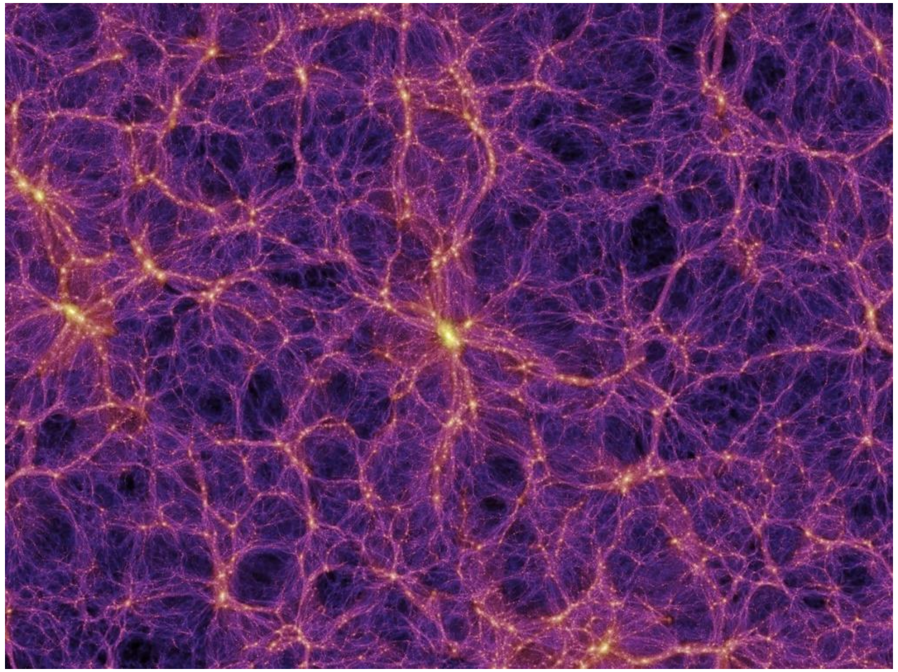
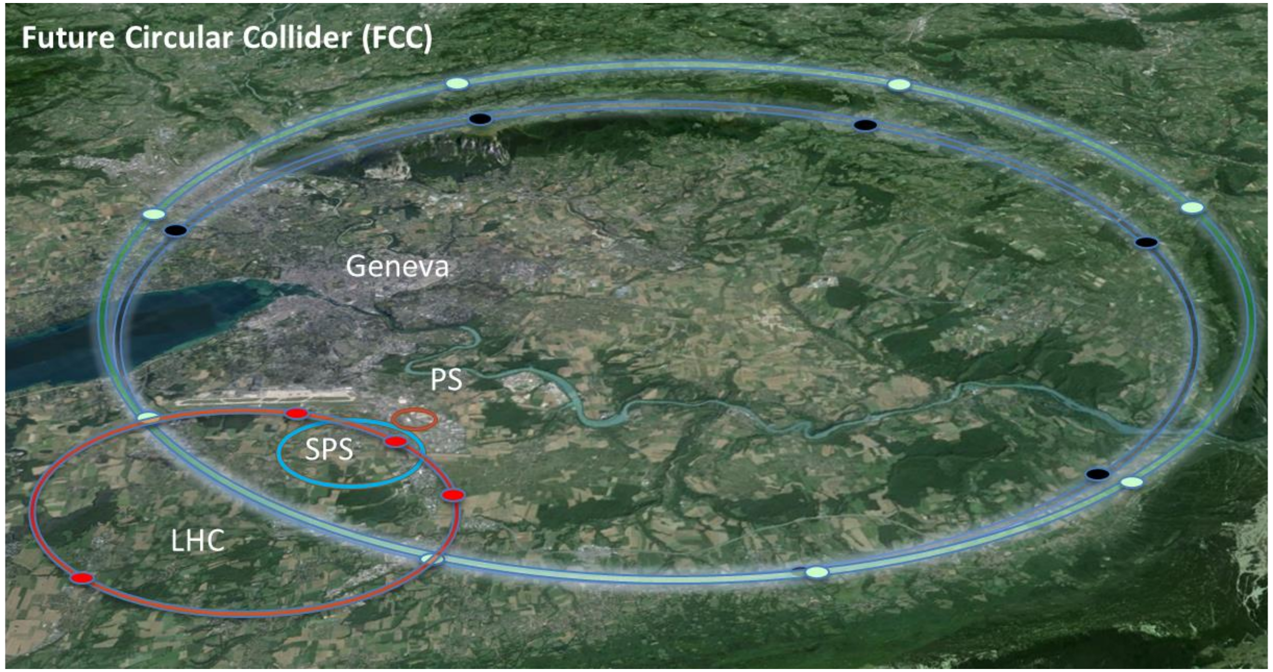
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Invited presentation given at EUCAS 2023, September 5, 2023, Bologna, Italy

REBCO superconducting coatings for high-energy physics applications at high magnetic fields


V. Springel et al. 2005



ICMAB INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA
EXCELENCIA SEVERO OCHOA
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
CERN
ALBA
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EUCAS2023

Joffre Gutierrez Royo*

A. Romanov, G. Telles, N. Lamas, I. Ahmed, N. Tagdulang, O. Traver, P. Krkotic, J. O'Callaghan, X. Granados, I. Korolkov, R. Miquel, F. Perez, M. Pont, J. Golm, B. Dobrich, W. Wuensch, S. Calatroni, T. Puig

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Outline

1 – REBCO Coated Conductors and their surface impedance under large magnetic fields

2 – How we coat surfaces with CC

3 – Coated Conductors coatings in high-energy physics

4 – Outlook and Conclusions

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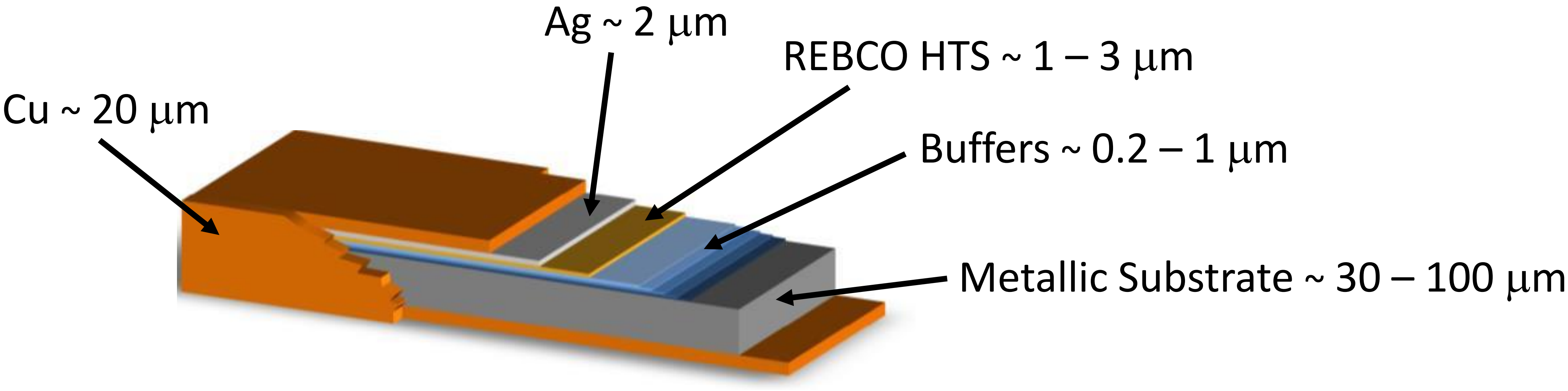
REBCO Coated Conductors are commercially available with different widths in Km length



Ag ~ 2 μm

REBCO HTS ~ 1 – 3 μm

Cu ~ 20 μm

Buffers ~ 0.2 – 1 μm

Metallic Substrate ~ 30 – 100 μm

Coated Conductor

SuNAM

BRUKER
Bruker HTS GmbH

SuperOx

Fujikura

THEVA

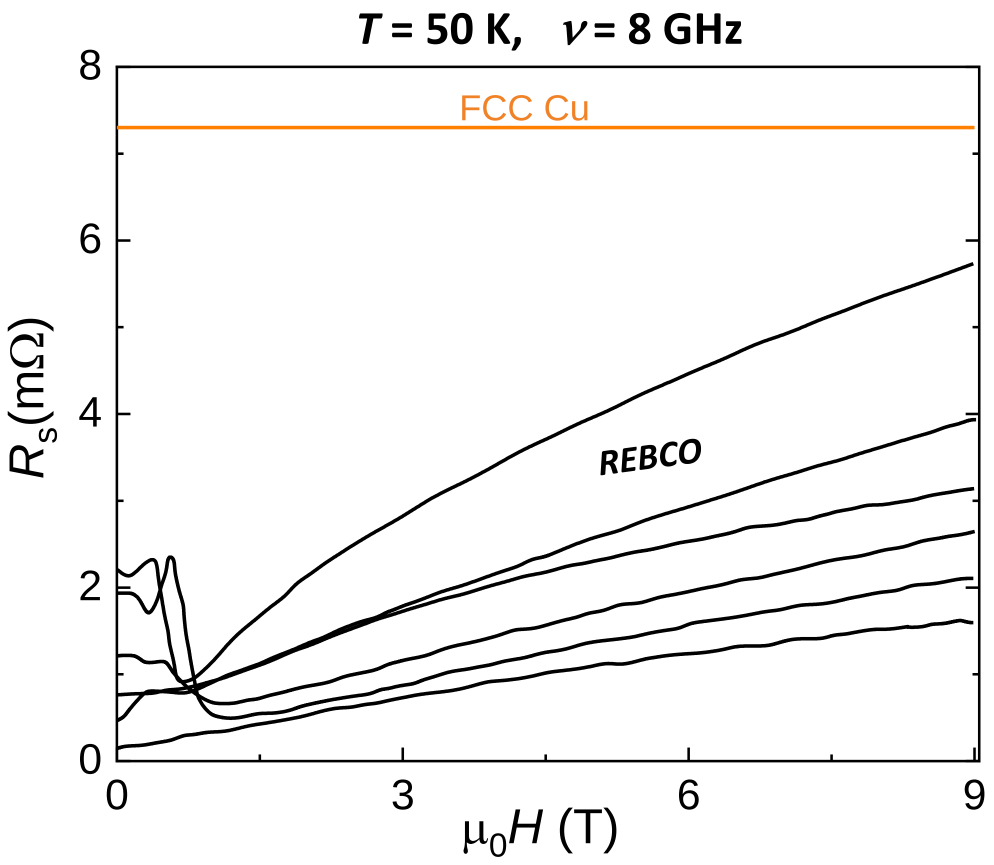
SuperPower Inc.
A Furukawa Company

$T_c \approx 91$ K

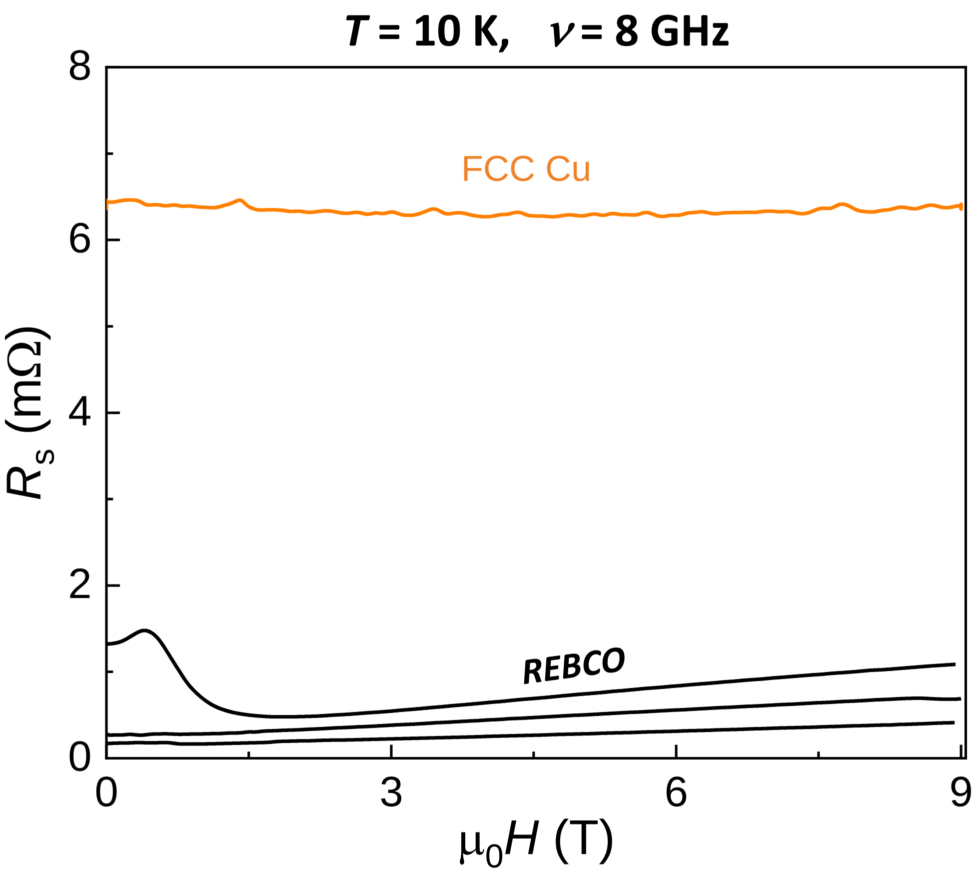
H_{c2} (4.2K) > 100 T

H_{irr} (4.2K) > 60 T

REBCO CCs have lower R_s than Cu → Better RF performance

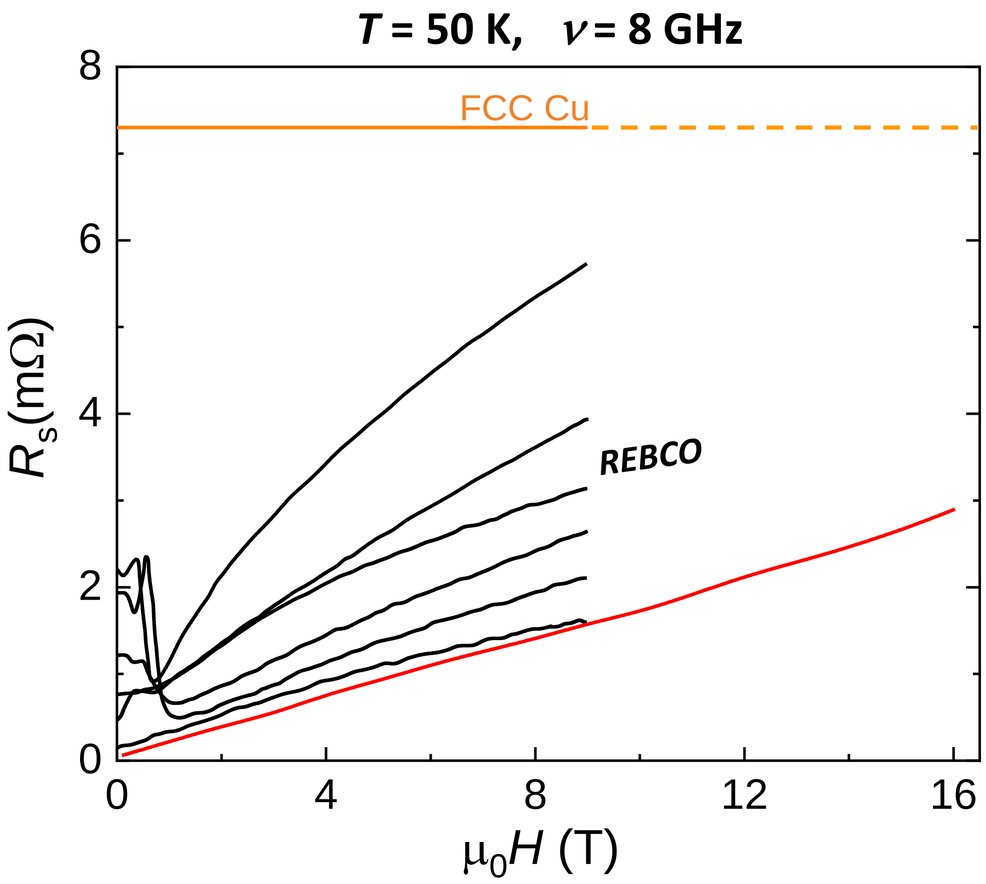


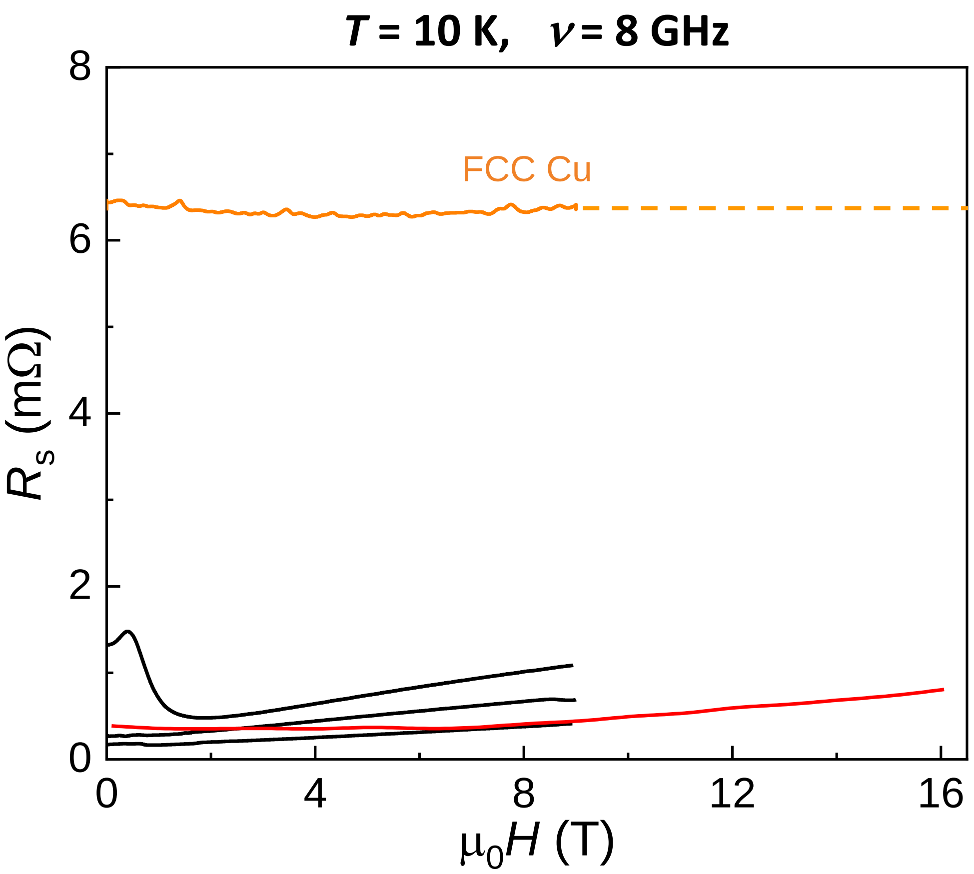
*T. Puig et al, Supercond. Sci. Technol. **32** (2019)*



