High Temperature Superconducting coatings in microwave cavities for dark matter search

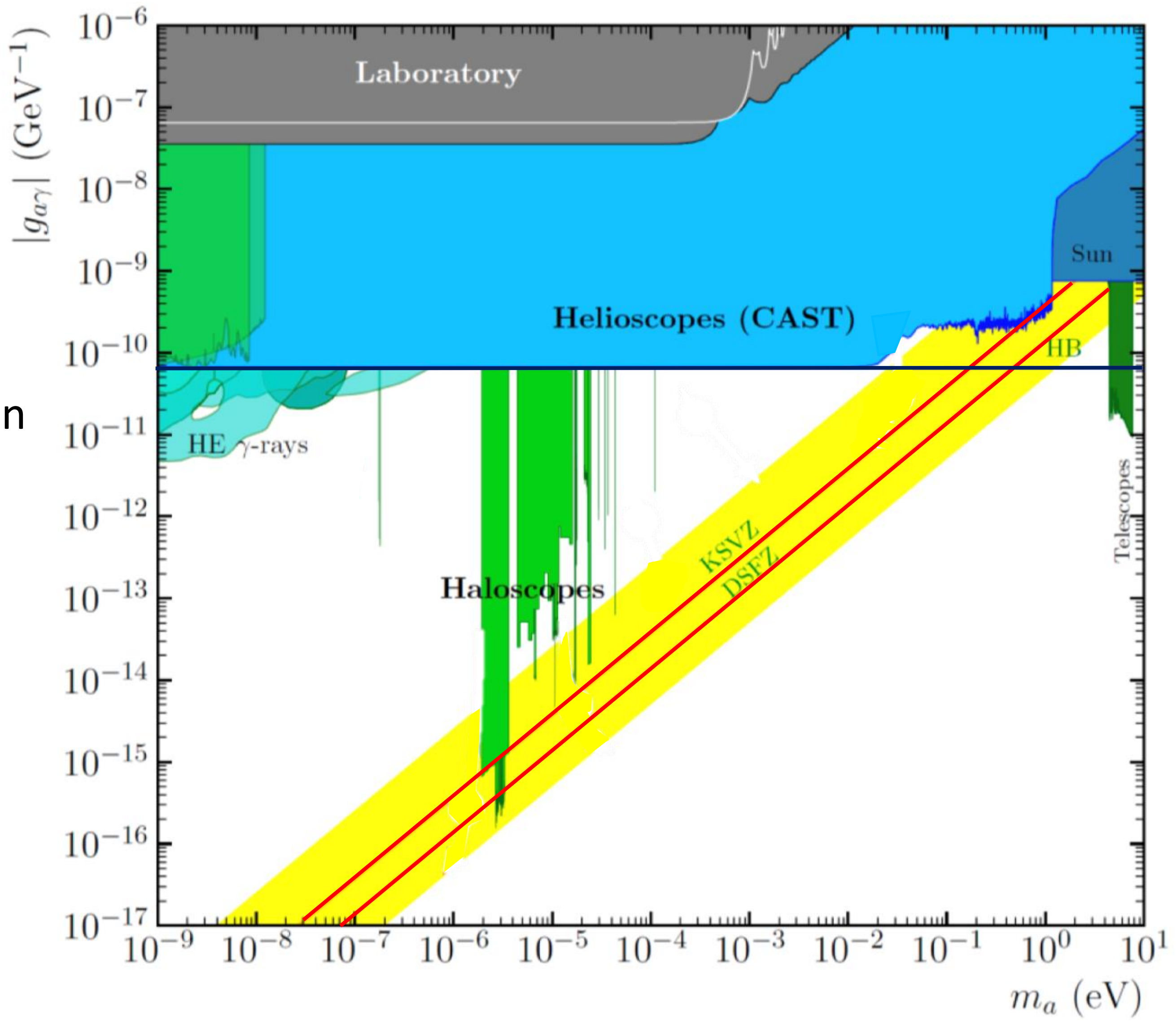
Teresa Puig[1], J. Gutiérrez[1], G. Telles[1], N. Lamas[1], I. Ahmed[1], L. Benedetti[1], X. Granados[1], P. Llanes[2], R. García[2], J Mundet[2], I. Korolkov[2], J. Golm[3], W. Wuensch[3], S. Calatroni[3], A. Diaz-Morcillo[4], J. Miralda-Escude[5], B. Dobrich[6], I. G. Irastorza[7]

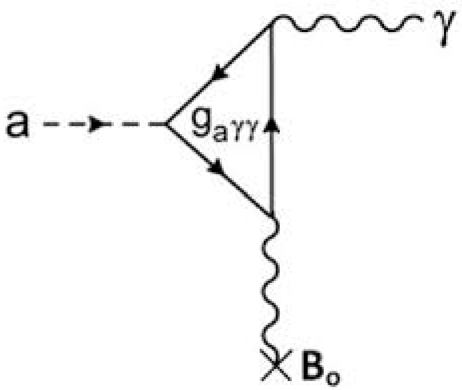
[1] Institut de Ciència de Materials de Barcelona, **ICMAB-CSIC**, Bellaterra (Spain)
[2] Institut de Física d'Altes Energies, **IFAE**, Bellaterra (Spain)
[3] **CERN** - The European Organization for Nuclear Research, Geneva (Switzerland)
[4] Information and Communications Technologies Dept., **Technical University of Cartagena** (Spain)
[5] Institut de Ciencies del Cosmos, **ICCUB**, Universitat de Barcelona, Barcelona (Spain)
[6] Max-Planck-Institut fur Physik, **MPP**, Garching (Germany)
[7] Center for Astroparticles and High Energy Physics (**CAPA**), Universidad de Zaragoza (Spain)

