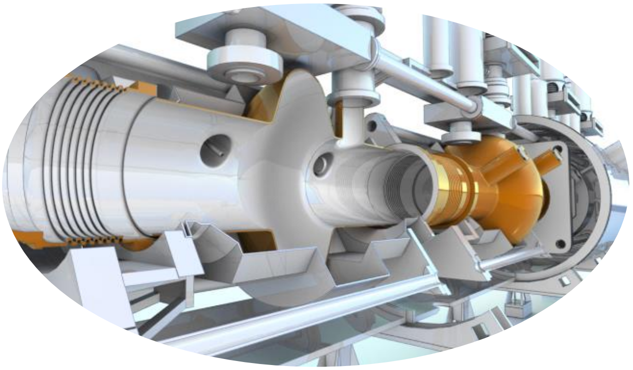
CERN

Superconducting Coatings for future RF Cavities

Guillaume ROSAZ
CERN: TE-VSC/SCC

On behalf of:
HIE-ISOLDE working group
LHC spare cavities working group
FCC WP3



OUTLINE

1. SRF Thin films : interest
2. Coating techniques
3. Past and on-going projects
4. Recent achievements
5. On-going R&D
6. Conclusion

1. SRF Thin Films: Interest

1.1

Original Motivation

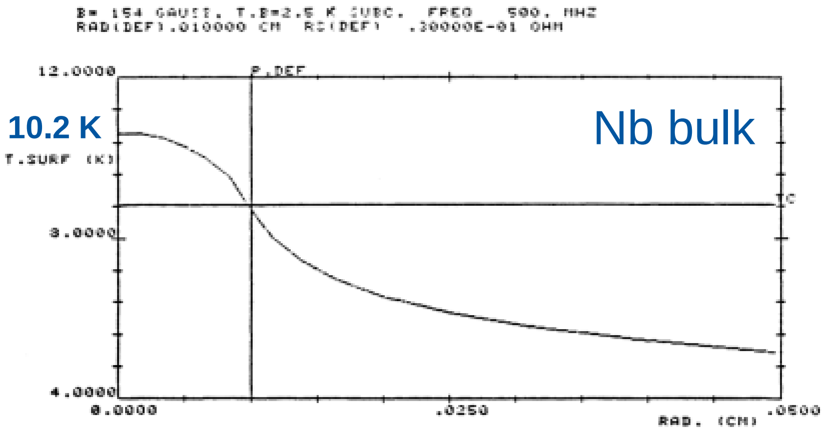
COST

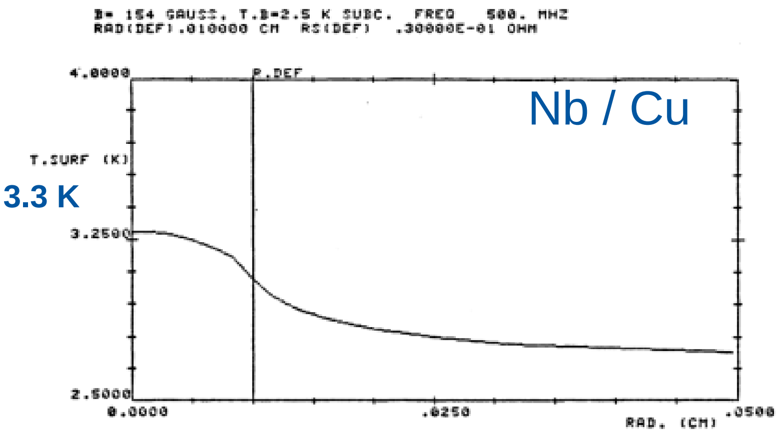
Manufacturing: Cu OFE (10euros/kg) vs Nb RRR300 (800euros/kg)

Operation: Operation @ 4.2 K / Simpler cryostat (stainless steel vs Titanium)

Thermal Stability

Cu substrate ensures SC film stabilization wrt thermo-magnetic breakdown





Temperature distribution calculation for a 100 micron radius steel defect embedded either in niobium or in copper

Joachim Tuckmantel - Thermal effects in superconducting RF cavities: some new results from an improved program
CERN-EF-RF-84-6. - 1984.

1.2 LEP era

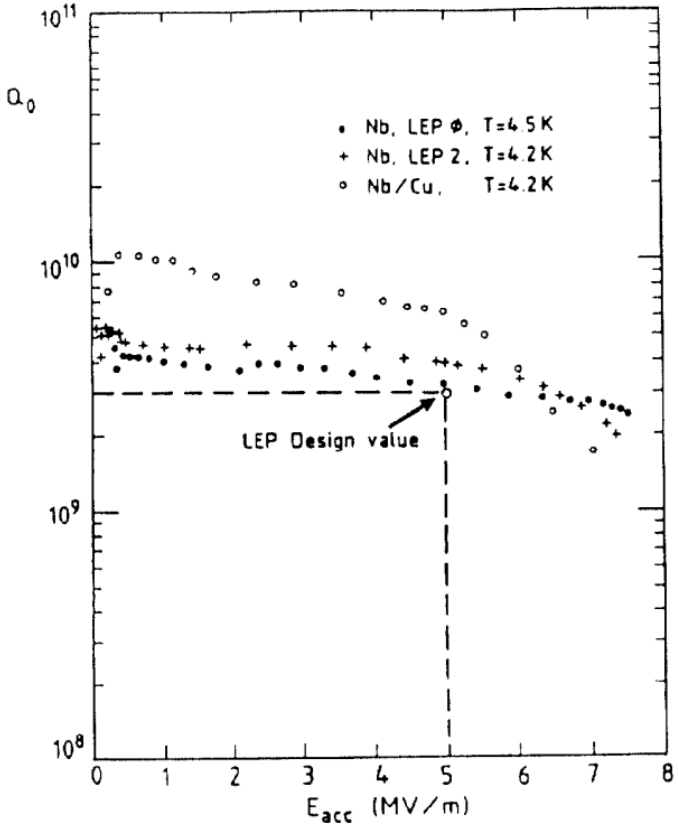


Fig. 1 Dependence of Q-values on E_{acc}. Final values for 4-cell Nb cavities LEP 0 and LEP 2 and for a 350 MHz 4-cell Cu cavity with a magnetron sputtered Nb layer.

P. Bernard et al, Superconducting cavities for LEP, Status report, https://accelconf.web.cern.ch/accelconf/e88/PDF/EPAC1988_0958.PDF

SRF: higher CW accelerating gradient wrt copper

Increase beam stability by increasing stored energy

1-MW klystrons for Cu@55GeV enough to obtain 90Gev with SC

Bulk Nb: Expensive and subject to quenching

@ 4.2K Nb/Cu more efficient

Nb/Cu less sensitive to earth magnetic field → avoid expensive shielding

Very satisfying from an operational point of view.

Decision taken to use the same technology toward the hadronic machine version: LHC

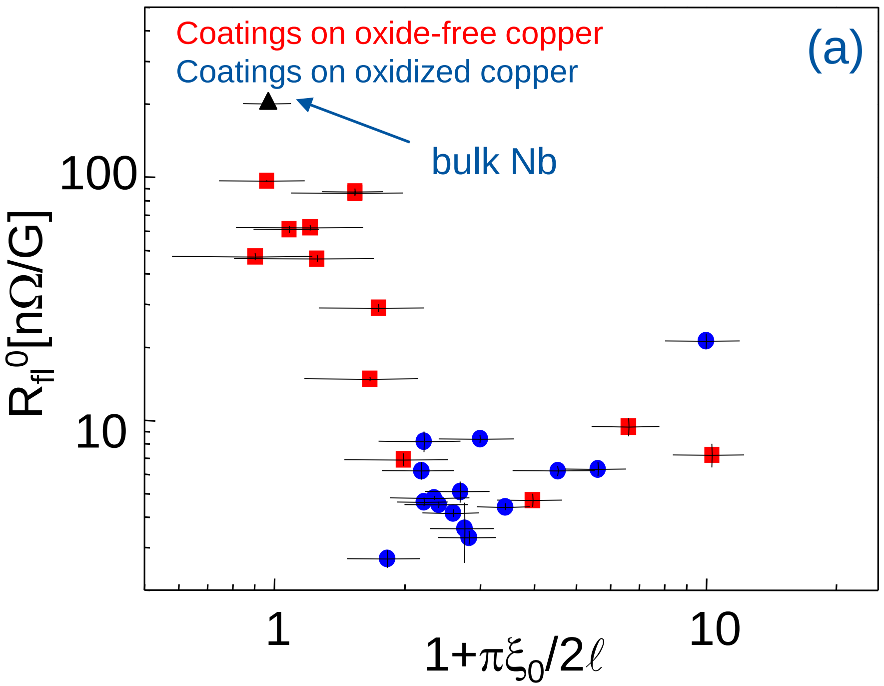
1.3 Magnetic field sensitivity

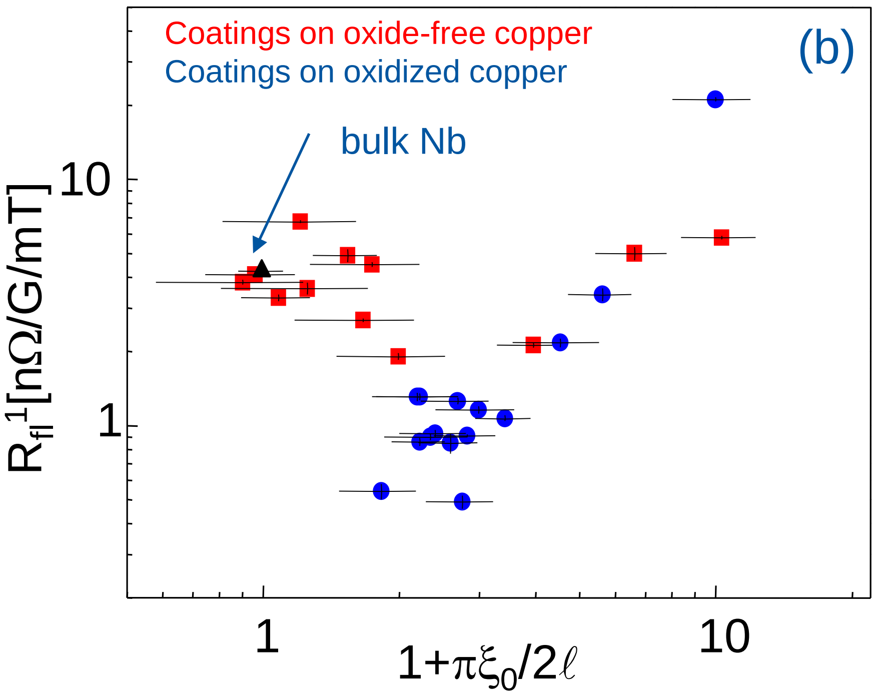
Losses due to trapped external magnetic field at 1.7 K are characterized as

$$R_{fl} = (R_{fl}^{0} + R_{fl}^{1} H_{RF}) H_{ext}$$

The minimum values are obtained using krypton as sputter gas:

$R_{fl}^{0} = 3 n\Omega/G$ $R_{fl}^{1} = 0.4 n\Omega/G/mT$

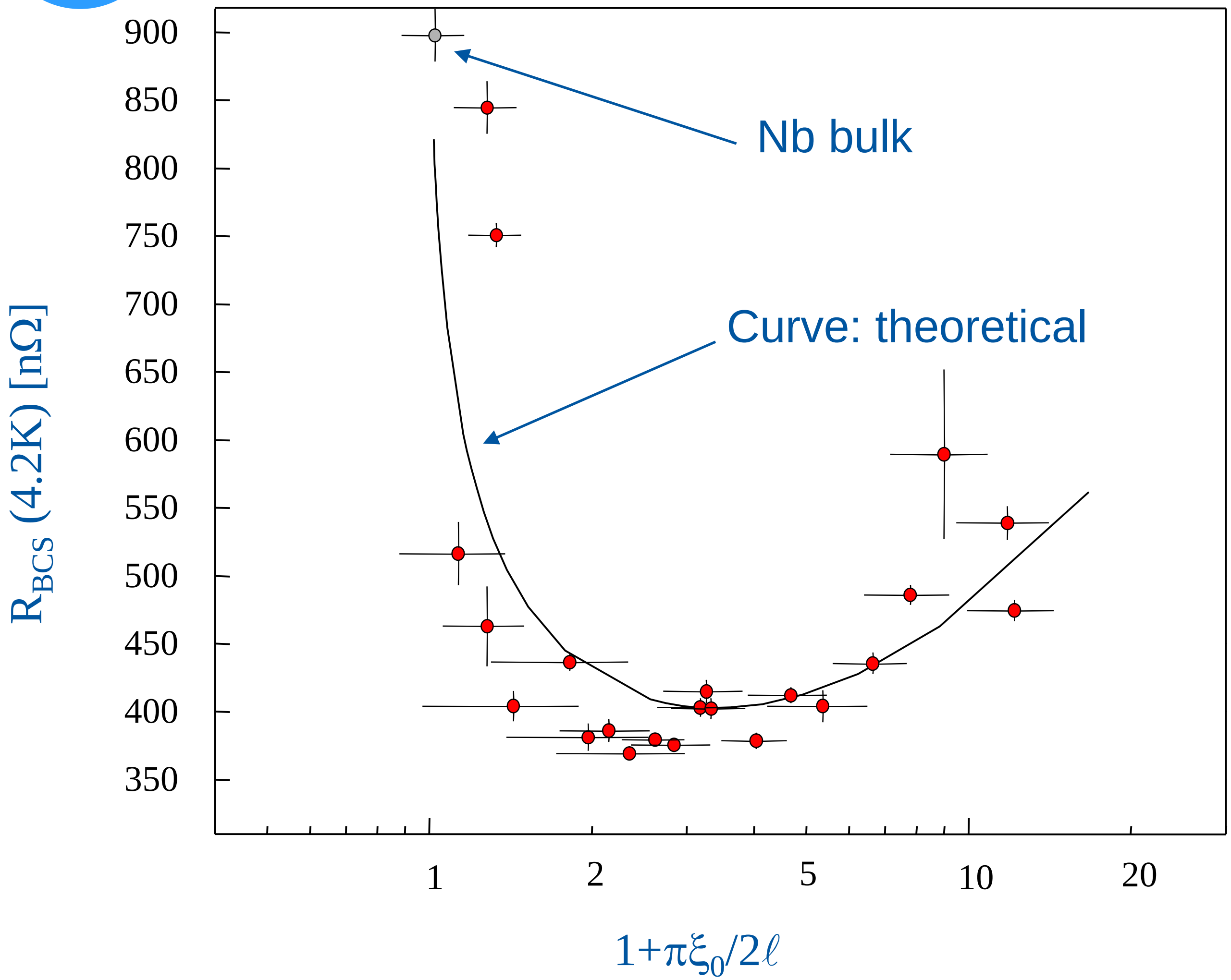




No need for magnetic shielding considerably simplifies cryostat design

Courtesy of S. Calatroni

1.4 BCS resistance at zero RF field



R_{BCS} at 4.2 K (1.5 GHz)

Nb bulk: ~900 nΩ

Nb films: ~400 nΩ

R_{BCS} at 1.7 K (1.5 GHz)

Nb bulk: ~2.5 nΩ

Nb films: ~1.5 nΩ

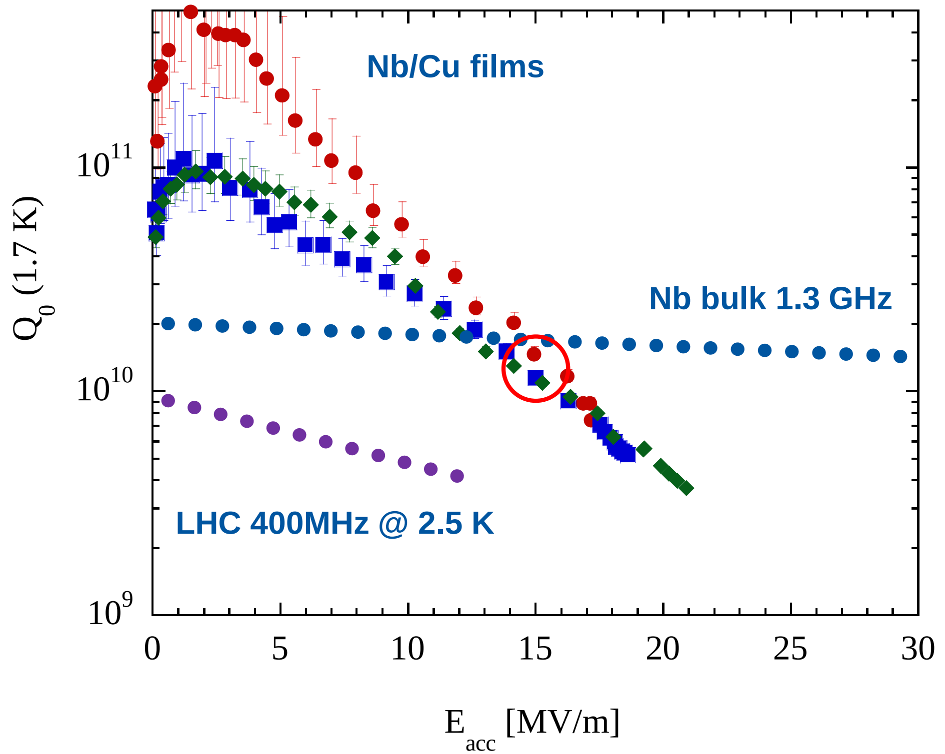
Lowest R_{BCS} allows achieving highest Q values even at 1.7 K

1.5 90's Activity

Strong efforts on optimizing Nb films using 1.5 GHz Cu cavities

- **Easy to handle**
- **Both R_{BCS} and R_{res} accessible at 4.2K and 2K**

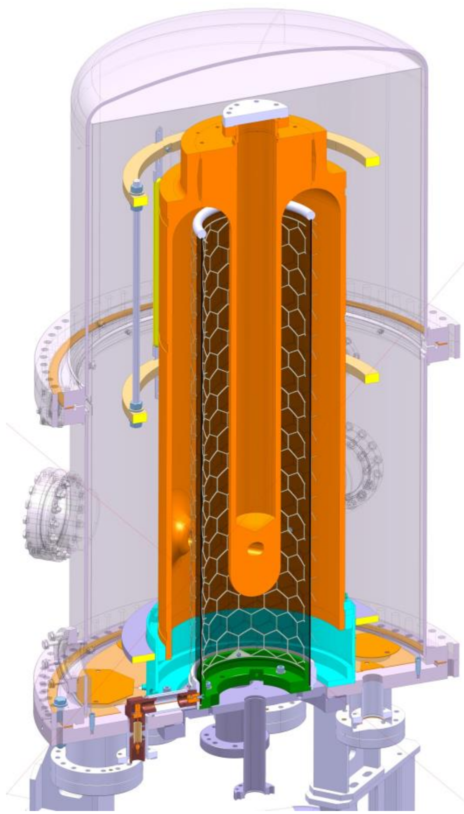
1.5 GHz Nb/Cu cavities, sputtered with Kr @ 1.7 K (Q_0=295/R_s)