The lower the operating temperature, the larger the benefit from using REBCO

REBCO CCs have lower R_s than Cu → Better RF performance



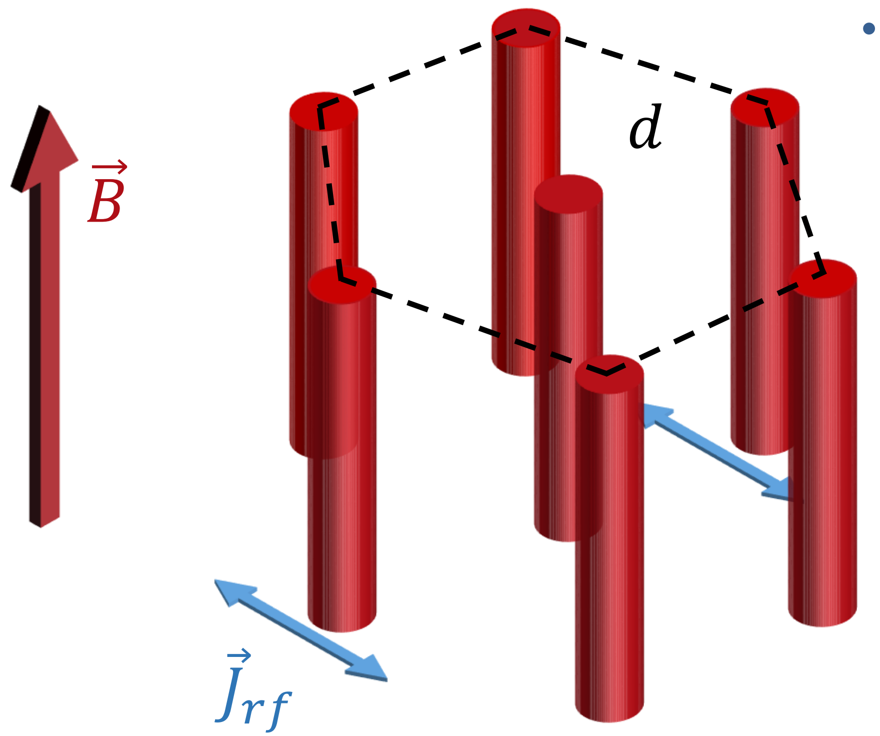


At intermediate and low temperatures, R_s of high-pinning REBCO shows a weak magnetic field dependence

The Gittleman-Rosenblum model describes the microwave response of the mixed state

The Gittleman-Rosenblum model in a nutshell

Flux tube lattice



- Not considering thermal contributions
- Assuming $\vec{F}_{v-v} \gg \vec{F}_{pinning}$

Equation of motion for fluxons:

$$m\ddot{x} + \eta\,\dot{x} + kx = J_{rf}\Phi_0$$

↓

The vortex resistivity is :

$$\rho_{vm} = \frac{B\Phi_0}{\eta}\frac{1}{1 - i\frac{\omega_p}{\omega}}$$

Fitting parameter

$$\eta = 1.45\frac{\phi_0 B_{c2}}{\rho_n}$$

From transport measurements

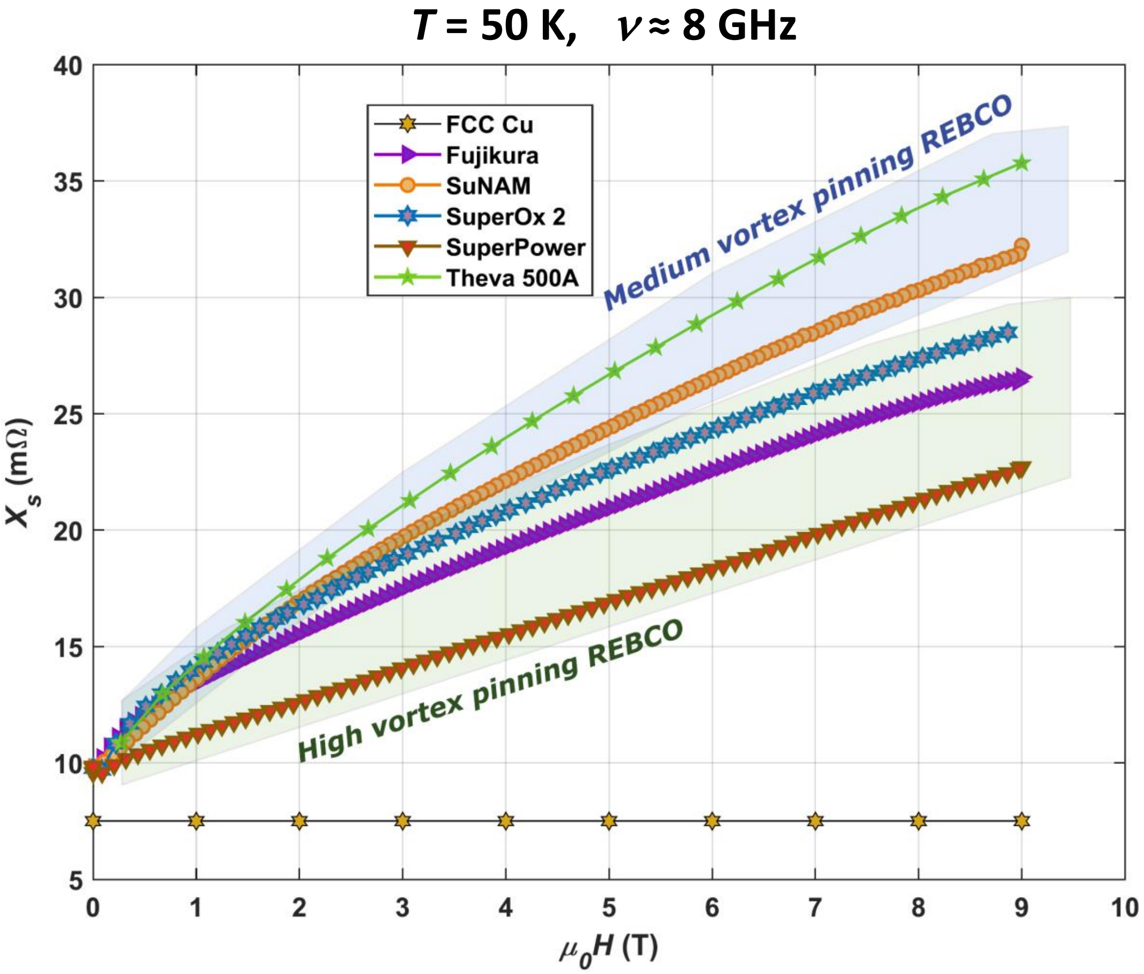
$$Z_s = R_s + iX_s = i\omega\mu_0\sqrt{\lambda_l^2 - i\frac{\rho_{vm}}{\mu_0\omega}}$$

Gittleman-Rosenblum model predictions based on our Z_s experimental data

$$\rho_{vm} = \rho'_{\mathrm{vm}} + \mathrm{i}\rho''_{\mathrm{vm}} \quad \begin{cases} \rho'_{\mathrm{vm}} = \mathrm{f}'(R_s, X_s) \\ \rho''_{\mathrm{vm}} = \mathrm{f}''(R_s, X_s) \end{cases}$$

Gittleman-Rosenblum model predictions based on our Z_s experimental data

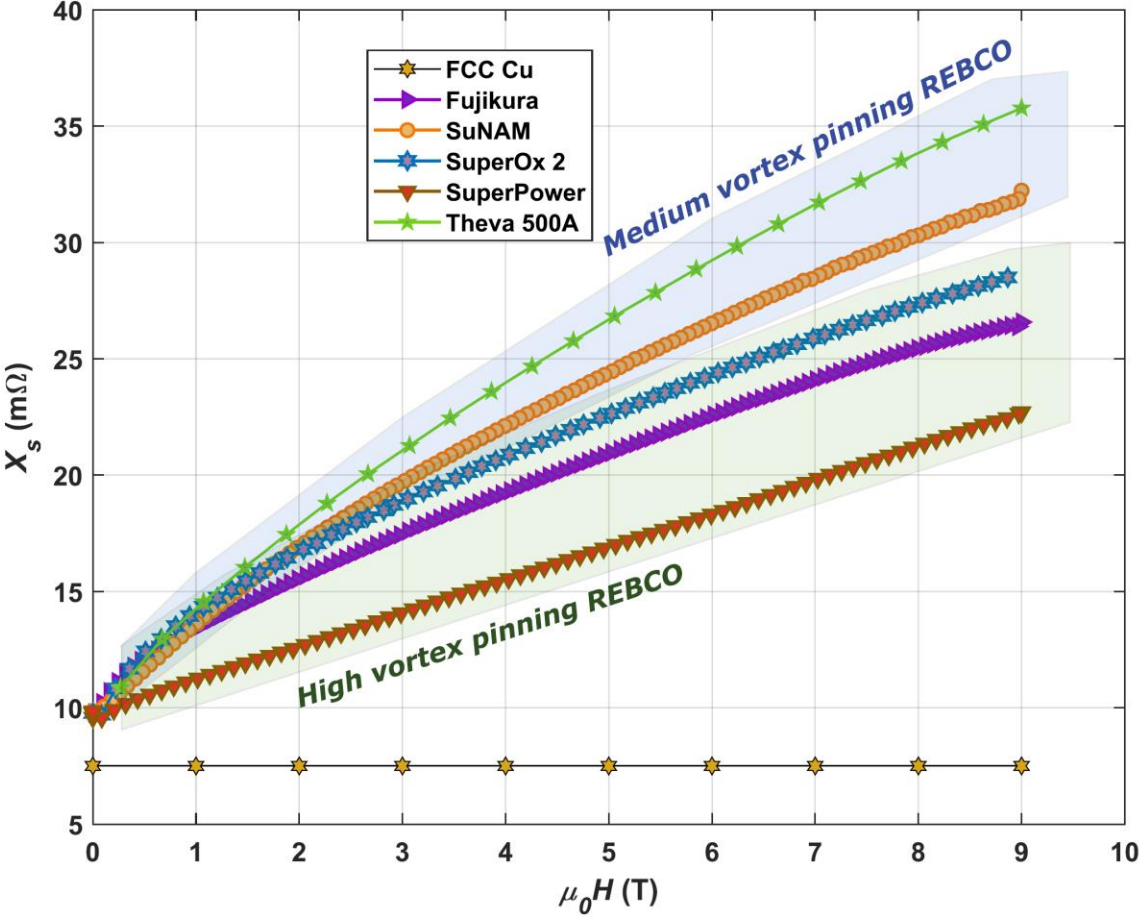
$$\rho_{vm} = \rho'_{vm} + i\rho''_{vm} \quad \begin{cases} \rho'_{vm} = f'(R_s, X_s) \\ \rho''_{vm} = f''(R_s, X_s) \end{cases}$$



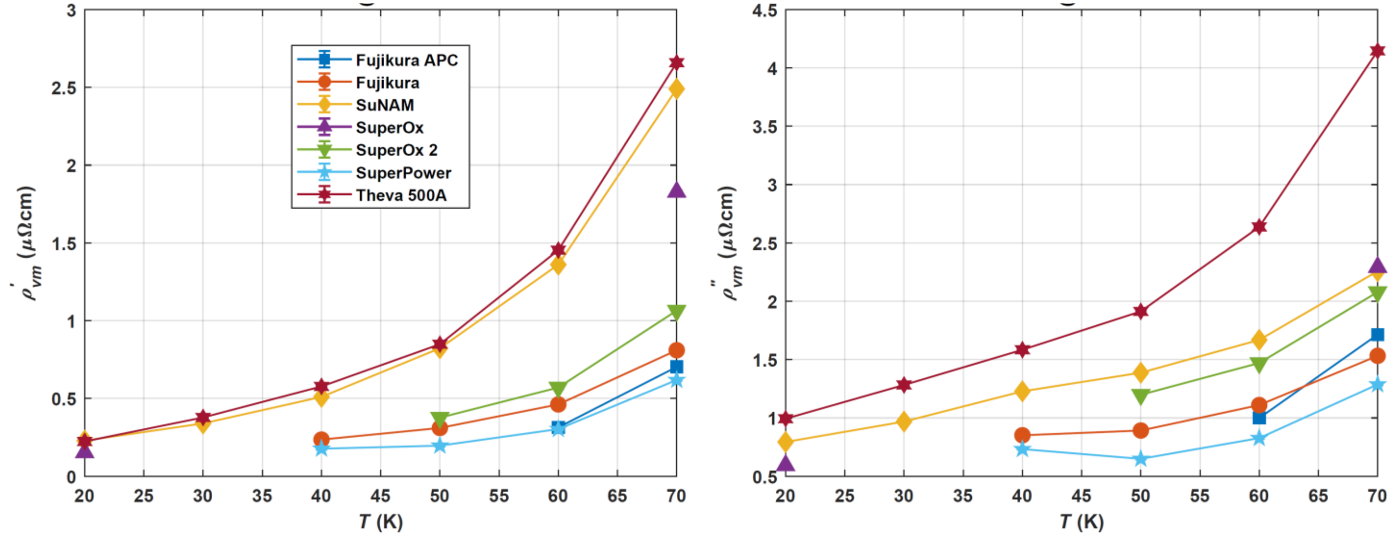
***A. Romanov**, et al. PhD thesis 2022*

Gittleman-Rosenblum model predictions based on our Z_s experimental data

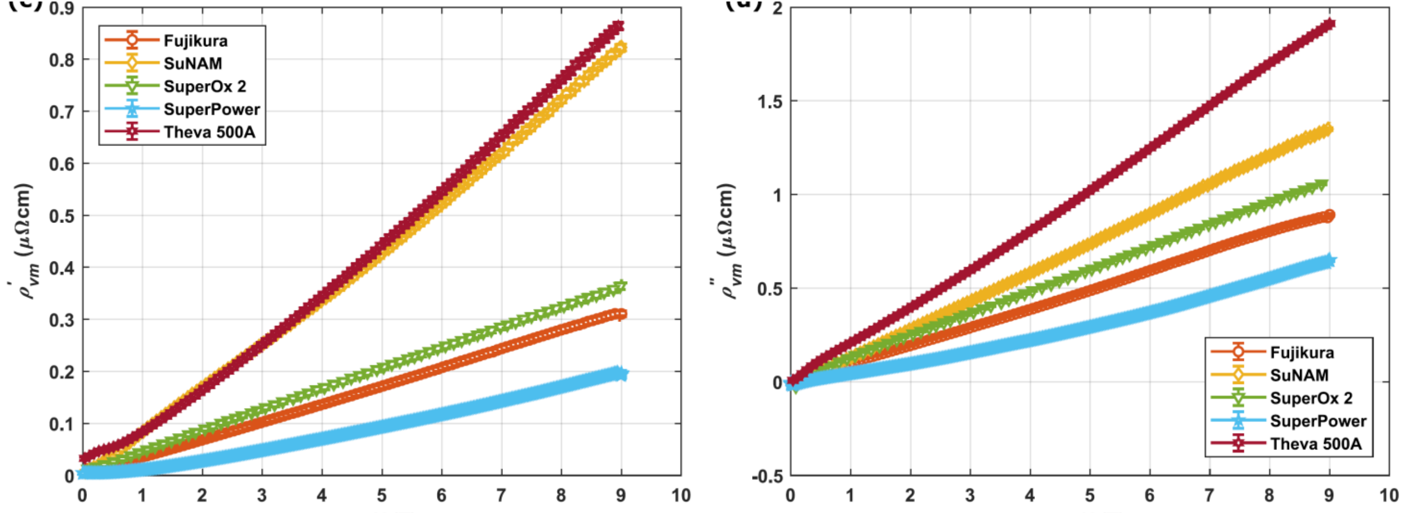
T = 50 K, $\nu \approx$ 8 GHz



9T complex vortex motion resistivity



50K complex vortex motion resistivity



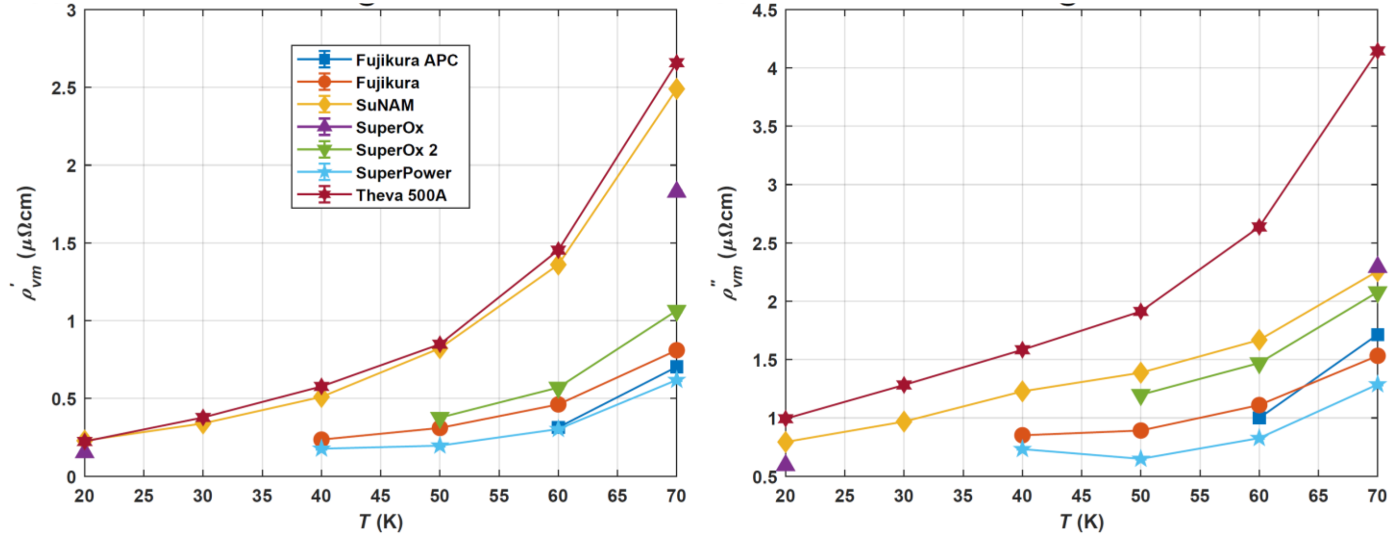
***A. Romanov**, et al. PhD thesis 2022*

