CERN

Alternative coating techniques and materials for SRF cavities

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1: CERN: TE-VSC/SCC

2: CERN: BE-RF/SRF

3: CERN: TE-VSC/VSM

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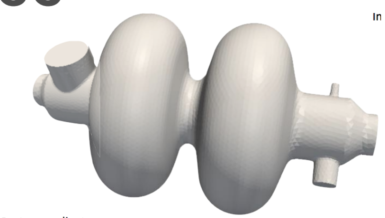
Outline

1. Context

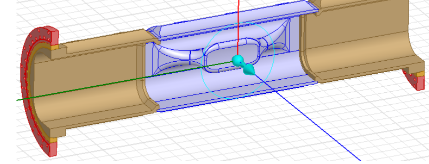
1.1 Coated SRF Cavities

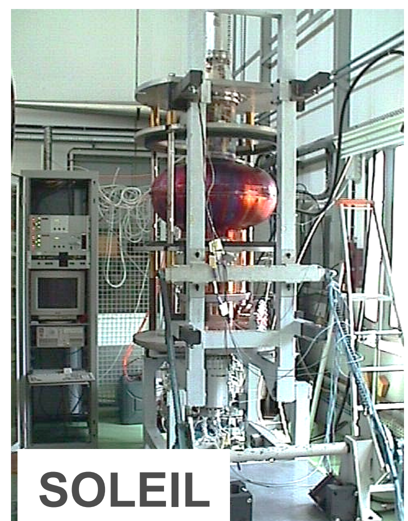
- Thermal stability
  - No quench
  - Higher working temperature
- Low magnetic field sensitivity
- Low fabrication costs

FCC

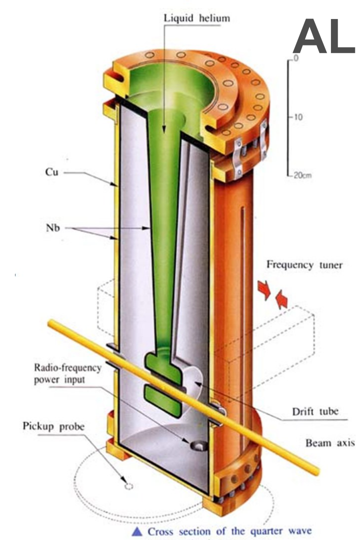


FCC-WOW





ALPI



1.2 Coating Techniques

Direct **C**urrent **M**agnetron **S**puttering

Adapted to elliptical cavities

Low working pressure (10^{-4} up to 10^{-2} mbar)

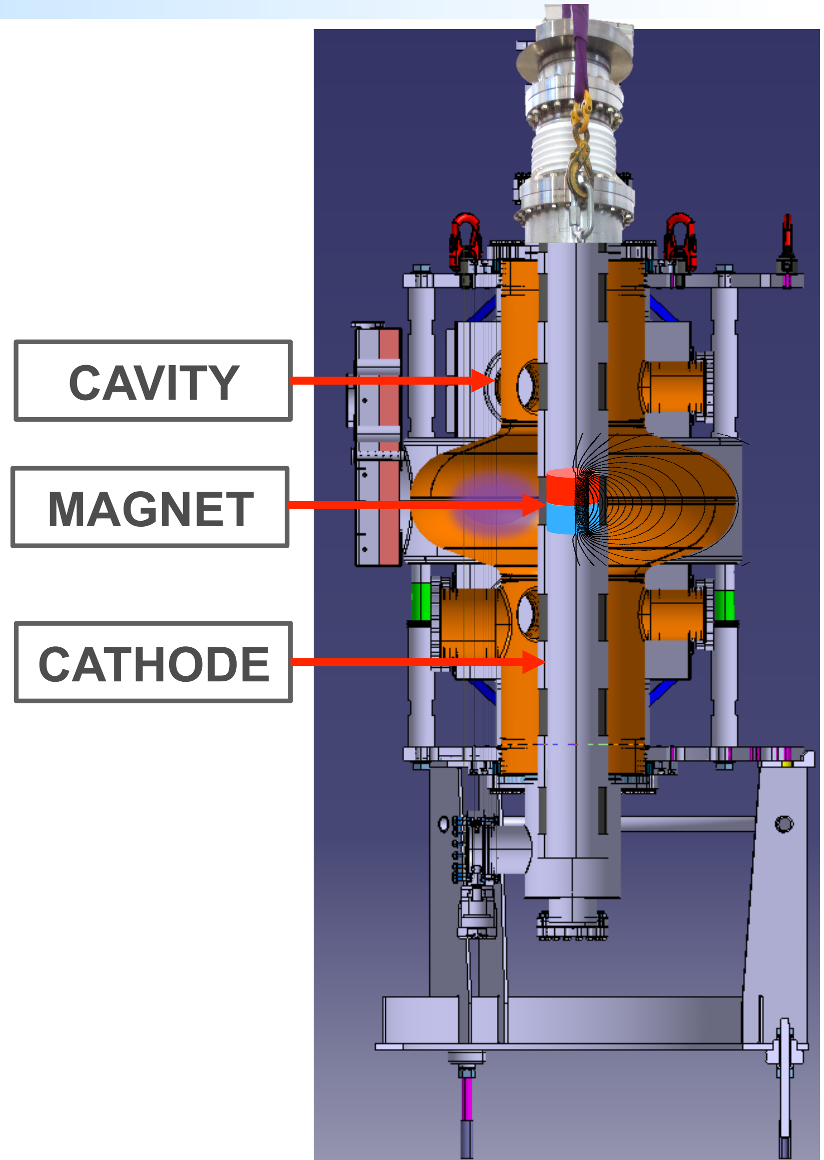
Kr or Ar as sputtering gas

10's $W.cm^{-2}$

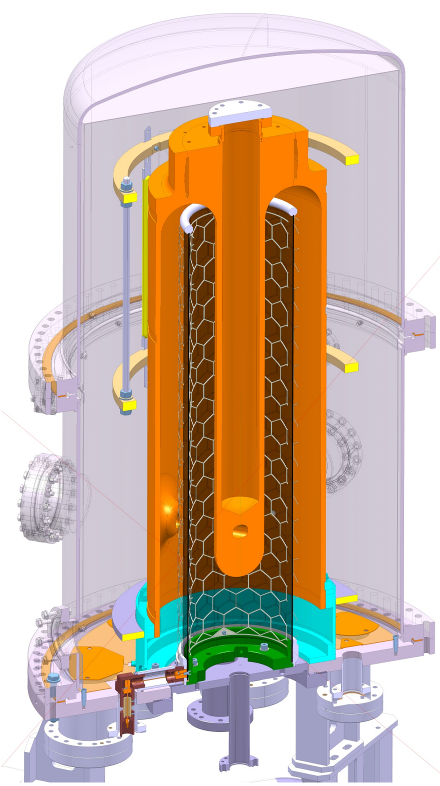
High coating rate (up to 100's nm/min)

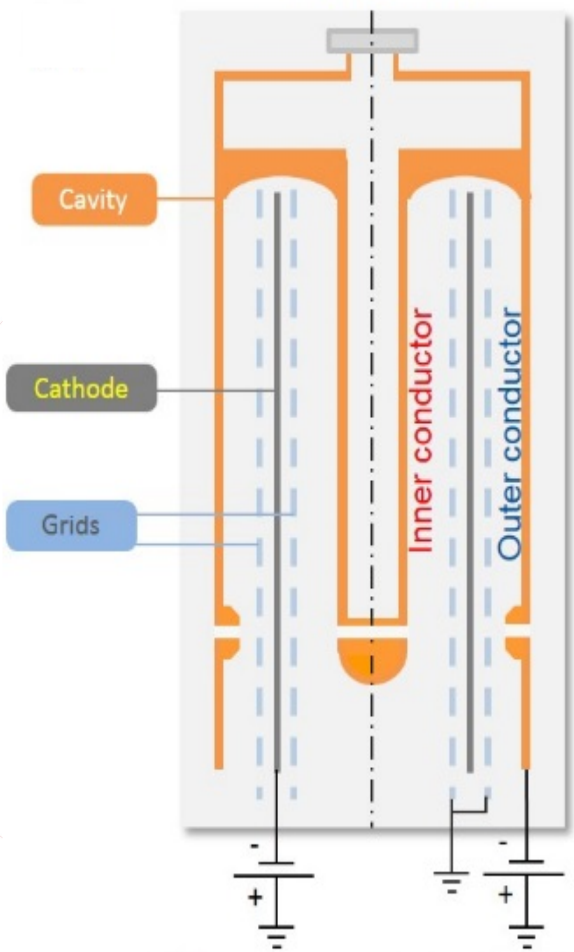
"low temperature" coatings

Cavity used as vacuum chamber



1.2 Coating Techniques





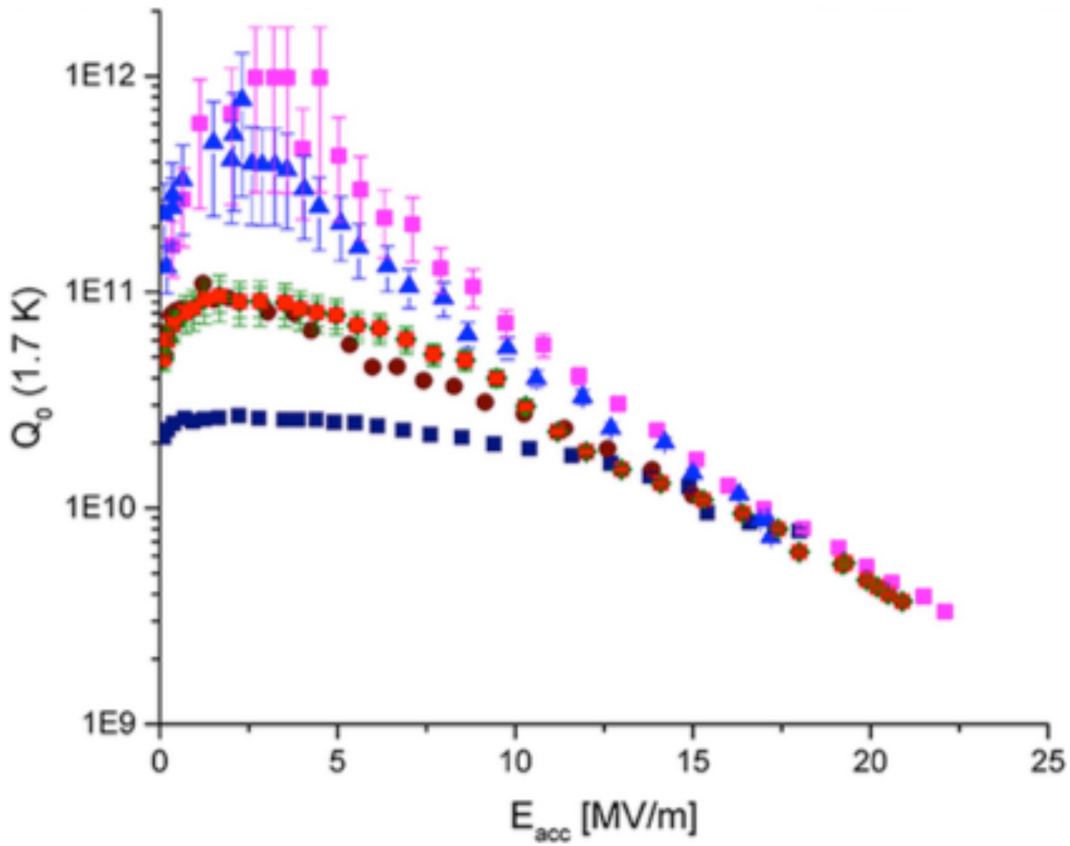
Biased Diode Sputtering

QWR type
Limited available space
Higher working pressures (10^{-2} – 10^{-1}mbar)
Ar or Kr as sputtering gas
~1W.cm^{-2}