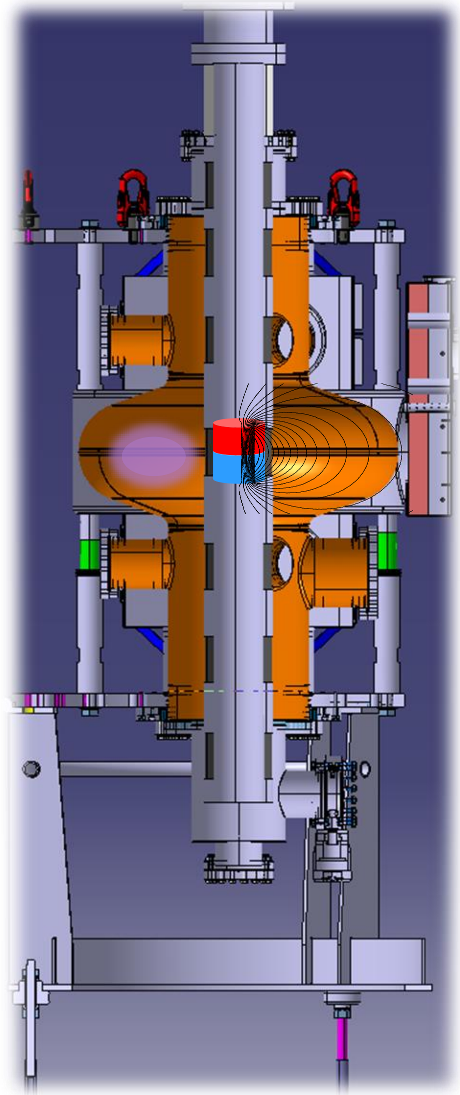


Courtesy of S. Calatroni

Q = 1x10^10 @ 15 MV/m is a value that would make film cavities a competitive option for new high energy proton accelerators (high-beta)

2. Coating Techniques



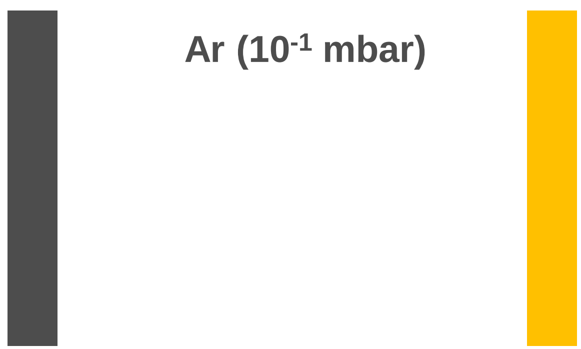


Physical Vapor Deposition (PVD)

Nb very sensitive to hydrogen and oxygen contamination
- **Pure Nb starting material preferred (RRR 300)**
- **Low coating pressure**

UHV environment required to ensure low R_{BCS} and low R_{res}
- **UHV class vacuum system**
- **Bake Out**

Diode Sputtering



Simple set-up

High working pressure

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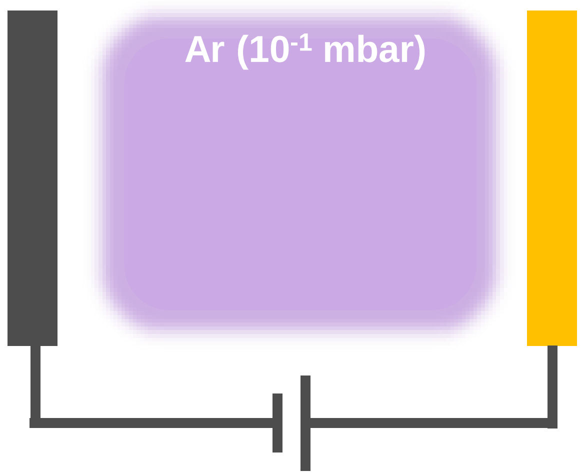

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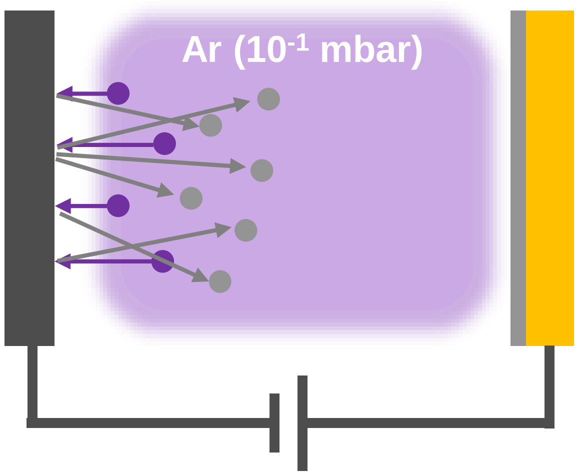

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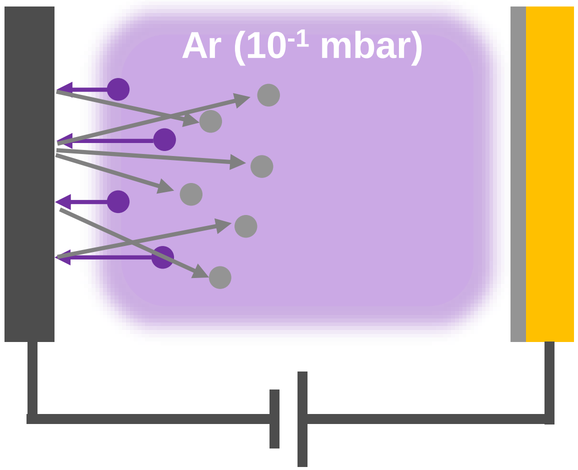

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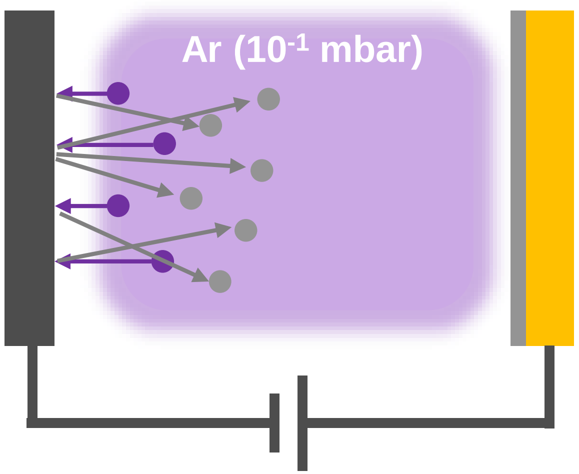

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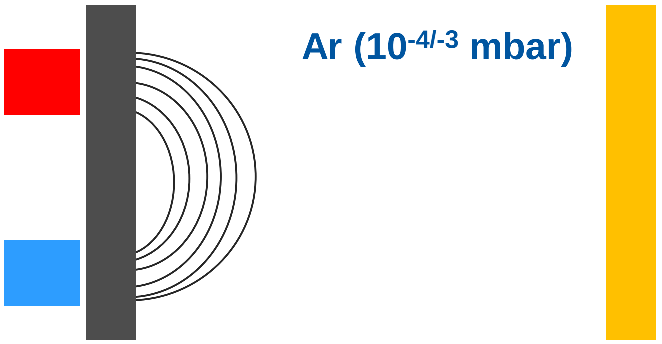
High working pressure

Magnetron Sputtering



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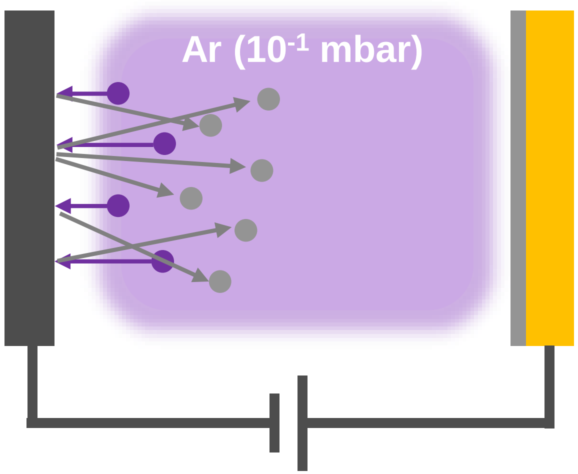

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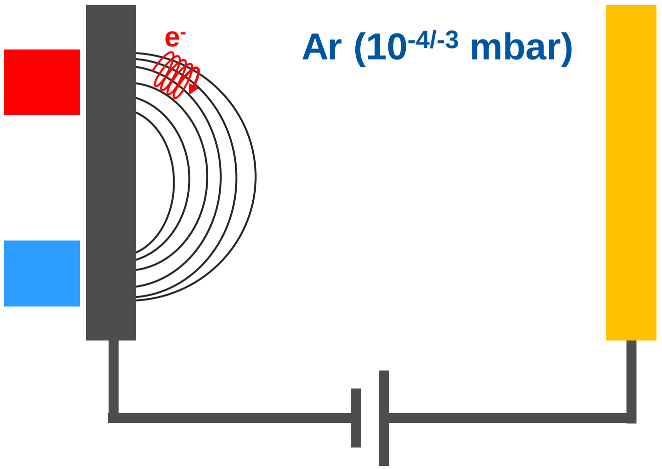

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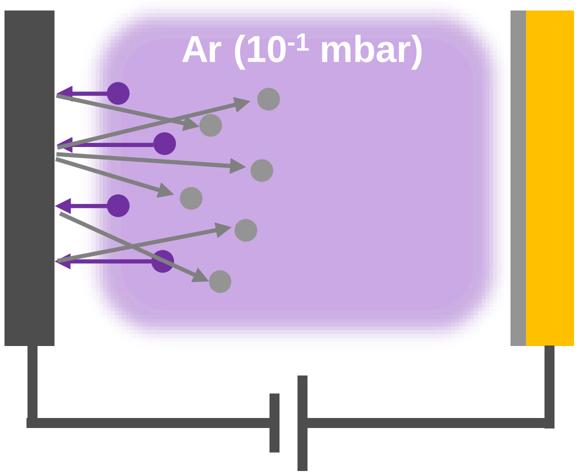

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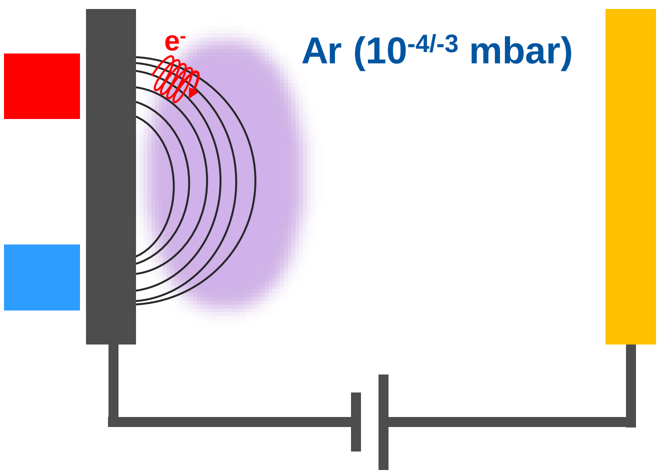

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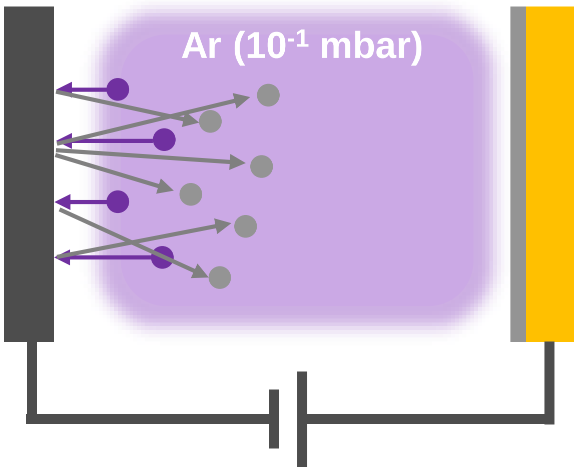

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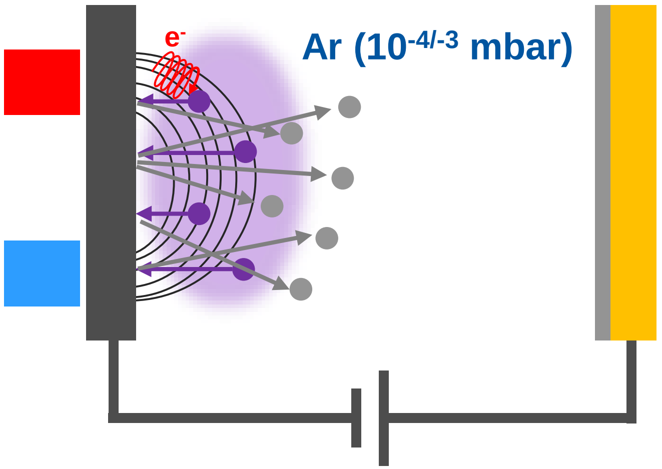

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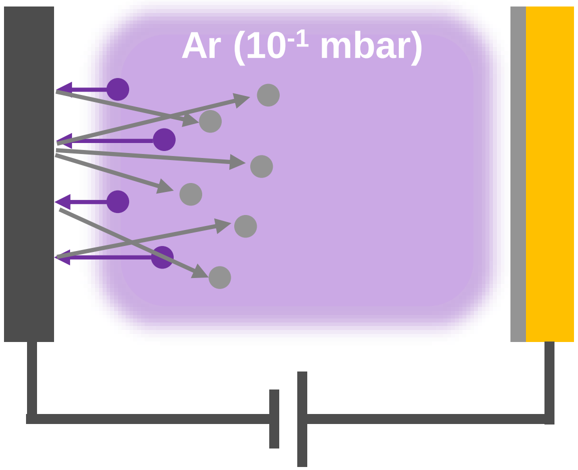
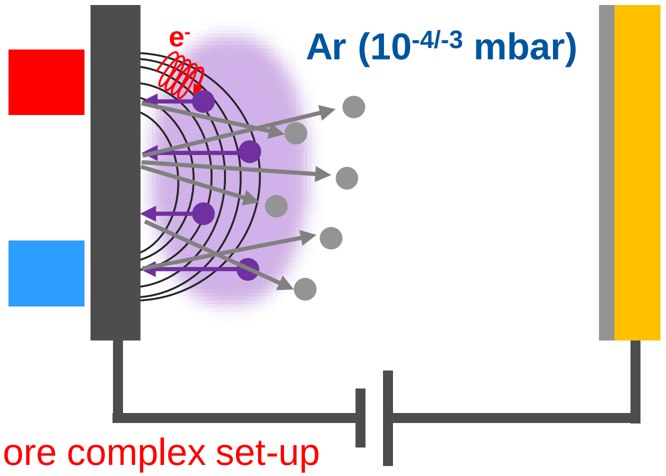


Simple set-up
High working pressure

Magnetron Sputtering



More complex set-up
Temperature control required on cathode
Higher coating rate
Lower contamination

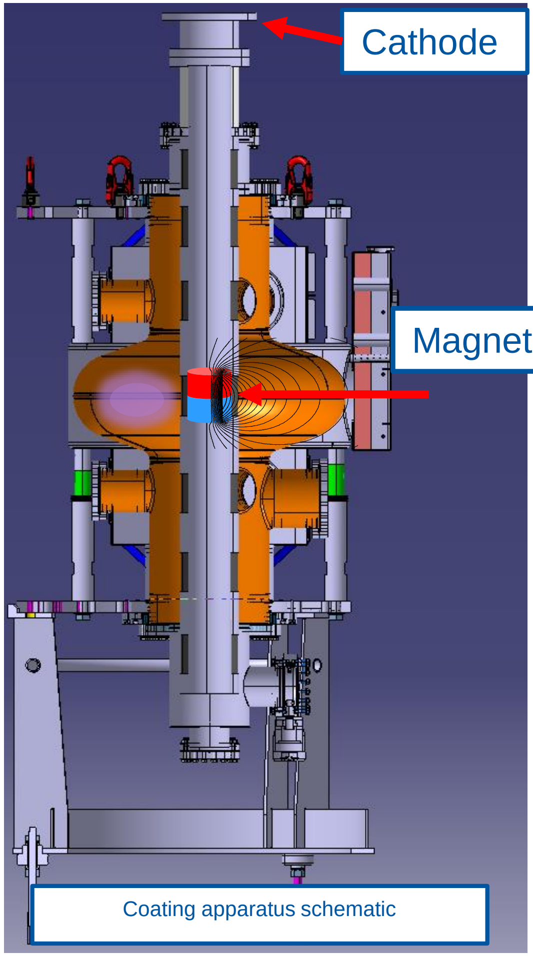
2.2 At CERN

Historically :
Magnetron sputtering for elliptical cavities
Diode trials on elliptical were not convincing
Diode sputtering for QWR (inspired from ALPI upgrade)

2.3 Other Methods

Main R&D efforts focus on
High Power Impulse Magnetron Sputtering (Jlab and CERN cf next chapter)
Electronic Cyclotronic Resonance (Jlab)
Atomic Layer Deposition (Argonne, Saclay, Old Dominion, STFC…)
UHV Cathodic Arc (alameda, NCBJ, INFN…)

2.4 Elliptical cavities coatings



Coating apparatus schematic

- **Cavity as UHV chamber**
  (10^{-10} mbar base vacuum)
- Cavity = anode, grounded
- Nb cylindrical cathodes tubes
- **movable electromagnet inside**, liquid cooled

→ **DC-magnetron sputtering, 6 kW, 1.10^{-3} mbar Kr**

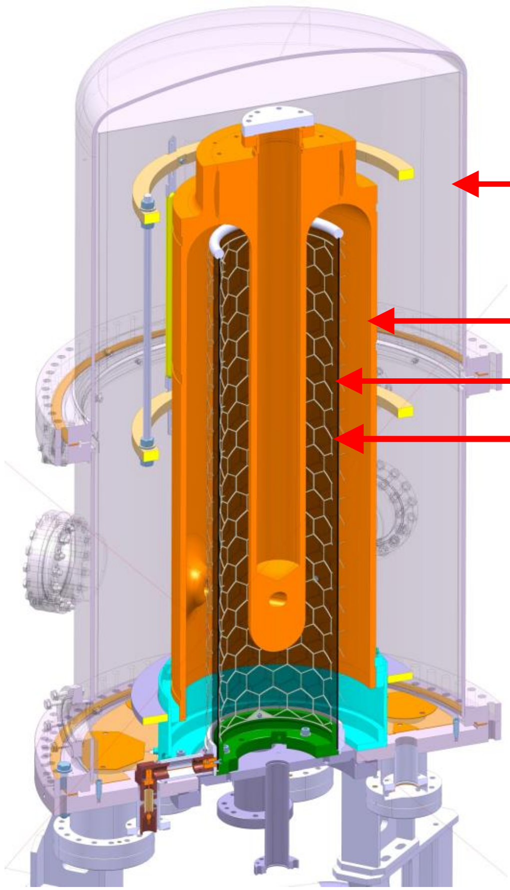
→ Cavity bake-out (bake-out tent) to 180°C

→ Coating 7 steps for the 7 different electromagnet positions

→ Duration = 1h 20' at low temperature (150°C)

→ Nb layer thickness ~ 2 μm

QWR coatings



- **Cavity in UHV chamber**
  (10^{-8} mbar base vacuum)
- Cu cavity substrate, biased at -80 V
- Nb cylindrical cathode **used on both sides**, not cooled
- Anode grids on both sides of cathode, grounded

→ **DC-bias diode sputtering, 8 kW, 0.2 mbar Ar**

→ Cavity bake-out to 650°C (IR lamps) prior to coating

→ Coating at high temperature (300 → 620°C)

→ 15 runs of 25' each, net coating duration = 6h

→ Multi-layers due to coating run/cool-down cycles

→ Nb layer thickness ranging from 1.5 μm to 12 μm

3. Past and on-going projects

Overview

LEP

216 elliptical cavities (352 MHz) coated in industry

LHC

21 elliptical cavities (400MHz) coated in industry

8 new spares to be manufactured

SOLEIL

2 elliptical cavities (352 MHz) coated at CERN

HIE-ISOLDE

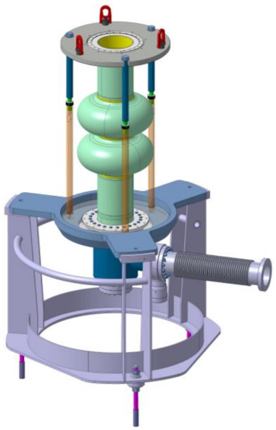
23 quarter wave cavities (101 MHz) coated at CERN

