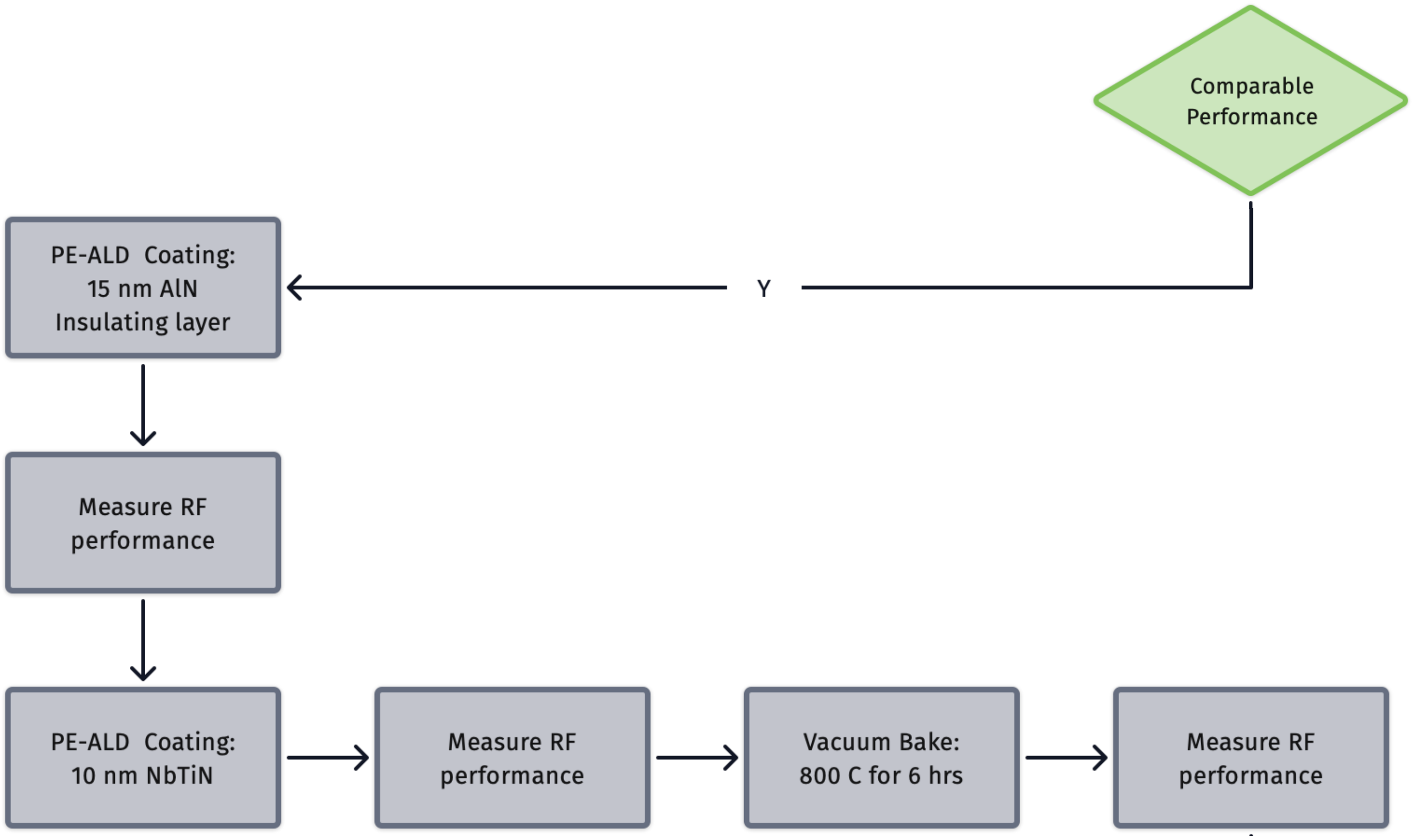
Nb-on-Nb: plans for the future

Apply insulating layer

- on this, or a similar cavity
- PE-ALD: 15 nm of AlN

Apply NbTiN

- Test RF performance of SIS
- Test enhanced magnetic flux expulsion (flux ratcheting)
    - See talk of Dan Turner on Wednesday



Summary

Nb-on-Cu cavities

- HiPIMS recipe finalized
- Q increased significantly
- Q-slope was mostly mitigated
- Main limitation is posed by the thermoelectric currents
  - Mitigation strategies under study

At 1.3 GHz the FCC requirements are in reach. Improving reproducibility and transferring the technology to 400 MHz is the current goal.

Nb-on-Nb cavity

- A bulk Nb cavity was coated by HiPIMS Nb
- The measurement showed
  - Almost unchanged low field Q
  - A steep Q-slope
  - Several Q-switches
- Heat treatment at DESY (800 °C, 6 h)
  - Low field Q is lower
  - Q-slope is mitigated
  - Record breaking power reached (for this setup)
- Further heat treatments and coatings foreseen

Thank you for your attention!

This presentation included the work of several colleagues at CERN, KEK and DESY.

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