Cavity under UHV
→ Not UHV leak tight cavity
High temperature reachable (~650°C)
(outgassing, Nb mobility, adhesion)

1.2 Coating Techniques

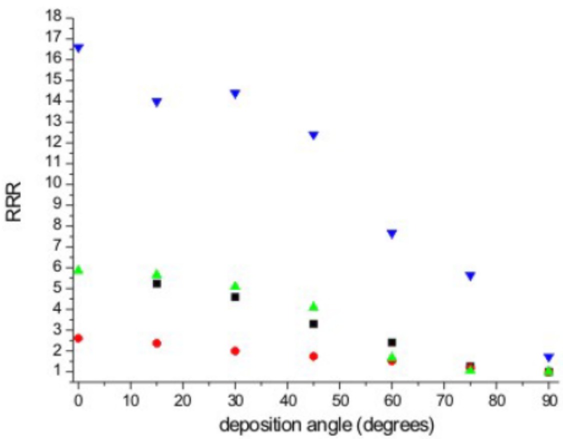
Proven to be good at low field

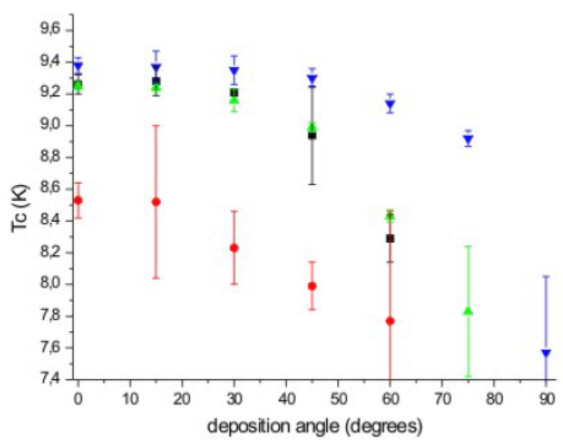


Benvenuti C et al 2001 Physica C 351 421–8

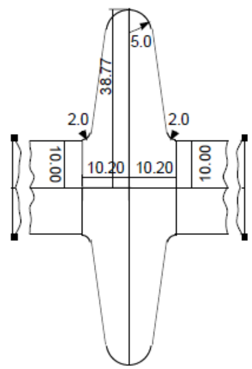
1.3 Limitations

Samples [1]

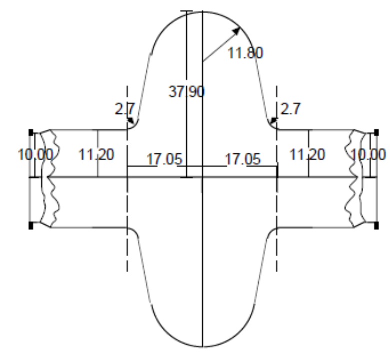




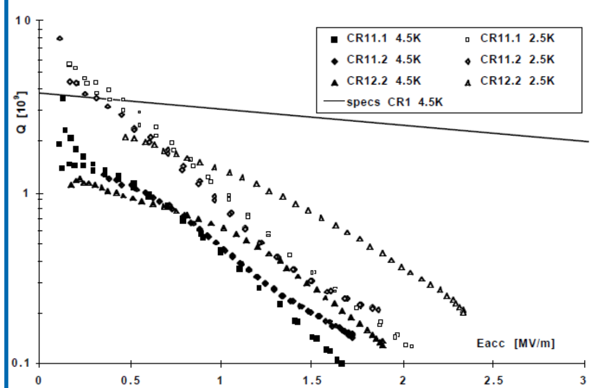
352 MHz Cavities [2]

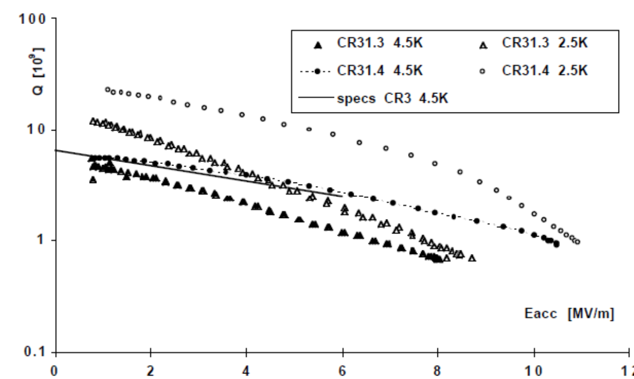


β = 0.48



β = 0.8





[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

Which Solutions?

2. Overview

2.1 Energetic condensation

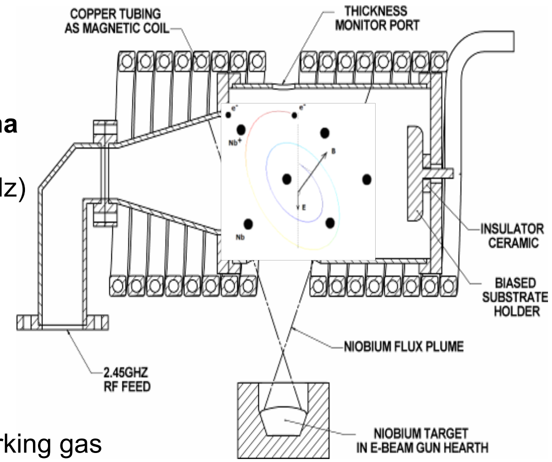
PROPOSAL: Use ionized Nb to coat cavities instead of neutrals.
→ Coating conformality, density

HOW?

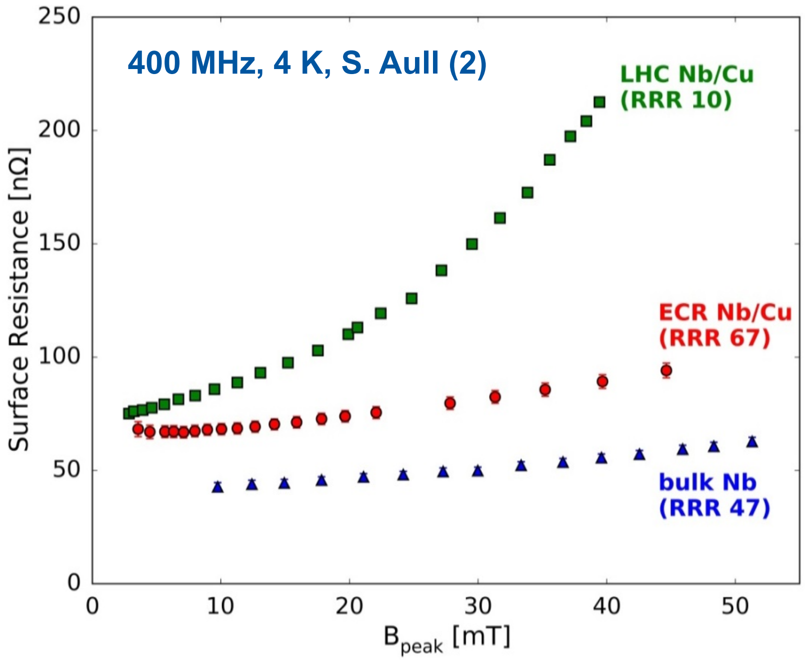
Electron Cyclotron Resonance	UHV Cathodic Arc	High Power Impulse Magnetron Sputtering
Jlab, Fermilab	Alameda, NCBJ, INFN	CERN, Jlab, Fermilab, STFC

2.2 ECR @ Jlab (courtesy of A.M. Valente-Feliciano)

Generation of plasma
Neutral Nb vapor
RF power (@ 2.45GHz)
Static B ⊥ E_{RF}
with ECR condition



No working gas
Singly charged ions **(64eV)** **produced in vacuum**
Controllable deposition energy with Bias voltage
Excellent bonding , No macro particles



QPR results are more than promising:
- Low R_{res} combined to mitigated Q-slope
- Good adhesion
- What else has to be done?

Pros
- Gasless
- No macroparticles

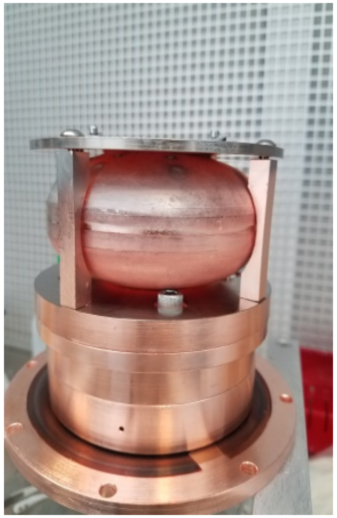
Cons
- Scalability?

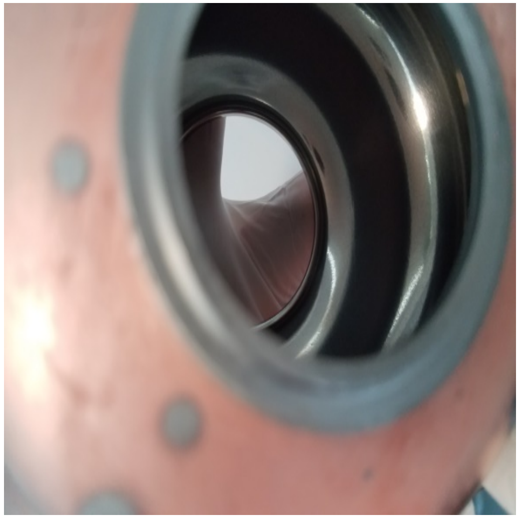
1: A. M. Valente-Feliciano, Supercond. Sci. Technol. 29 (2016) 113002

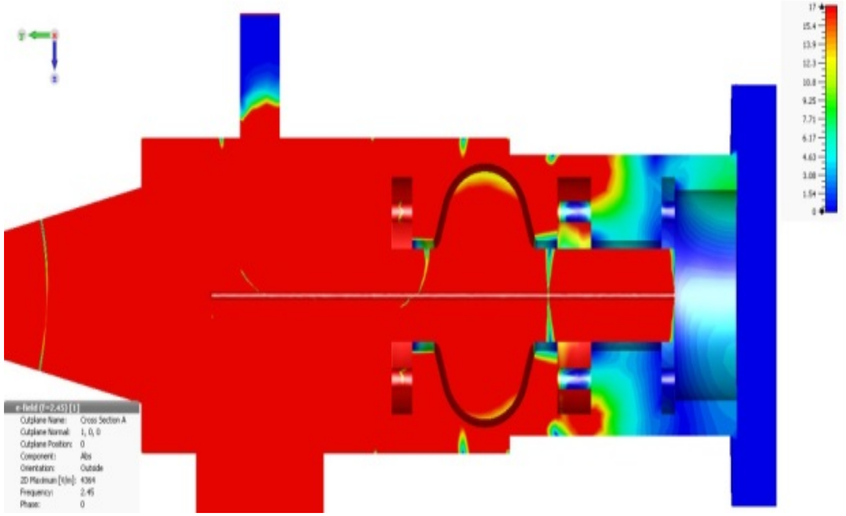
2: Aull S et al 2015 Proc. 17th Int. Conf. on RF Superconductivity (Whistler, BC, Canada, 13–18 September) TUBA03 494