Dark Matter Axions hypothesis

Axion-photon coupling

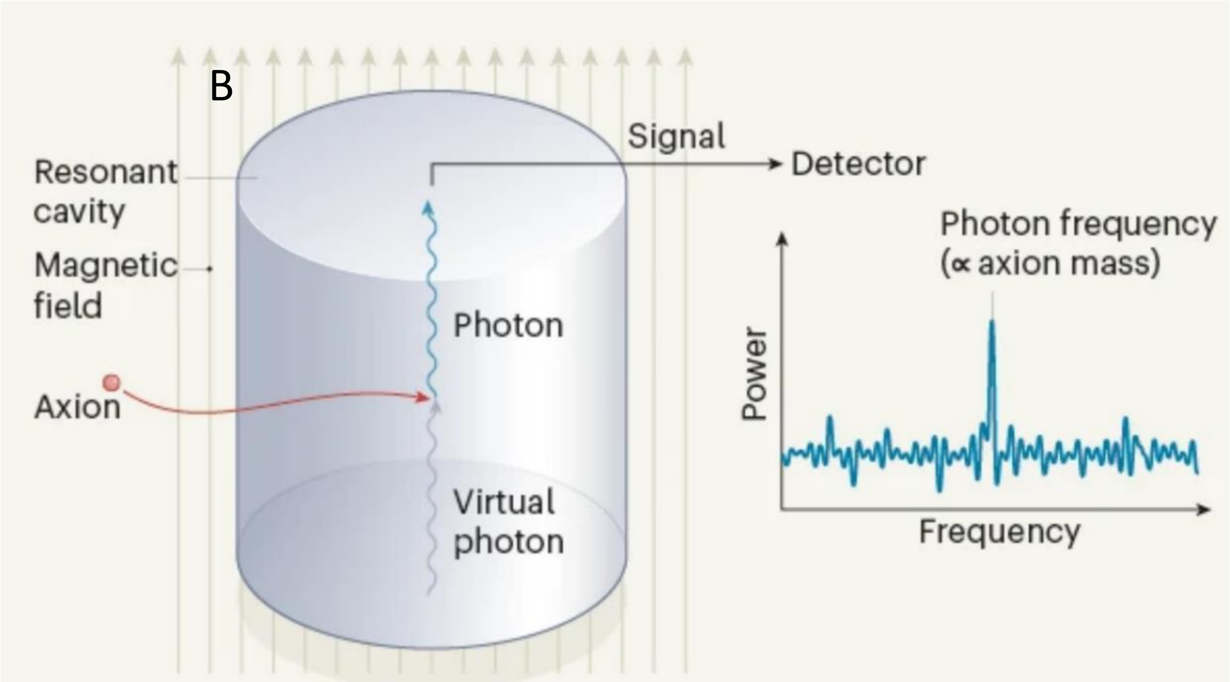
- Originated from the early universe
- Form part of the galactic dark matter halo
- Expected to interact very weakly with ordinary matter and radiation
- Predicted as abundant, long life, low energy within spread for orders of magnitude (meV-μeV)
- Could be detected in Haloscope resonant cavities by converting axions into photons under a strong magnetic field





Dark Matter Axion Detection

Axion haloscopes in MW



Coupling constant

Axion density

Axion mass

Power signal $$P_s \propto g_{a\gamma}^2 \, Q \, B^2 \, V \, \frac{\rho_a}{m_a^2}$$