R&D Programs

1.3 / 1.5 GHz / low beta 704MHz Cu cavities

Others

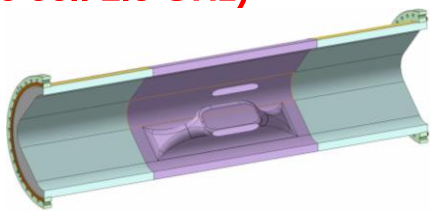
Cornell Cavity (200MHz), Super-3HC cavities (double cell 1.5 GHz)



FCC

400/800 MHz elliptical cavities

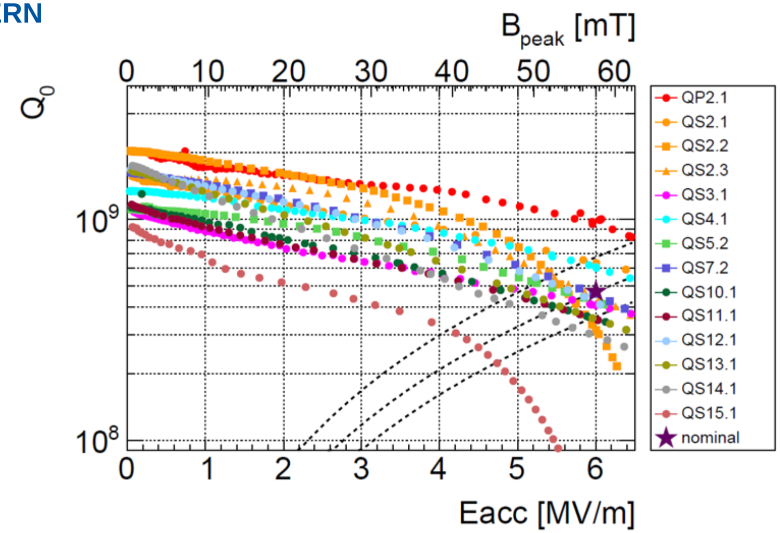
WOW (Nb/Cu crabbing cavities)



HIE-ISOLDE Upgrade

Superconducting booster for ISOLDE radioactive ion beam facility at CERN
39 MV needed to reach 10 MeV/u
for A/q = 4.5 (highest possible at ISOLDE)
25 Quarter Wave Resonators cavities
→ cavities production for phase 2 completed,
→ 4th cryomodule under commissioning,
→ + 3 spare cavities produced out of 5

Frequency	101.28 MHz
Specification	6 MV/m @ $Q_0 = 4.7x10^8$



LHC Spares Program

3.3

→ 8 Spare cavities to be manufactured, Nb coated and dressed with He-tank

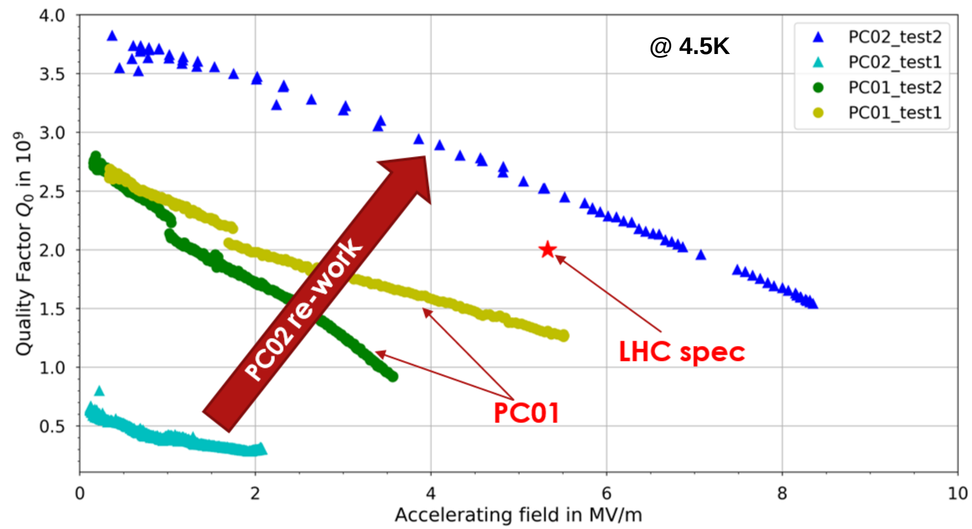
Practice cavities (PC): 3 coatings

PC01 recoated: substrate structural defect

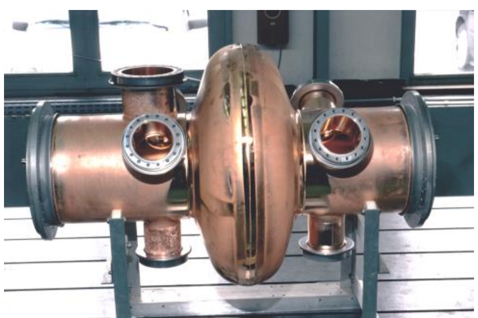
PC05: coated, RF test pending

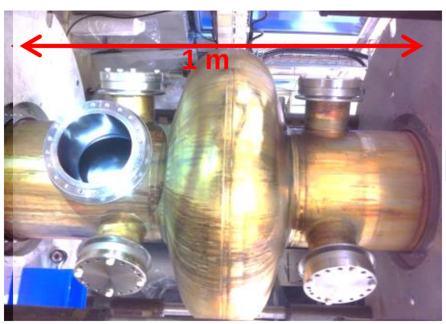
PC02 recoated:

- **Cavity at specs ($Q_0 = 2.2.10^9$ at 6 MV/m)**
- **Coating recipe and assembly flow validated**
- **Ability to recover a heavily damaged cavity by surface machining**

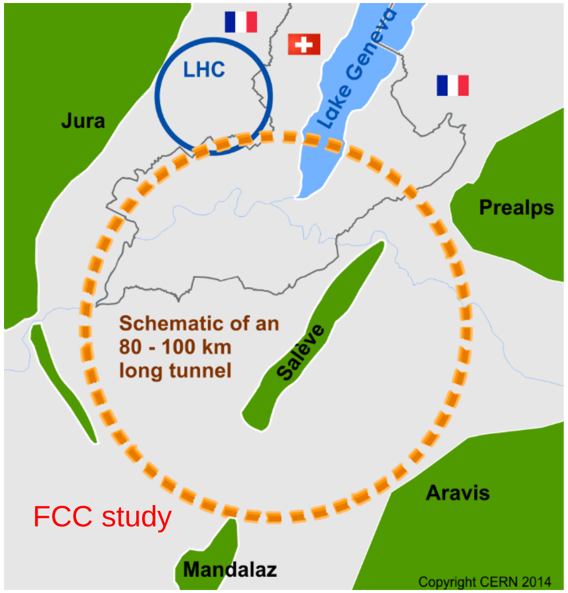


Frequency	400.8 MHz
Specification	5 MV/m @ $Q_0 = 2x10^9$



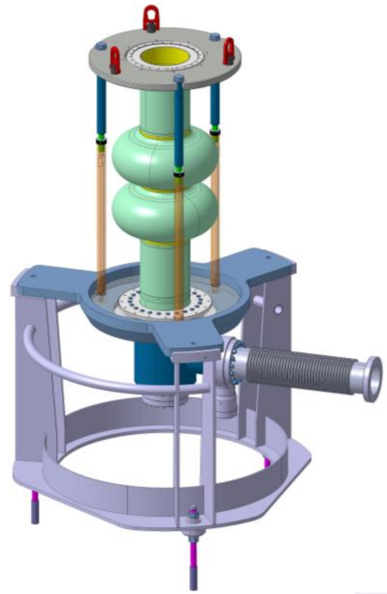


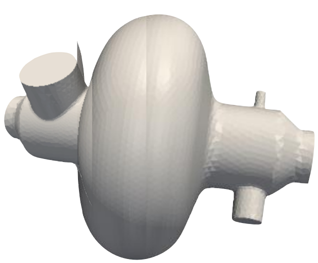
FCC Study

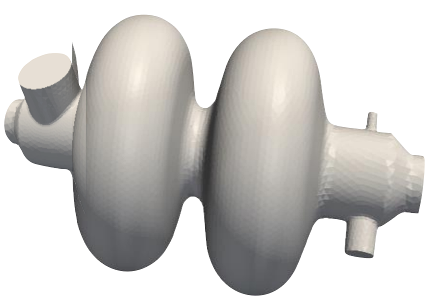


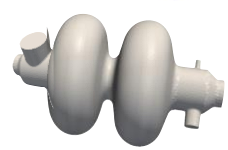
Future: **FCC** (Future Circular Collider) study

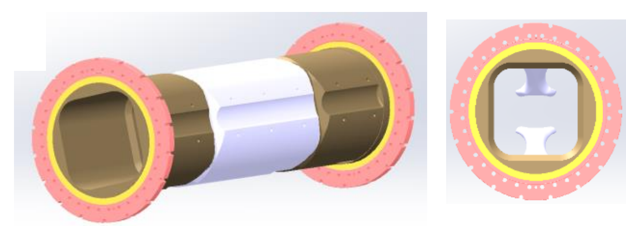
- 400 MHz elliptical single cell, **quantities ~ 300**
- 400/800 MHz elliptical multi-cells, **quantities > 1000**
- 400 MHz Wide Open Waveguide for "crabbing"



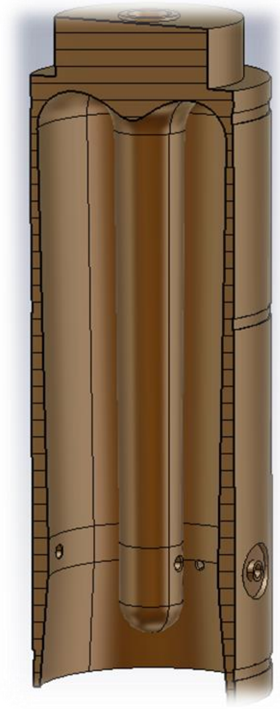


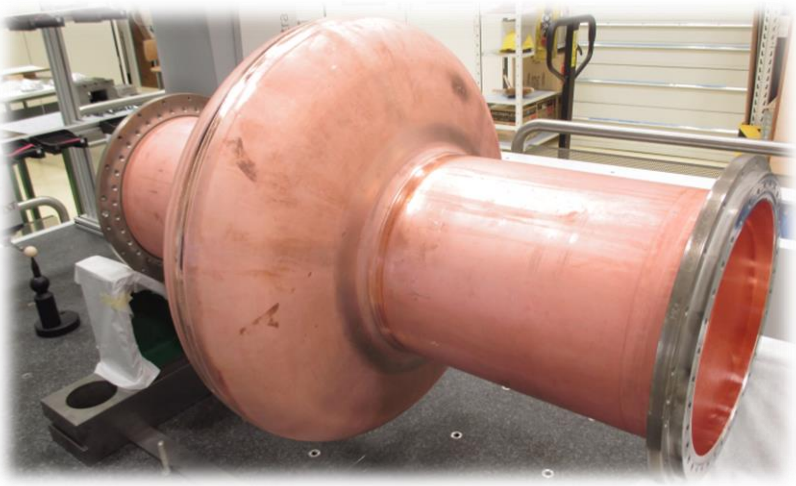






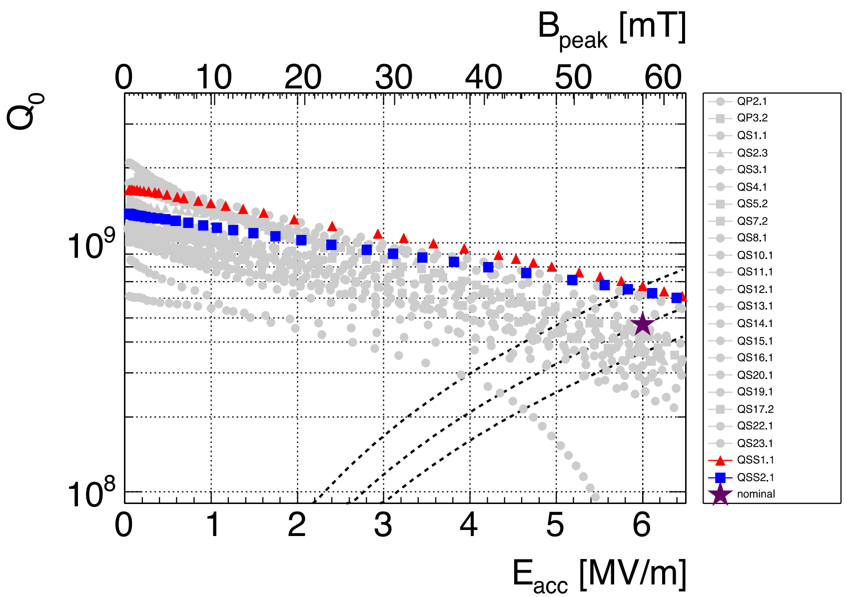
4. Recent Achievements





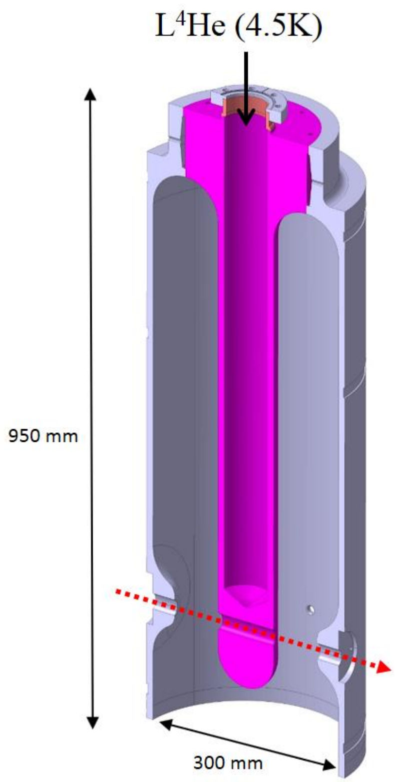
4.1 HIE-ISOLDE

HIE-ISOLDE

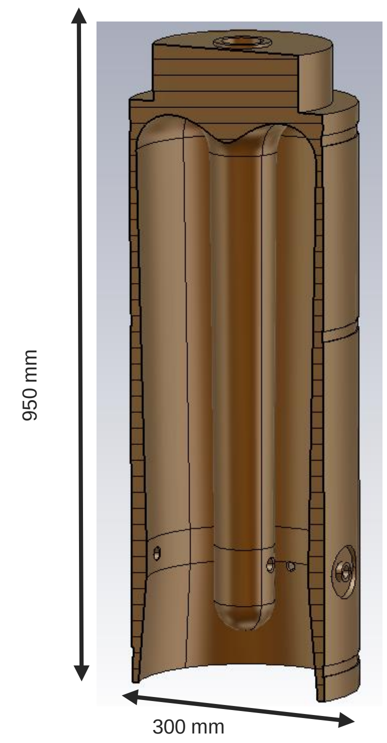


2 seamless cavities produced and coated
Best performances ever obtained

Original design



Seamless design



HIE-ISOLDE

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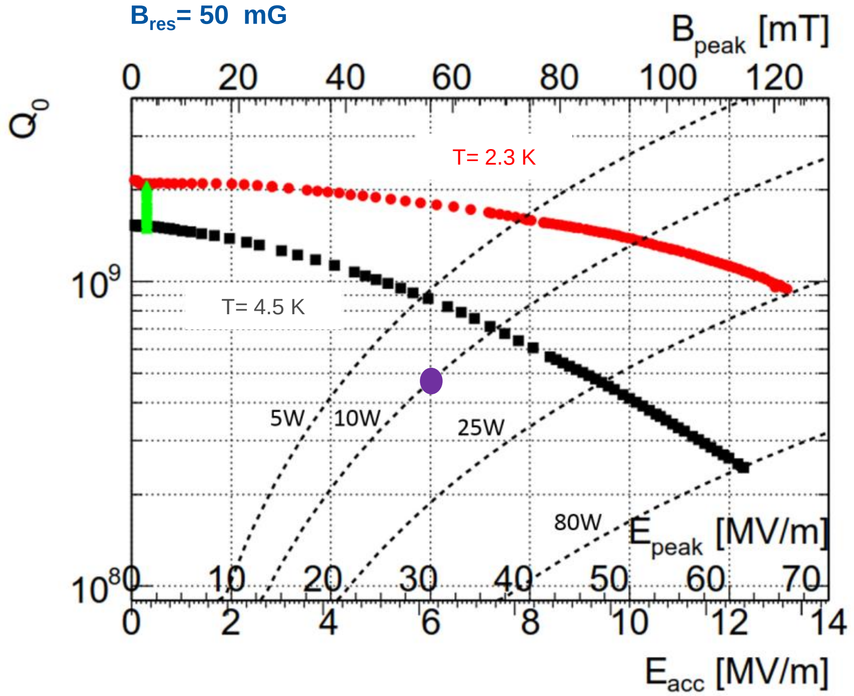
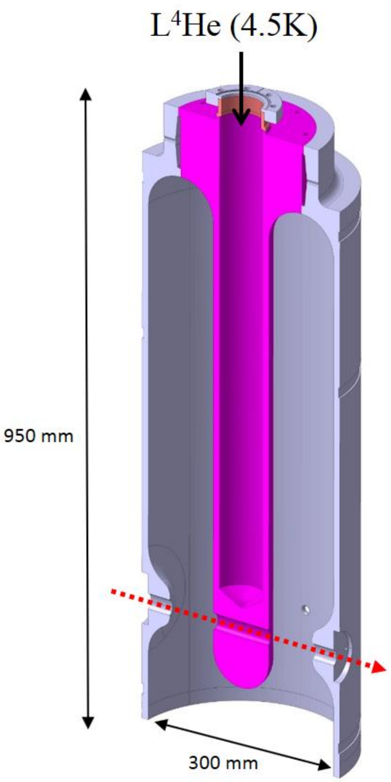


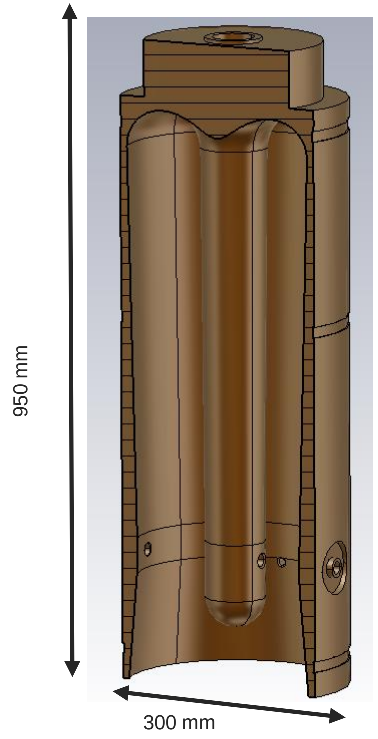
Highest field ever reached by a Nb/Cu cavity

(~30MV/m in elliptical shape)