Gittleman-Rosenblum model predictions based on our Z_s experimental data

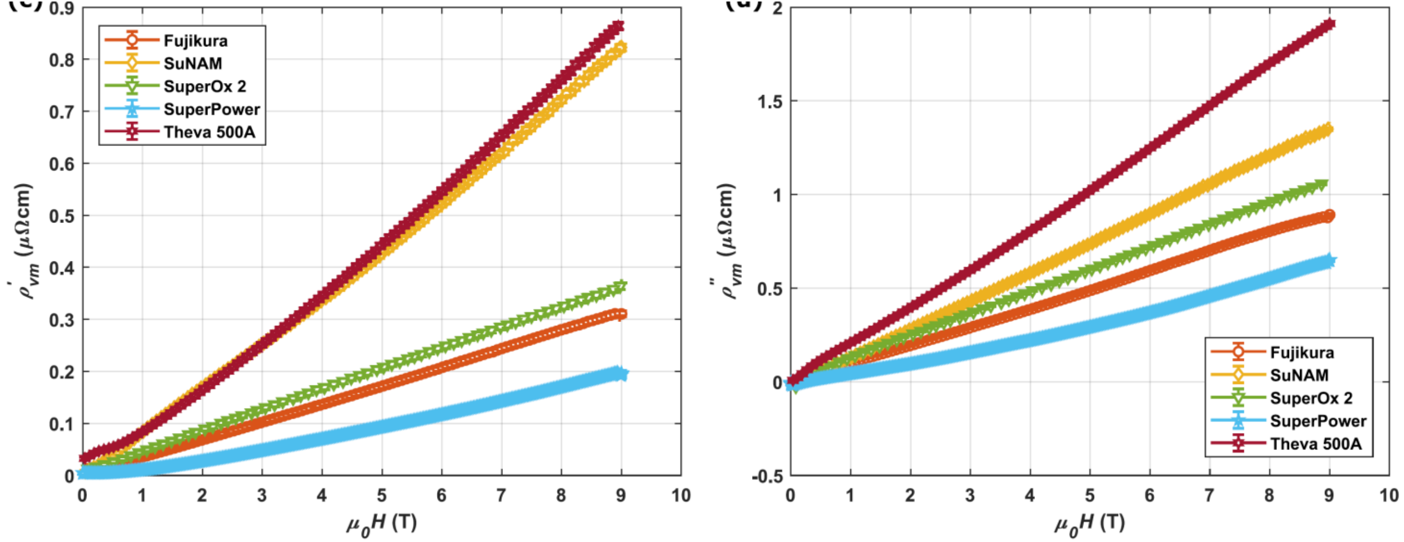
$$\eta = \phi_0 B \frac{\rho'_{vm}}{{\rho'_{vm}}^{2} + {\rho''_{vm}}^{2}}$$

$$\nu_p = \nu \frac{\rho''_{vm}}{\rho'_{vm}}$$

9T complex vortex motion resistivity



50K complex vortex motion resistivity

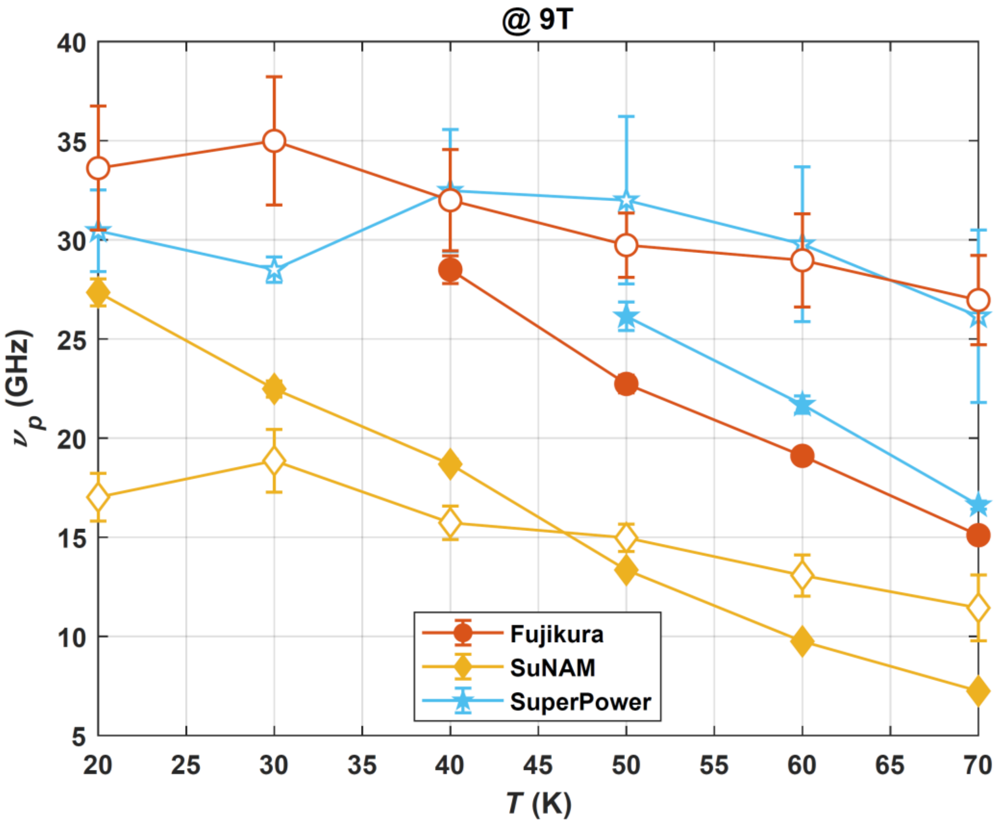


A. Romanov, *et al. PhD thesis 2022*

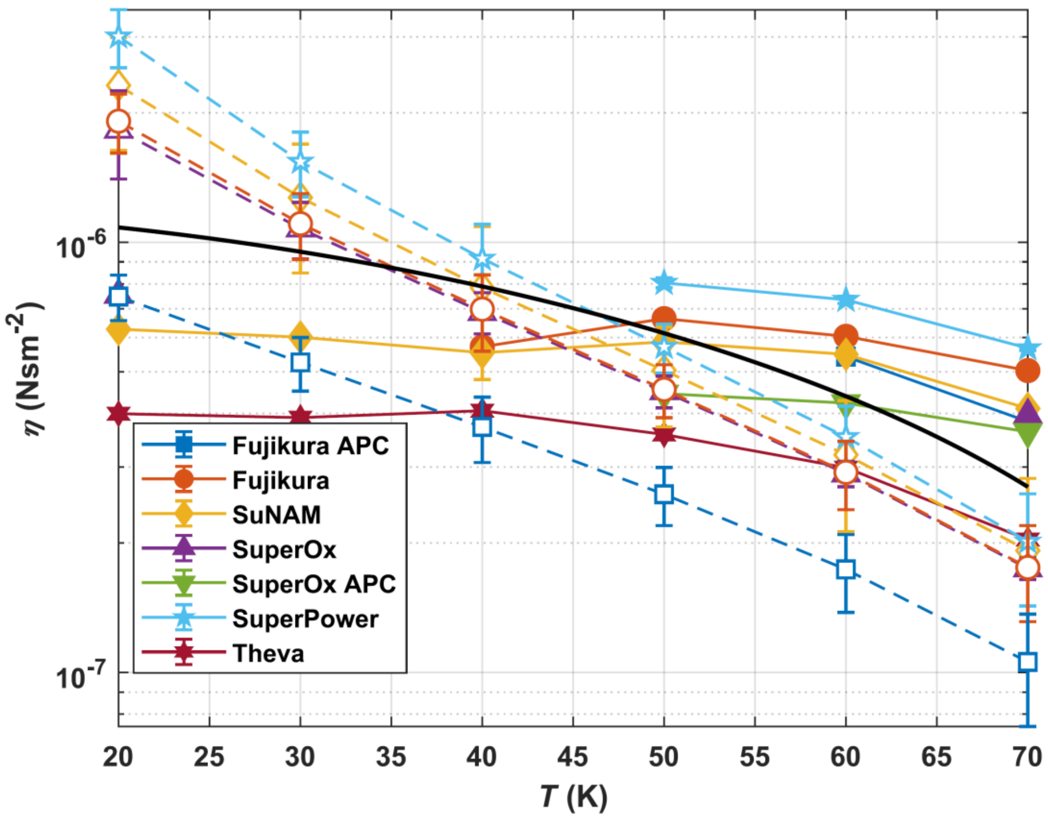
Gittleman-Rosenblum model predictions based on our experimental data

***A. Romanov**, et al. Scientific reports **10** (2020)*

*Estimation of depinning frequency ν_p



*Estimation of vortex viscosity η



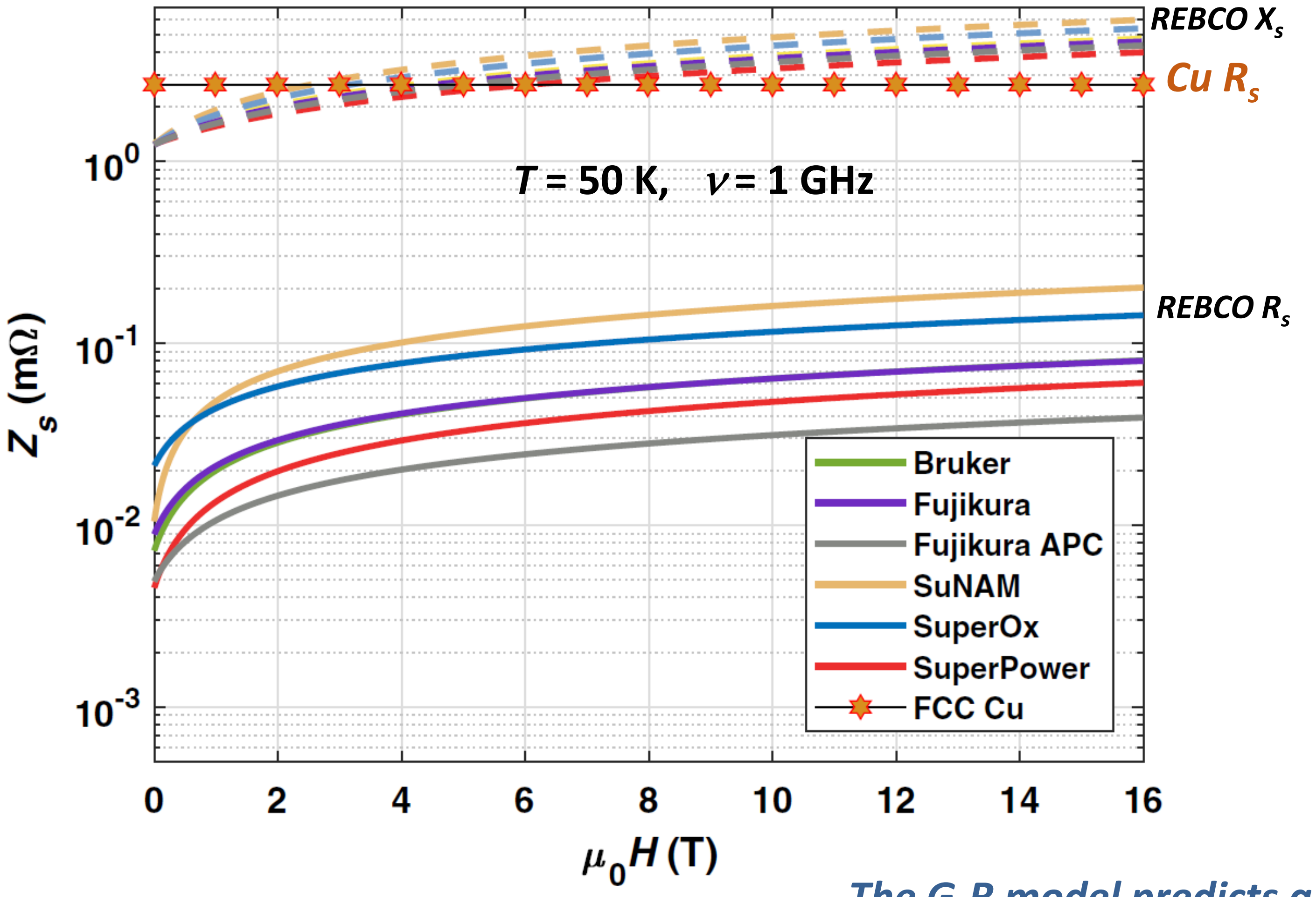
REBCO CCs have high depinning frequencies

Enables operation up to high frequencies

*The filled symbols relate to surface impedances measurement. The open symbols to transport measurement and R_s fitting.

Gittleman-Rosenblum model predictions based on our experimental data

Gittleman-Rosenblum model ***prediction of Z_s***



***A. Romanov**, et al. Scientific reports **10** (2020)*

The G-R model predicts a much larger benefit from REBCO at lower operating frequencies

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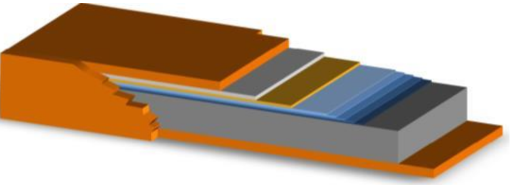
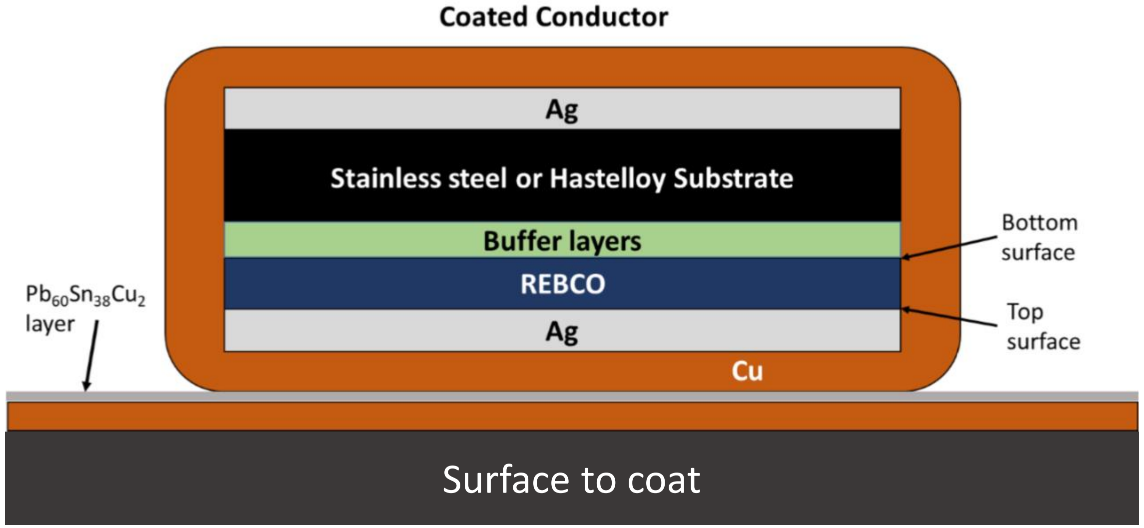
Scalable CC coating technique for large surfaces



Attach

Welding of CC on top of a surface

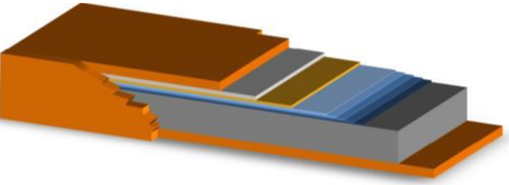


Thickness & homogeneity of the solder is critical

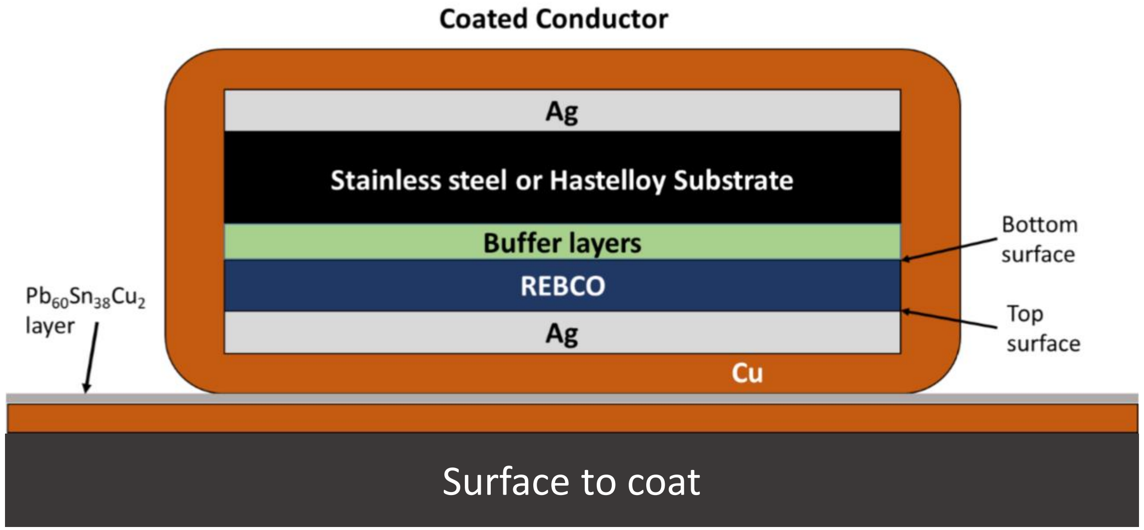
Homogeneous pressure and temperature are crucial

***N. Lamas**, et al. (to be submitted)*

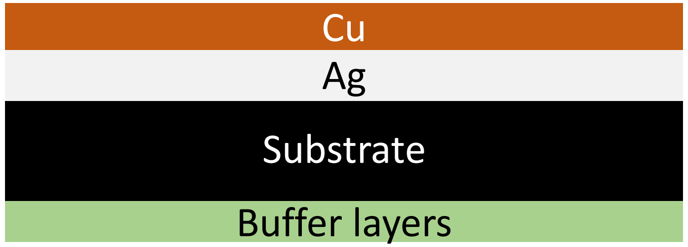
Scalable CC coating technique for large surfaces