Cavity Quality factor

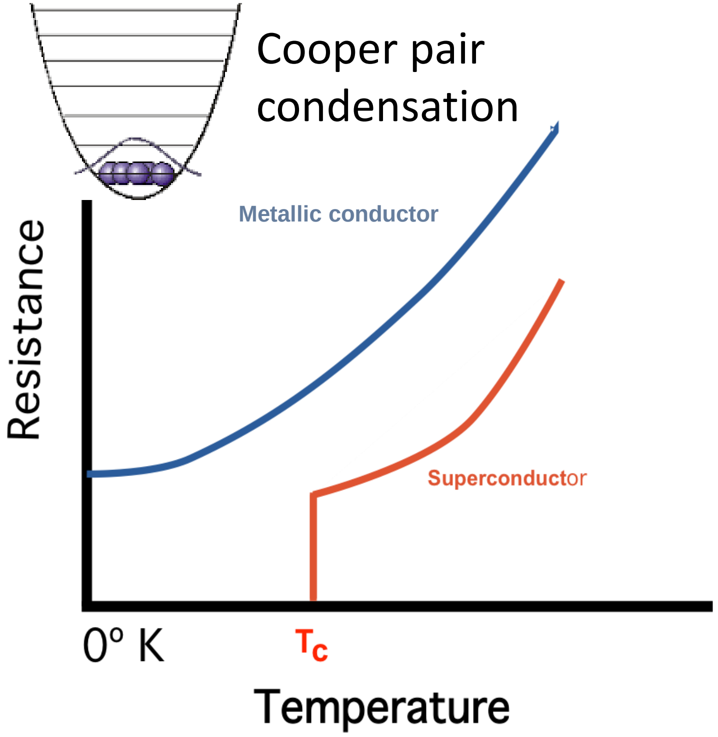
Magnetic field

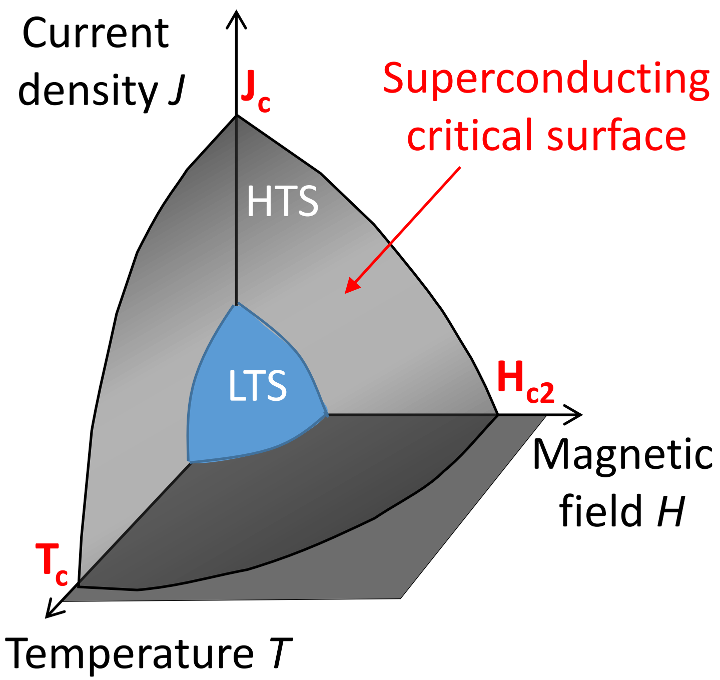
Cavity volume

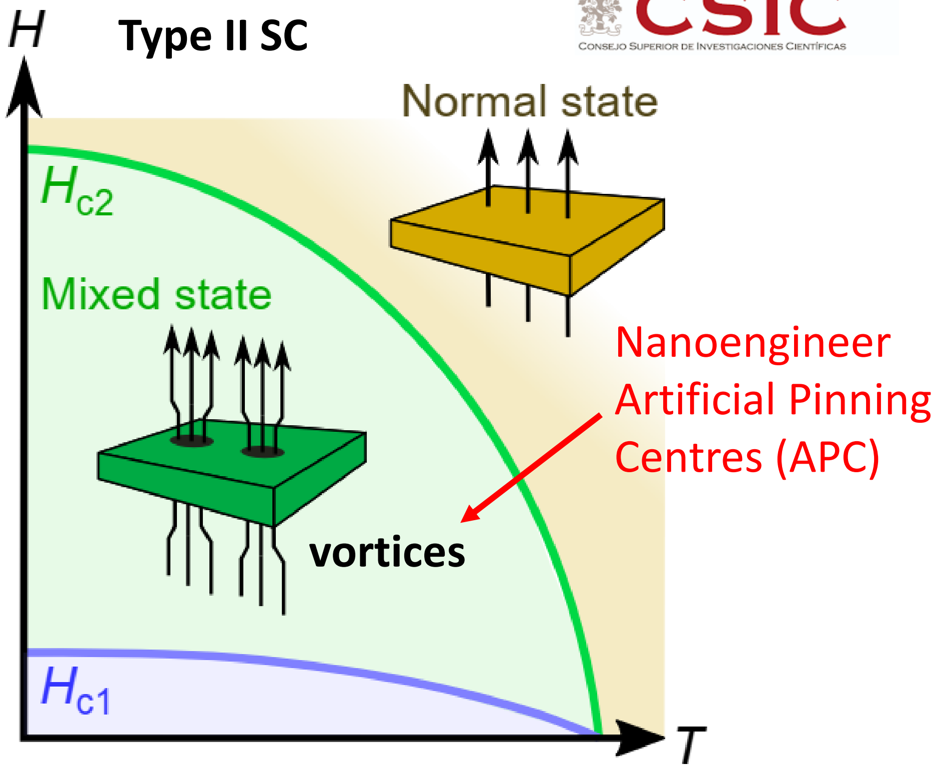
We want cavities of high Q at high magnetic fields B: ↑Q → ↓R_s

High Temperature Superconductors (HTS) can be ideal materials

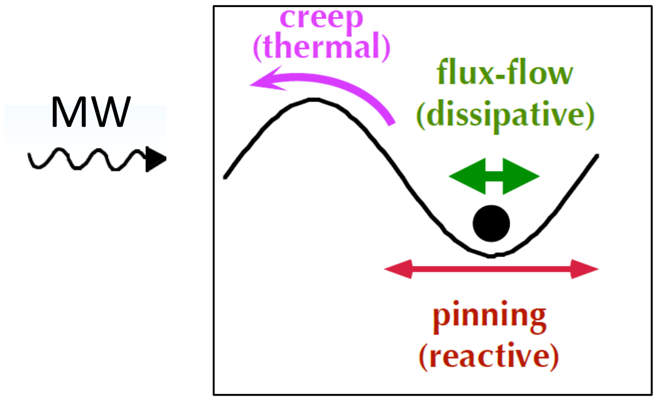
Superconductors







Vortices under Microwave radiation



$$R_s(H_{MW}, B, T) = R_{BCS}(H_{MW}, 0, T) + R_{res}\left(H_{rf}, 0{,}0\right) + \boldsymbol{R_{vm}(H_{MW}, B, T)}$$

Surface Resistance

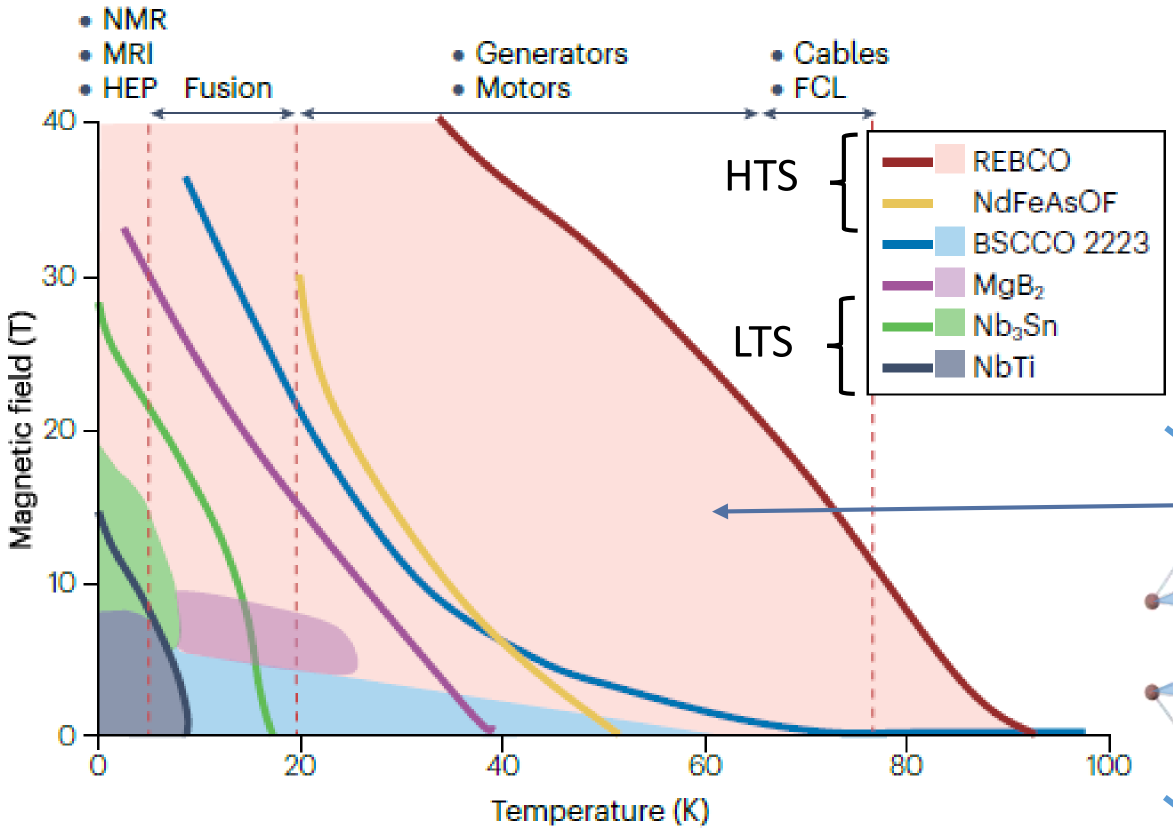
$R_{BCS} \cong$ Deduced from BCS formalism