2.2 ECR – Next steps

Scale-up to cavities





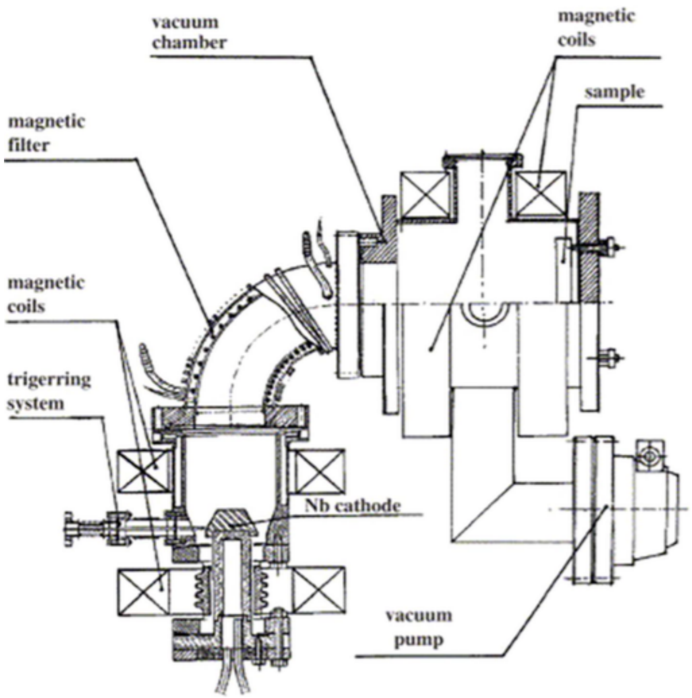


3 GHz Cavity with beam tubes: 5GHz frequency cut-off

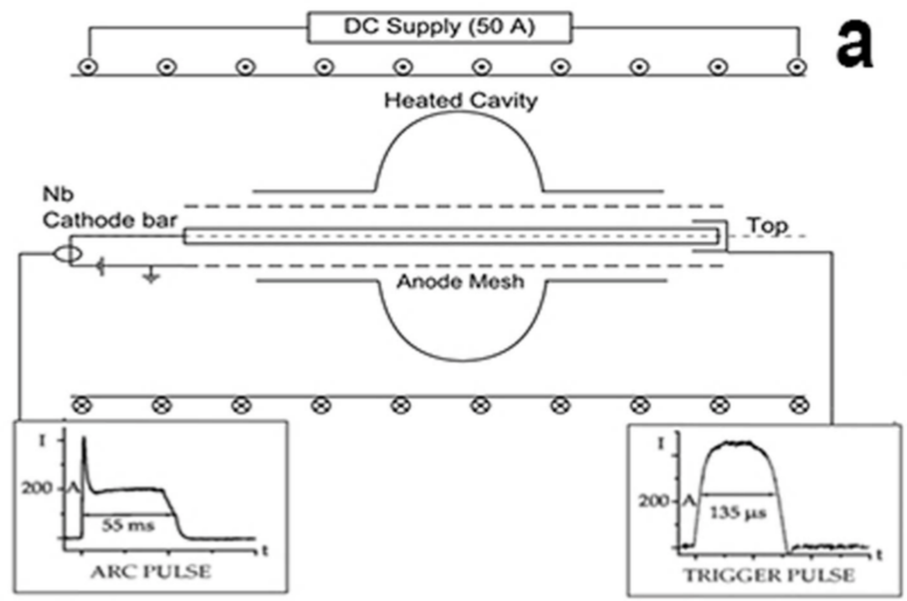
Adjust coating geometry to allow RF fields to penetrate the cell and get adequate plasma conditions

A. M. Valente-Feliciano, Supercond. Sci. Technol. 29 (2016) 113002

2.3 – UHV Cathodic Arc



Langner J et al 2006 Vacuum 80 1288–93



Krishnan M et al 2012 Phys. Rev. Spec. Top. Accel. Beams 15 032001

Pros

High coating rates

High ionization degree (+3)

Cons

Macroparticles formation

Delamination

Not yet satisfactory on cavities

→ Not technique related

3. @ CERN: HiPIMS

3.1 HiPIMS Setup

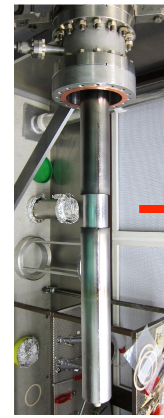
DCMS System already existing
Pulsed power supplies (Huttinger-TRUMPF)
DC Bias

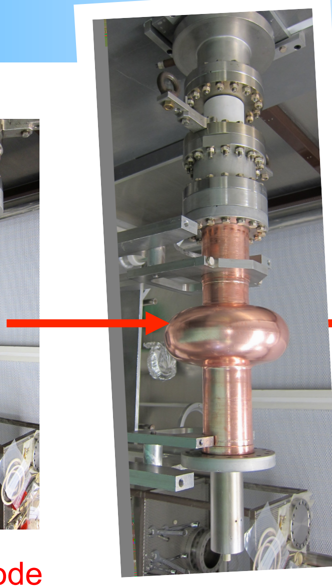
Modification:

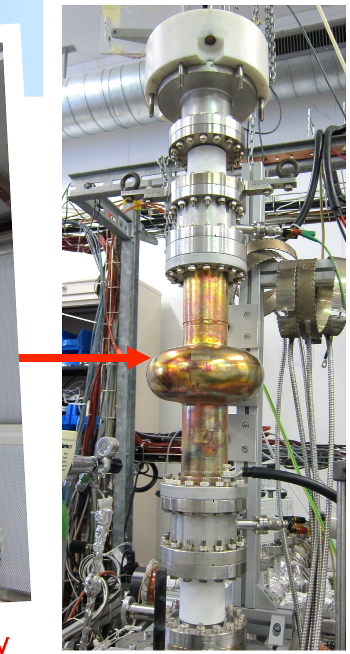
- **Anodes implementation**
  - **Enables bias configuration**

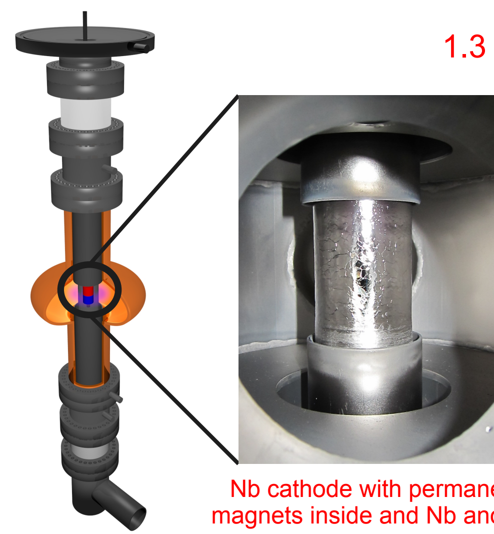
Typical parameters

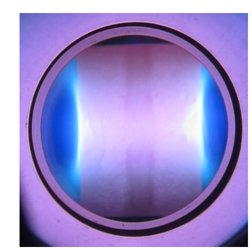
Parameter	Typical value/range
Gas	Kr
Pressure	$2.10^{-3} – 1.10^{-2}$ mbar
Power (Avg)	1 kW
Peak Power	80 kW (1kW.cm^{-2})
Peak Current	150 - 250 A (2-3A.cm^{-2})
Pulse duration	50 - 200 μs
Pulse Frequency	20 - 500 Hz
Temperature	150°C