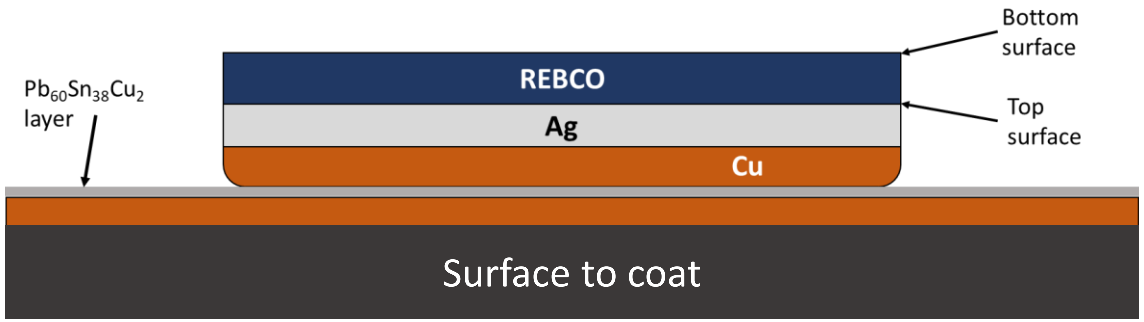


Attach
Welding of CC on top of a surface



Delamination
Mechanical peeling





Thickness & homogeneity of the solder is critical

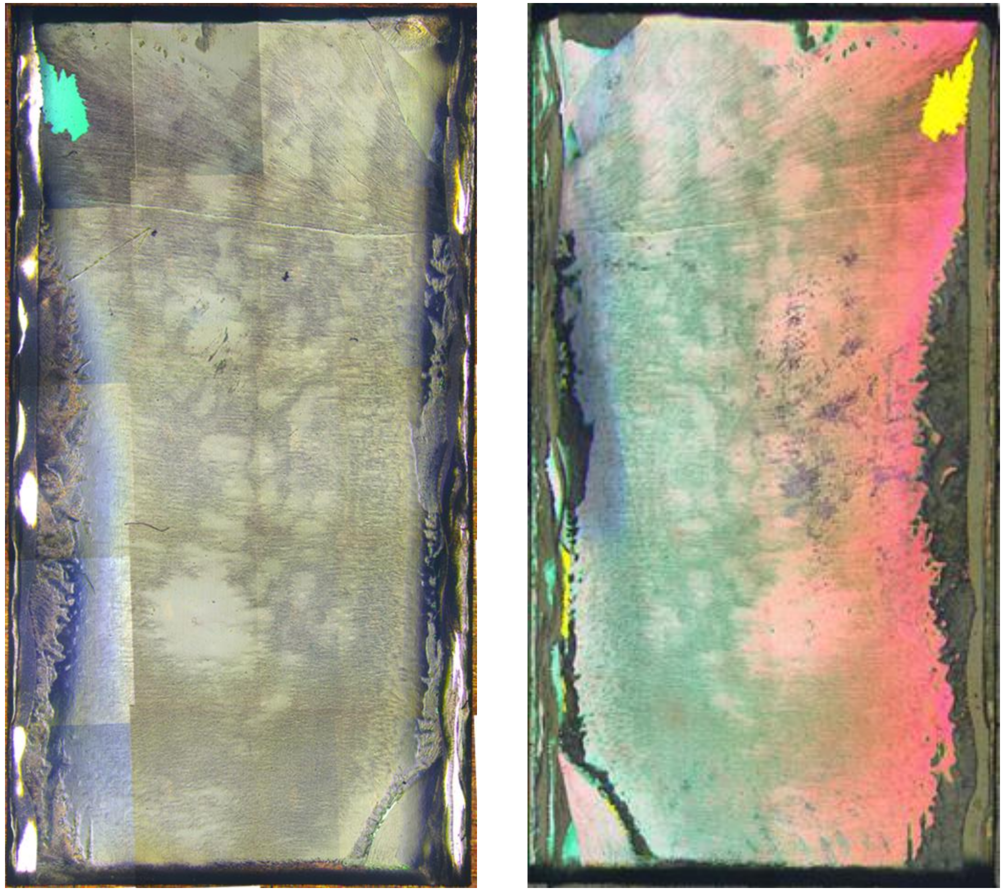
Homogeneous pressure and temperature are crucial

Angle and speed of substrate extraction are crucial

***N. Lamas**, et al. (to be submitted)*

We have developed a fast characterization of the coatings

Optical microscope picture of a delaminated tape



REBCO side

Substrate Side

HSV Colours observed on the substrate correspond to different coating surface compositions determined by EDX.

***N. Lamas**, et al. (to be submitted)*

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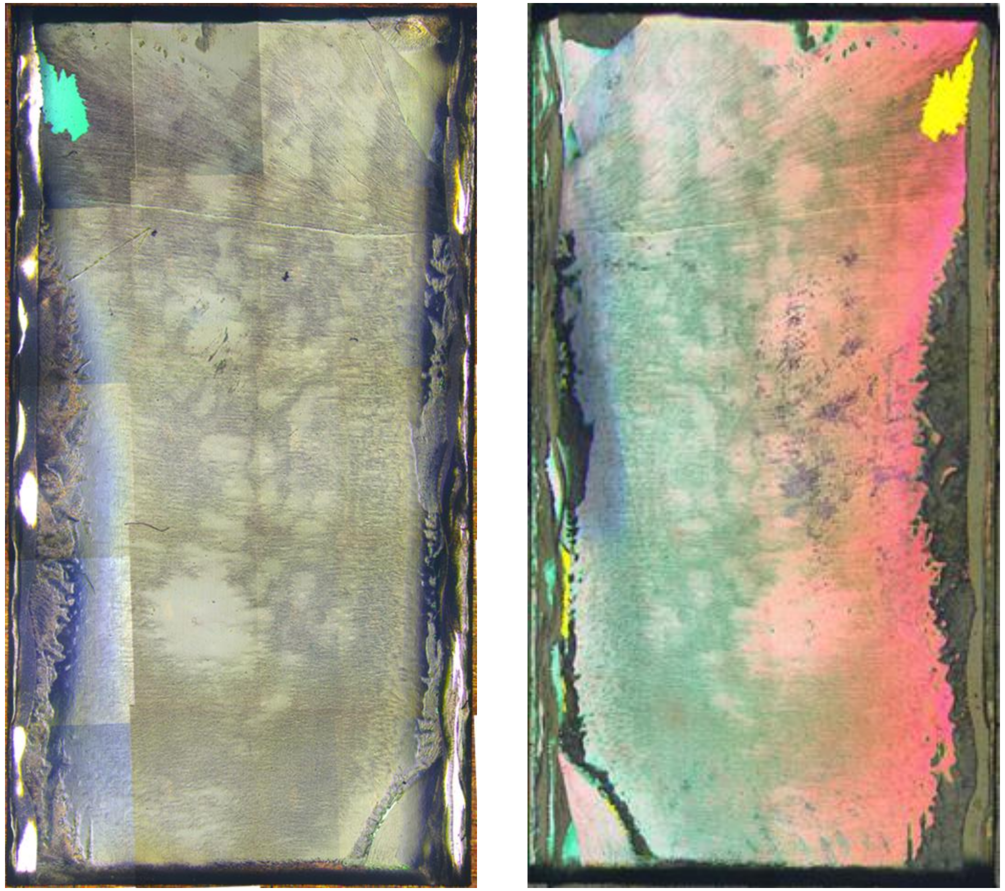
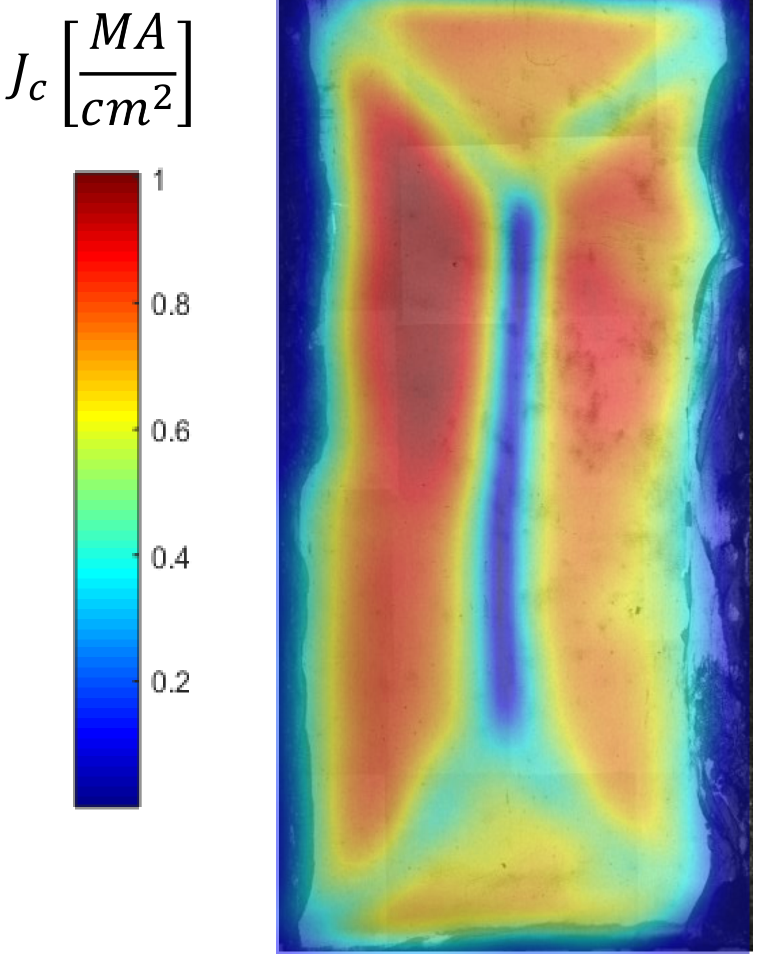


REBCO side

Substrate Side

Correlation between EDX and SHPM



HSV Colours observed on the substrate correspond to different coating surface compositions determined by EDX.

***N. Lamas**, et al. (to be submitted)*

Complete assessment of the sample quality from optical microscopy only

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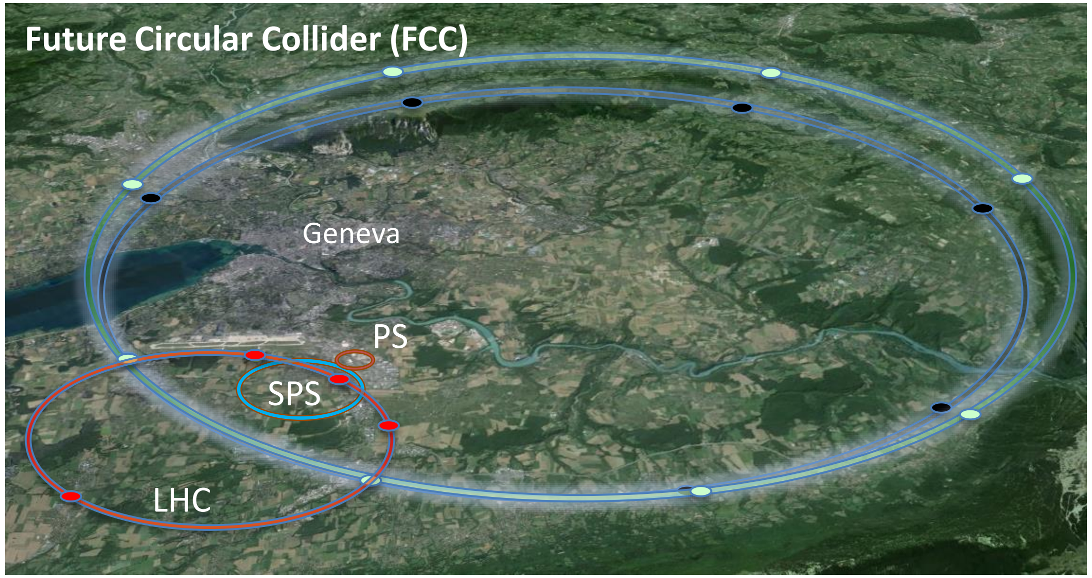
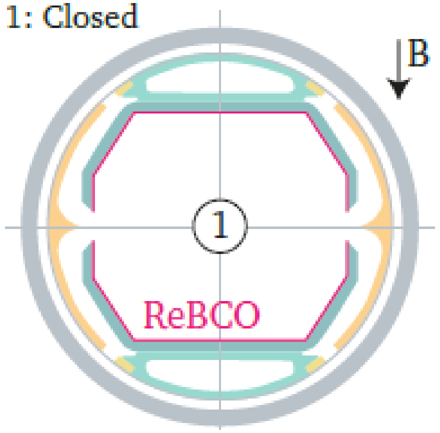
CCs as low-impedance coating for the FCC-hh beam-screen chamber

FCC working conditions:
16 T, 40 – 60 K, 1 GHz & 25 A peak



Cross sectional image of the FCC beam screen coated with REBCO

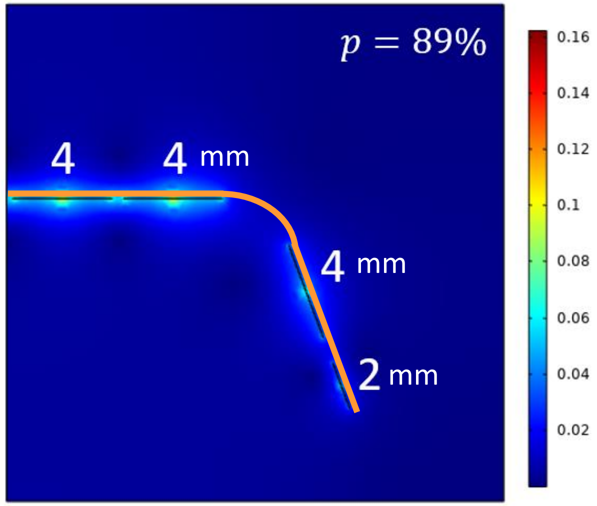


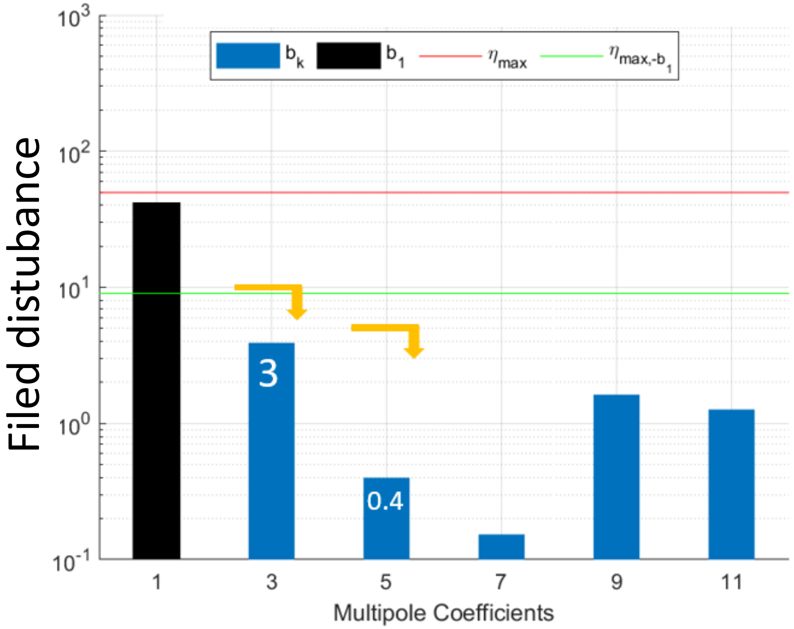
Trapped fields in REBCO will disturb the magnetic field homogeneity producing proton beam instabilities

Numerical Analysis on the Application of a ReBCO Superconducting Coating on the Beam Screen,
J. van Nugteren et al., Technical Report CERN

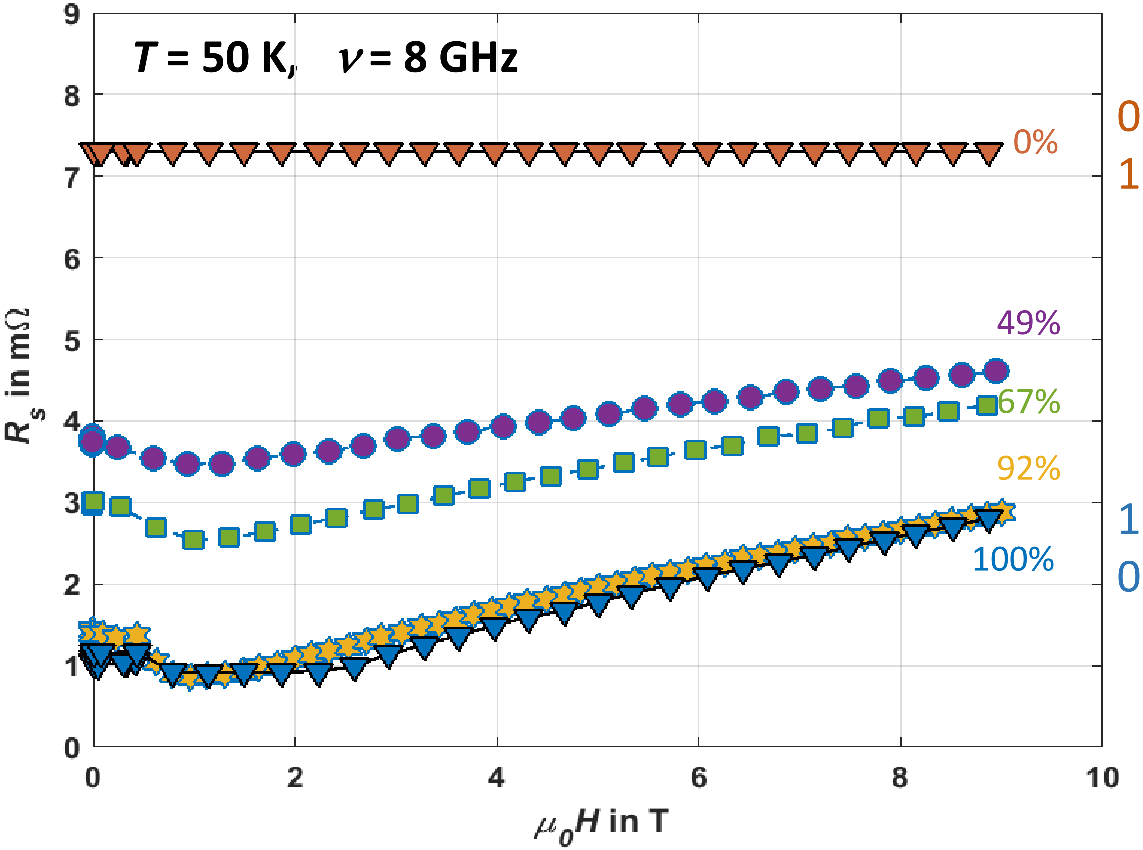
Hybrid REBCO – Cu coating with lower than Cu R_s minimizes trapped fields