Original design

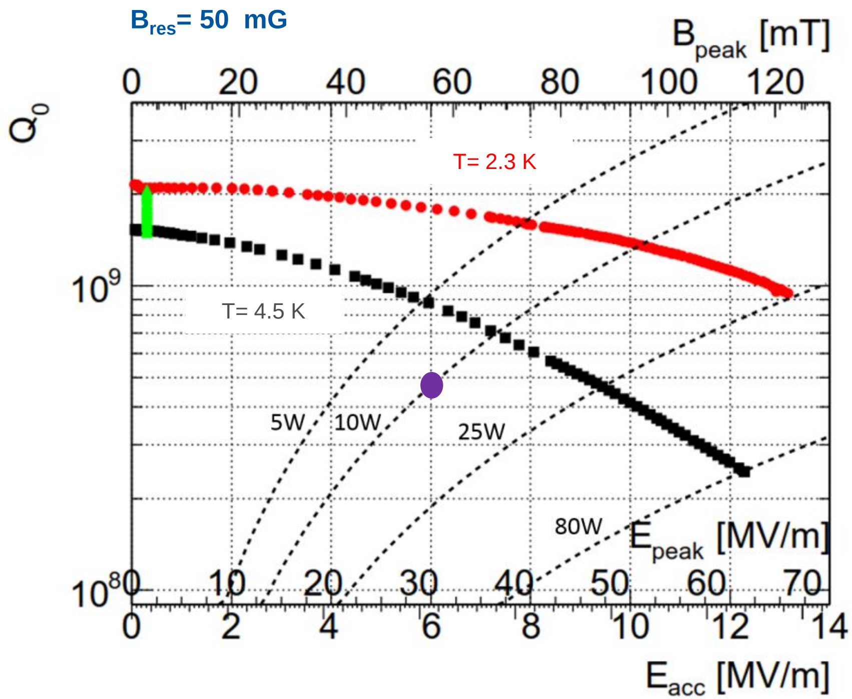


Seamless design



HIE-ISOLDE / LHC

HIE-ISOLDE



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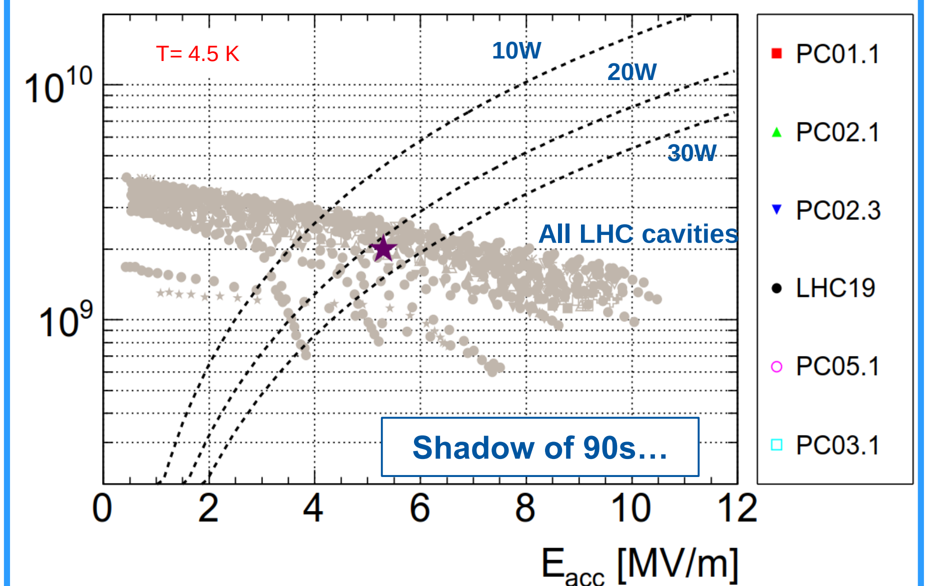

HIE-ISOLDE / LHC

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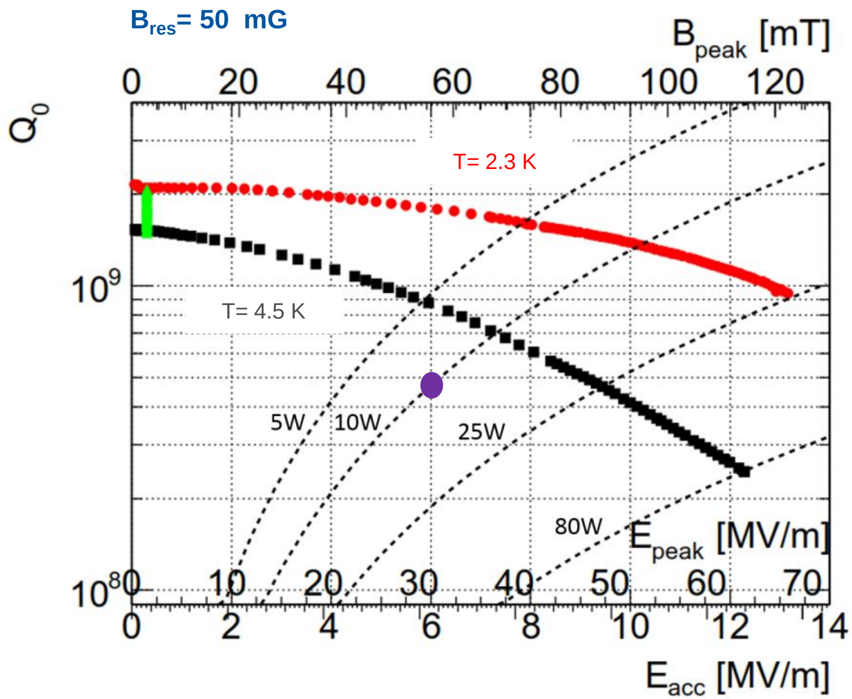

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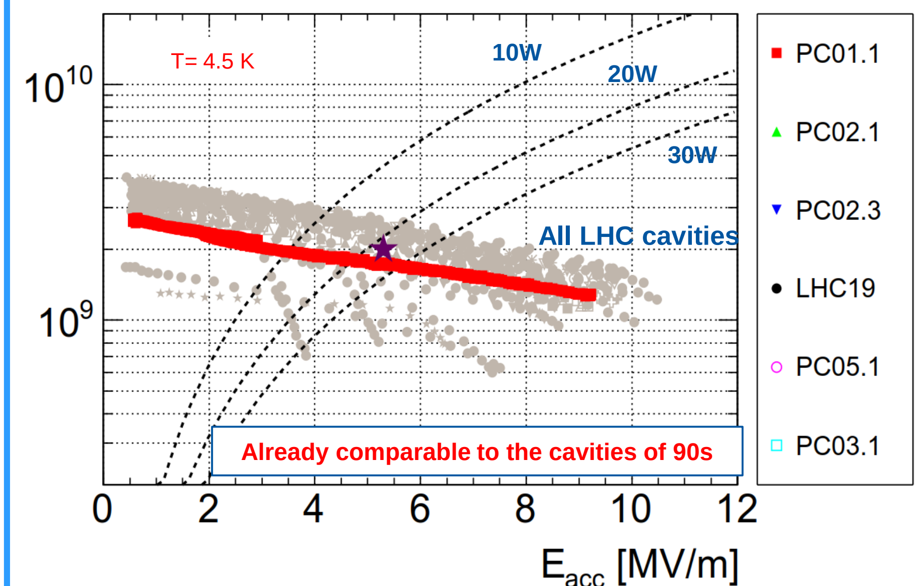
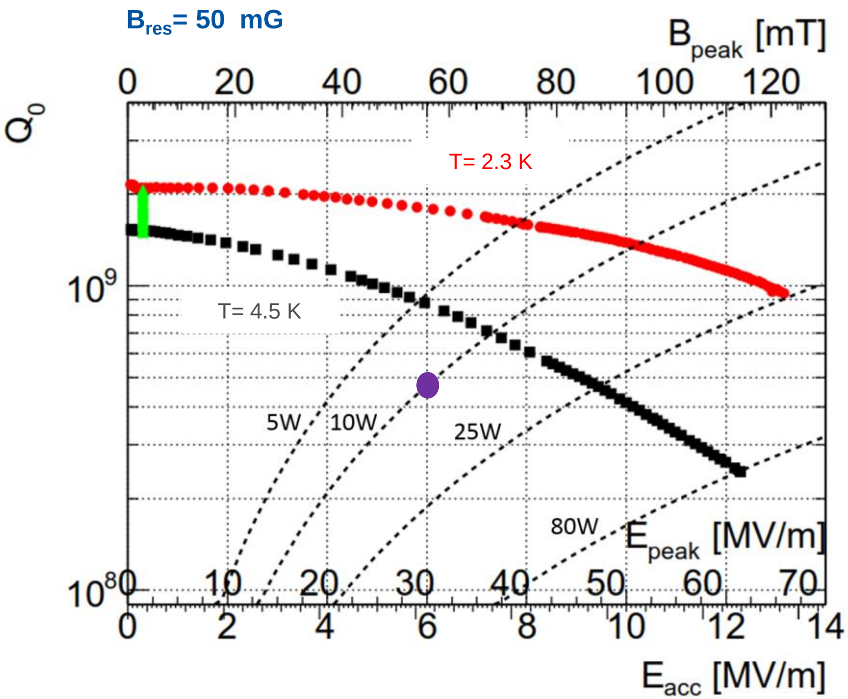
LHC



HIE-ISOLDE / LHC

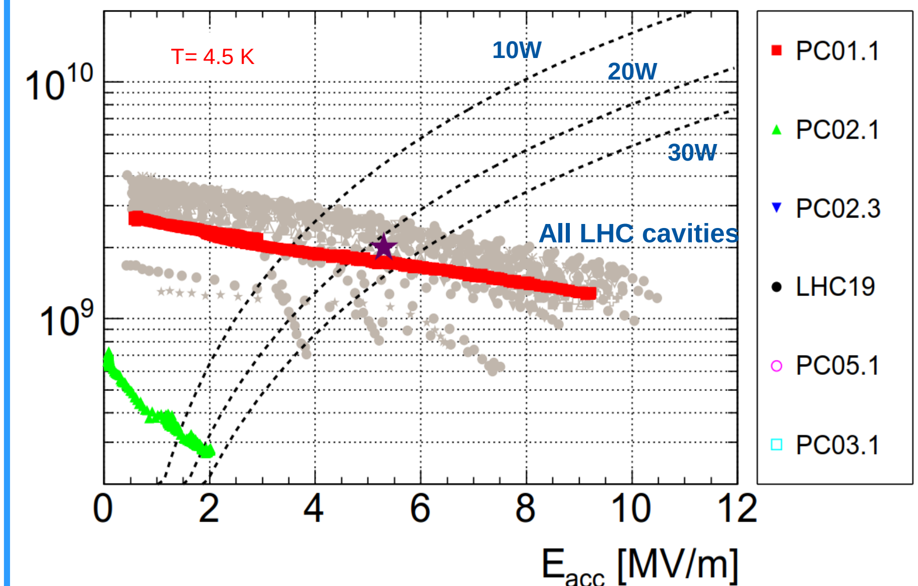
HIE-ISOLDE



Highest field ever reached by a Nb/Cu cavity

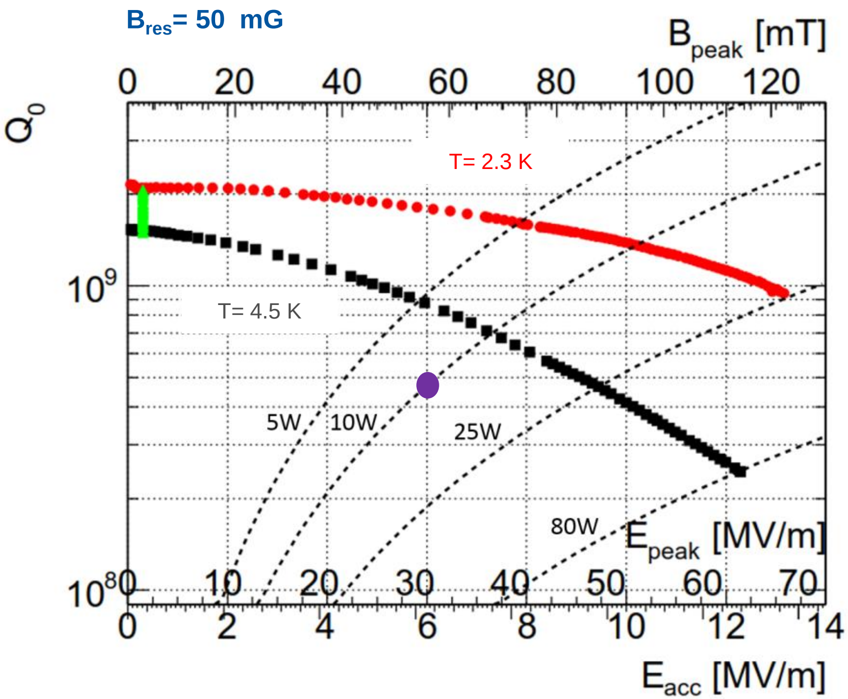
(~30MV/m in elliptical shape)

LHC



HIE-ISOLDE / LHC

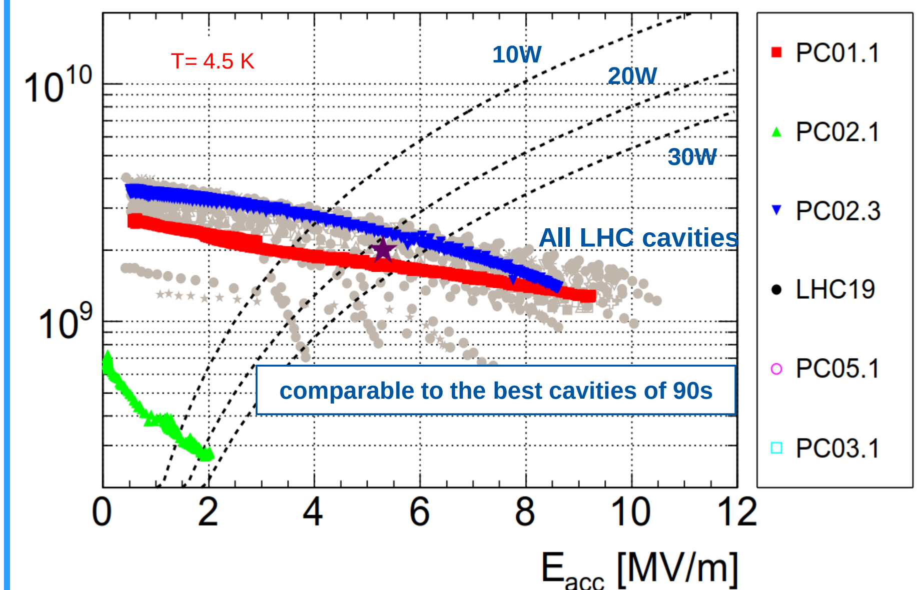
HIE-ISOLDE



Highest field ever reached by a Nb/Cu cavity

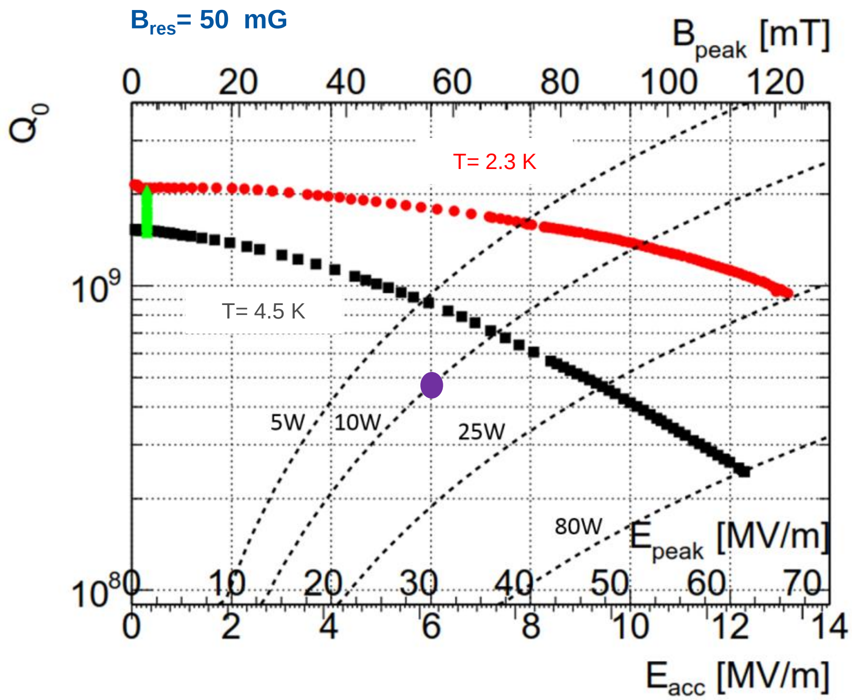
(~30MV/m in elliptical shape)

LHC



HIE-ISOLDE / LHC

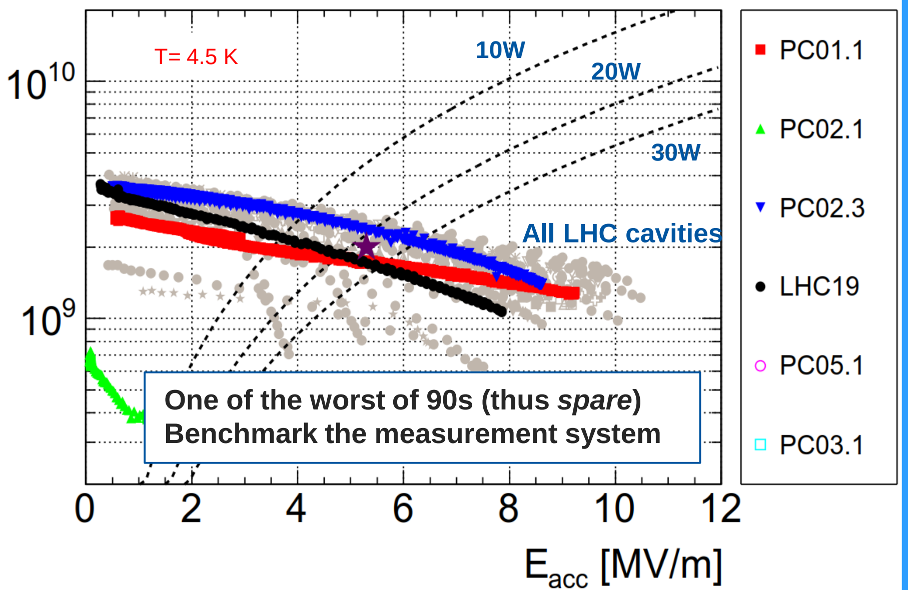
HIE-ISOLDE



Highest field ever reached by a Nb/Cu cavity

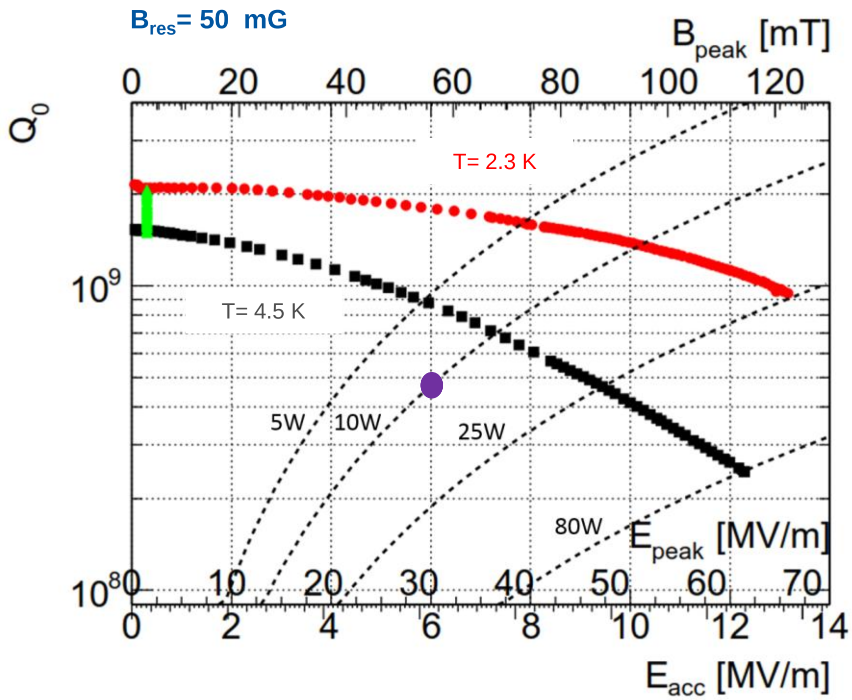
(~30MV/m in elliptical shape)