$R_{res} \cong$ Contribution from impurities and defects

$\boldsymbol{R_{vm}} \cong$ **Losses induced by vortices**

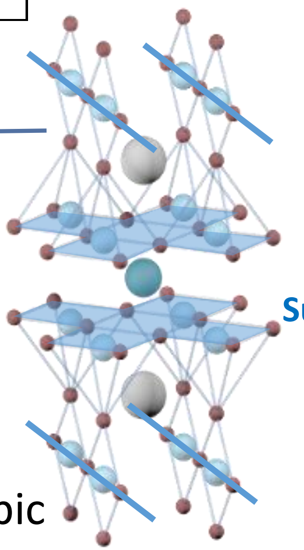
$\boldsymbol{\nu_{MW} < \nu_{depining}} \rightarrow$ APC modulate dissipation

Superconducting operational limits: HTS



T. Puig et al, Nat Rev Phys (2024)

HTS REBCO



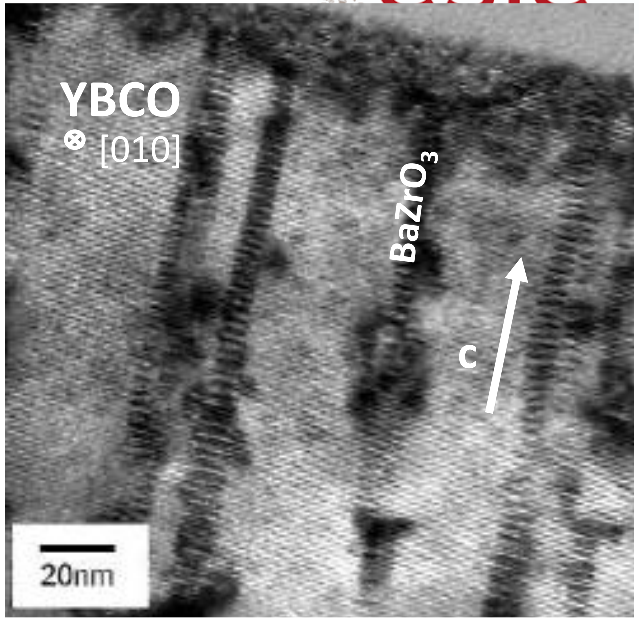
Oxide, brittle, anisotropic

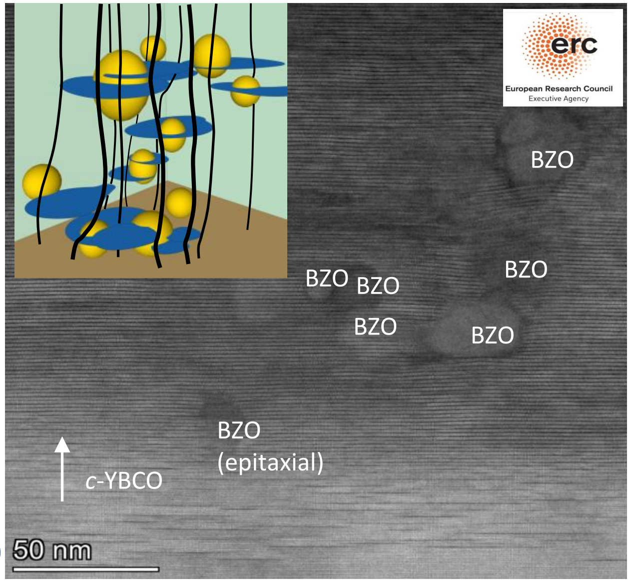
Oriented growth is mandatory

Nanocomposites:

Very efficient APC

S. Kang, Science 311 (2006)



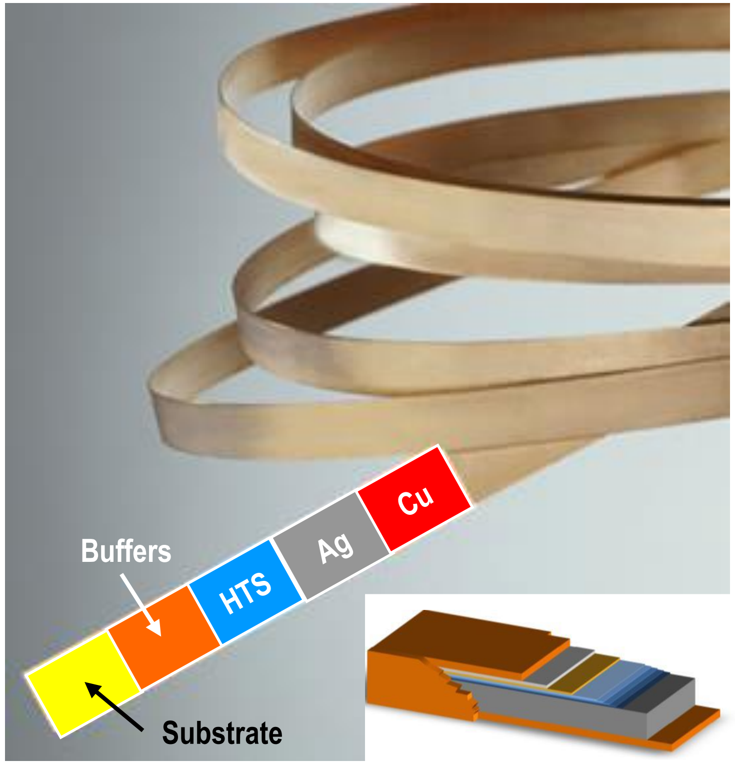


L. Soler, T. Puig et al, Nat Comm (2020)

A. Llordes, T. Puig et al, Nat Mat (2012)

HTS Coated Conductors

ICMAB – Institut de Ciència de Materials de Barcelona – Excelencia Severo Ochoa
CSIC – Consejo Superior de Investigaciones Científicas



$T_c \approx 92$ K , H_{c2} (4.2K) > 100 T, H_{irr} (4.2K) > 60 T

I_c(20T,4.2K)= 1000-1600 A/cm-w

in km length

THEVA
SuperPower Inc.
SuNAM
Faraday Factory Japan
上海超导 Shanghai Superconductor
"Tsunagu" Technology Fujikura
上创超导 Shanghai Creative Superconductor

↑ I(B)

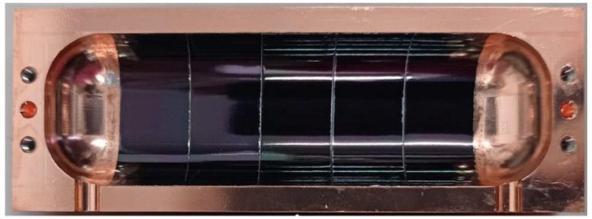
↓ R_s(B) at MW

HEP: HTS Magnets > 20 T (4.2 K- 20 K)
FCC-hh, muon collider, test magnets …

Feather M2 HTS dipole accelerator magnet

L. Rossi et al, Instruments (2021)

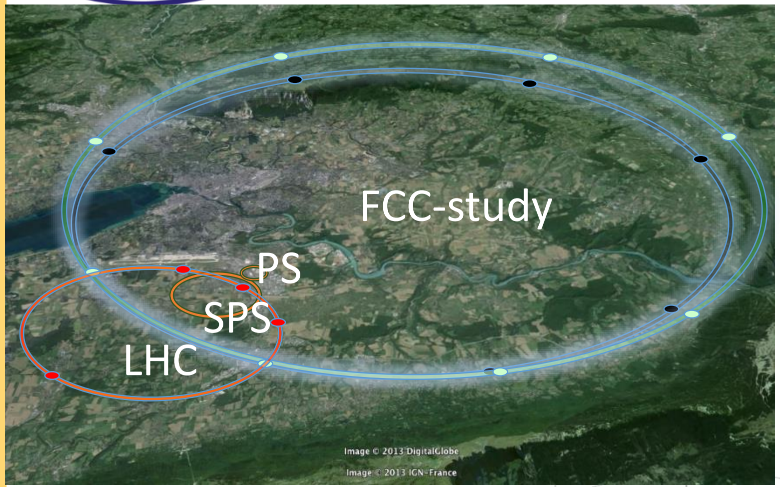
HEP: HTS coatings for ↑ Q cavities
Beam screen FCC-hh, RADES, linear collider, muon collider, …



RADES cavity

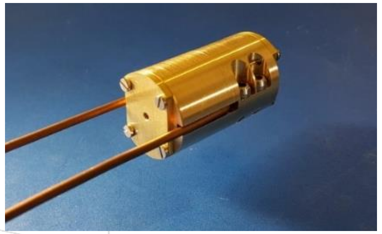
J. Golm et al, IEEE TAS (2022)

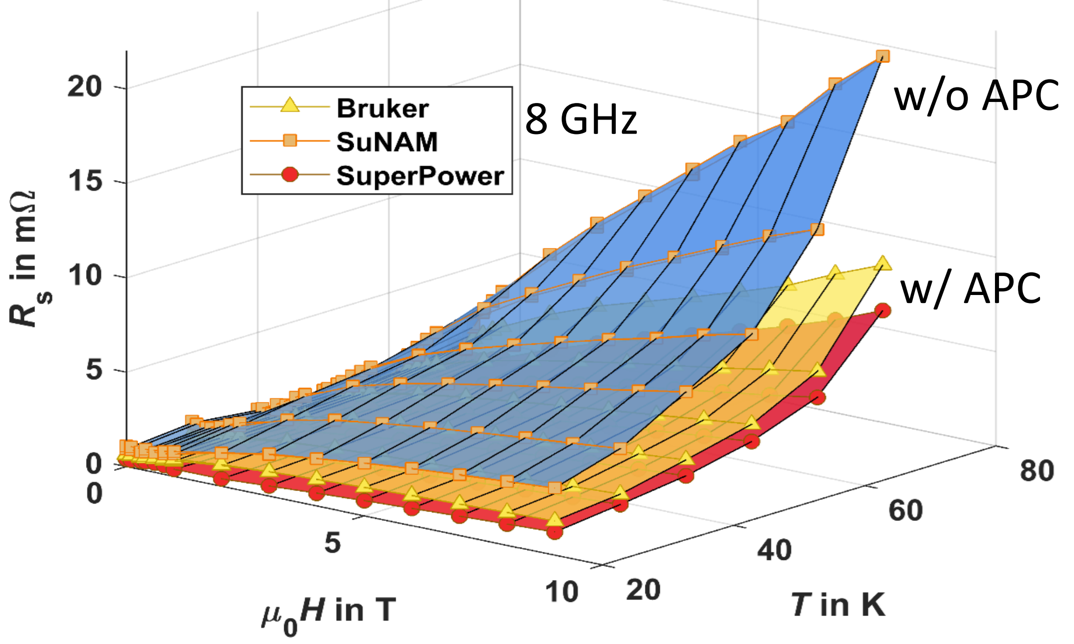
HTS Coated Conductors response to MW: Surface resistance