Nb cathode


1.3 GHz cavity

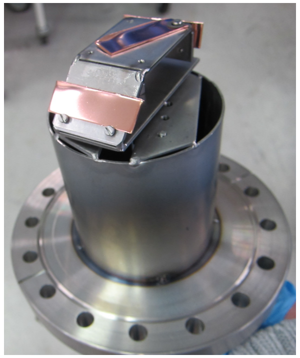

1.3 GHz cavity coating setup


Nb cathode with permanent magnets inside and Nb anodes


HiPIMS discharge

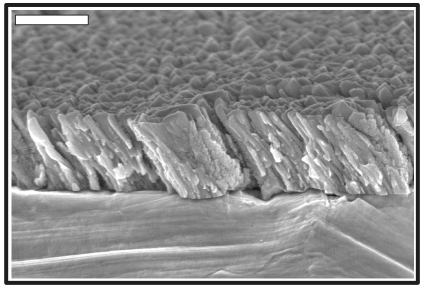
3.2 HiPIMS results : Morphology

- Samples - Coupons

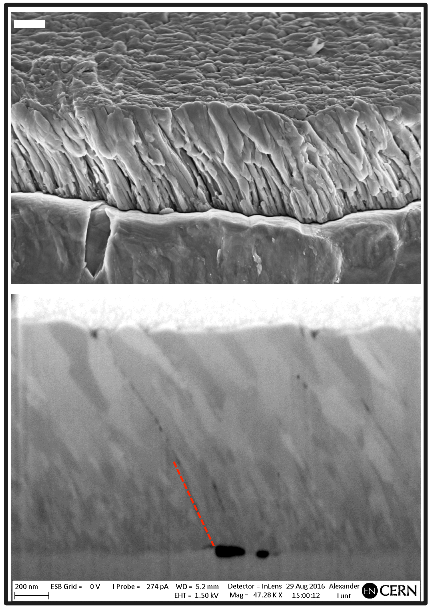


Grounded HiPIMS = Grounded DCMS
Bias compulsory to densify the layer

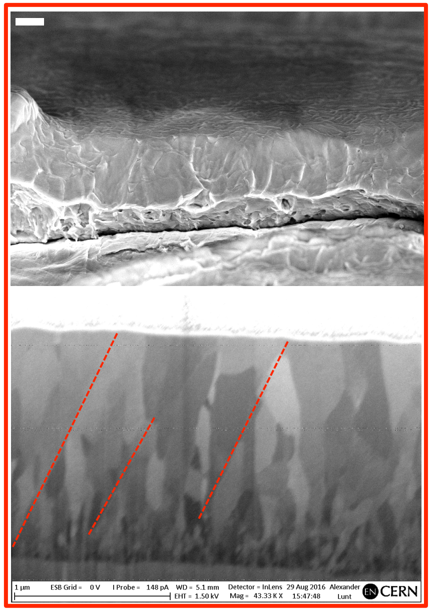
0V DCMS



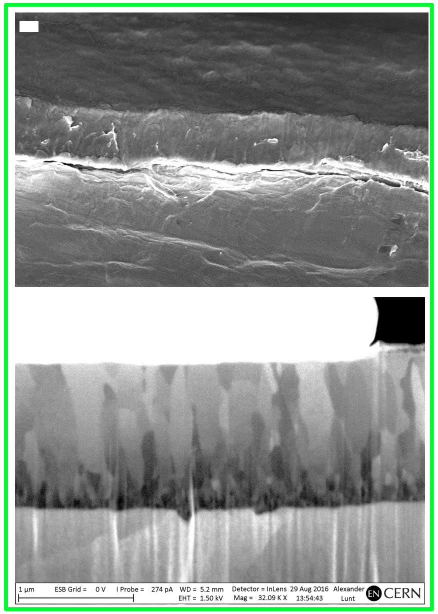
0V HiPIMS



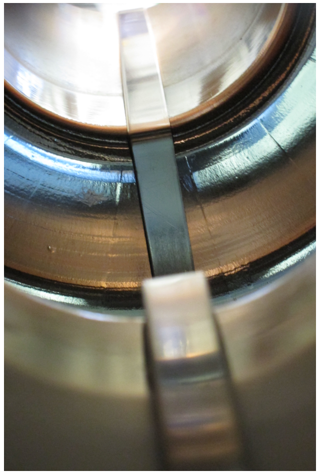
-50V

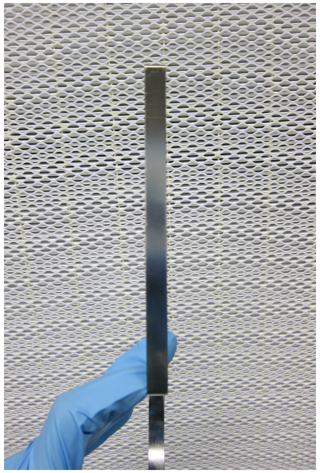


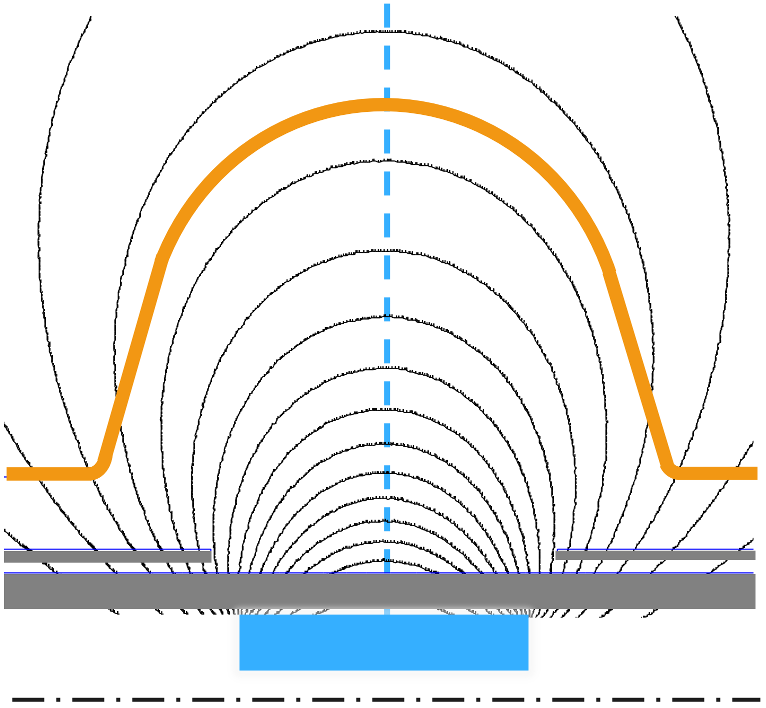
-100V



3.4 HiPIMS results : Morphology

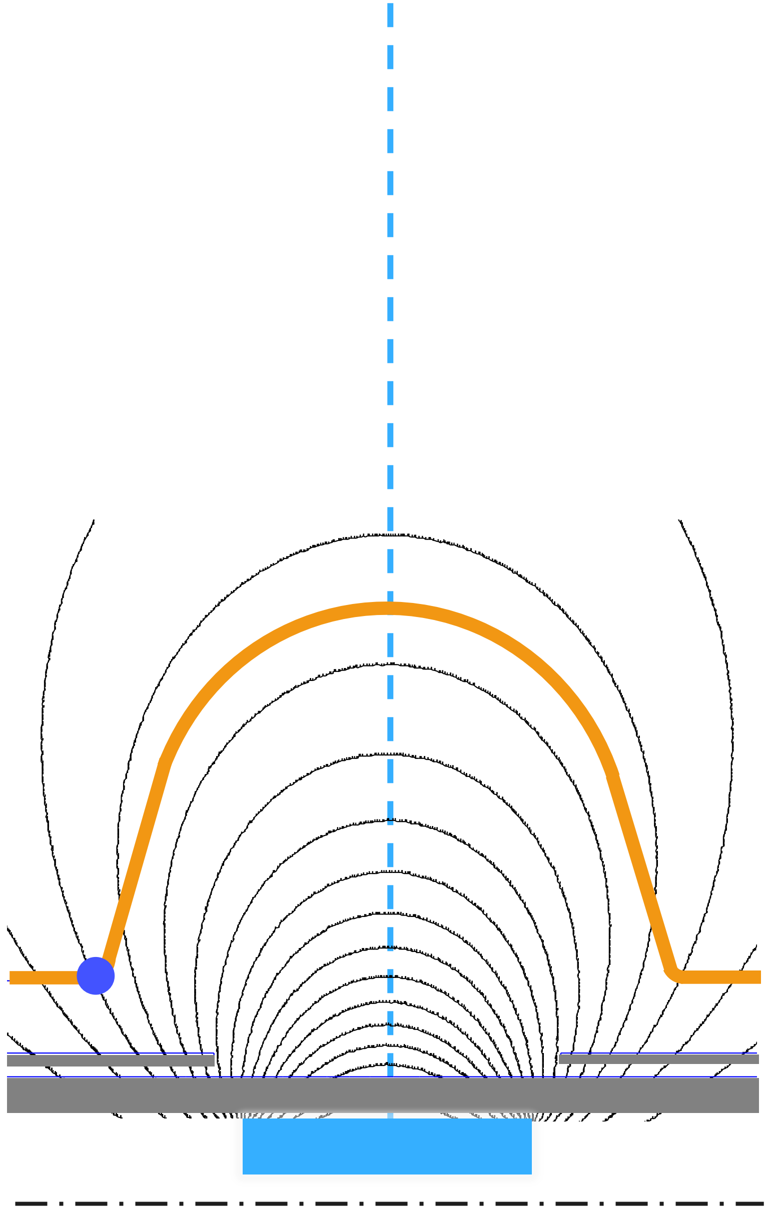


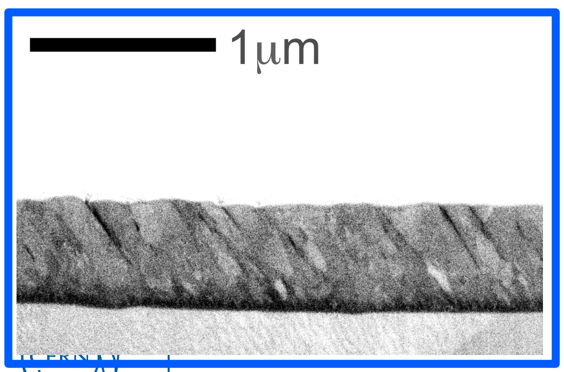




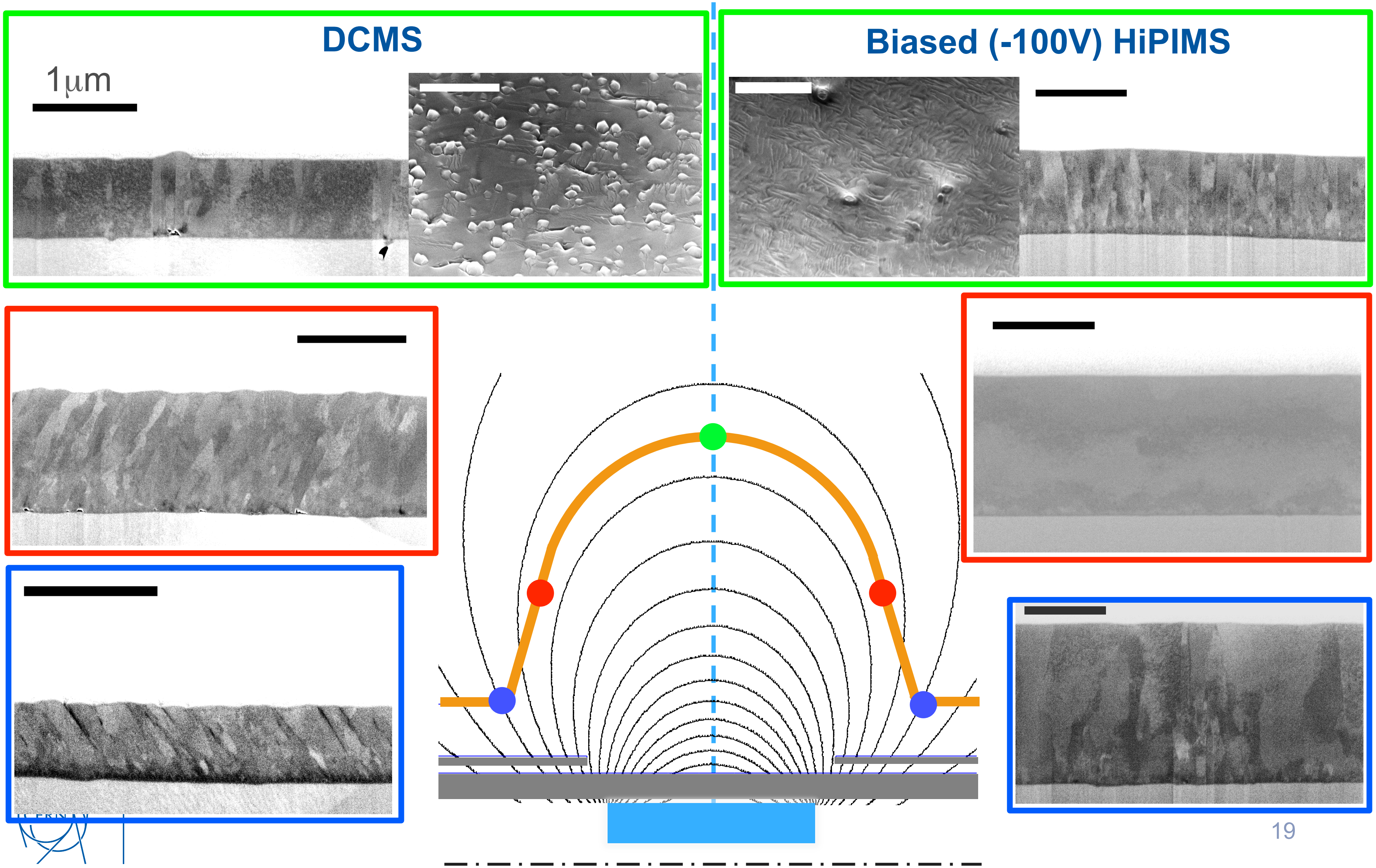
3.4 HiPIMS results : Morphology

DCMS





3.4 HiPIMS results : Morphology



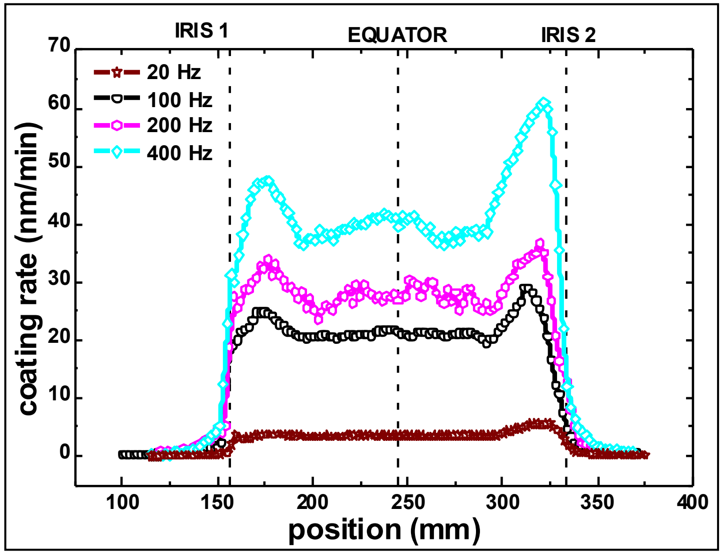
3.3 HiPIMS results : Frequency

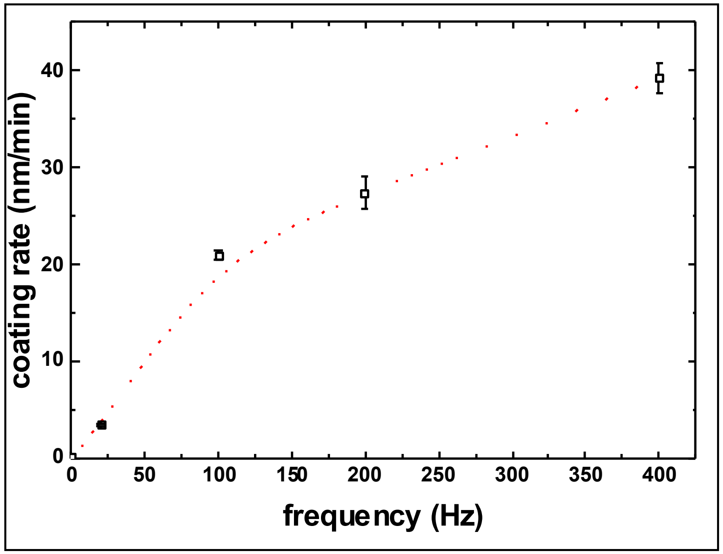
- Samples – cavity replicates