LHC



4.2 HIE-ISOLDE / LHC

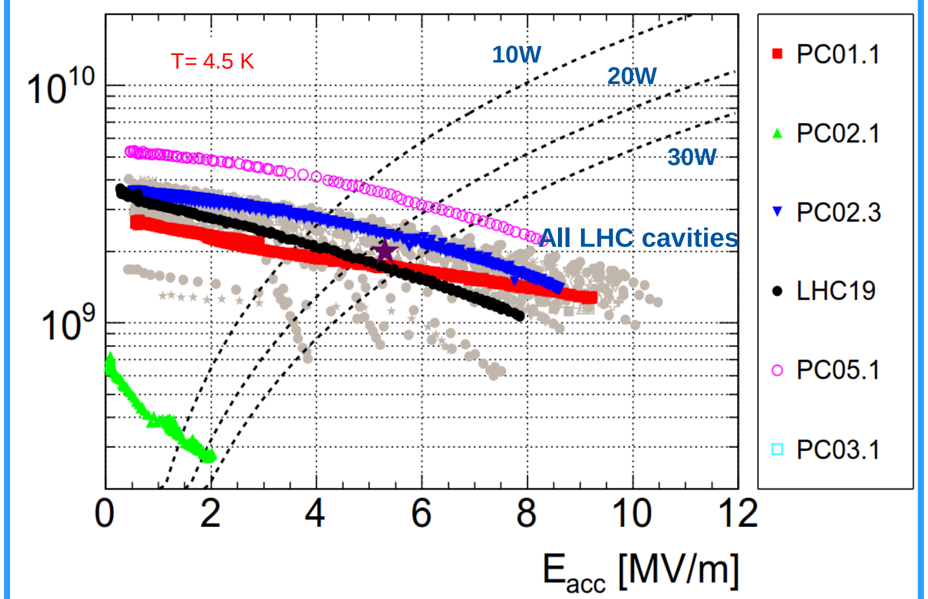
HIE-ISOLDE



Highest field ever reached by a Nb/Cu cavity

(~30MV/m in elliptical shape)

LHC

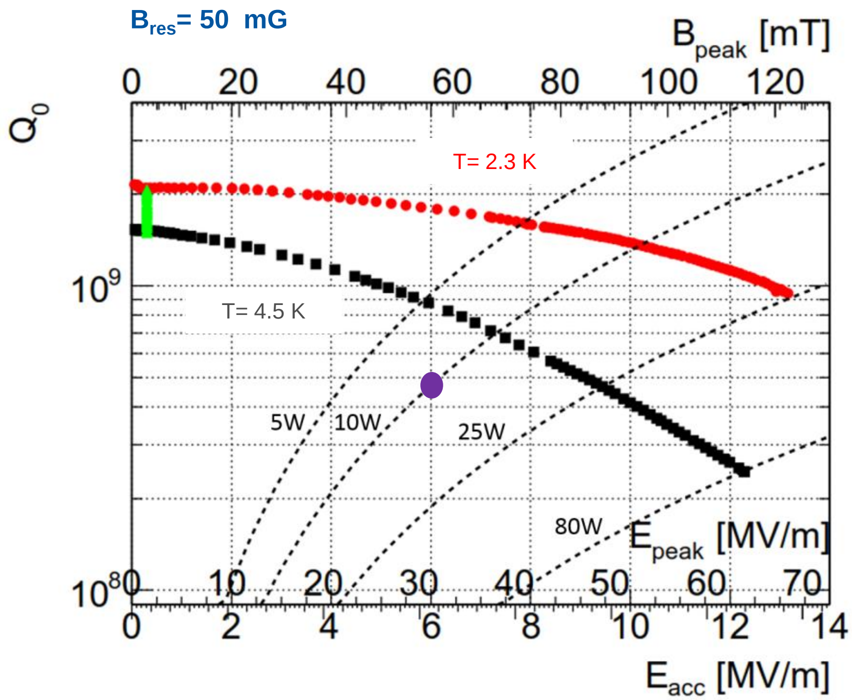


PC05: (spun half cells) shows the **best performances among all LHC cavities ever produced**

Root cause not fully identified. Investigations on-going

HIE-ISOLDE / LHC

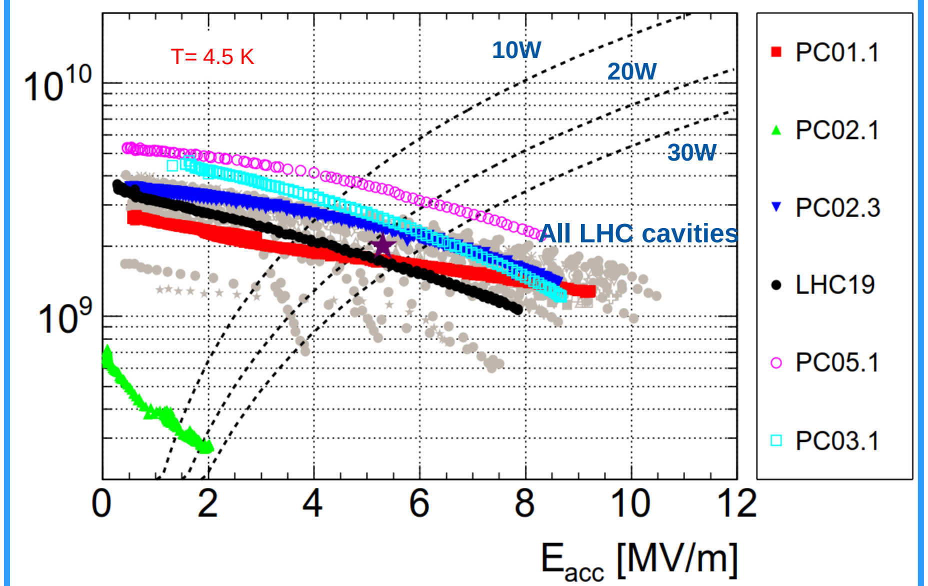
HIE-ISOLDE



Highest field ever reached by a Nb/Cu cavity

(~30MV/m in elliptical shape)

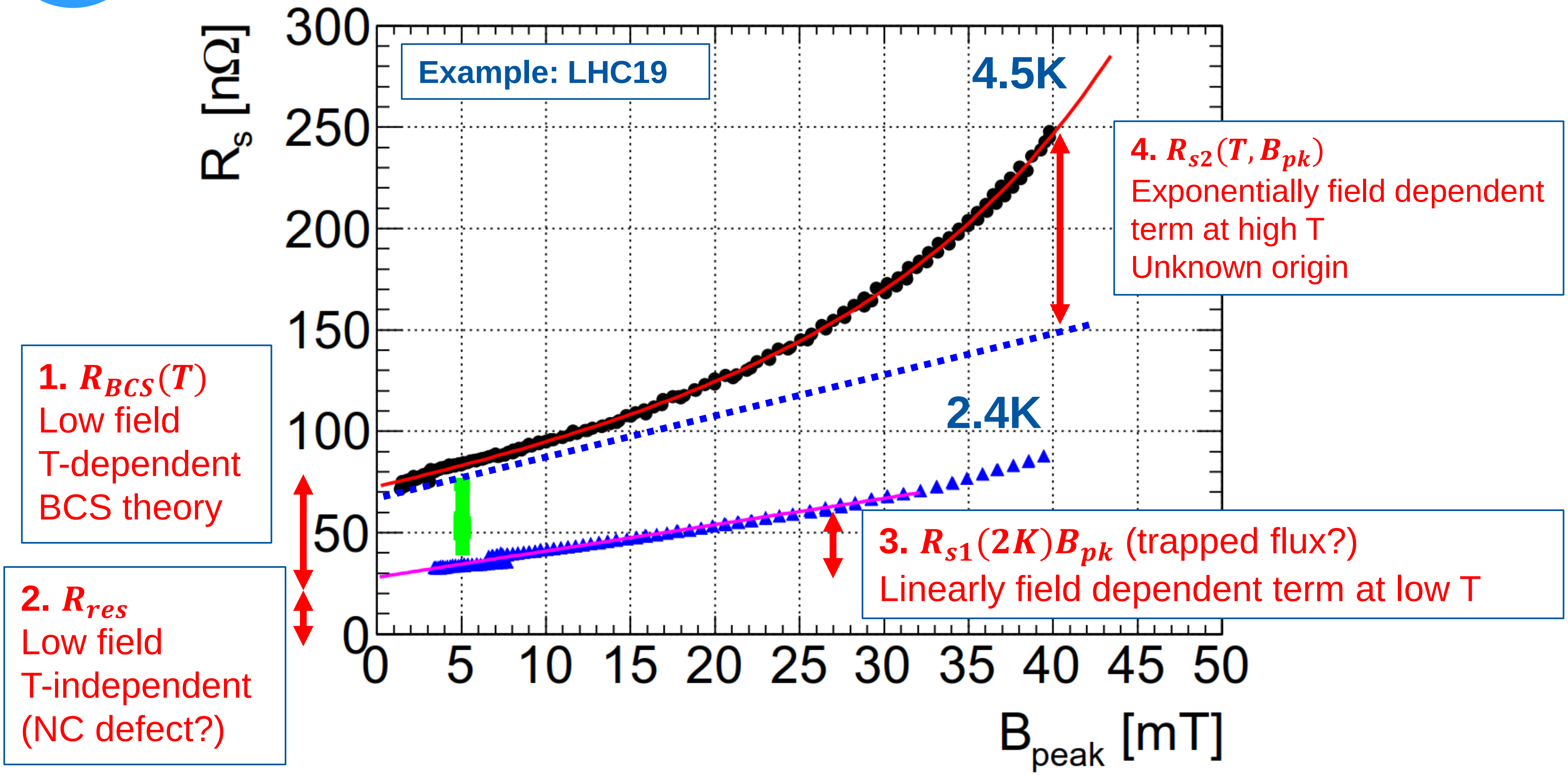
LHC



PC03: (EHF half cells) very good performances. Equatorial weld not polished

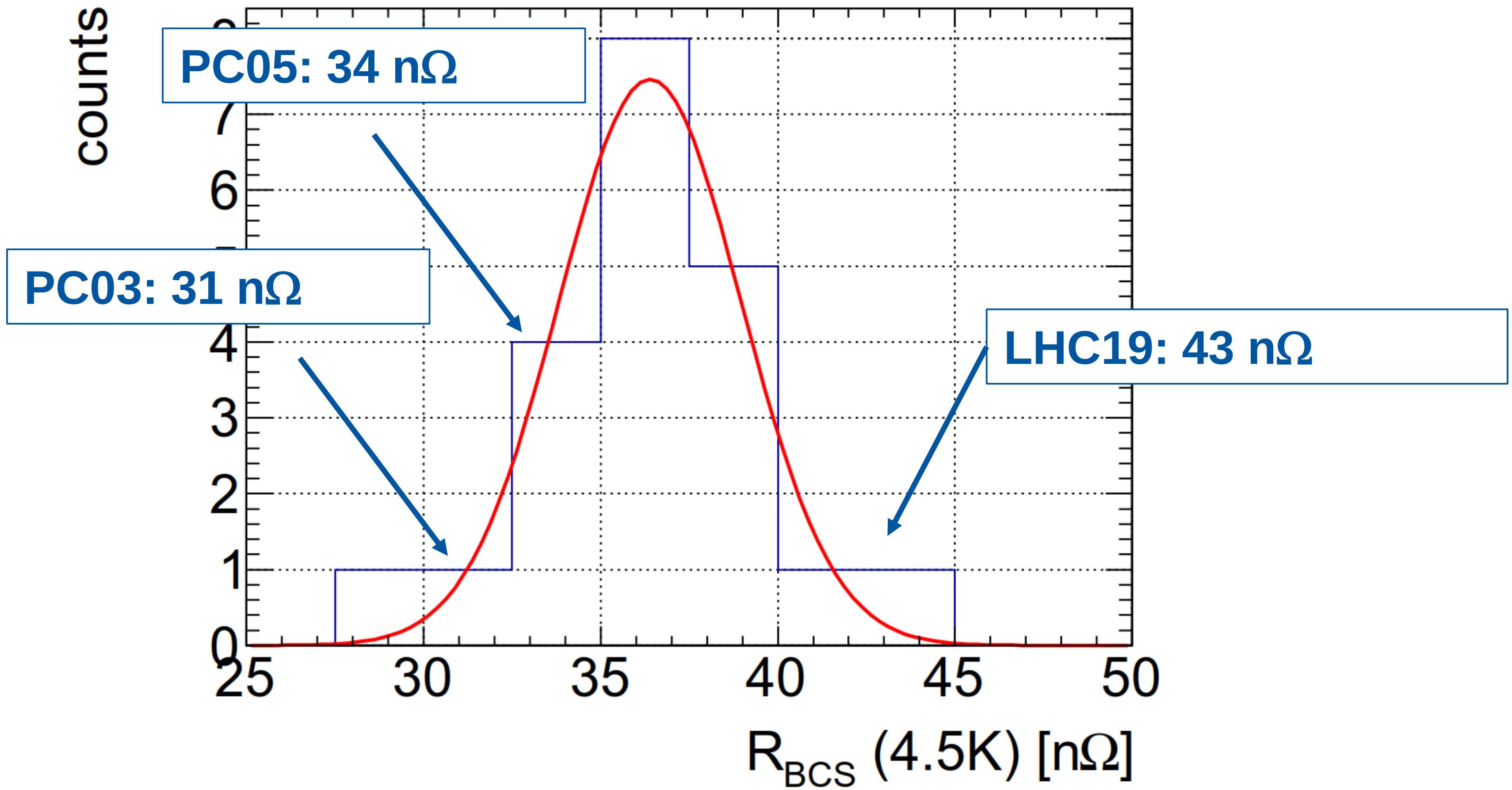
Root cause not fully identified. Investigations on-going

LHC



Courtesy of A. Miyazaki

LHC – R_{BCS} (4.5K)   LHC 90s statistics $R_{BCS} = 36.4 \pm 2.6$ nΩ



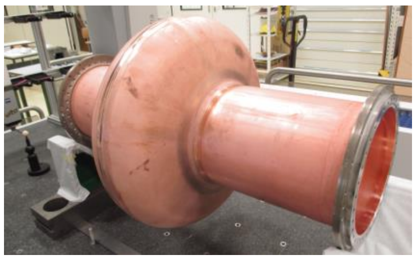
BCS resistance is consistently around 36 nΩ

→ Basic material parameters $(\xi_0, \lambda_L, l, \Delta_0/k_BT_c)$ may be very close

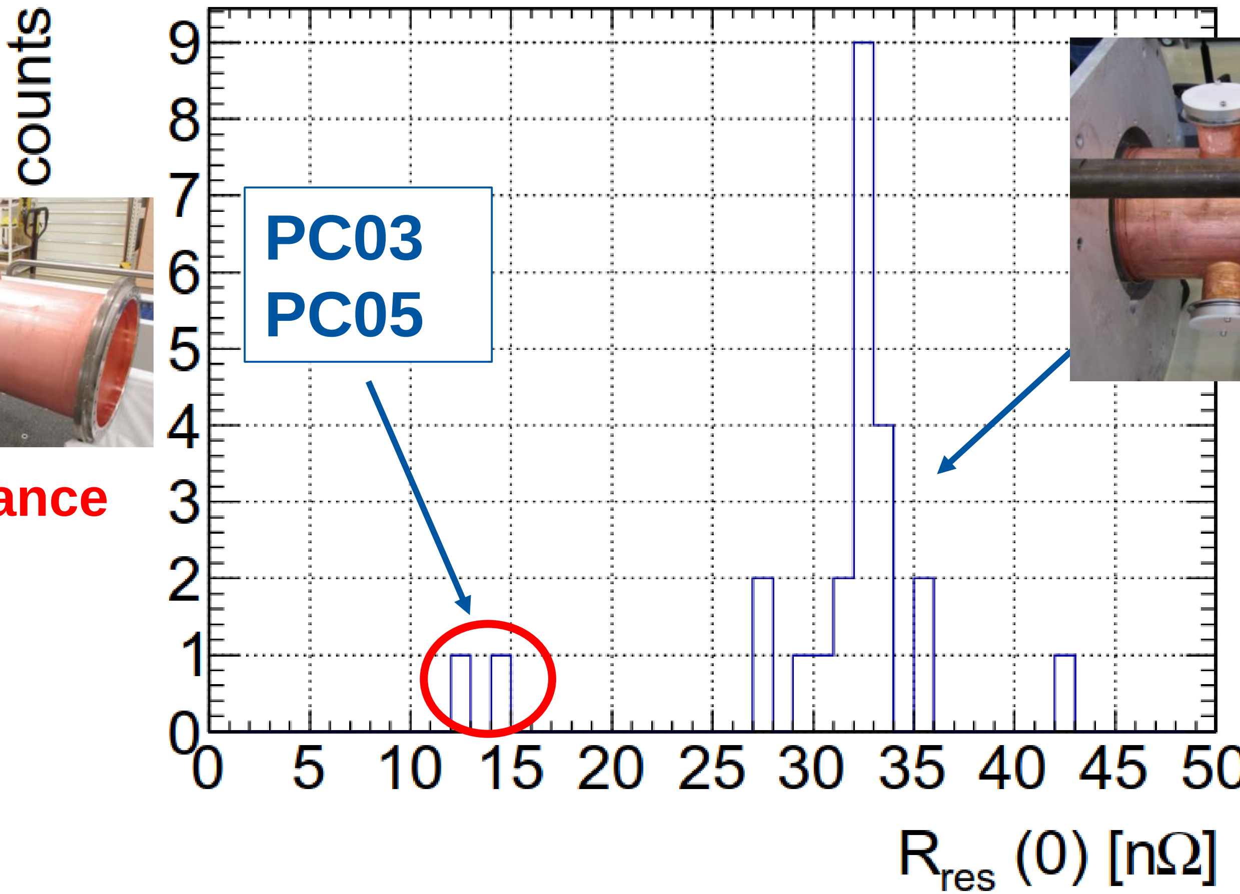
→ **Crystal structure of the film is comparable**

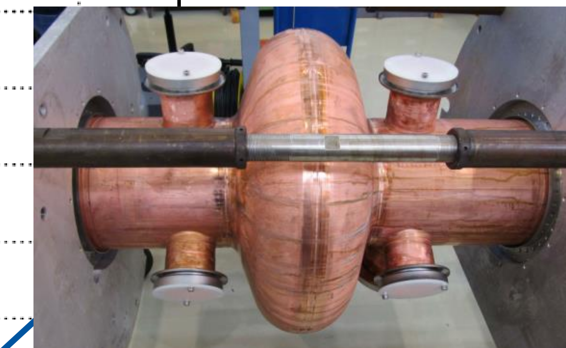
Courtesy of A. Miyazaki

4.5 LHC – R_{res} (2.3K) LHC 90s statistics $R_{res} = 32.9 \pm 1.1$ nΩ



significance
17 s.t.d





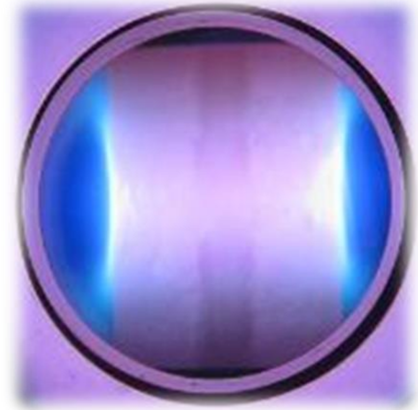
Residual resistance was drastically improved in PC03 and PC05

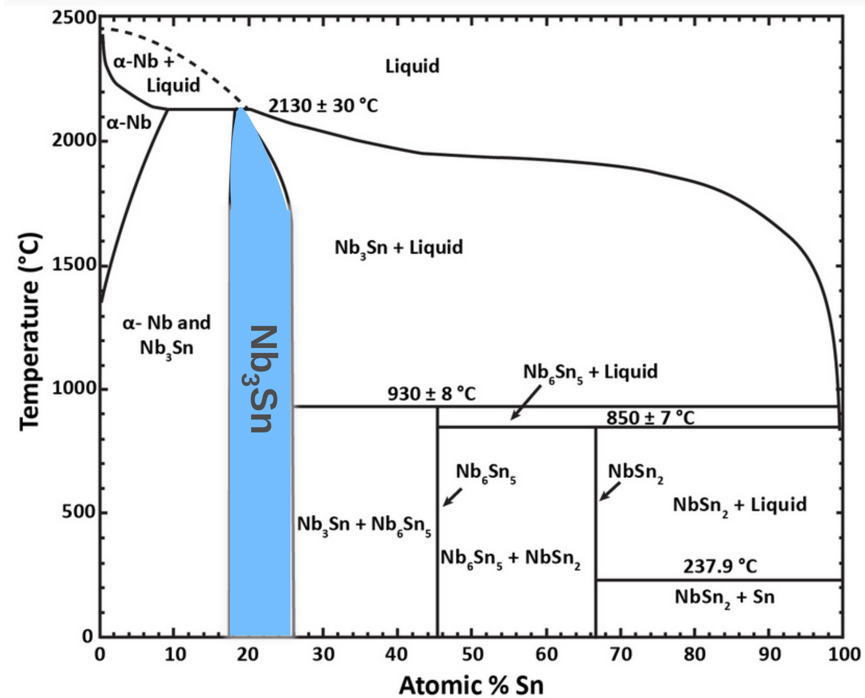
→ Less normal conducting defect in the Nb film?