REBCO – Cu hybrid coating simulations





Experimental data of surface resistance for different hybrid coatings



0% REBCO
100% Cu

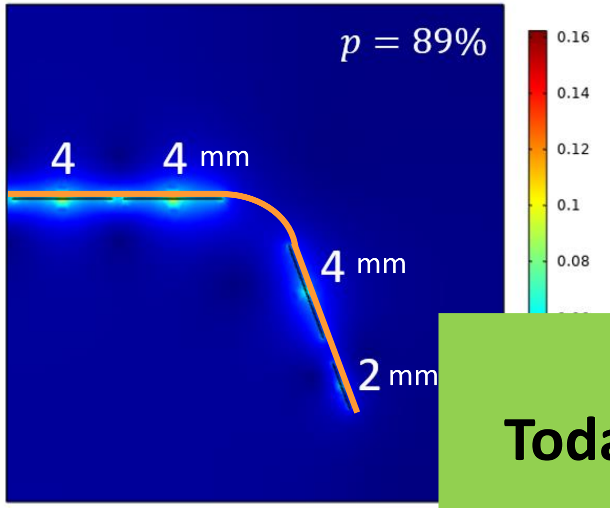
100% REBCO
0% Cu

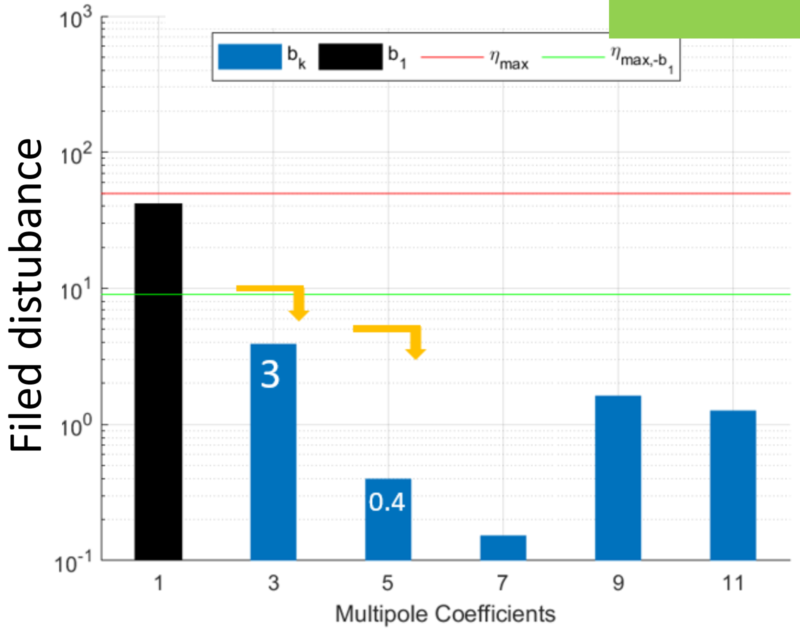
***G. T. Telles**, et al. Supercond. Sci. Technol.* SUST-105137.R *(2022)*

The R&D and successes of CC coatings for the FCC-hh beam-screen chamber open the door for this application to other high-energy physics fields.

Hybrid REBCO – Cu coating with lower than Cu R_s minimizes trapped fields

REBCO – Cu hybrid coating simulations



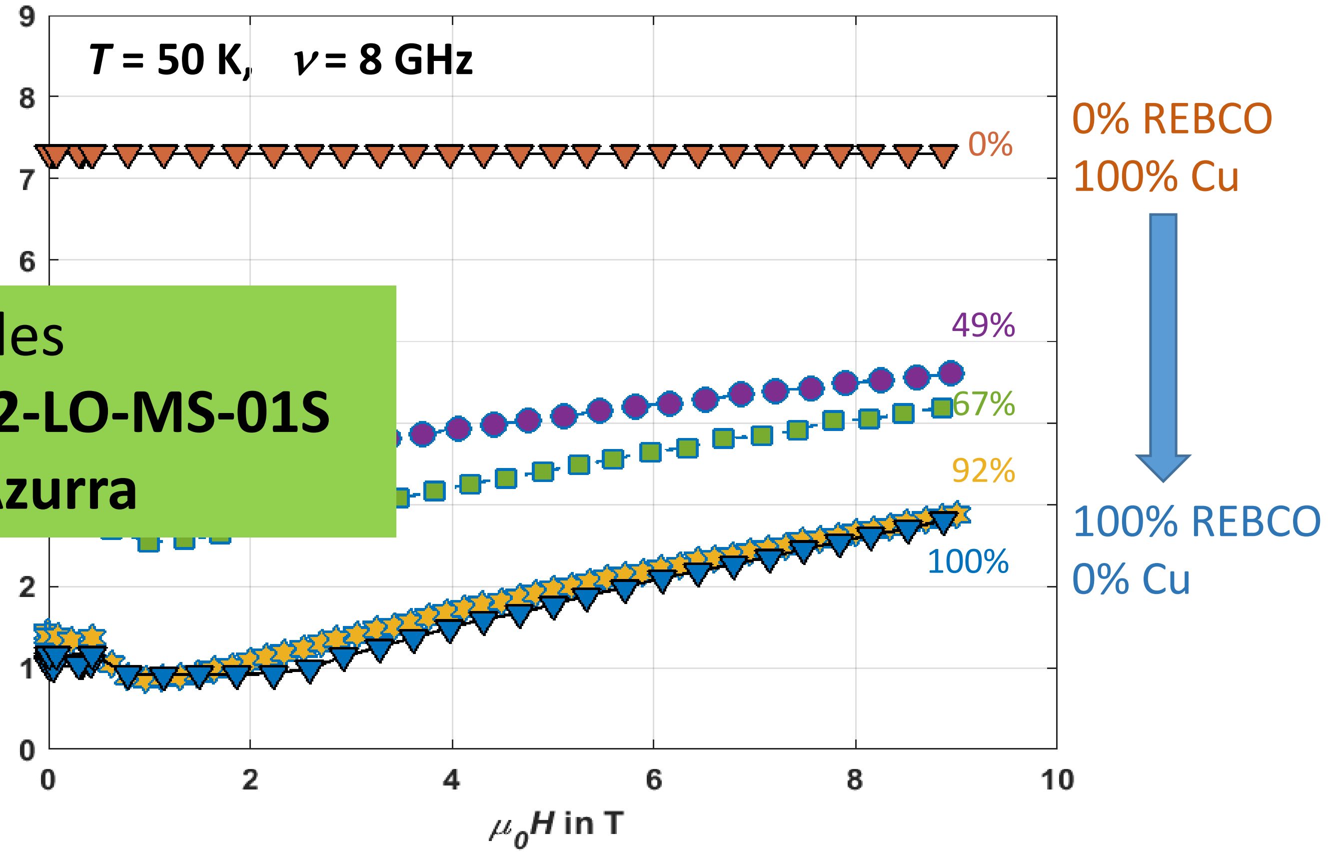


G. Telles

Today @ 15:20 2-LO-MS-01S

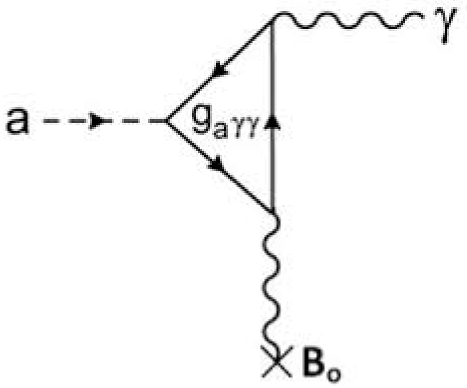
Room: Azurra

Experimental data of surface resistance for different hybrid coatings



***G. T. Telles**, et al. Supercond. Sci. Technol.* SUST-105137.R *(2022)*

CCs as low-impedance coating for haloscopes for cold DM axions search



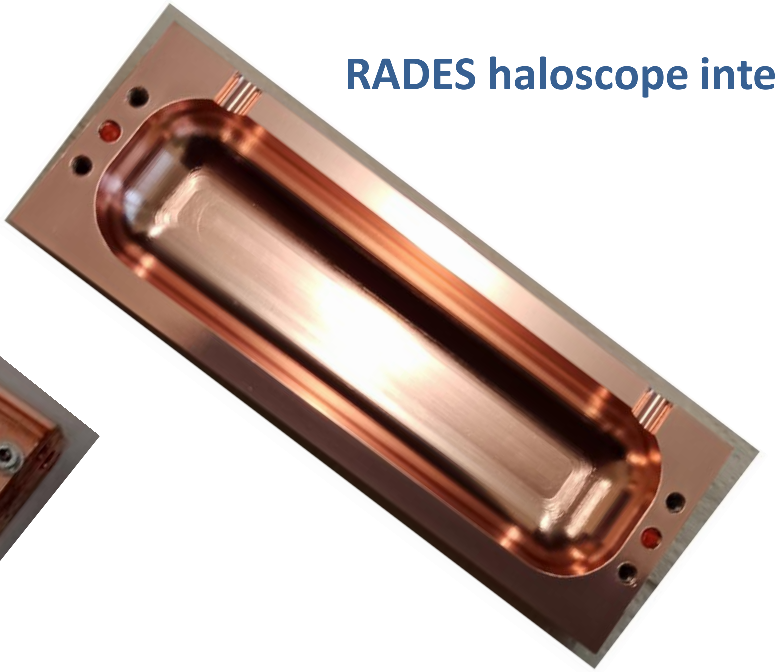
$P \propto B_e^2 QVG$

High Q → T = 4.2K
&
High B_e

RADES

RADES haloscope exterior

RADES haloscope interior

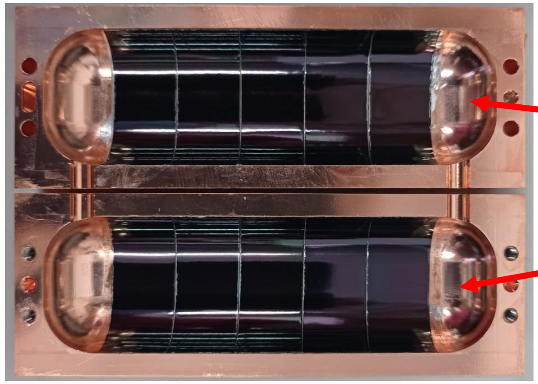


RADES haloscopes have a 18 mm - Ø curved inner surface that will induce strain in the REBCO layer

Proof-of-concept:
CC coated RADES haloscopes

With some R&D efforts we made it work on curved surfaces

1st RADES cavity



2nd RADES cavity

Curvature
R9 mm

CC coated 1st Axion cavity
Q(0T, 4.2K) ~ 80k
Q(11T, 4.2K) ~ 60k vs

Cu only
Q(11T, 4.2K) ~ 40k

CC coated 2nd Axion cavity
Q(0T, 4.2K) ~ 227k

Cu only
Q(0T, 4.2K) ~ 40k

Higher than Cu Q-value RADES halsocopes @ GHz are achieved with CC.
Flat cavities specifically design for CCs are preferable and will perform much better.

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New facility at ICMAB to study vortex matter under broad RF up to 16T

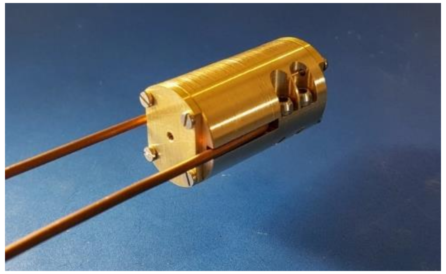
New cryostat equipped with

50mm Ø bore 16 T solenoid magnet

High (1 mK) temperature Stability

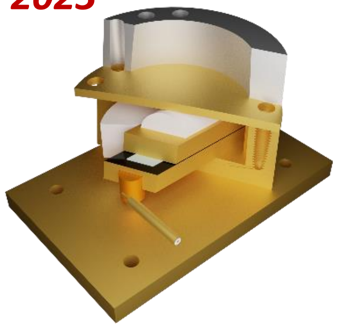
Height of the magnet 360+ mm

Currently Operational



- *8 GHz & 26 GHz dielectric resonator: 12x12 mm samples*
- *Operating in the TE_{011} mode*
- *6.5, 8.2 and 10 GHz dielectric resonator: 12x12 mm samples*
- *Operating in the TE_{011} , TE_{012} and TE_{013} modes*

Coming Autumn – Winter 2023



- *Multimode 1.8 GHz – 11 GHz PPR: 12x50 mm samples*
- *Compatible with ICMAB's new cryostat:*

  50mm Ø bore 16 T magnet

New facility at ICMAB to study vortex matter under broad RF up to 16T

New cryostat equipped with

50mm Ø bore 16 T solenoid magnet

High (1 mK) temperature Stability

Height of the magnet 360+ mm

Currently Operational

N. Tagdulang

Poster: 3-MP-CM-08S

Wednesday 6th @ 11:30 - 13:20

- *8 GHz & 26 GHz dielectric resonator: 12x12 mm samples*

resonator: 12x12 mm samples

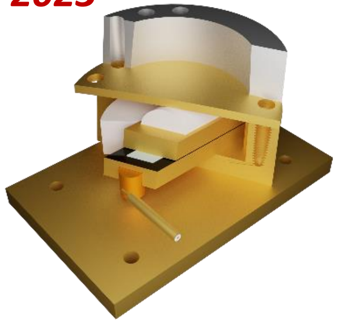
$_2$ and TE_{013} modes

J. O’Callaghan

3-MO-CF-03S

Wednesday 6th @ 17:20 - 17:35

Coming Autumn – Winter 2023



- *Multimode 1.8 GHz – 11 GHz PPR: 12x50 mm samples*
- *Compatible with ICMAB’s new cryostat:*

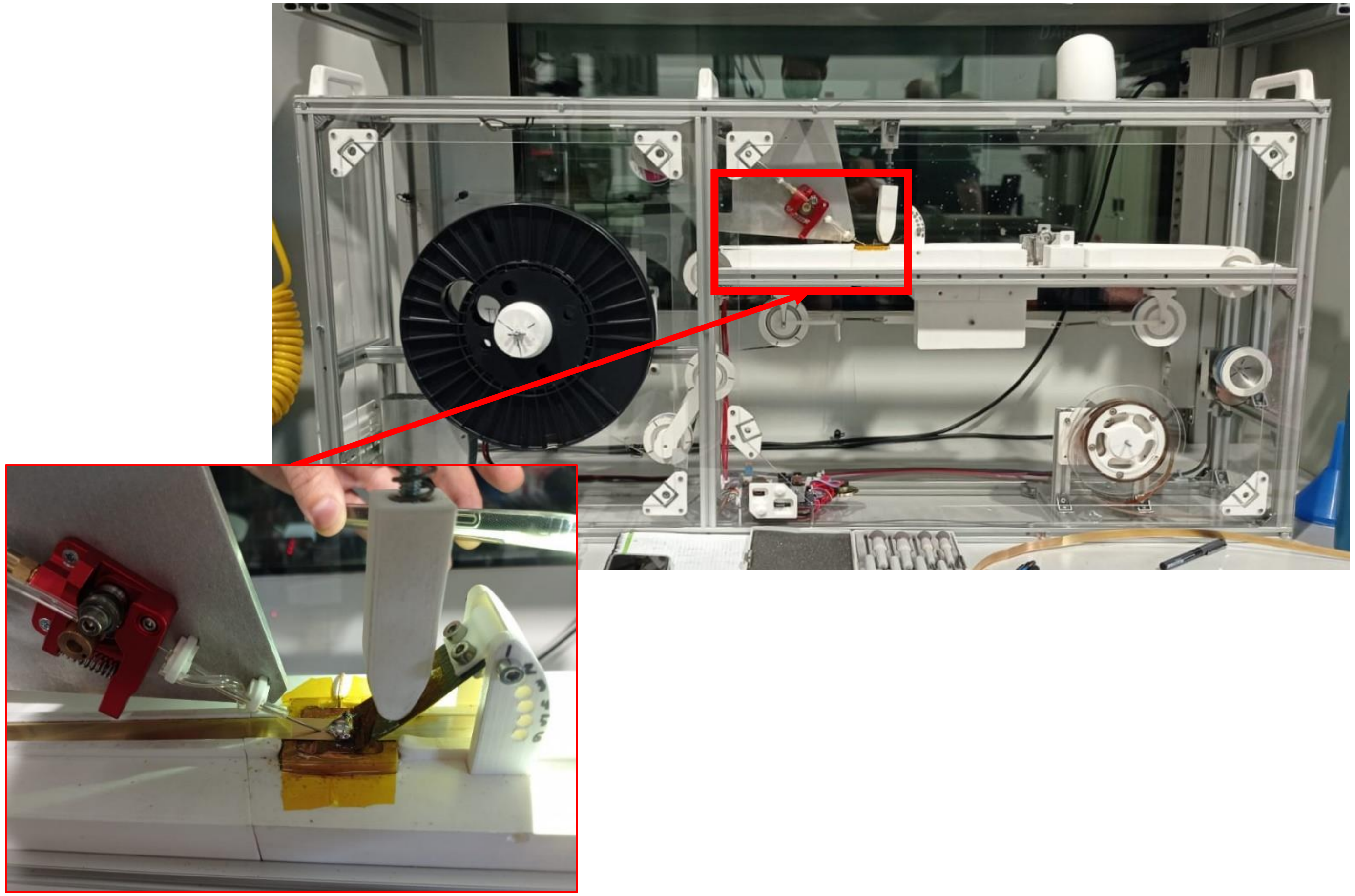
50mm Ø bore 16 T magnet

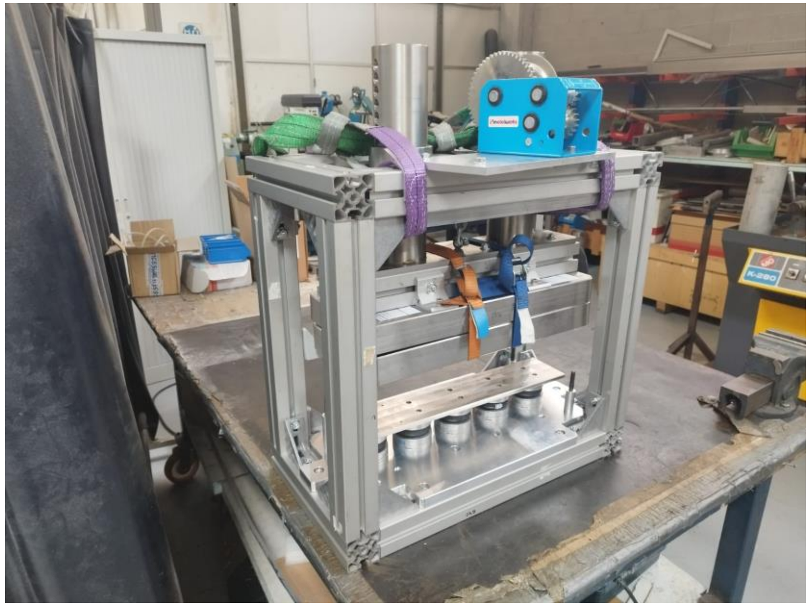
In Collaboration with:

Institut de Física
d'Altes Energies

Automatization of the different steps is crucial

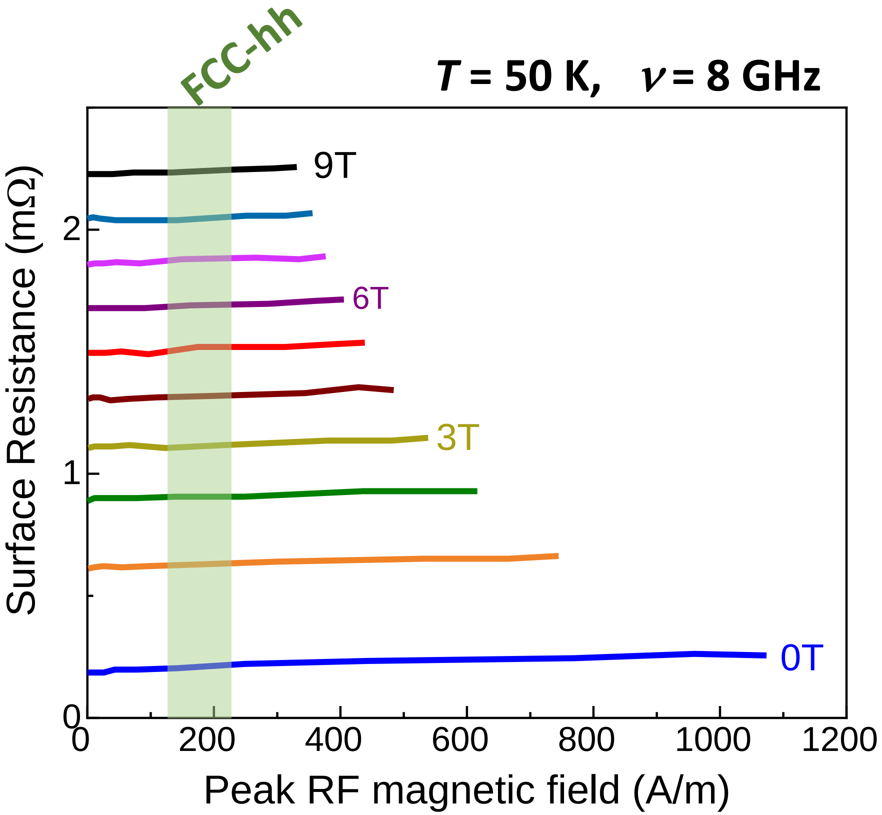
Pre-tinning unit ready





The unit for the soldering is in an advanced construction phase

Initial study shows that CCs have a weak dependence with the RF power



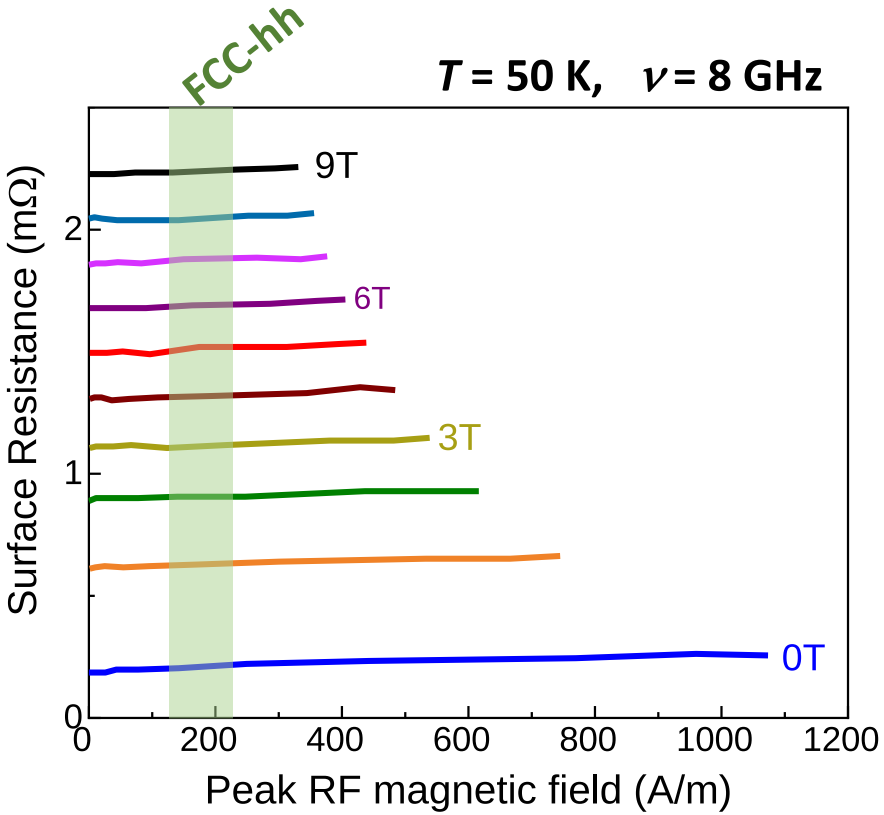
P. Krkotic*, et al. Supercond. Sci. Technol.* **35** (2022)

Opens the possibility for high-power applications

Future high-energy or high-power linacs

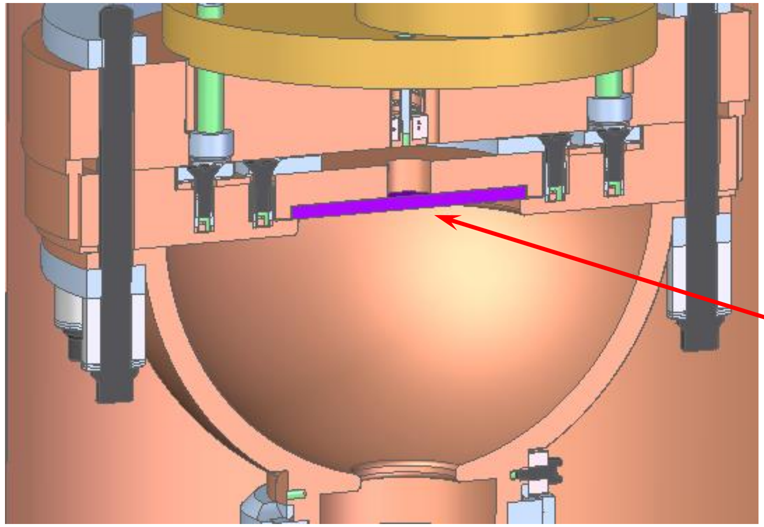
Muon collider

Preliminary results show that CCs have a weak dependence with the RF power

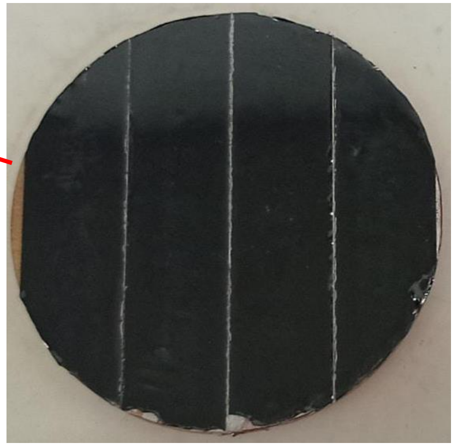


***P. Krkotic**, et al. Supercond. Sci. Technol.* **35** (2022)

Can REBCO operate at accelerating gradients E > 150MV/m?



“mushroom” cavity



2” Ø REBCO coated sample

Opens the possibility for high-power applications

Future high-energy or high-power linacs

Muon collider

Conclusions

CCs are very appealing materials for High-energy physics due to their low R_s , high H_{irr} and high currents under magnetic field.

REBCO CCs coatings provide a solution to reduce the surface impedance of the FCC-hh beam-screen chamber and hence operate the system at high temperatures with the consequent decrease in running cost .

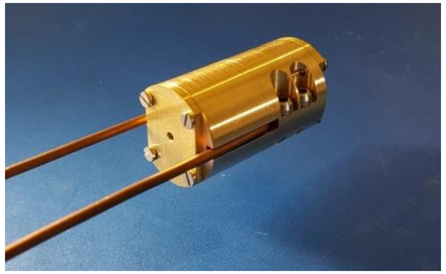
We have demonstrated that haloscopes coated with REBCO have a higher Q-value in the GHz range. Flat cavities specifically design for CCs are preferable and will perform much better.

We are undergoing a process of automatization of the coating which will increase the quality and the yield.

Initial results encourage further research at high-RF powers, with impact in areas like high-power linacs and “muon” colliders.

At ICMAB we have a broad range of experimental facilities

Present at ICMAB



- *8 GHz dielectric resonator: 12x12 mm samples*
- *Operating in the TE_{011} mode*
- *Compatible with ICMAB's cryostat:*

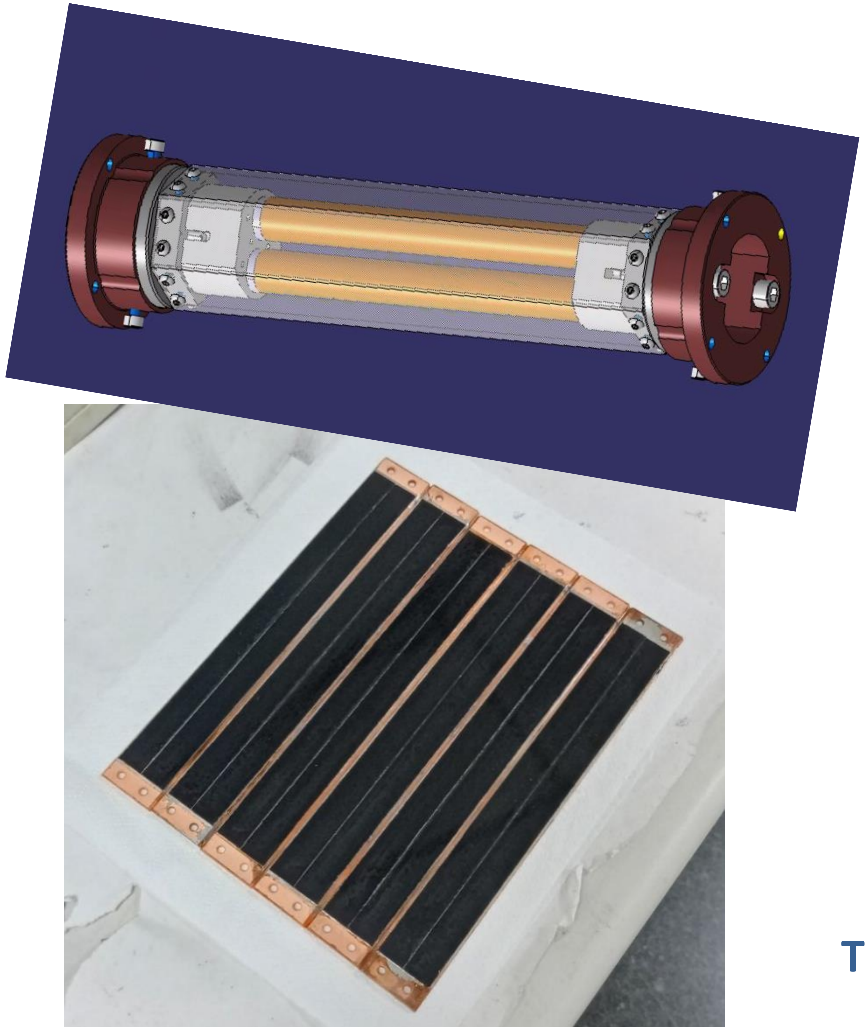
25mm Ø bore 9 T solenoid magnet

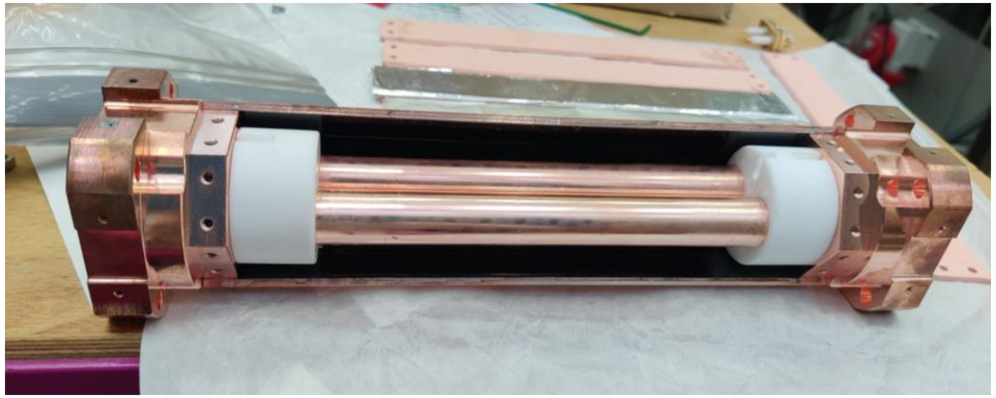
New cryostat equipped with

50mm Ø bore 16 T solenoid magnet

Height of the magnet 360+ mm

Proof-of-concept:
CC coated FCC-hh beam screen chamber





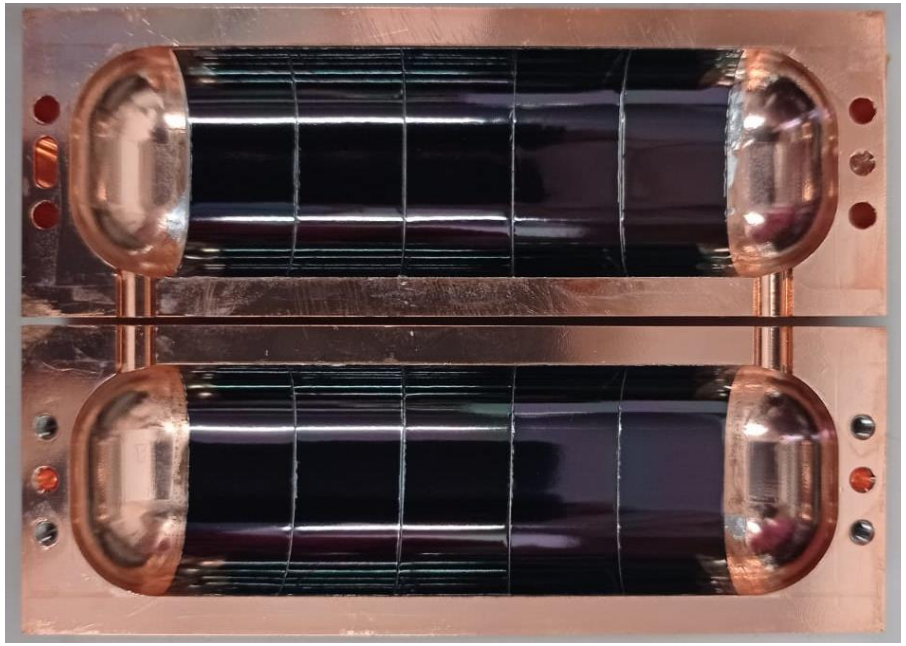
Courtesy of K. Brunner, P. Krkotić and S. Calatroni

Initial characterization of the REBCO coated BS shows that its surface resistance is lower than that of Cu coated BS

The R&D and successes of CC coatings for the FCC-hh beam-screen chamber open the door for this application to other high-energy physics fields.