Thickness profile obtained by XRF

Lower frequencies lead to

- Lower coating rates
- Modified coating profile





3.3 HiPIMS results: Magnet

- Samples – cavity replicates

Thickness profile obtained by XRF

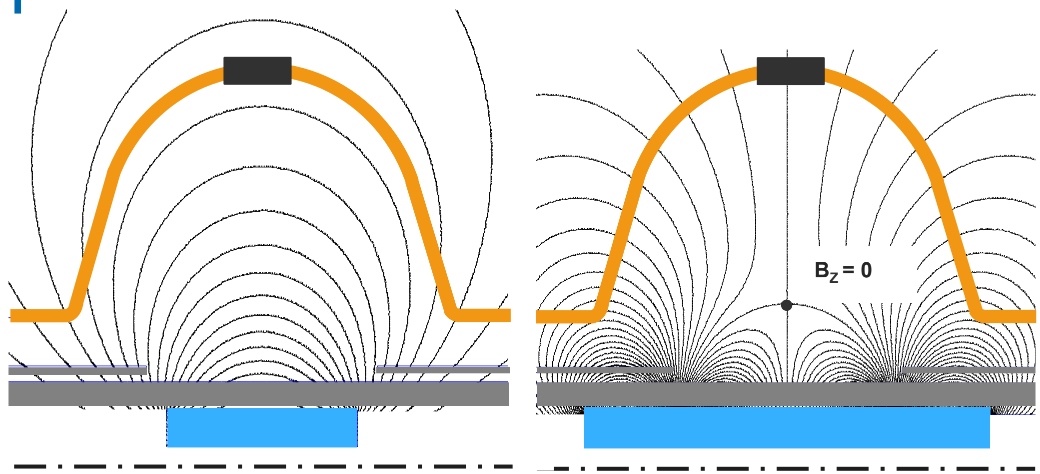
Lower frequencies lead to

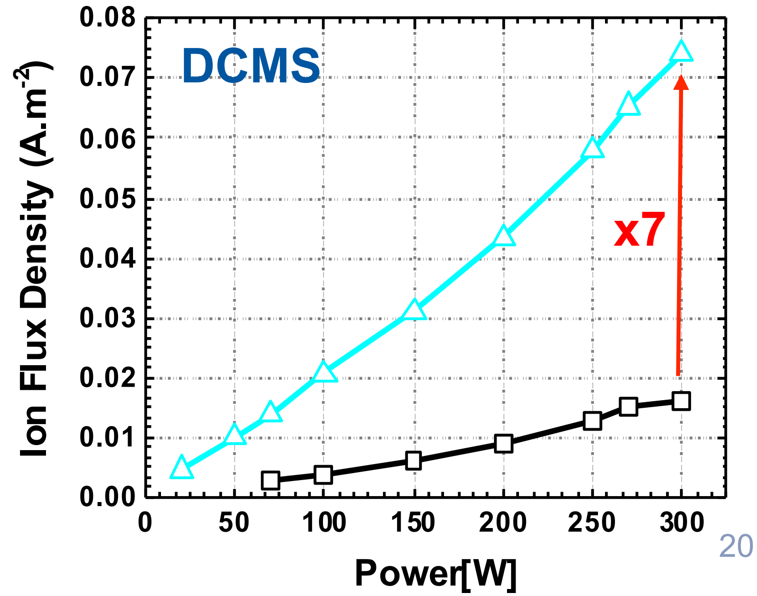
- Lower coating rates
- Modified coating profile

Possibility to tune the ion flux density

Impact on the layer to be assessed

- Samples
- Cavity





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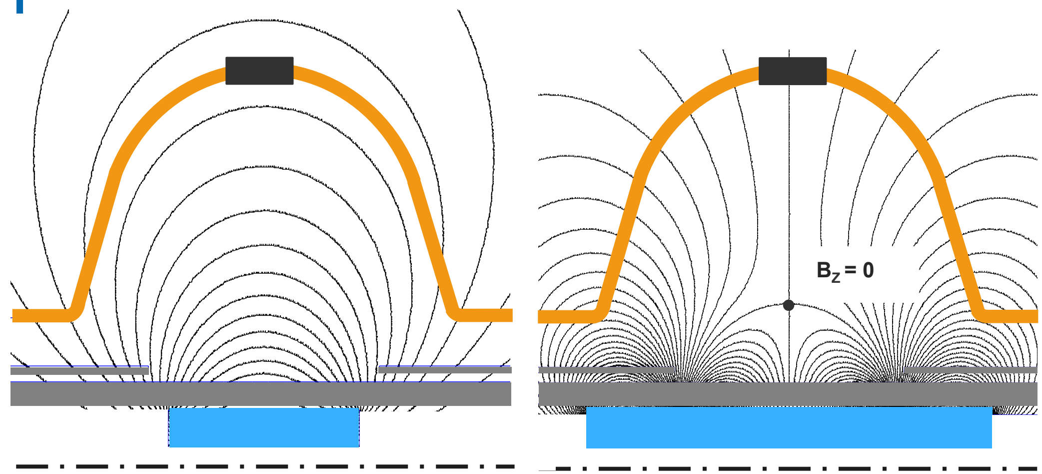
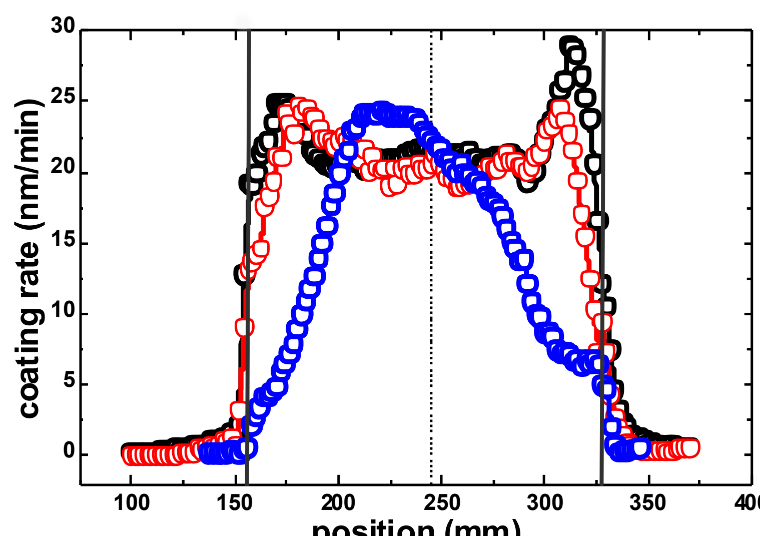
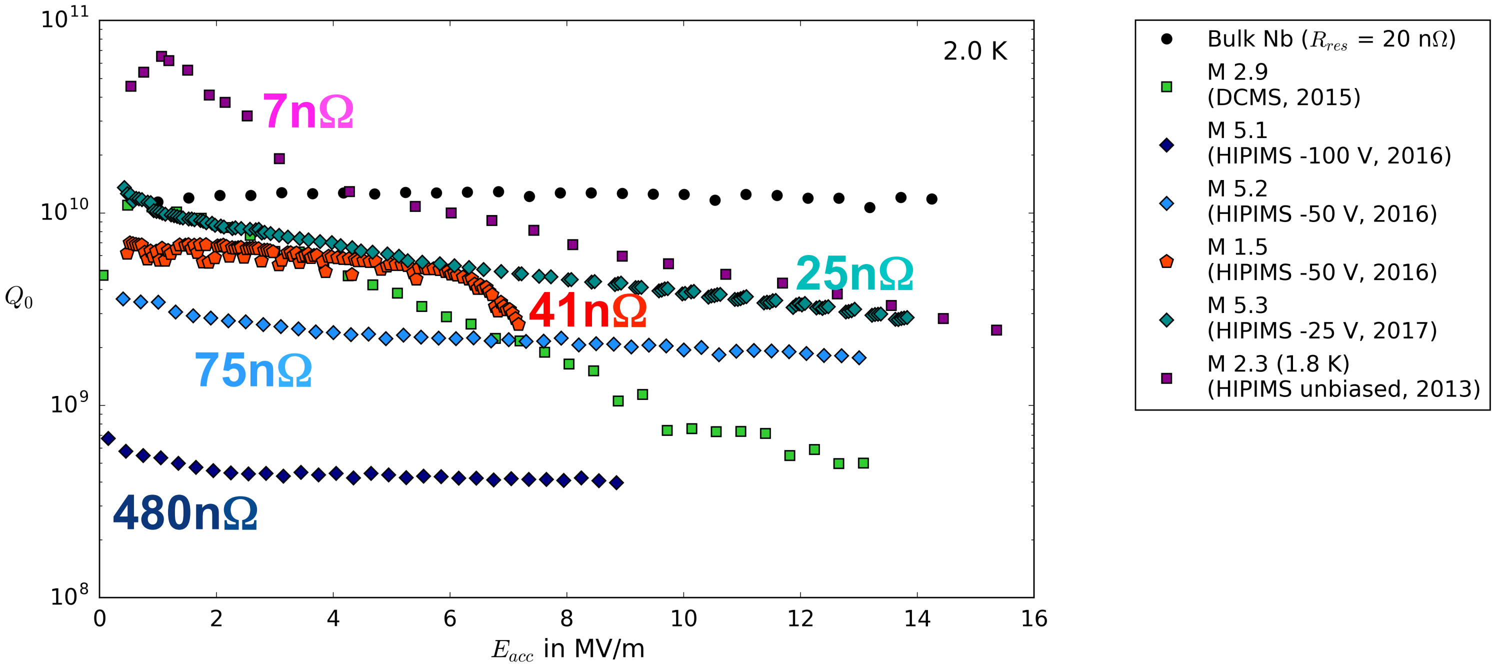


IMPACT ON LAYER AND RF PERFORMANCES?
COATINGS ON CAVITIES NEEDED



3.5 HiPIMS results: Cavities

- 1.3 GHz Cu Cavities

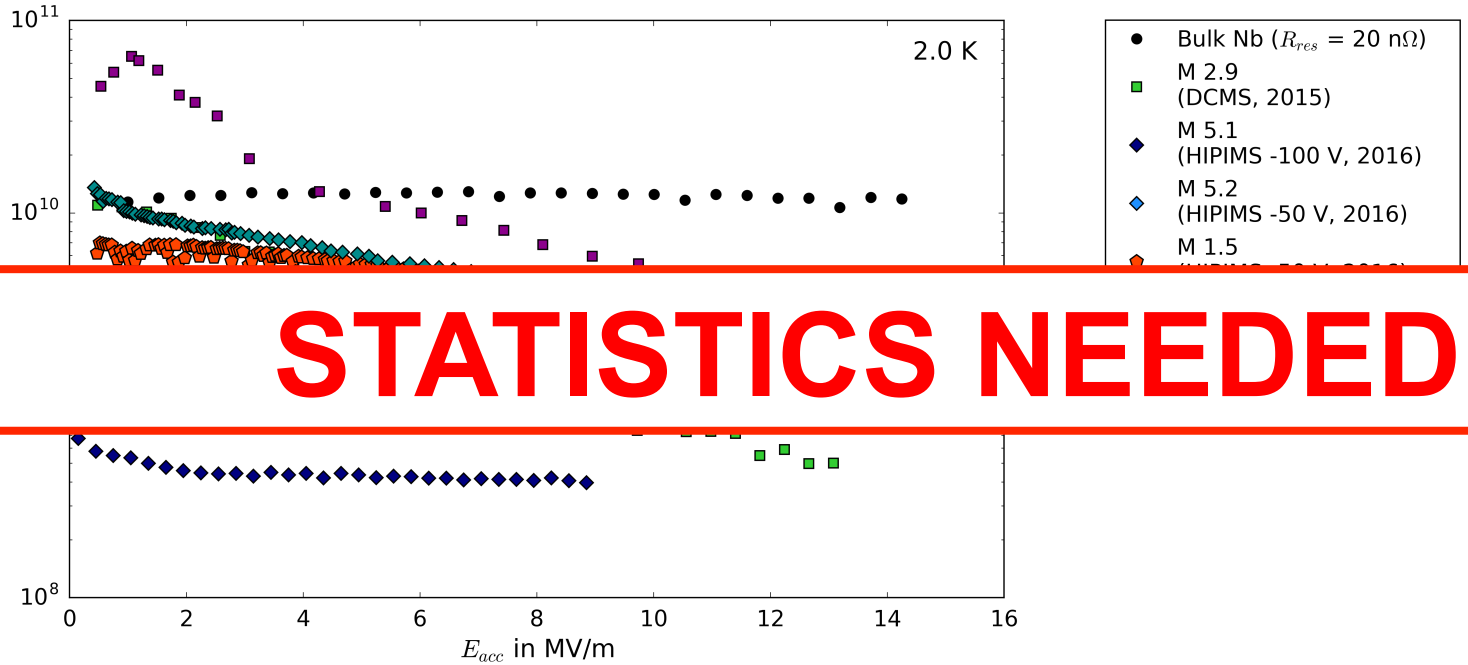


High Bias does not give good results (gas implantation , stress…)
Lower pressure tends to better performances (contamination, stress…)
Q-slope looks mitigated vs DCMS coating
Best HiPIMS : R_{res} = 5.2 nΩ