→ The **simplified shape** without ports may result in better coating

Courtesy of A. Miyazaki

5. On-going R&D

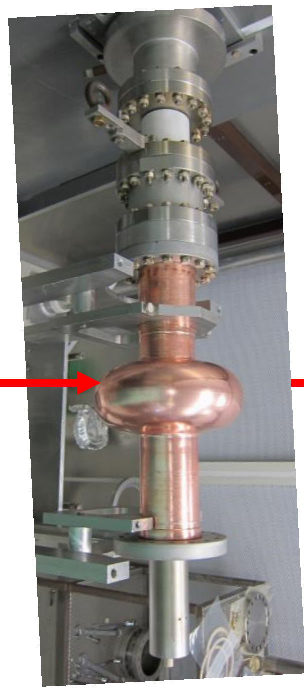



Temperature (°C)
Atomic % Sn
Liquid
α-Nb + Liquid
α-Nb
2130 ± 30 °C
Nb3Sn + Liquid
α- Nb and Nb3Sn
Nb3Sn
930 ± 8 °C
Nb6Sn5 + Liquid
850 ± 7 °C
Nb6Sn5
NbSn2
NbSn2 + Liquid
Nb3Sn + Nb6Sn5
Nb6Sn5 + NbSn2
237.9 °C
NbSn2 + Sn

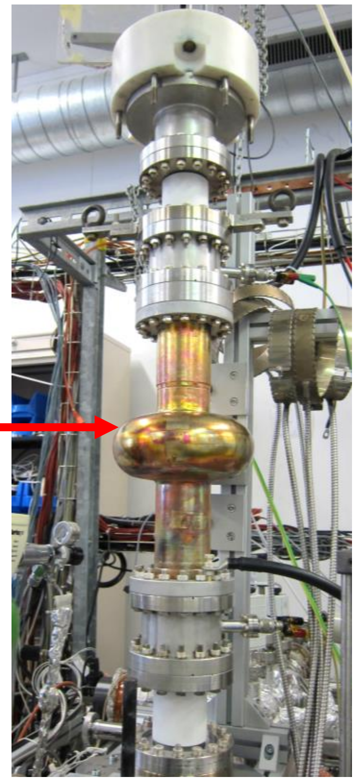
HiPIMS

- Base pressure ~ 6.10^{-10} mbar
- Nb cathodes and anodes (cut-off coating)
- Cell coating by HiPIMS + Bias using Kr
- → Process capabilities of 1 cavity/week

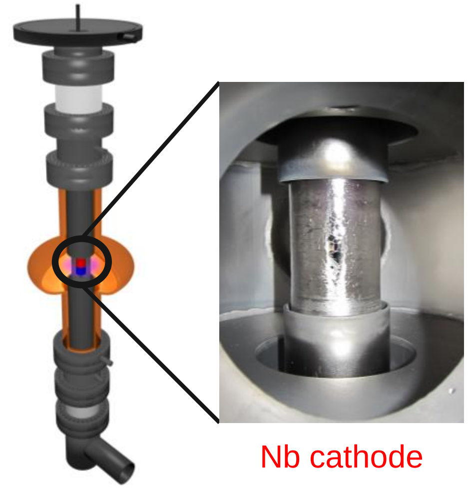
Nb cathode



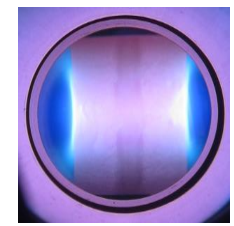
1.3 GHz cavity



1.3 GHz cavity coating s



Nb cathode



HiPIMS discharge

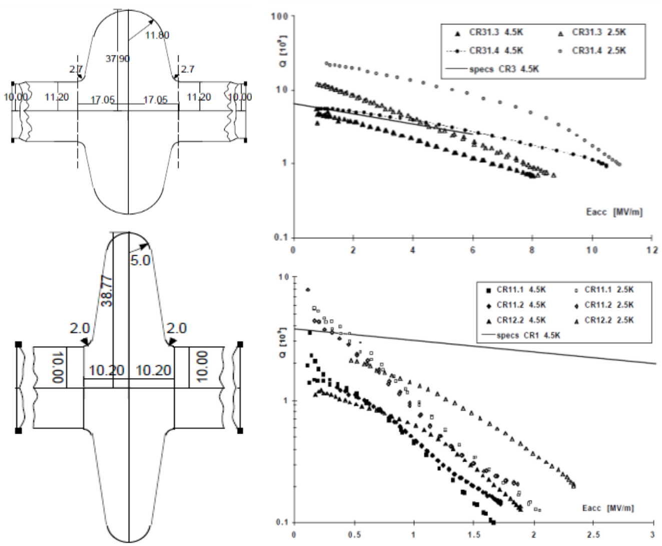
High **P**ower **I**mpulse **M**agnetron **S**puttering

- Same hardware as for DCMS
- Pulsed Power supply
  - 1% duty cycle
  - Short pulses: 200 µs
  - High peak current (200 A vs 3 A DCMS)
  - High peak power (80 kW peak for 1kW avg)
  - Ionization of sputtered species

→ Lower coating rate

Complex shapes and Q-Slope

Q-slope vs β factor



Low β

Nb atoms impinge the surface at grazing angle

Low density layer

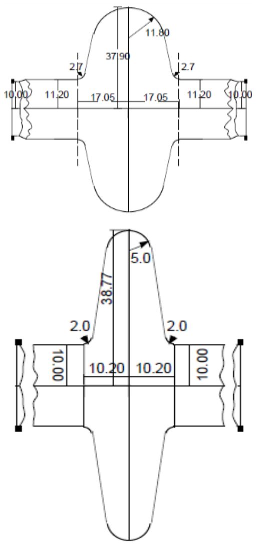
Higher Q-Slope

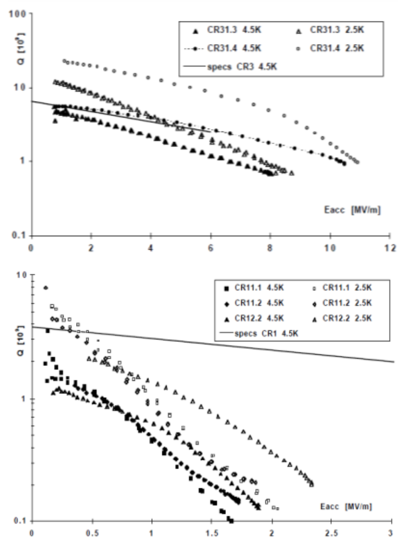
Good candidates to validate HiPIMS

[1] D. Tonini et al, Morphology of niobium films sputtered at different target-substrate angle, 11th workshop on RF superconductivity, THP11
[2] C. Benvenuti et al, Production and test of 352 MHz Niobium Sputtered Reduced Beta cavities, 1997, SRF97D25

Complex shapes and Q-Slope

Q-slope vs β factor





Low β

Nb atoms impinge the surface at grazing angle

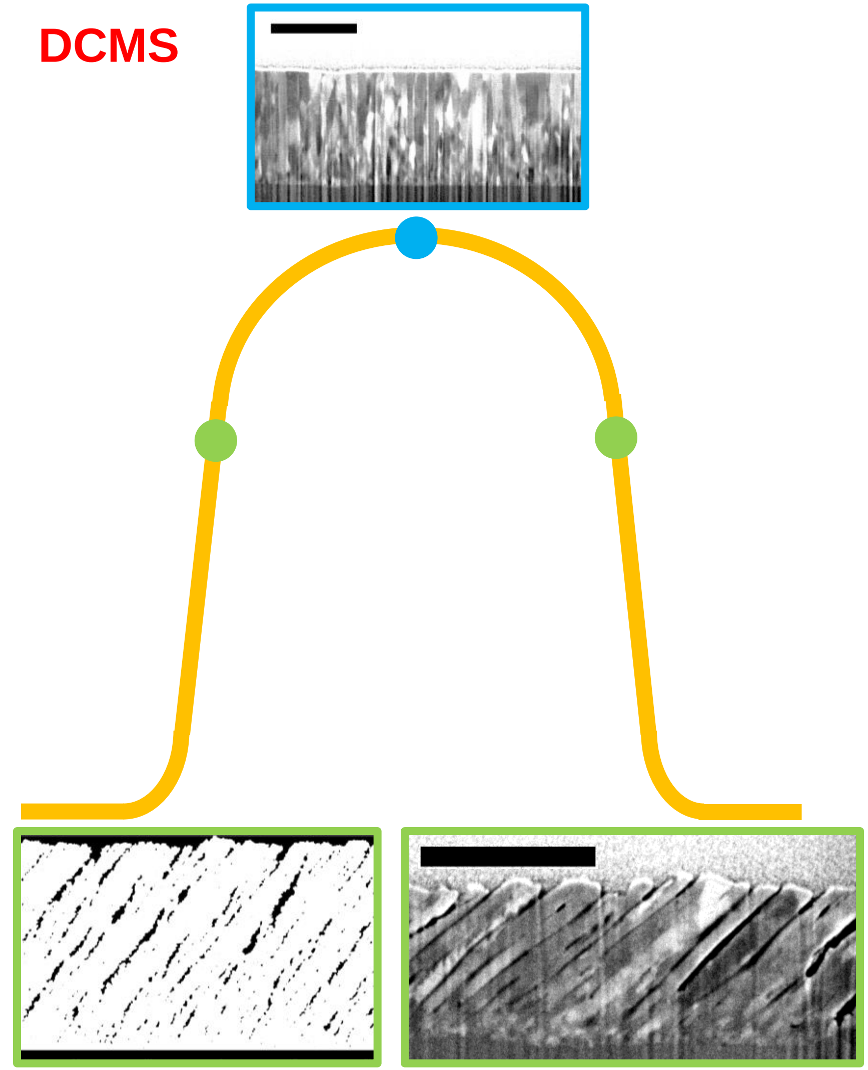
Low density layer

Higher Q-Slope

Good candidates to validate HiPIMS

704 MHz β=0.65 Single Cell Cavity profile

DCMS



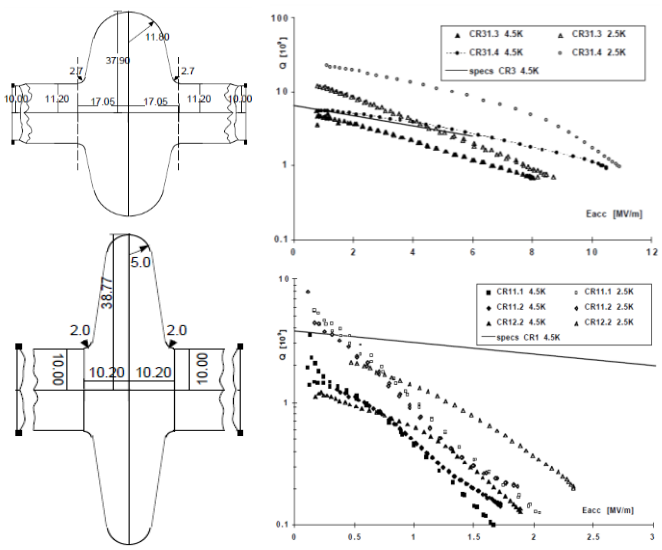
NASCAM simulation

S. Lucas, P. Moskovkin, Thin Solids Films (2010), Volume 518, Issue 18, 1 July 2010, Pages 5355-5361.

[1] D. Tonini et al, Morphology of niobium films sputtered at different target-substrate angle, 11th workshop on RF superconductivity, THP11
[2] C. Benvenuti et al, Production and test of 352 MHz Niobium Sputtered Reduced Beta cavities, 1997, SRF97D25

Complex shapes and Q-Slope

Q-slope vs β factor



Low β

Nb atoms impinge the surface at grazing angle

Low density layer

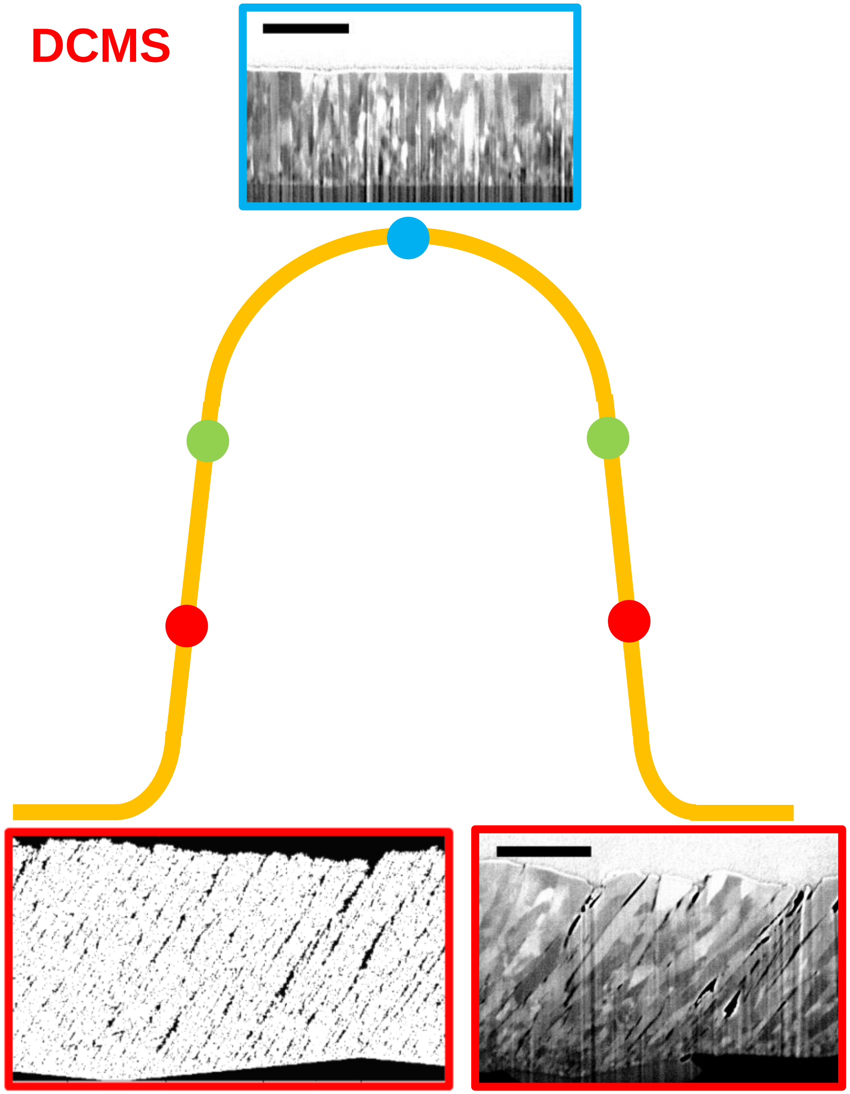
Higher Q-Slope

Good candidates to validate HiPIMS

Very porous structure in low beta cavities

Theoretically predictable and in agreement with experimental observations

704 MHz β=0.65 Single Cell Cavity profile



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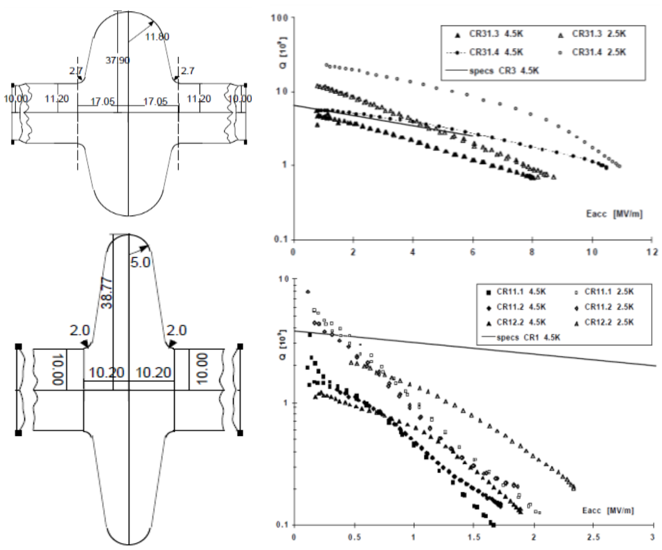
Complex shapes and Q-Slope