Proof-of-concept:
1^{st} CC coated RADES haloscope shows a 50% in-field Q improvement

1st RADES cavity



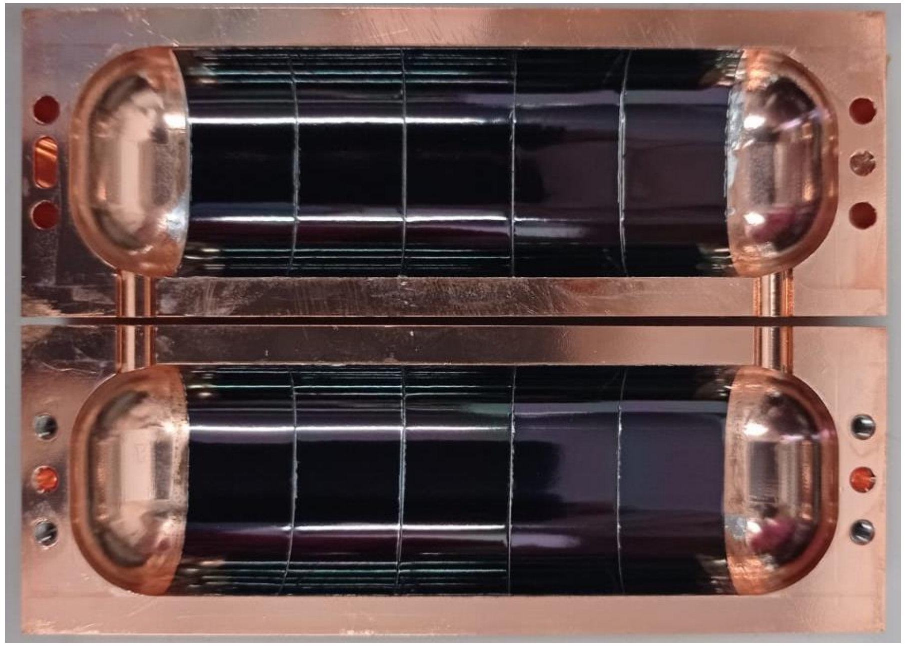
CC coated Axion cavity
Q(0T, 4.2K) ~ 80k
Q(11T, 4.2K) ~ 60k

vs

Cu only
Q(11T, 4.2K) ~ 40k

Proof-of-concept:
1st CC coated RADES haloscope shows a 50% in-field Q improvement

1st RADES cavity



CC coated Axion cavity
Q(0T, 4.2K) ~ 80k
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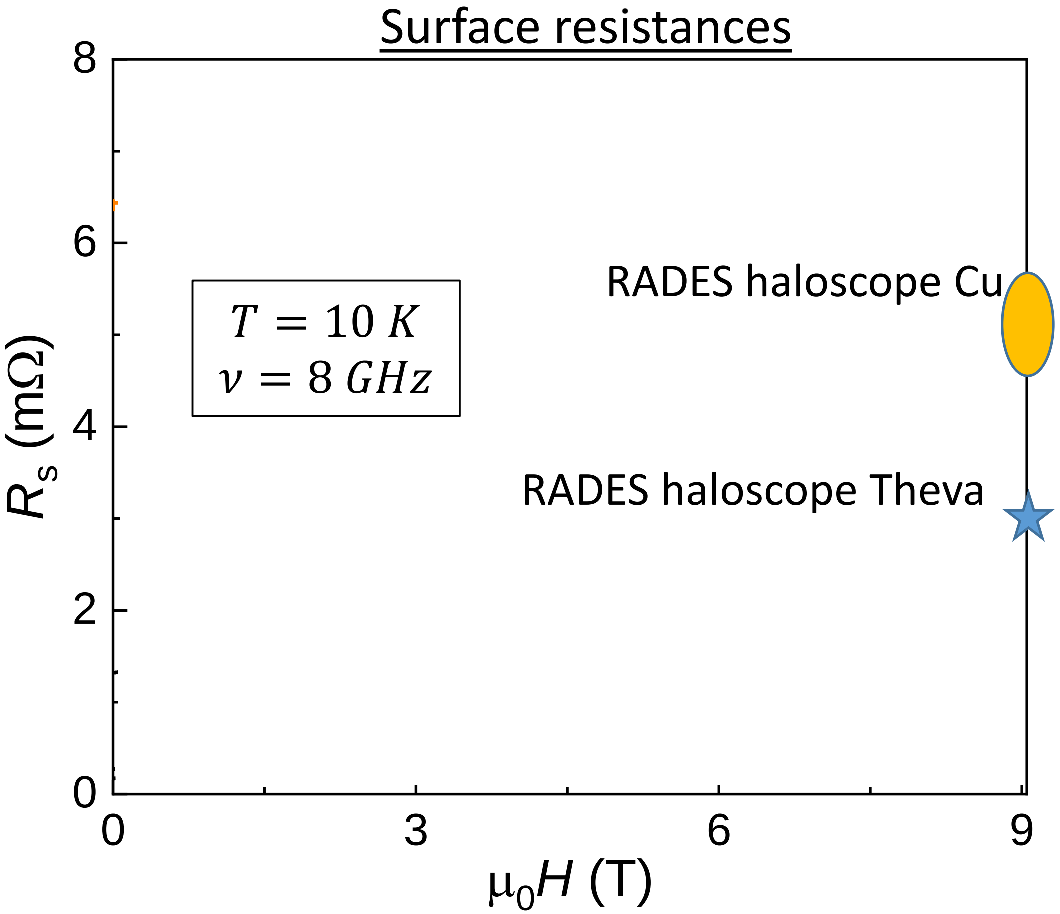
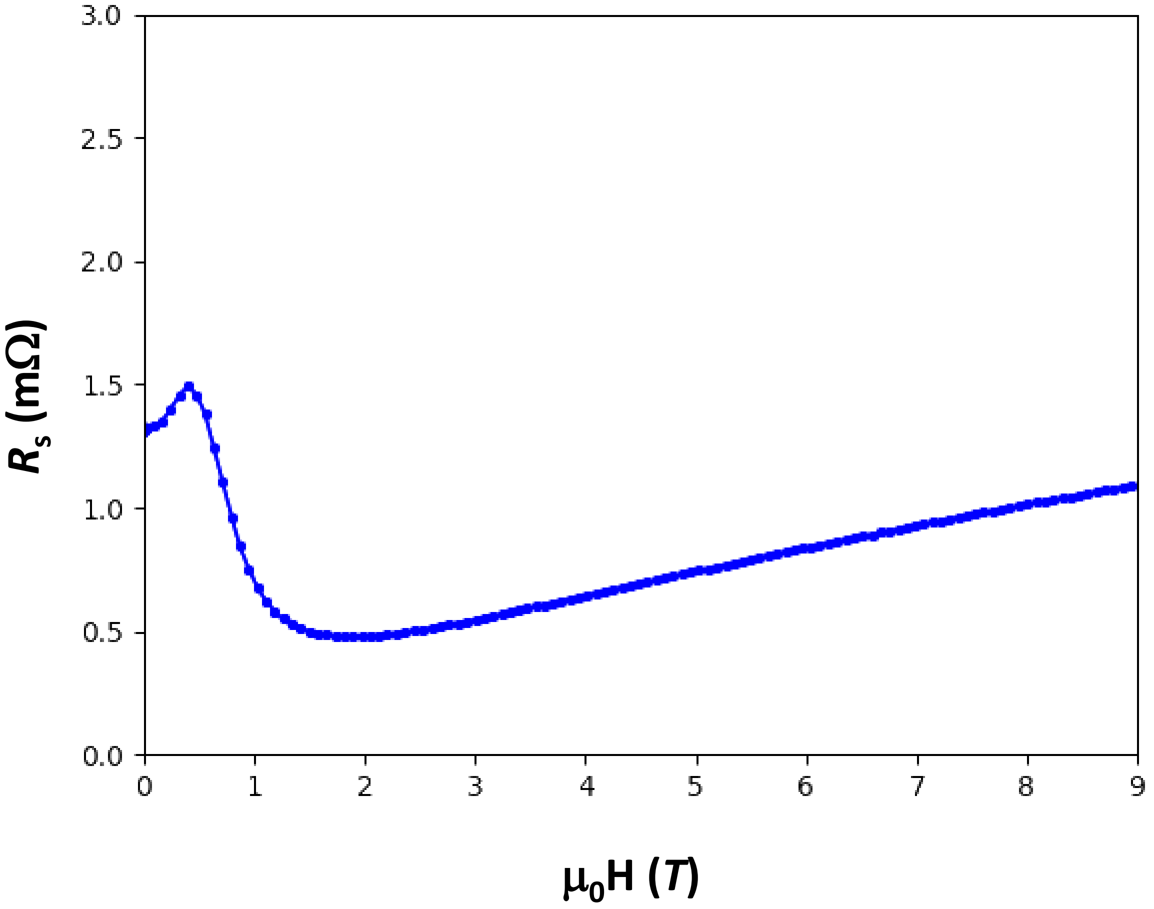
Q(11T, 4.2K) ~ 40k



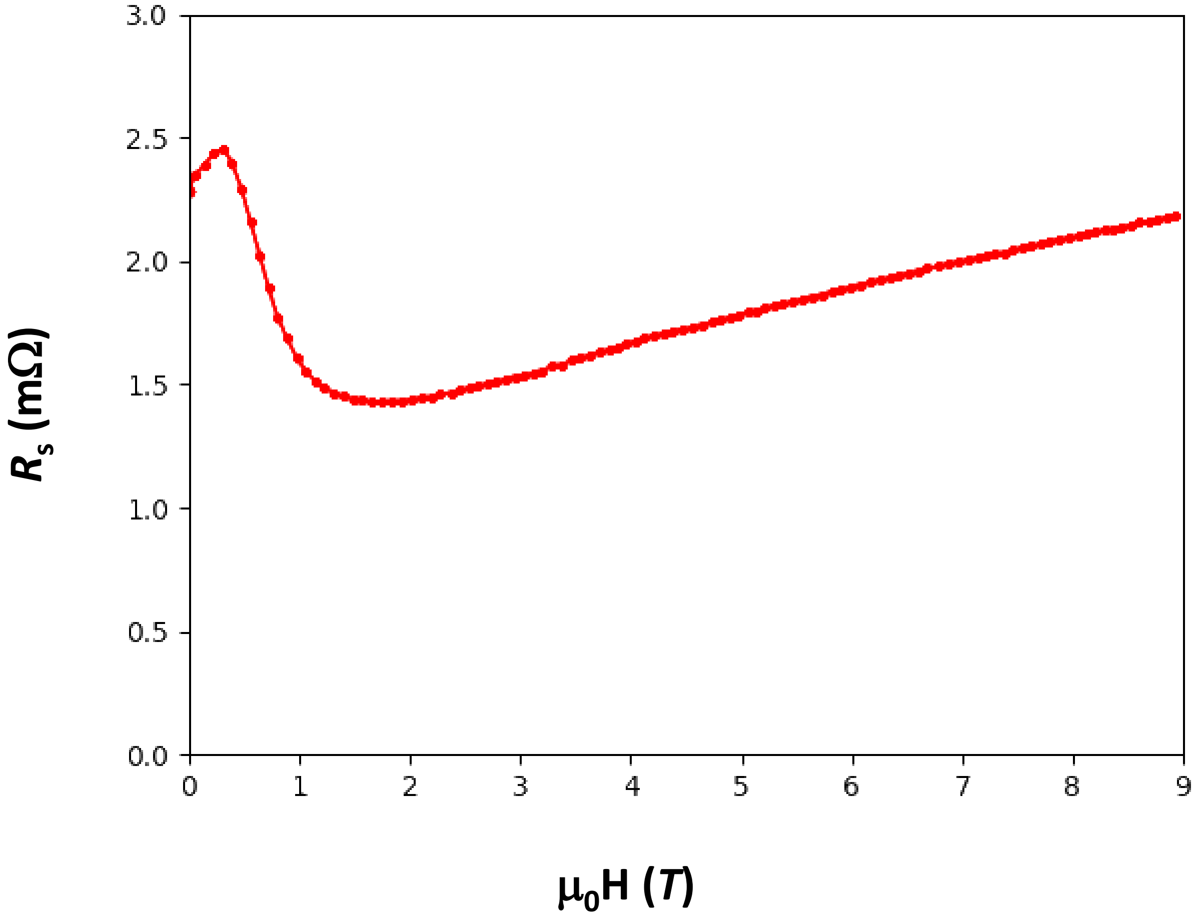
The R9 mm bending radius was a bit too much for the THEVA CC used

$T = 10\ K$
$\nu = 8\ GHz$

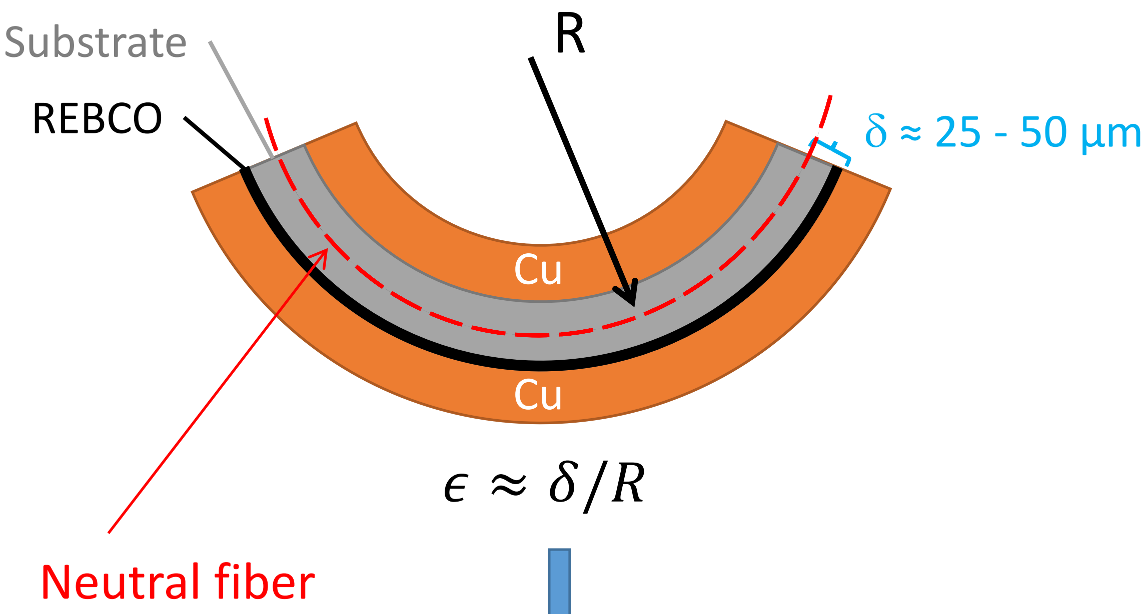
Flat



9mm Bent



Bending radius problem: SC properties depends on strain

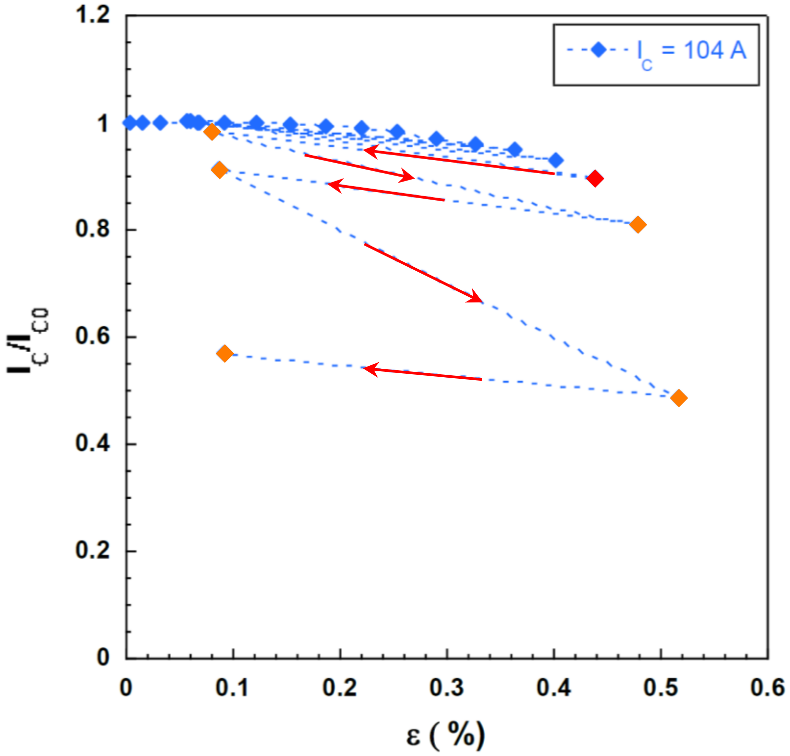


$$\epsilon \approx \delta / R$$

$$R = 9\,mm$$

Theva substrate's thickness is 100 μm
→ $\epsilon \approx 0.0055 > \epsilon_{max}$

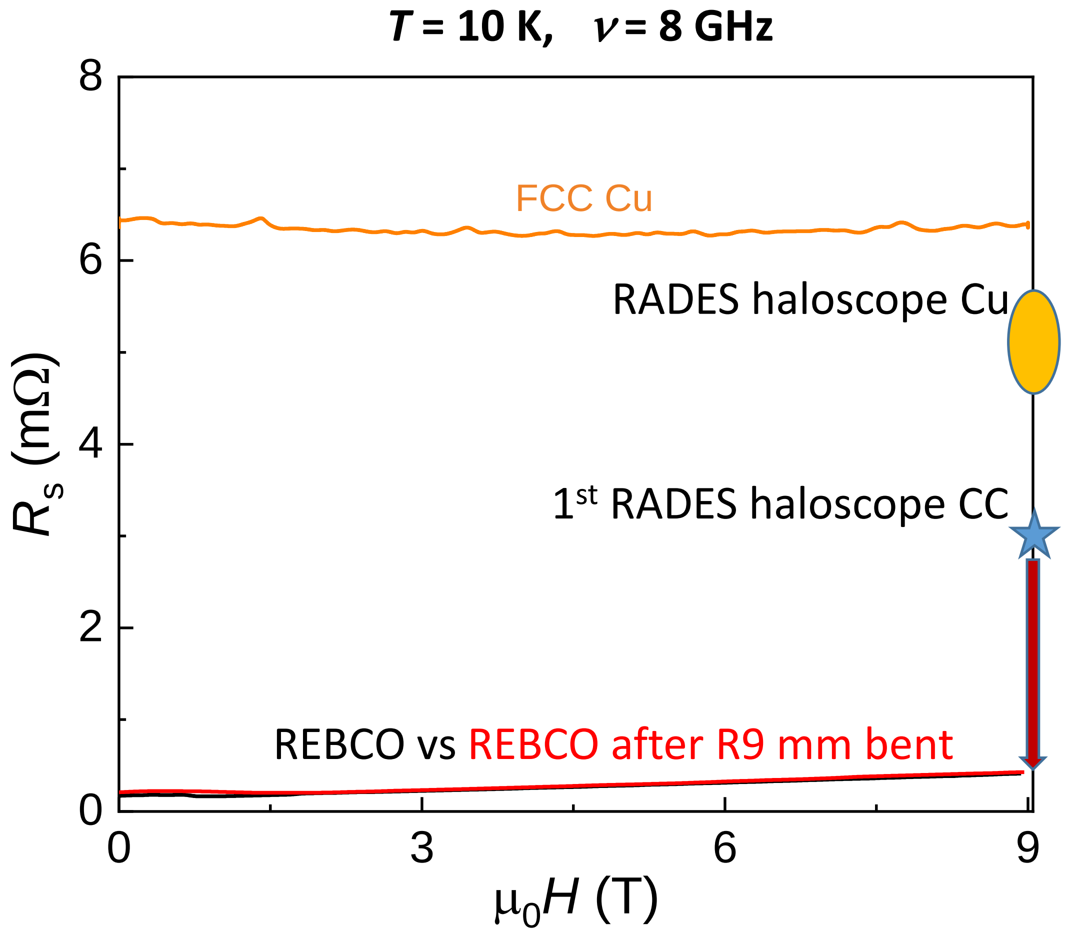
Fujikura substrate's thickness is 50 μm
→ $\epsilon \approx 0.0028 < \epsilon_{max}$



Maximum tensile strain for REBCO before entering the irreversible I_c regime
$\epsilon_{max} \approx 0.0045$

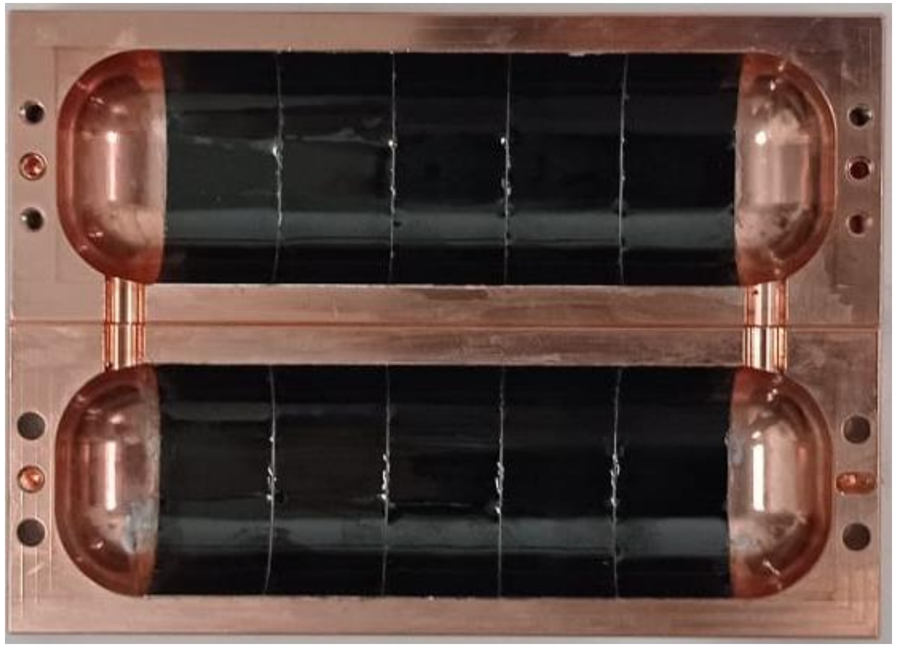
Konstantopoulou, Konstantina. Mechanical behavior of 2G REBCO HTS at 77 and 300 K. Diss. Caminos, 2015.