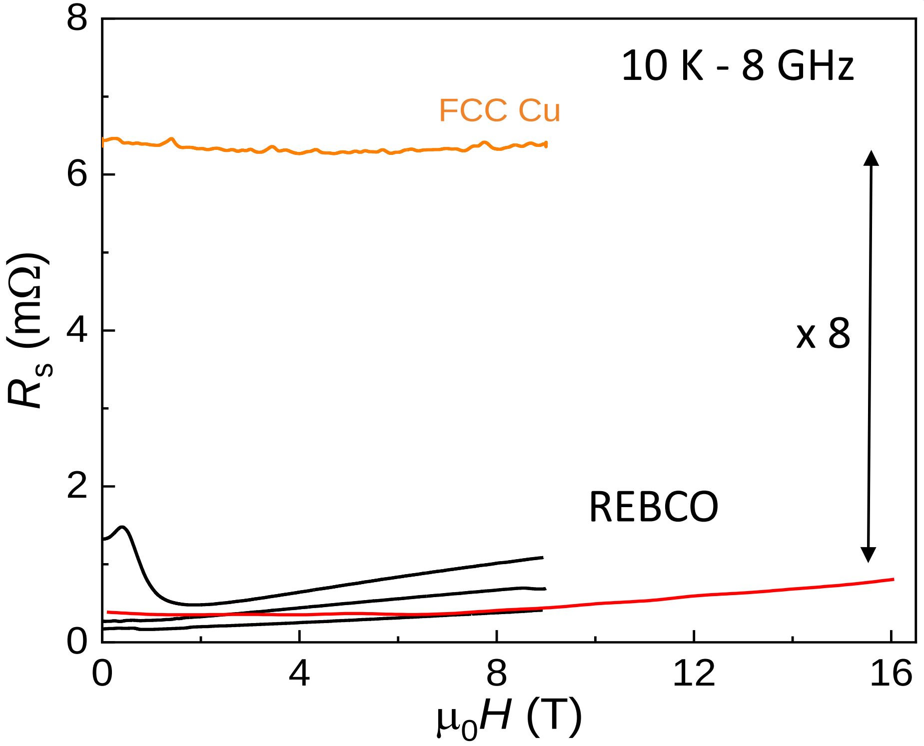


MW Range 1-10 GHz very much unexplored

- **8 GHz dielectric resonator**
- **Operating in the TE_{011} mode**







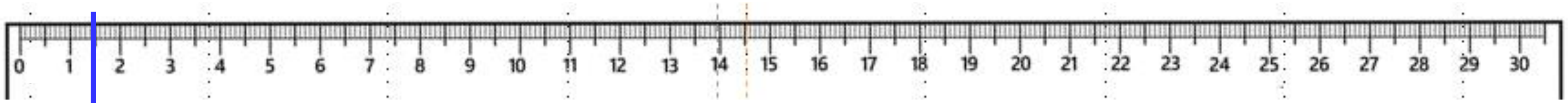
HTS is a very good replacement of Cu in MW cavities ($\downarrow R_s \rightarrow \uparrow Q$)

$\nu_{depining}\ (4.2 - 77\ K) \approx 20 - 40$ GHz

T. Puig et al, Supercond. Sci. Tech. (2019), A. Romanov, et al. Scientific Reports (2020)
A. Abada et al, Europ. Phys. J.- Special topics 228 (2019)

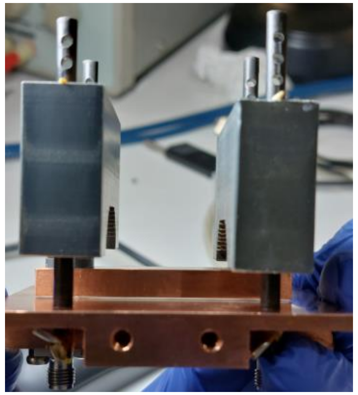
Technology developements

Frequency (GHz)

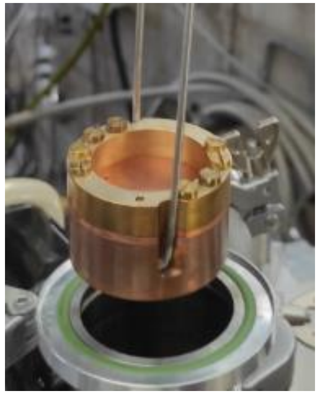


Parallel plate resonators

Under synchrotron radiation

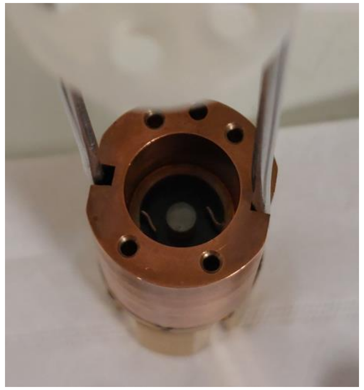


Under B for 16 T system

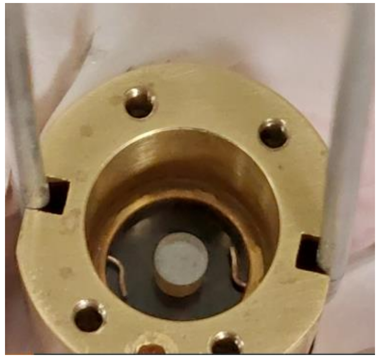


Dielectric resonators

Under B for both 9 T and 16 T system



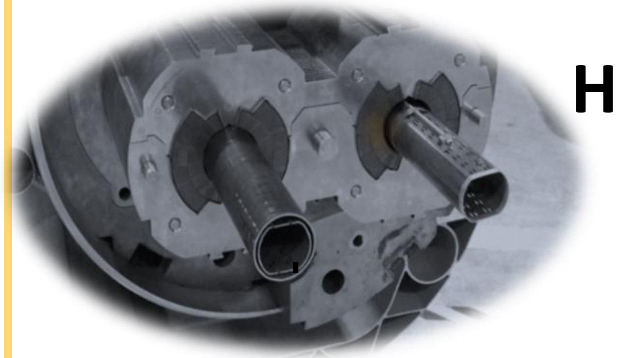
Multimode cavity (6.5, 8, 10 GHz)