Q-slope vs β factor



Low β

Nb atoms impinge the surface at grazing angle

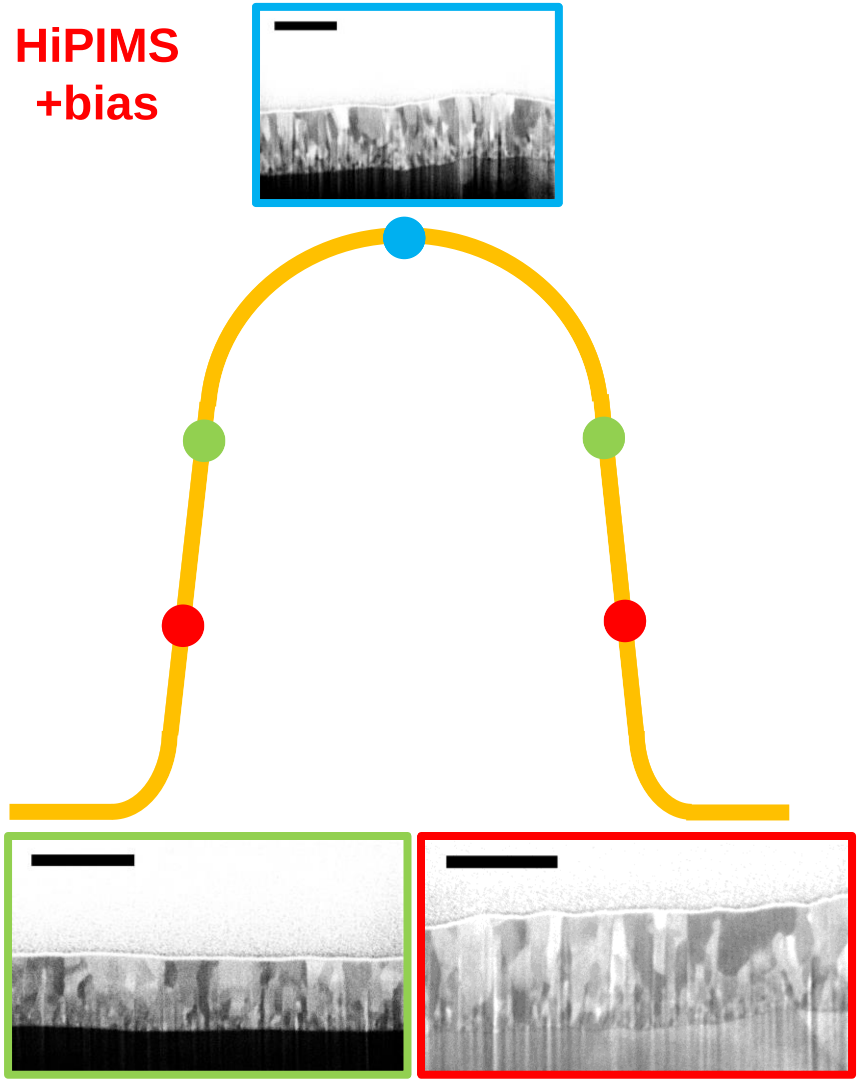
Low density layer

Higher Q-Slope

Good candidates to validate HiPIMS

704 MHz β=0.65 Single Cell Cavity profile

HiPIMS +bias



- **Very porous structure in low beta cavities**
- **Theoretically predictable and in agreement with experimental observations**
- **HiPIMS Leads to a layer densification all over the surface**

[1] D. Tonini et al, Morphology of niobium films sputtered at different target-substrate angle, 11th workshop on RF superconductivity, THP11
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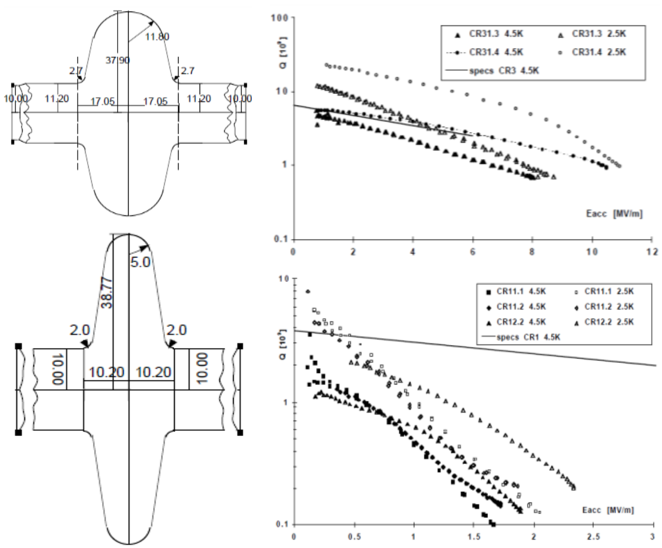
Complex shapes and Q-Slope

Q-slope vs β factor



Low β

Nb atoms impinge the surface at grazing angle

Low density layer

Higher Q-Slope

Good candidates to validate HiPIMS

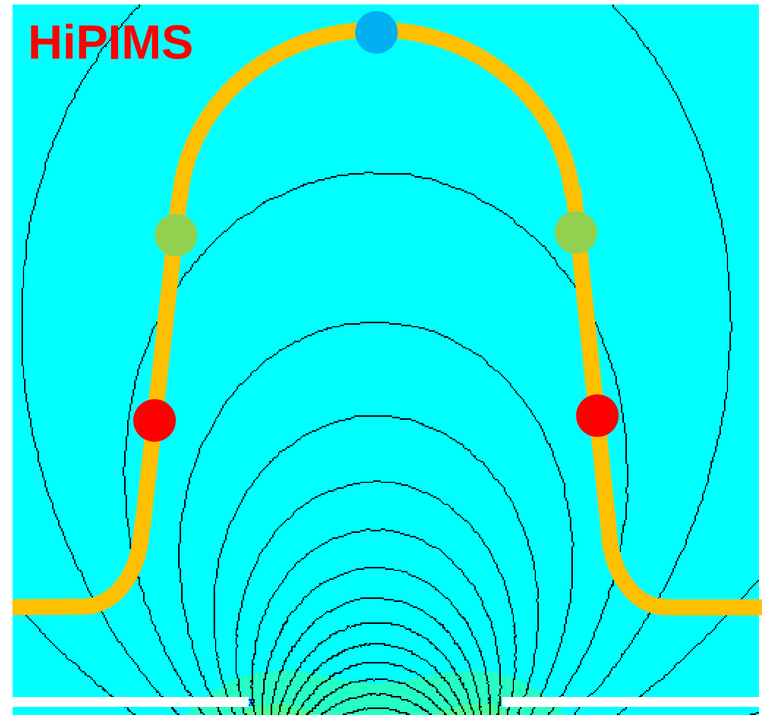
Very porous structure in low beta cavities

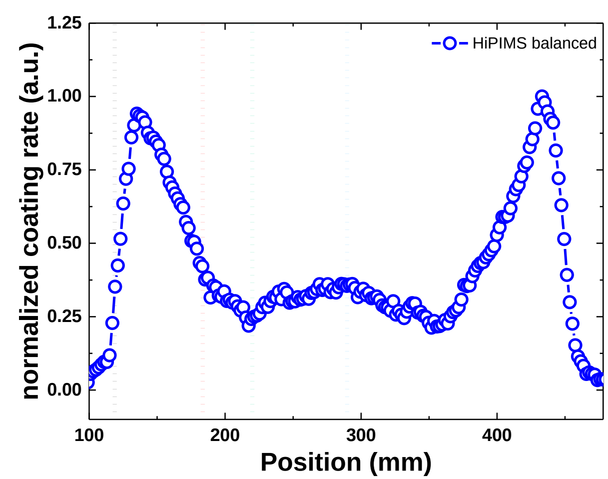
Theoretically predictable and in agreement with experimental observations

HiPIMS Leads to a layer densification all over the surface

Strong thickness difference → to get enough Nb at equator we will necessarily have a very thick layer close to the iris : likely to peel-off

704 MHz β=0.65 Single Cell Cavity profile





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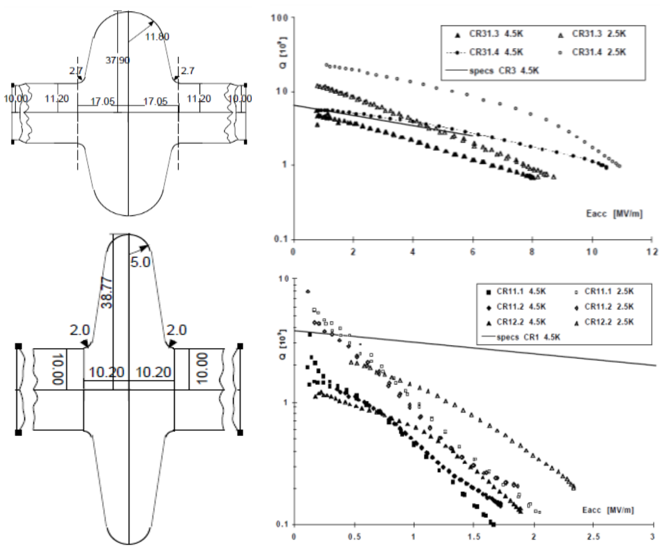
[2] C. Benvenuti et al, Production and test of 352 MHz Niobium Sputtered Reduced Beta cavities, 1997, SRF97D25

5.2 Complex shapes and Q-Slope

Q-slope vs β factor



Low β

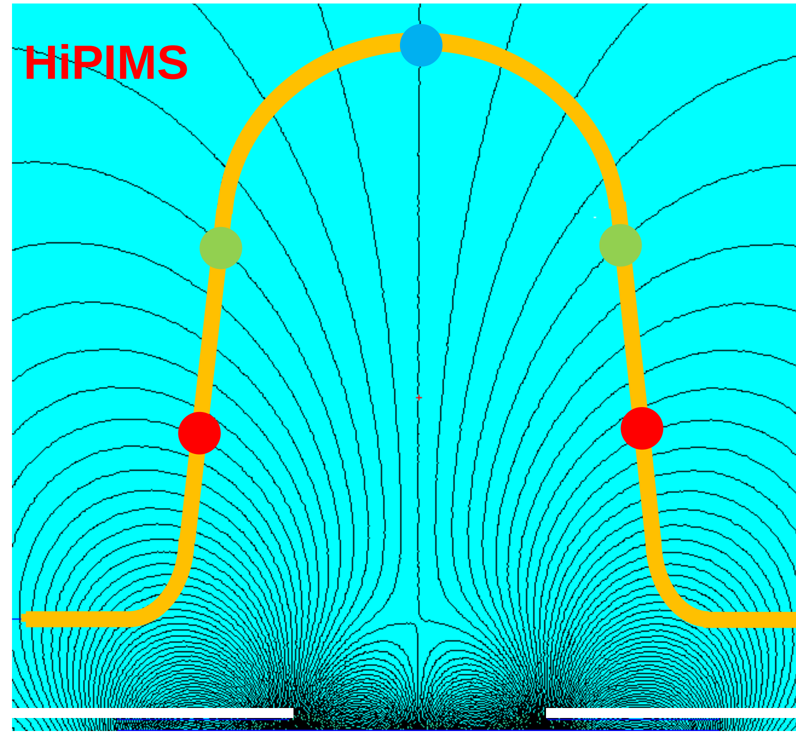
Nb atoms impinge the surface at grazing angle

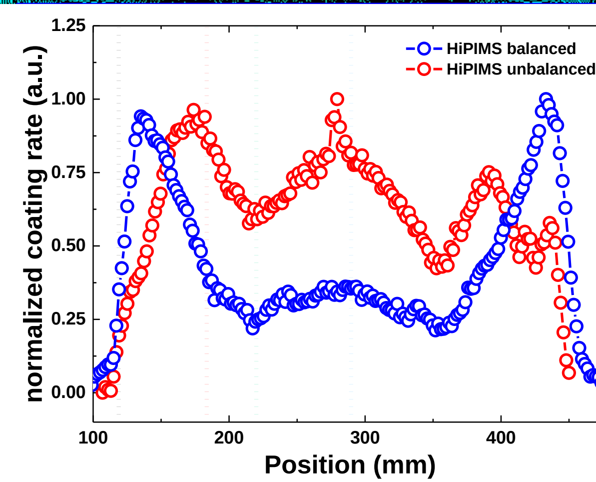
Low density layer

Higher Q-Slope

Good candidates to validate HiPIMS

704 MHz β=0.65 Single Cell Cavity profile





Very porous structure in low beta cavities

Theoretically predictable and in agreement with experimental observations

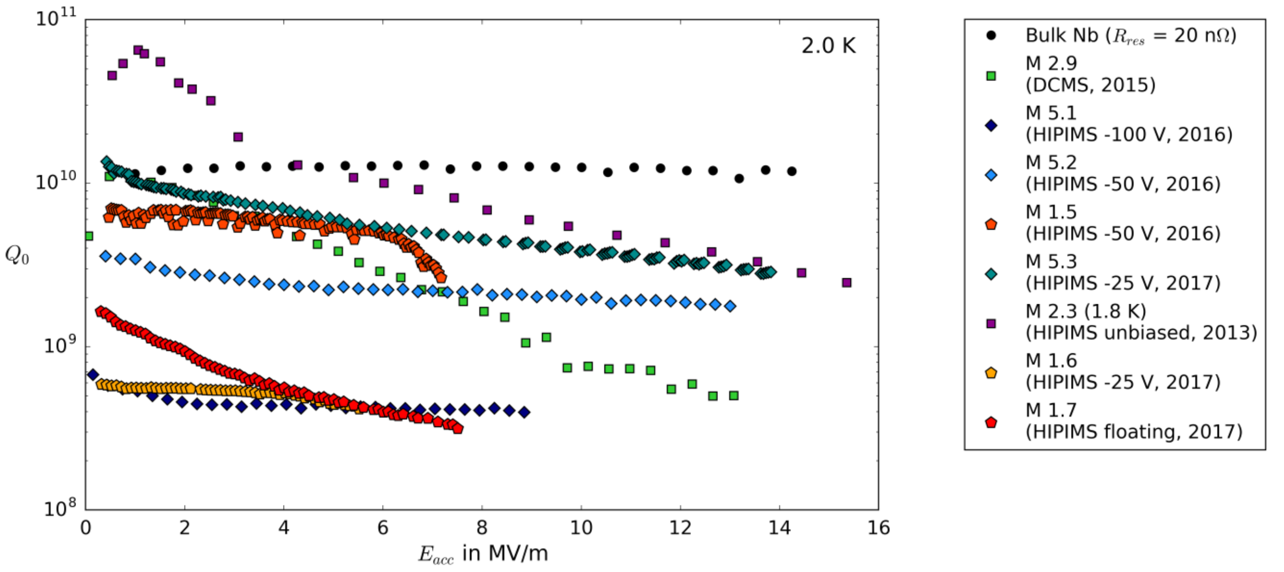
HiPIMS Leads to a layer densification all over the surface

Strong thickness difference → to get enough Nb at equator we will necessarily have a very thick layer close to the iris : likely to peel-off

Possibility to tune the coating profile by modifying the magnetic confinement profile (balanced vs unbalanced)

[1] D. Tonini et al, Morphology of niobium films sputtered at different target-substrate angle, 11th workshop on RF superconductivity, THP11
[2] C. Benvenuti et al, Production and test of 352 MHz Niobium Sputtered Reduced Beta cavities, 1997, SRF97D25

HiPIMS – RF Results



Higher level of stress in HiPIMS wrt DCMS

→ Higher instantaneous coating rate

→ Peel-off is a recurrent issue

R_{res}

- down to 5 nOhms with Q-slope (unbiased)
- 20nOhm with mitigated Q-slope (biased)

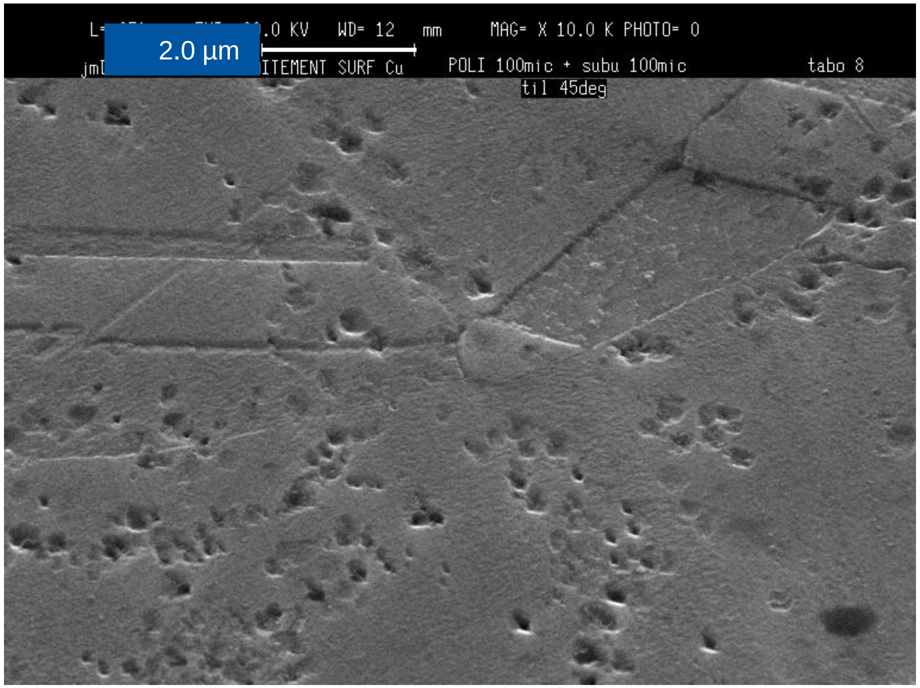
At the level of the best DCMS ones but not yet better