T. Junginger, Field dependent surface resistance of niobium on copper cavities, PRSTAB, 18, 072001 (2015)

3.5 HiPIMS results: Cavities

- 1.3 GHz Cu Cavities



STATISTICS NEEDED

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3. @ CERN: A15

K. Ilyina-Brunner

3.6 A15 Setup

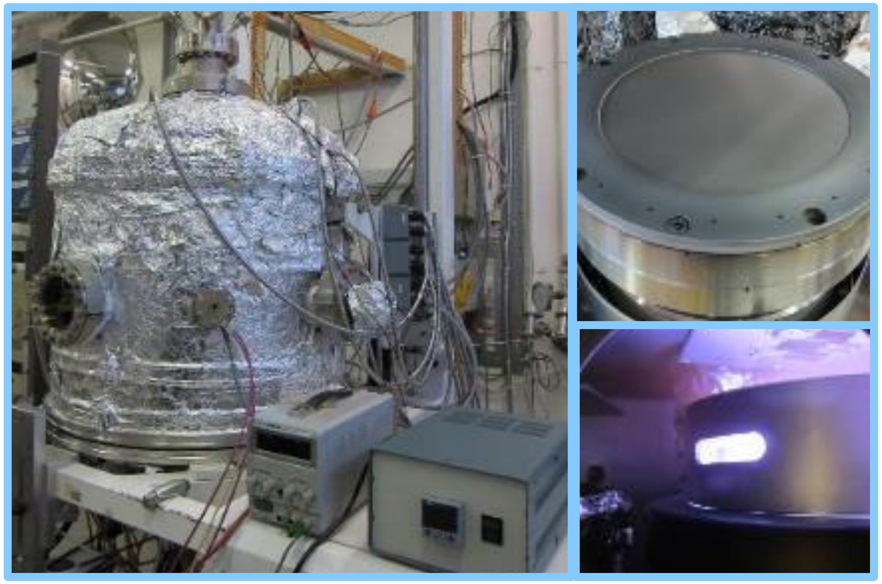
DCMS System

- **Heater integrated**
- **Single target Nb:Sn 3:1**

UHV furnace

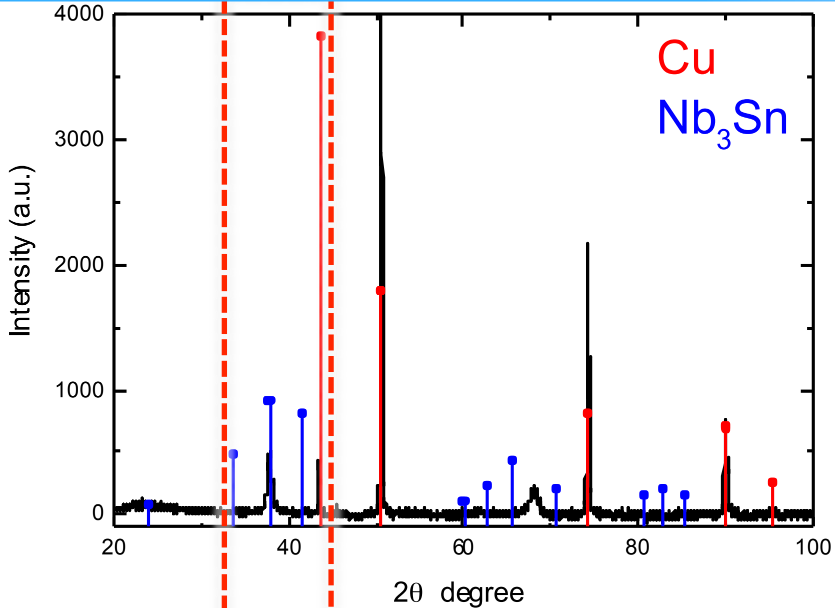
- **Post coating annealing**

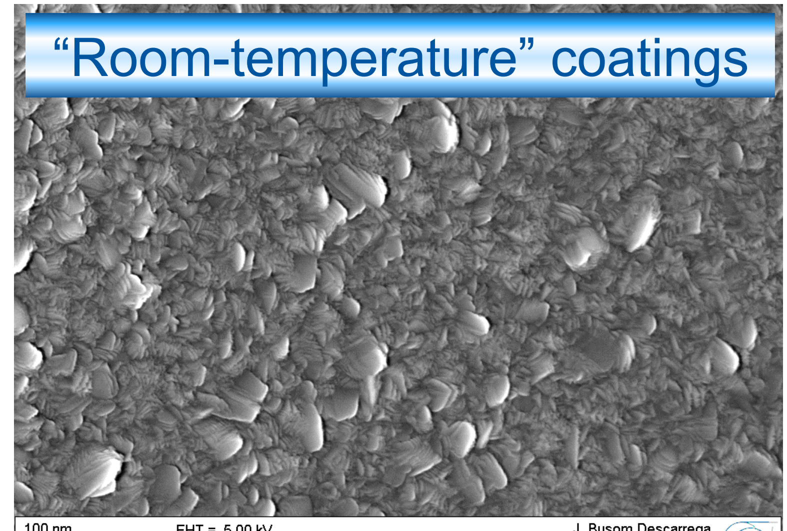
Parameter	Typical value/range
Gas	Kr/Ar
Pressure	$5.10^{-4} – 5.10^{-2}$ mbar
Power (Avg)	200 W
Temperature	From 150°C to 700°C in-situ