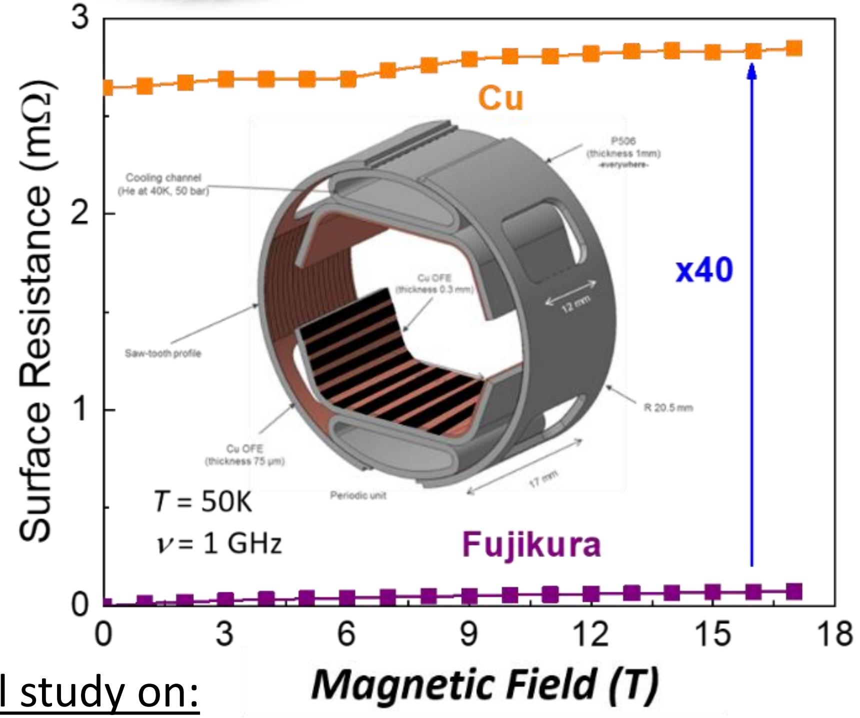
16 T system with 50 mm useful bore adapted to MW measurements

Plan de Recuperación, Transformación y Resiliencia

HTS coating of the beam screen of FCC-hh study

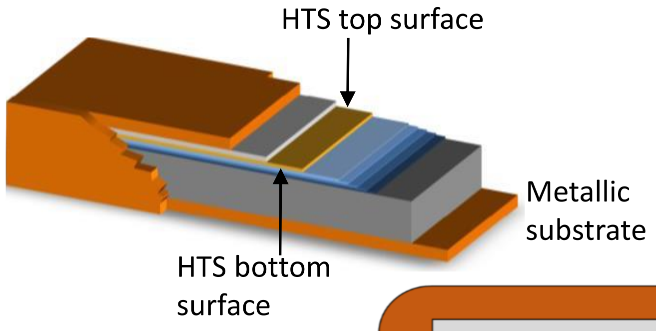


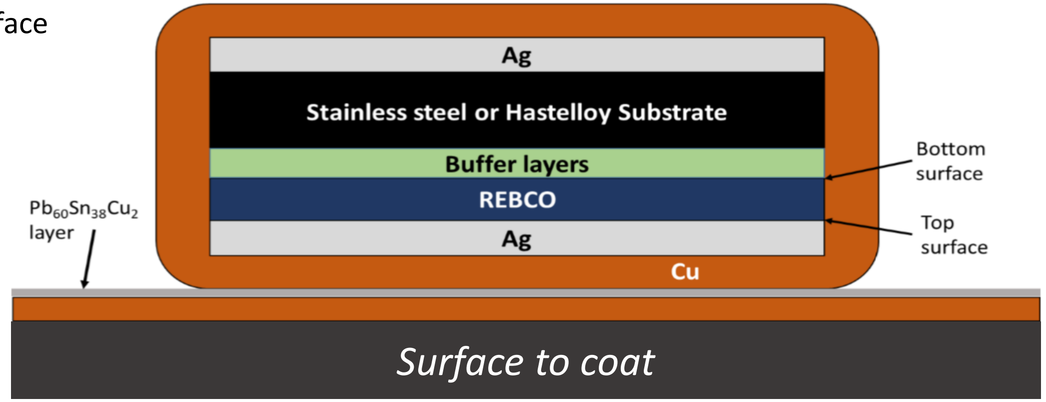
Scalable HTS coating technique based on CC soldering and substrate delamination

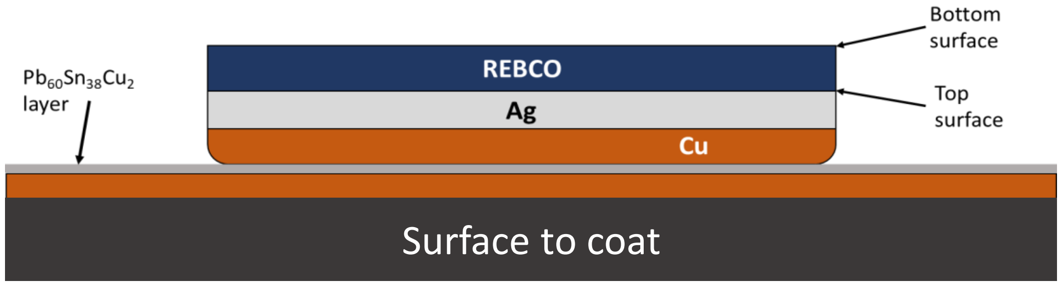


<u>Full study on:</u>
Field quality
Beam impedance
Synchrotron radiation effects
Photodesorption
SEY