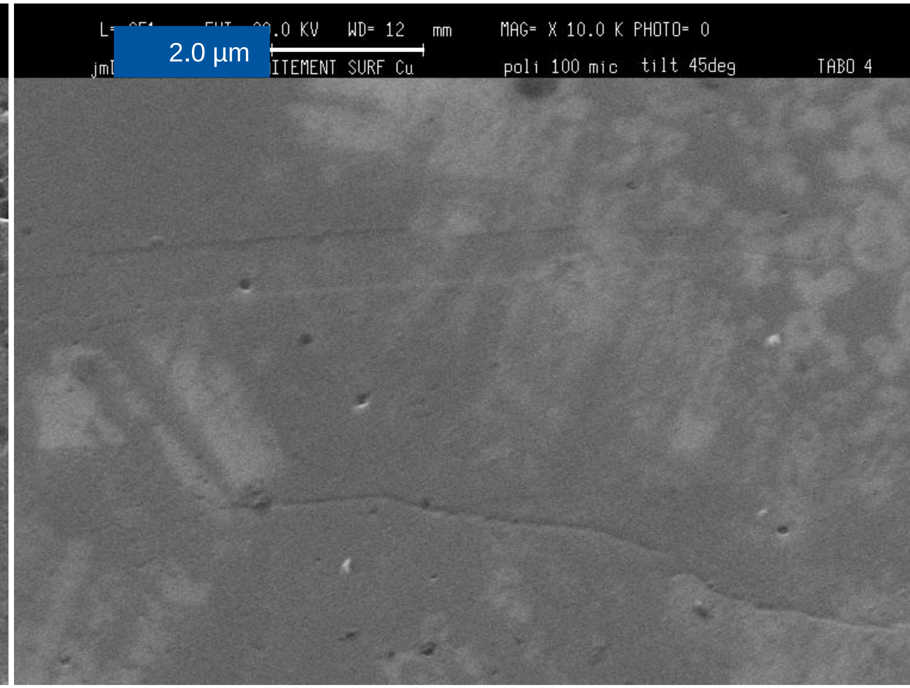
SUBSTRATE QUALITY IS CRITICAL

Study on going to qualify, quantify and mitigate residual stress

5.4 90’s Activity / Substrate

Importance of substrate quality





Chemically polished copper

- average roughness: 0.2 µm
- pinholes of 0.3 µm

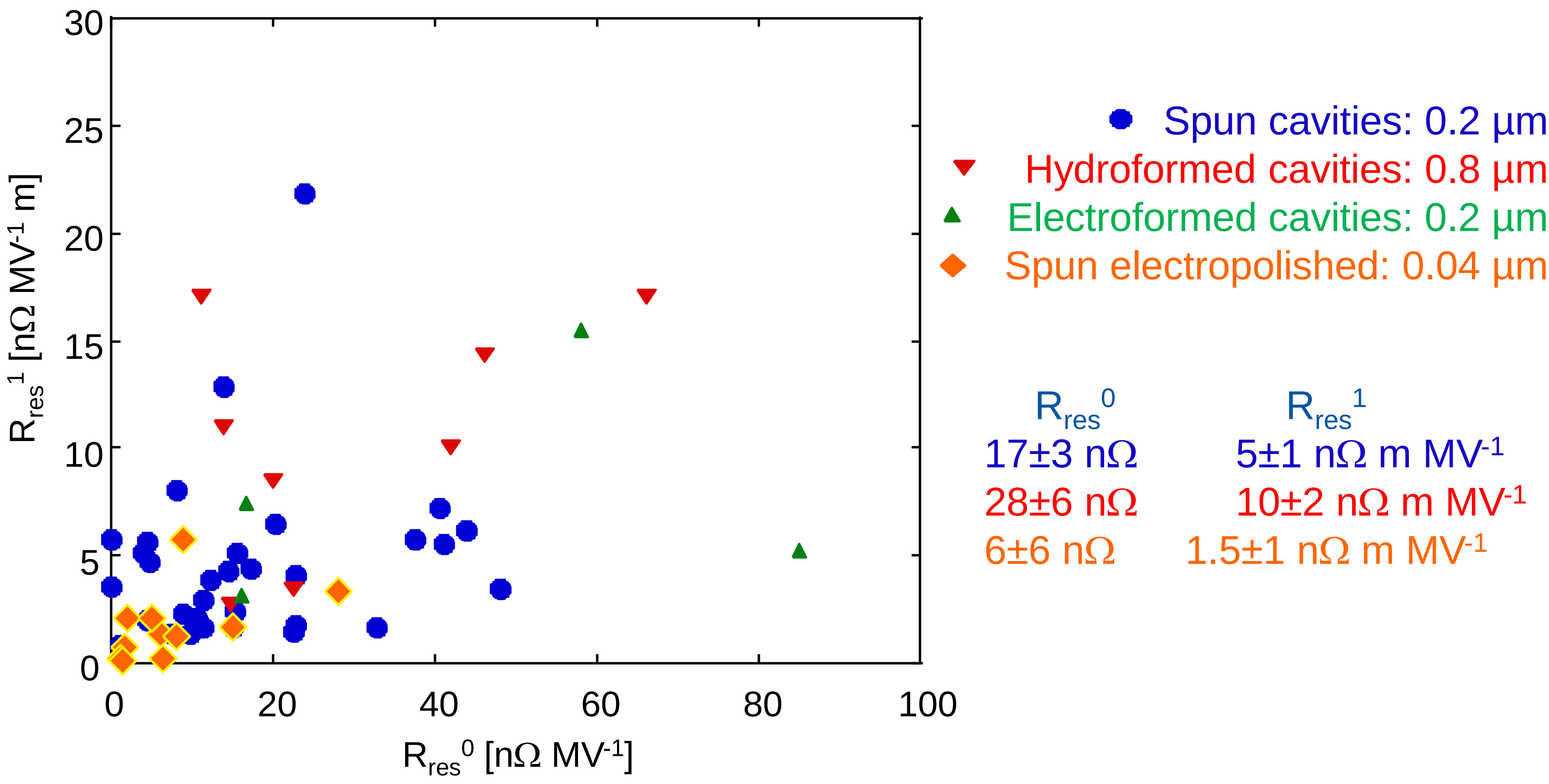
Electropolished copper

- average roughness: 0.02 µm
- nearly no defects

Courtesy of S. Calatroni

90's Activity / Substrate

Importance of substrate quality : cavity forming

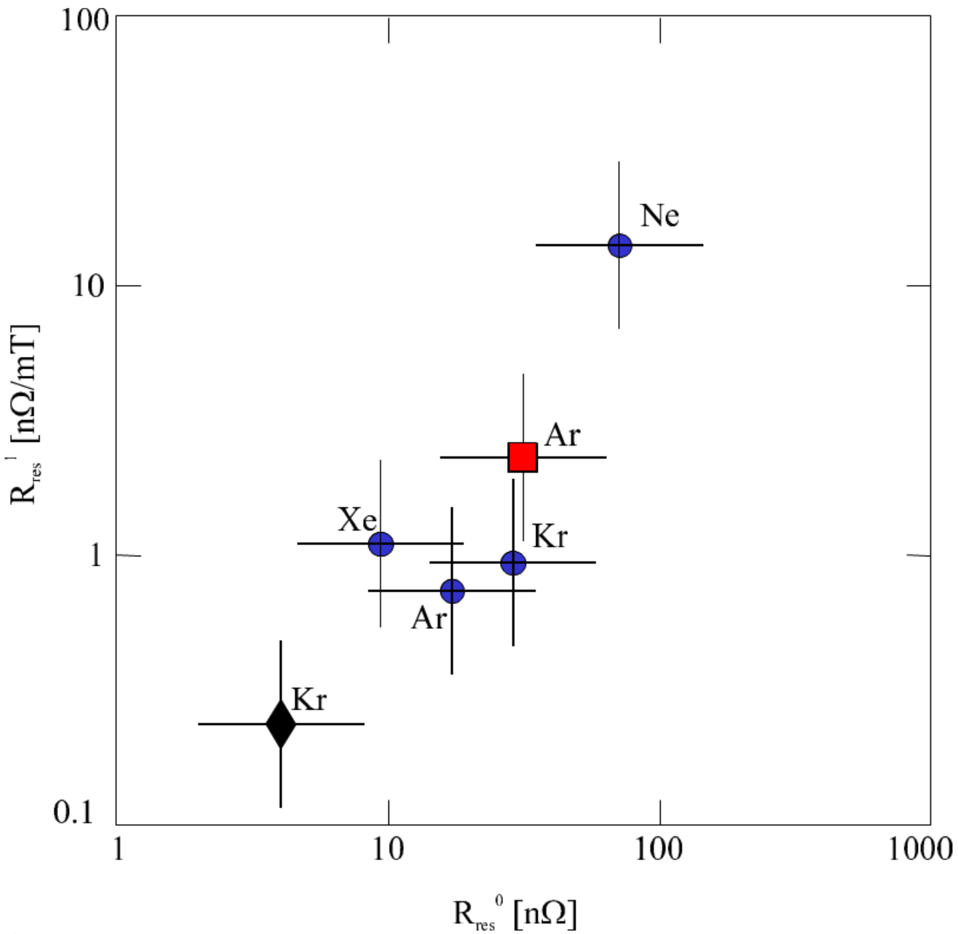


R_{res}^{0}	R_{res}^{1}
17±3 nΩ	5±1 nΩ m MV^{-1}
28±6 nΩ	10±2 nΩ m MV^{-1}
6±6 nΩ	1.5±1 nΩ m MV^{-1}

Courtesy of S. Calatroni

90's Activity / Substrate

Importance of substrate quality: chemical preparation



Standard coatings using Xe, Kr, Ar, Ne as sputter gas

Average roughness of chemically polished spun cavities: 0.2µm

Average roughness of chemically polished hydroformed cavities: 0.8µm

Average roughness of electropolished spun cavities: 0.04µm
Absence of defects (etching pits)

Courtesy of S. Calatroni

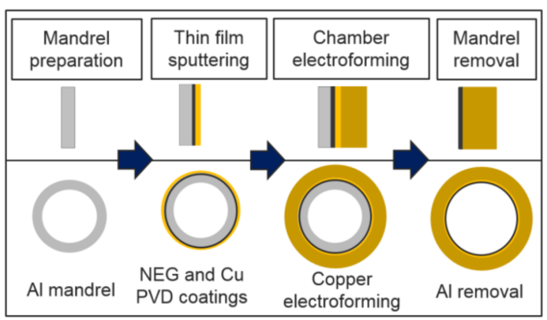
Activity / Substrate

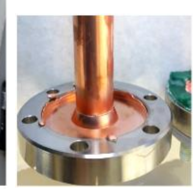
On going investigations

Welding impact on RF performances: PC03 (LHC) to be polished and re-measured to assess if the weld has an impact on the Q-slope.

Substrate forming:

Could we build an electroformed cavity? (no welds and potentially no brazing)
Cost saving
Seamless
Possibly flawless



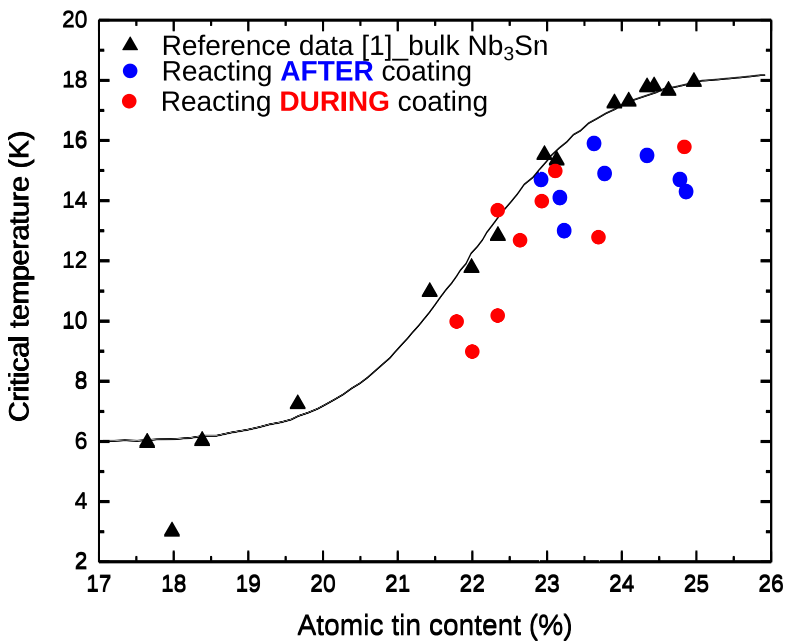
Inspired from the work of Lucia Lain Amador on small diameter vacuum chambers

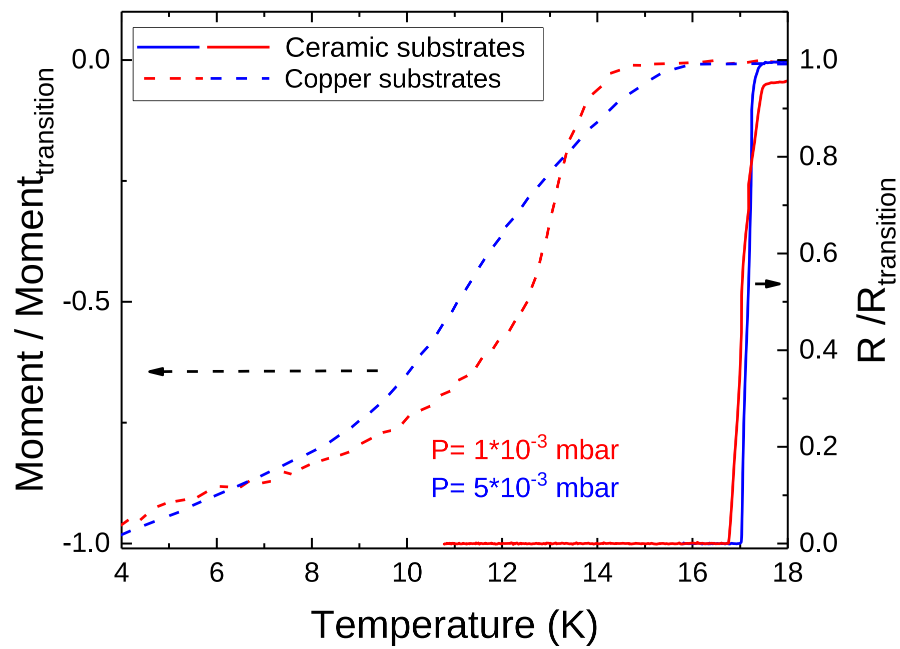
A15

Nb ⇨ Nb_3Sn

Courtesy of K. Ilyina-Brunner

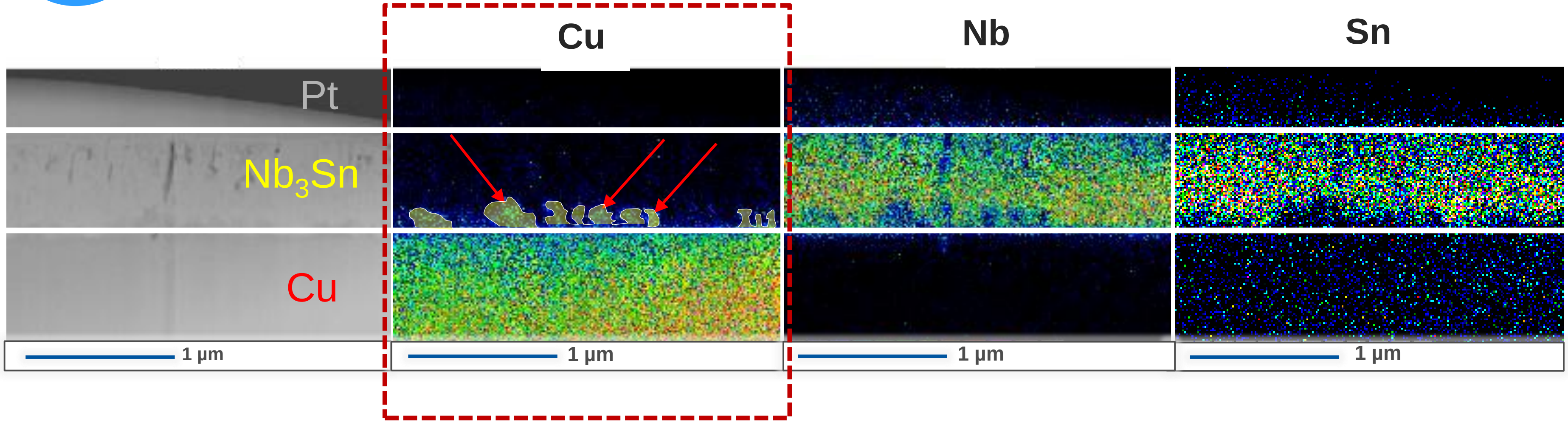
T_c	Nb_3Sn ~ 18.3 K
	Nb ~ 9.3 K
R_{BCS} @ 4.2K and 500MHz	Nb_3Sn ~ 0.4 nΩ
	Nb ~ 45 nΩ

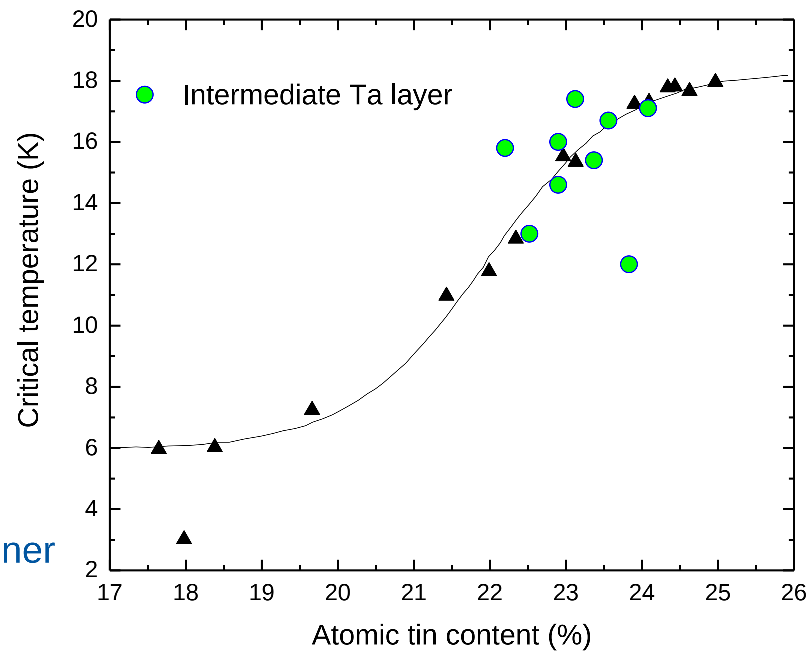




[1] *A. Godeke. Supercond. Sci. Technol., 19 (2006) R68-R80*

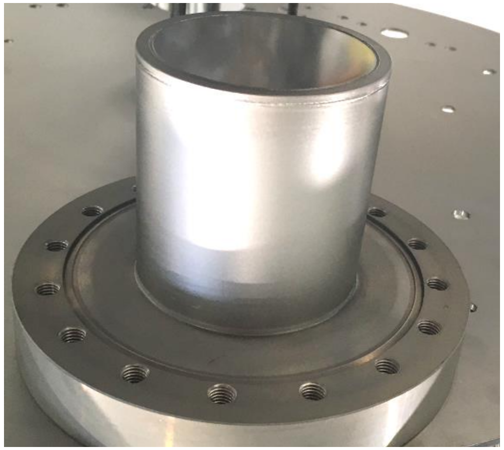
A15

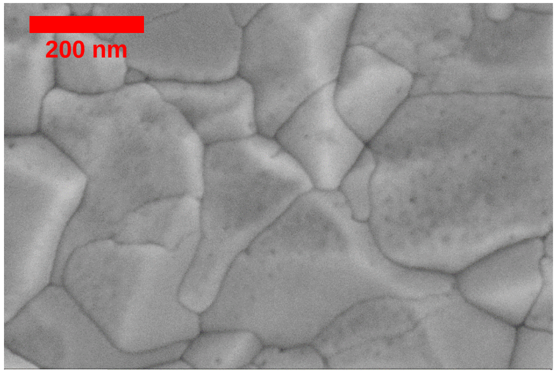


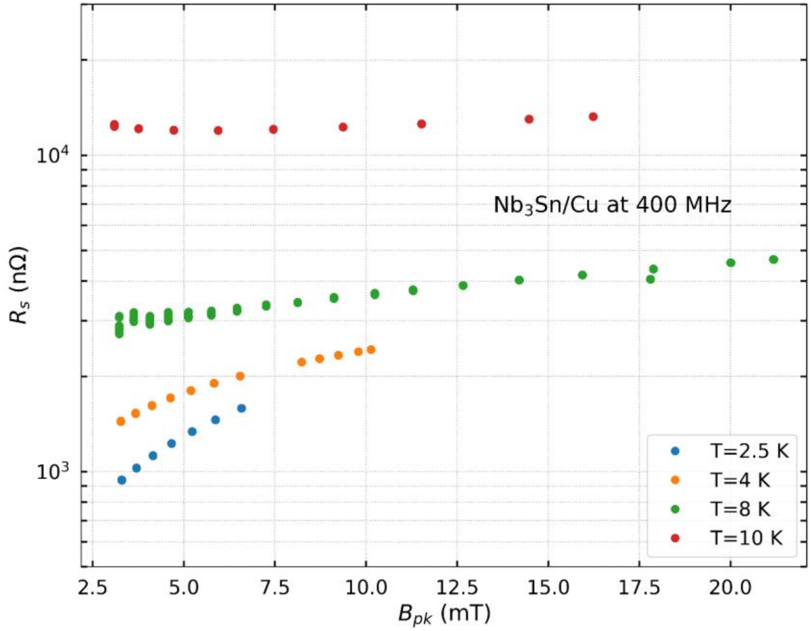


Courtesy of K. Ilyina-Brunner

A15







First RF measurement performed on Nb3Sn/Cu at CERN

Very modest start but an issue during the coating lead to non optimum coating parameters.

To be reproduced this year

Courtesy of Marco Arzeo

6. Conclusion / Perspectives

6.1 Conclusion

Strong know-how related to SRF thin films
- Surface treatment
- Coating techniques
- Vacuum expertise from TE-VSC

State of the art performances obtained on machine-type cavities
- HIE-ISOLDE
- LHC

Not only “lab” expertise but efficient transfer to production

Thin Films have a bright future

Substrate quality is 90% of the work : a good layer will never recover a bad substrate

Lot of efforts on-going to push toward higher gradient and higher Q

High gradient is reachable (cf HIE-ISOLDE) but needs to be demonstrated on elliptical devices

Low-Beta 704MHz cavities can be efficiently coated → RF test pending

Thank you for your attention

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