3.6 XRD - Morphology

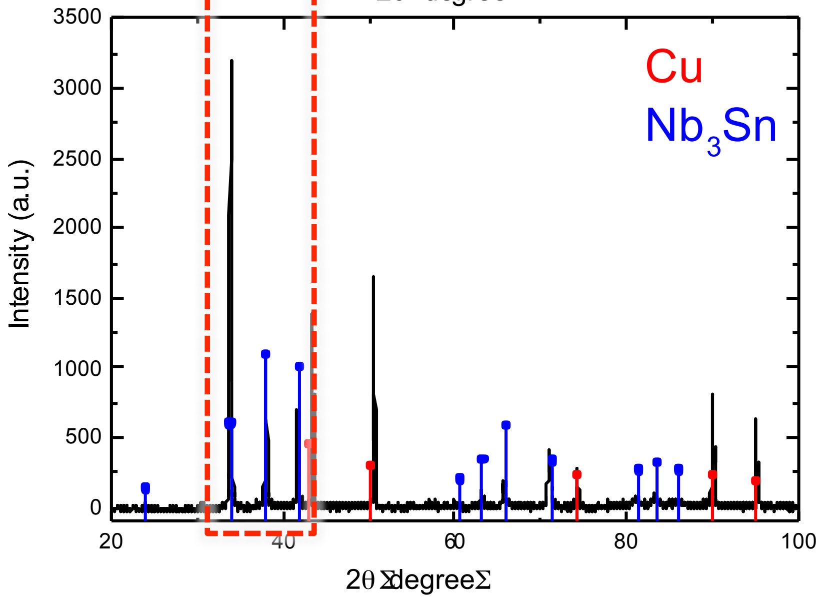
as-deposited

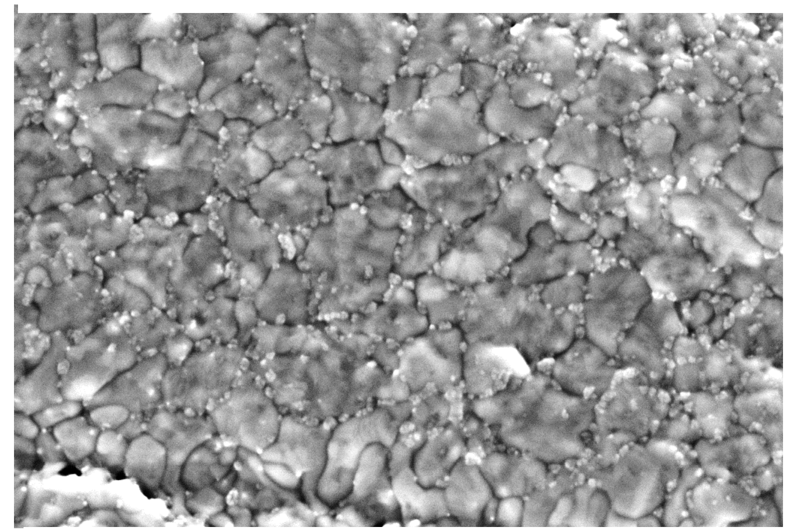




100 nm

after annealing





100 nm

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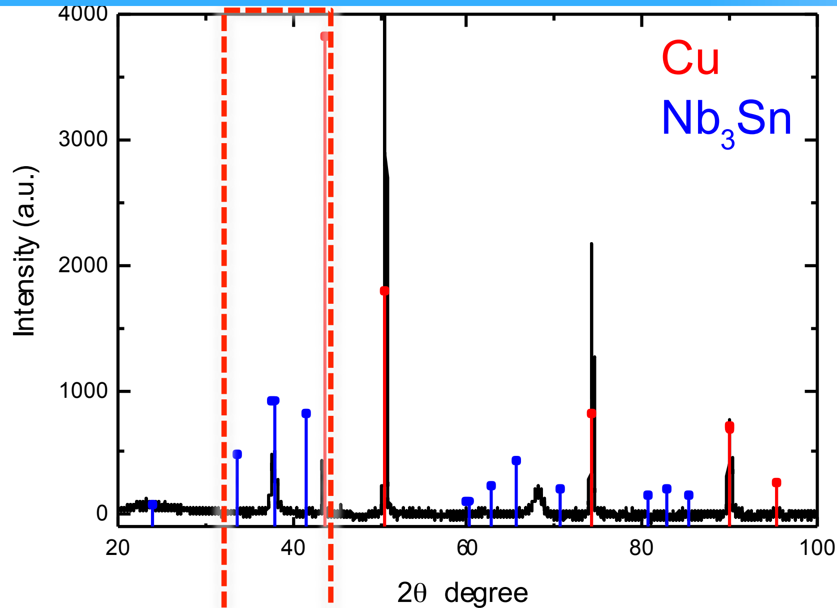
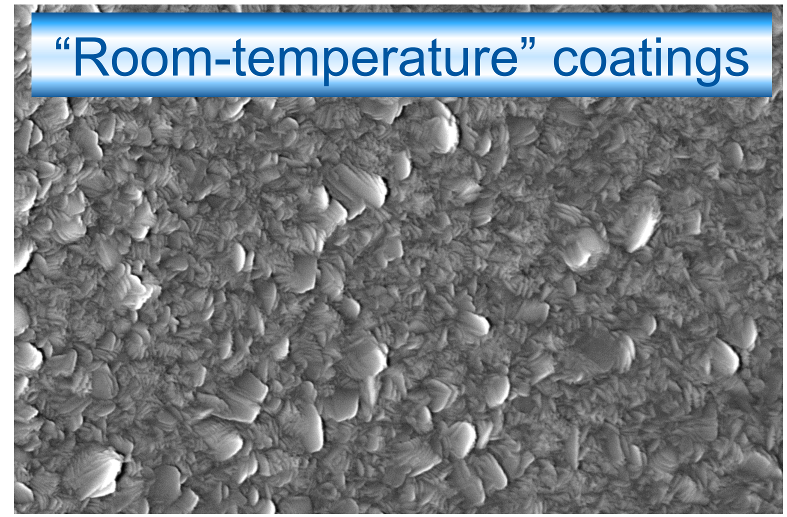
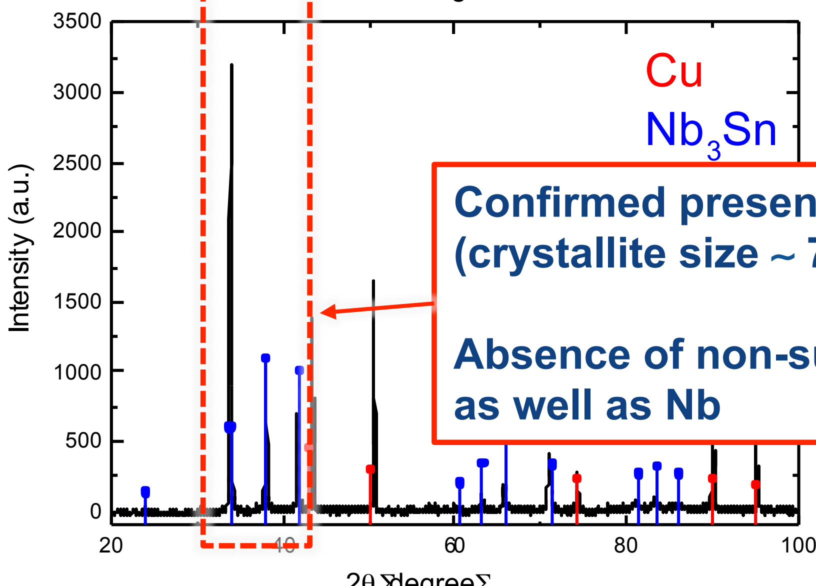
as-deposited

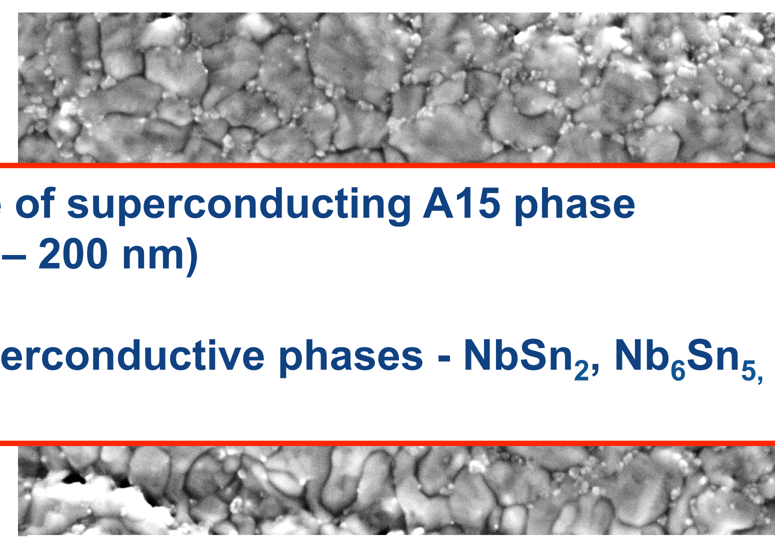




100 nm

after annealing





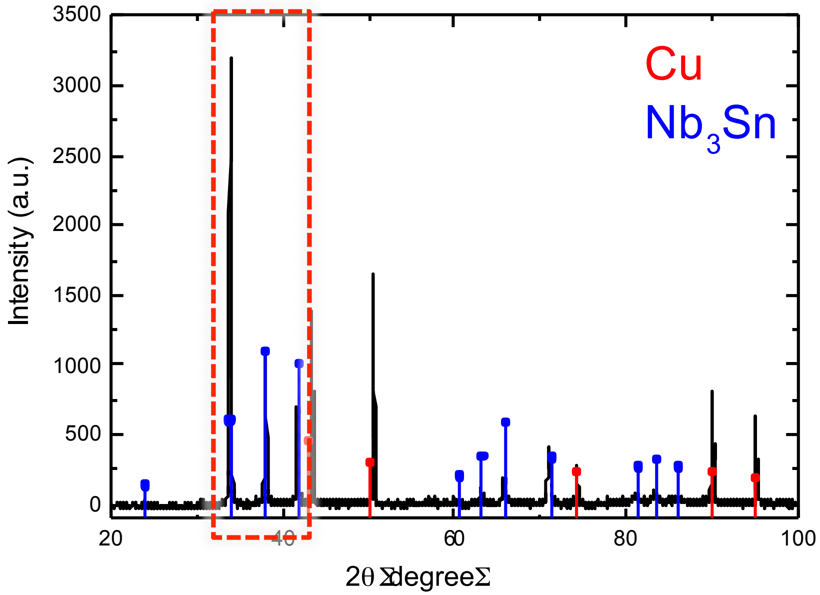
Confirmed presence of superconducting A15 phase (crystallite size ~ 70 – 200 nm)

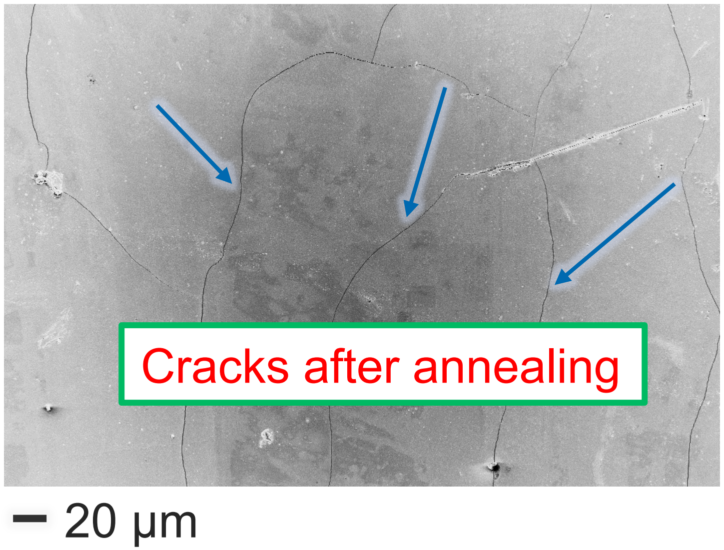
Absence of non-superconductive phases - $NbSn_2$, Nb_6Sn_5, as well as Nb

100 nm

3.6 XRD - Morphology

after annealing



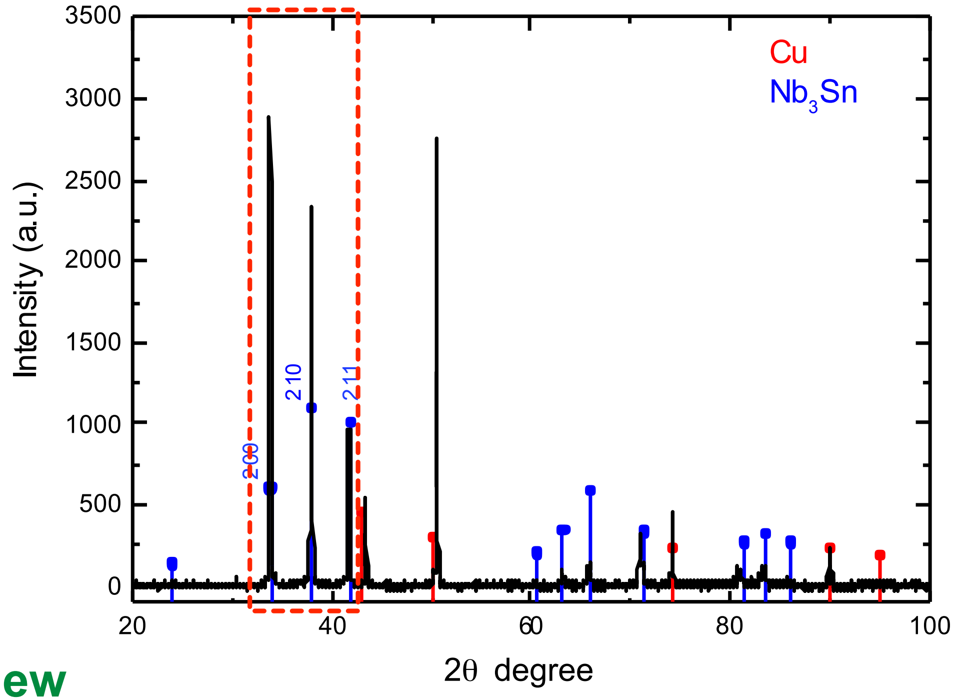


All "room temperature" samples are evincing cracks after annealing.

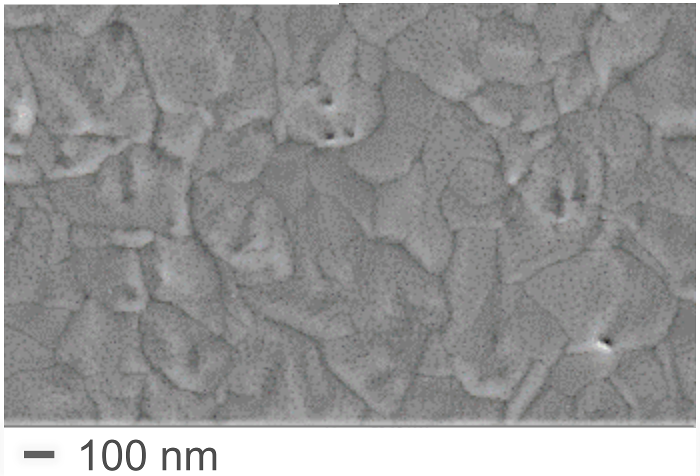
Now coating recipe to overcome this problem has been found !