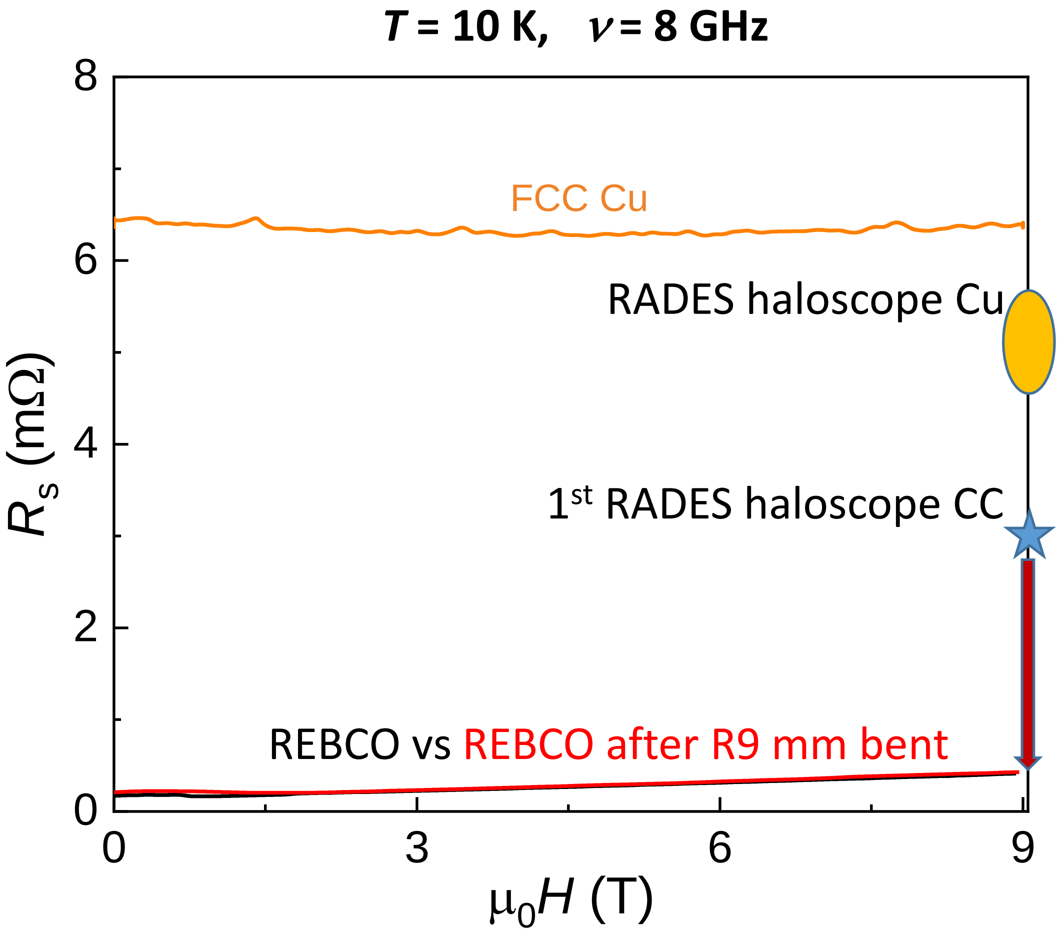
The 2nd RADES cavity presents a Q(0T) 2.5 times larger than the 1st cavity



The 2nd RADES cavity presents a Q(0T) 2.5 times larger than the 1st cavity

2nd RADES cavity



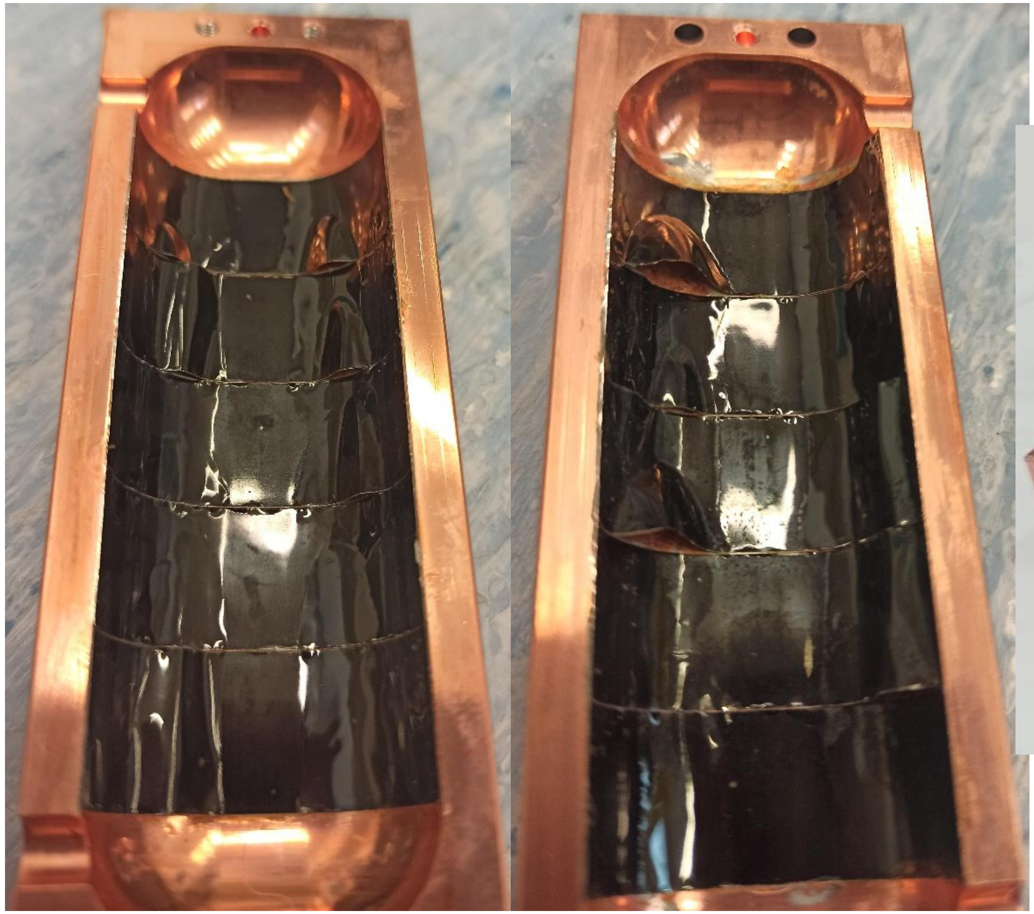


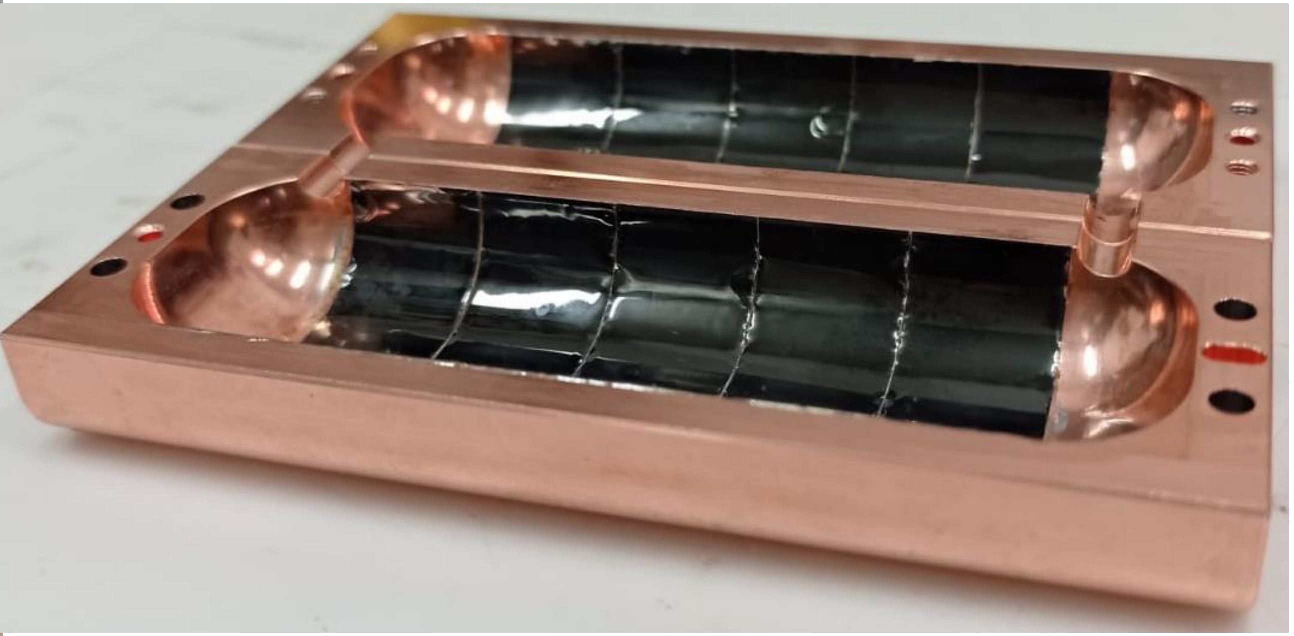
CC coated 2nd Axion cavity
Q(0T, 4.2K) ~ 200k
Q(2T, 4.2K) ~ 20k !!

Cu only
Q(0T, 4.2K) ~ 40k

What have we learnt?

Lorentz forces ripped the REBCO coating





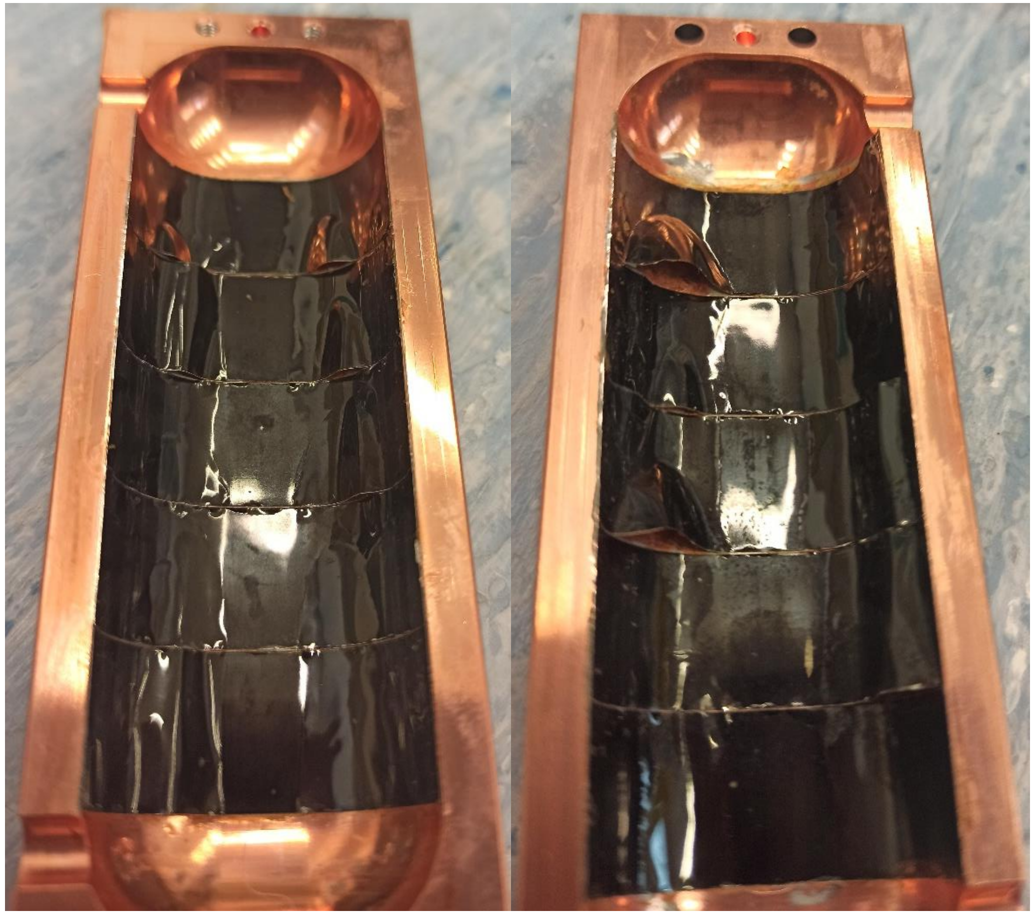
Courtesy of J. Golm

Currently all the steps during our coatings are manually done

Time consuming

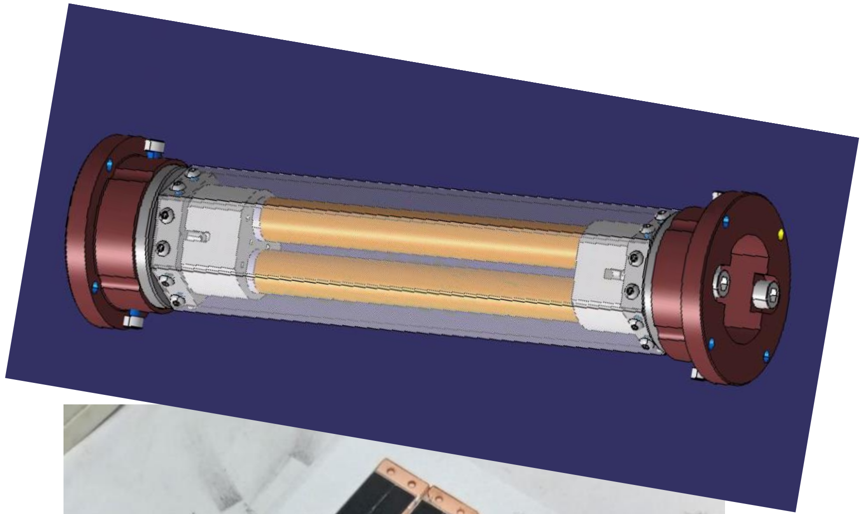
Reproducibility is subject to human errors

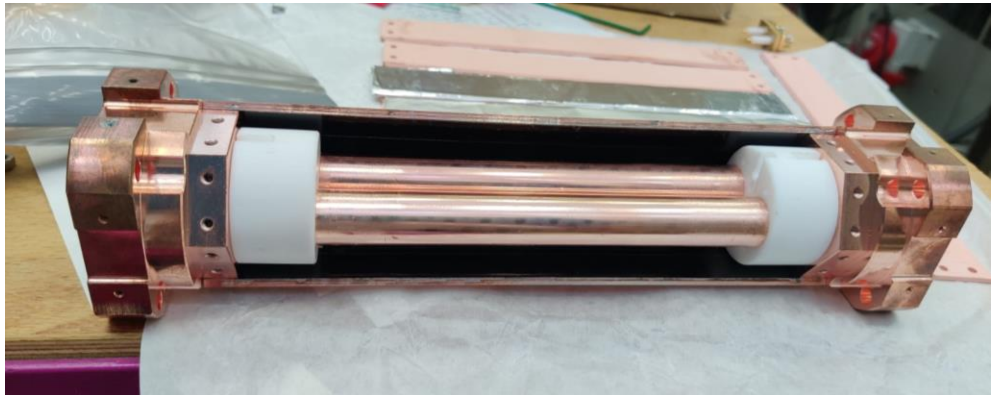
Lorentz forces ripped the REBCO coating

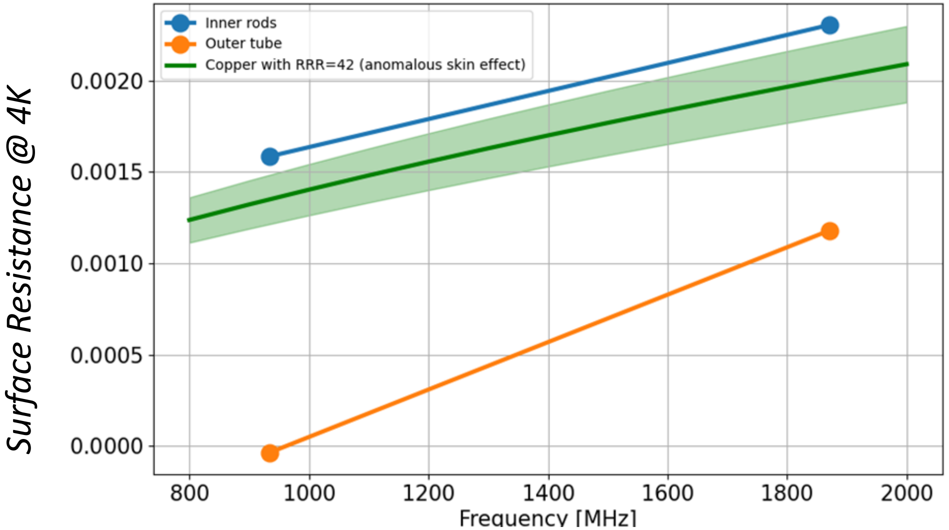


Courtesy of J. Golm

Proof-of-concept:
CC coated FCC-hh beam screen chamber







Courtesy of K. Brunner, P. Krkotić and S. Calatroni

The surface resistance of REBCO is very low as to give accurate quantitative results