3.6 High temperature coatings

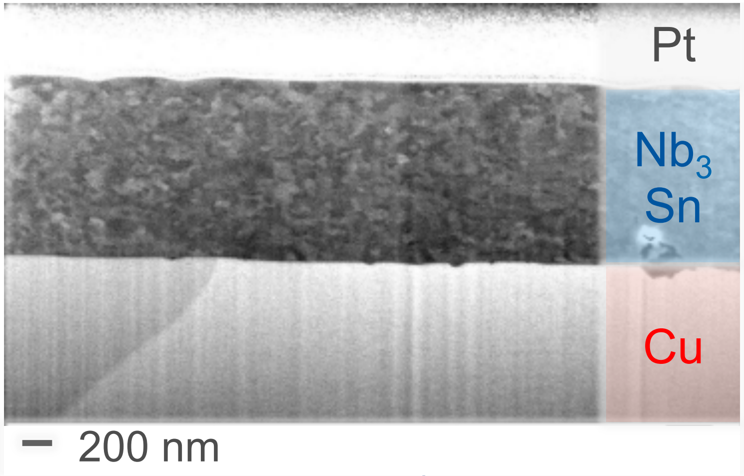
XRD



SEM top view

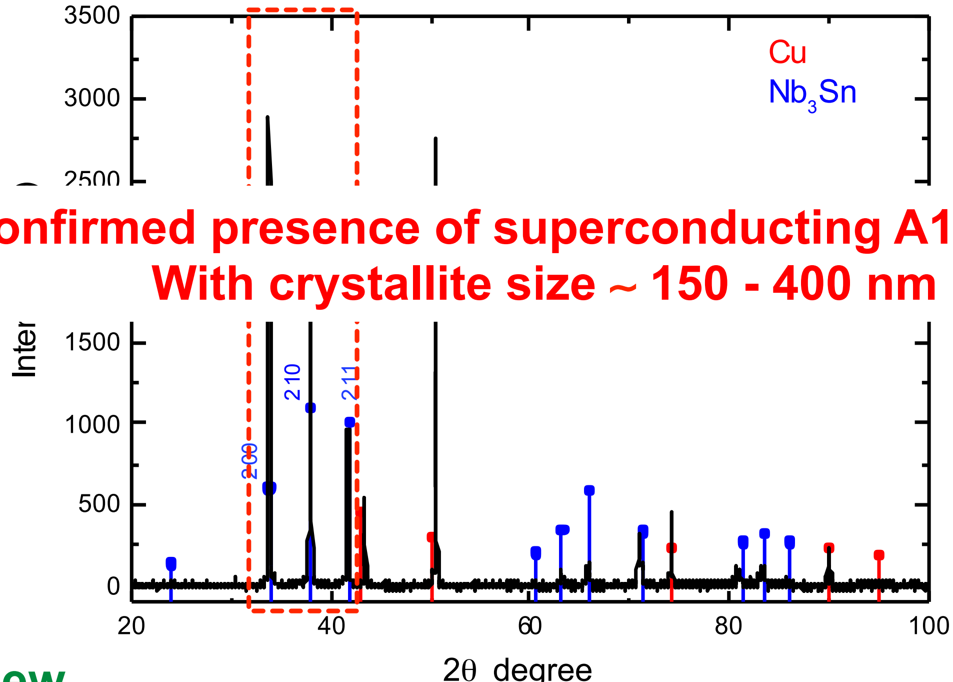


FIB cross section



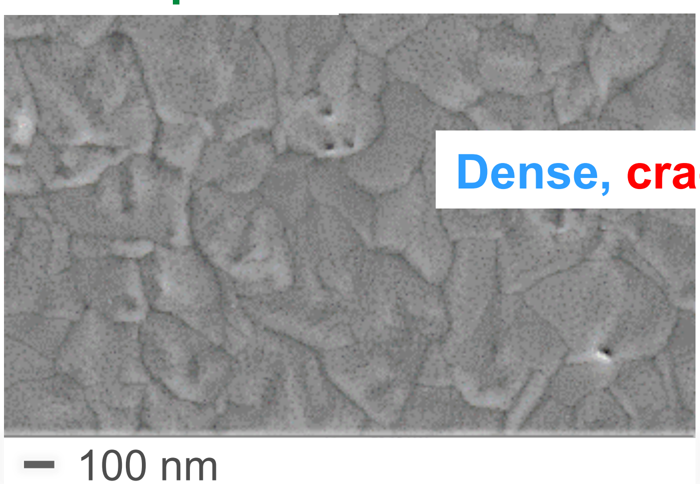
3.6 High temperature coatings

XRD

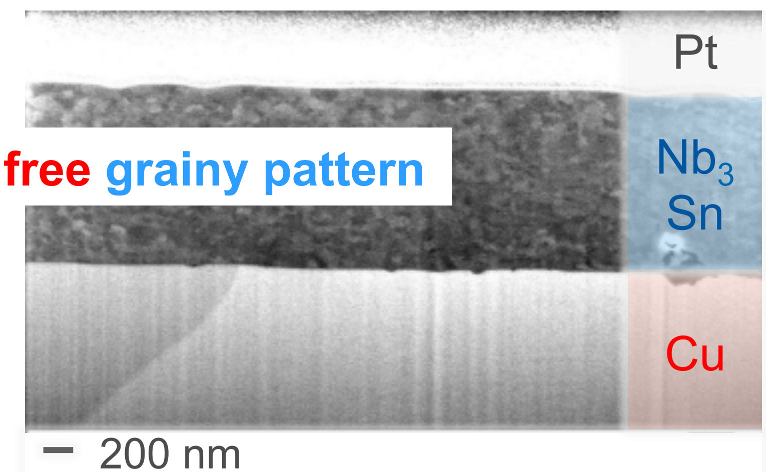


Confirmed presence of superconducting A15 phase
With crystallite size ~ 150 - 400 nm

SEM top view



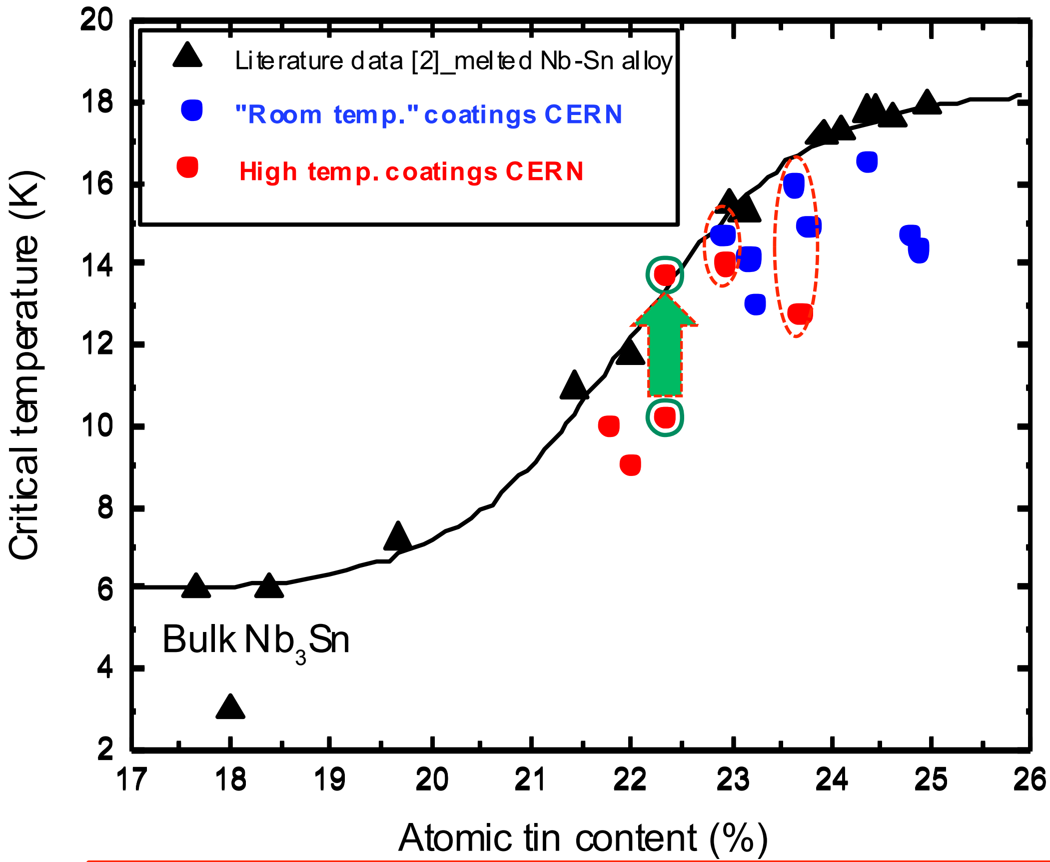
FIB cross section

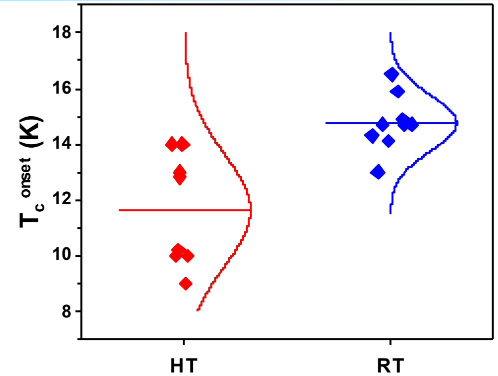


Dense, crack free grainy pattern

3.6 T_C vs composition

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





Room temperature coatings process lead to higher critical temperature values no matter coating parameters

High temperature coating + annealing post coating

Could be a good combination by modulating temperature and duration

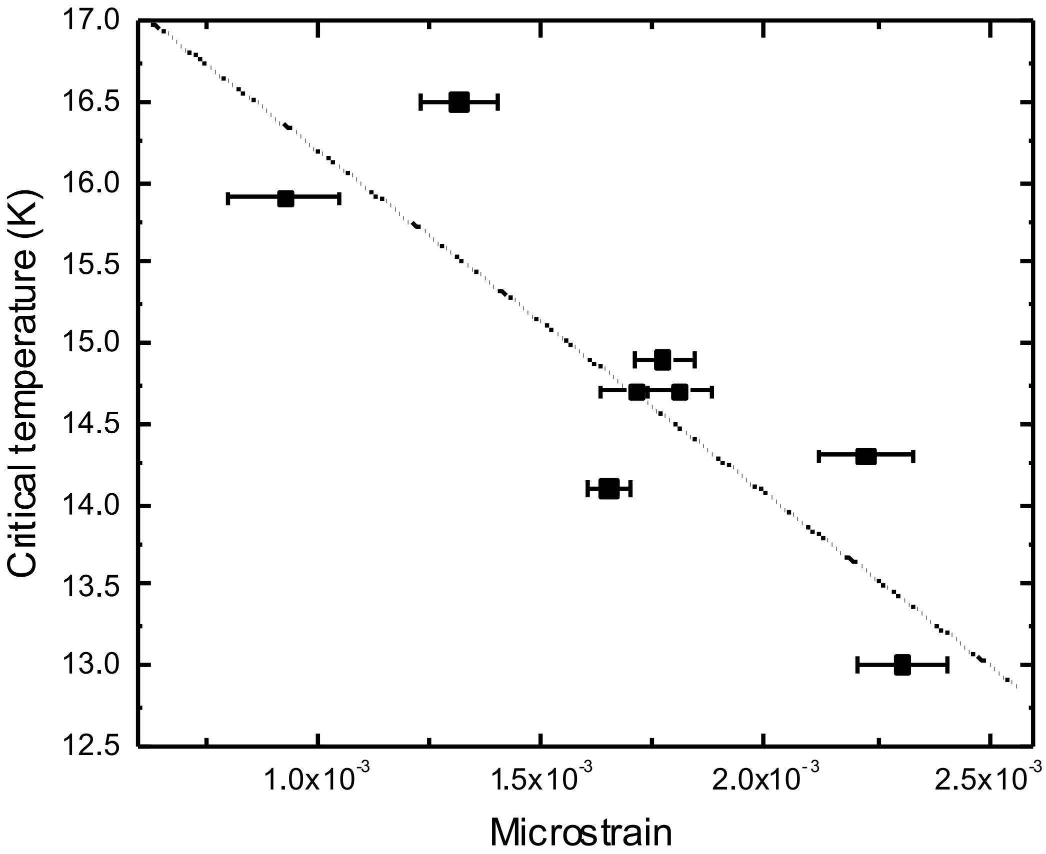
***T_c* values constantly lower for the films coated on copper substrates with respect to the bulk Nb_3Sn values**

Copper substrate influence? Stresses in the film??

3.7 T_C vs microstrain

- XRD rietveld analysis

"Room-temperature" coatings+annealing



Micro-strain mitigation seems to be critical to ensure highest possible Tc

→ small-range order matters too
→ Diffusion driven process

https://indico.cern.ch/event/556692/contributions/2484353/

4. Summary / Perspectives

1. ECR and HiPIMS have both shown promising SRF results

2. Work needed to stabilize / scale-up the processes

3. A15 onto copper: challenging but converging to promising recipes. Next step: RF

4. A15 scale-up promises new challenges

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- Cavities fabrication (V. Palmieri)

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