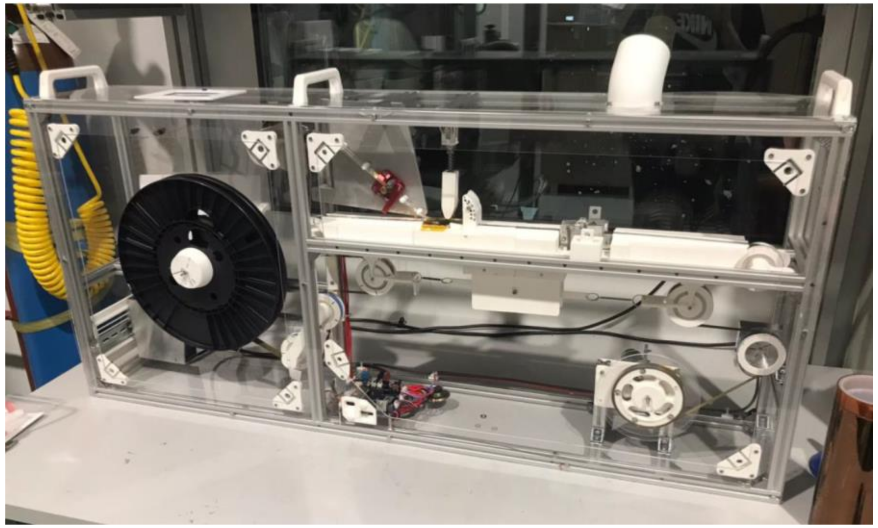
Incorporated in FCC-hh Conceptual Design Report





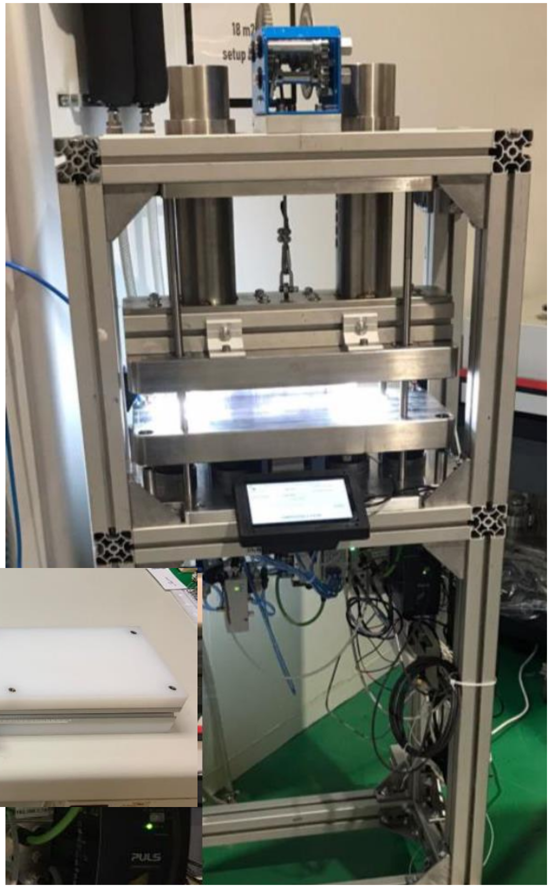


Machinery for reproducible coatings

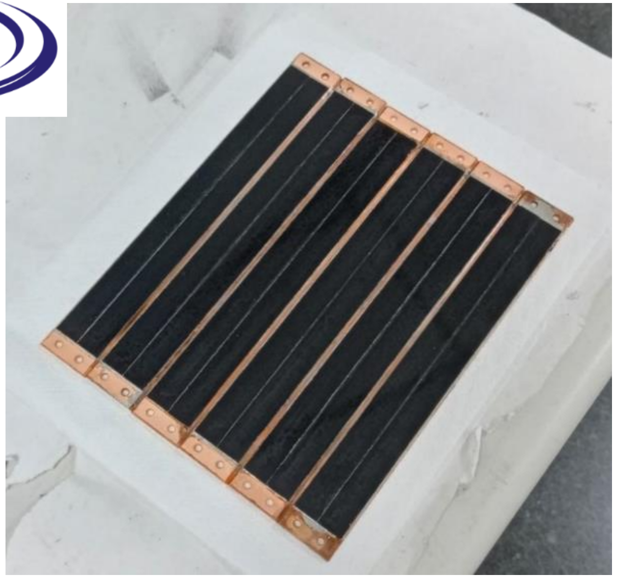


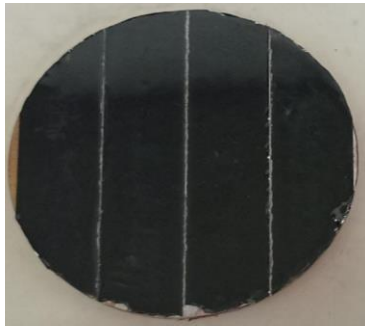
Pre-tinning

Substrate
extraction



Soldering



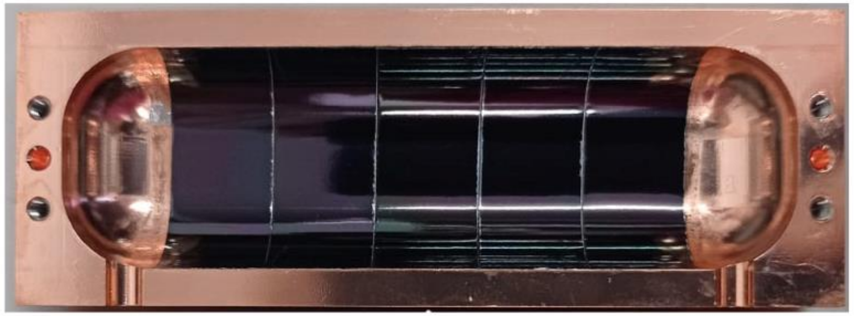


high MW power (1.6 kW)
11.5 GHz

x 100 improvement
compared to Cu at 4.2 K

Adapting to curved surfaces

RAD.ES



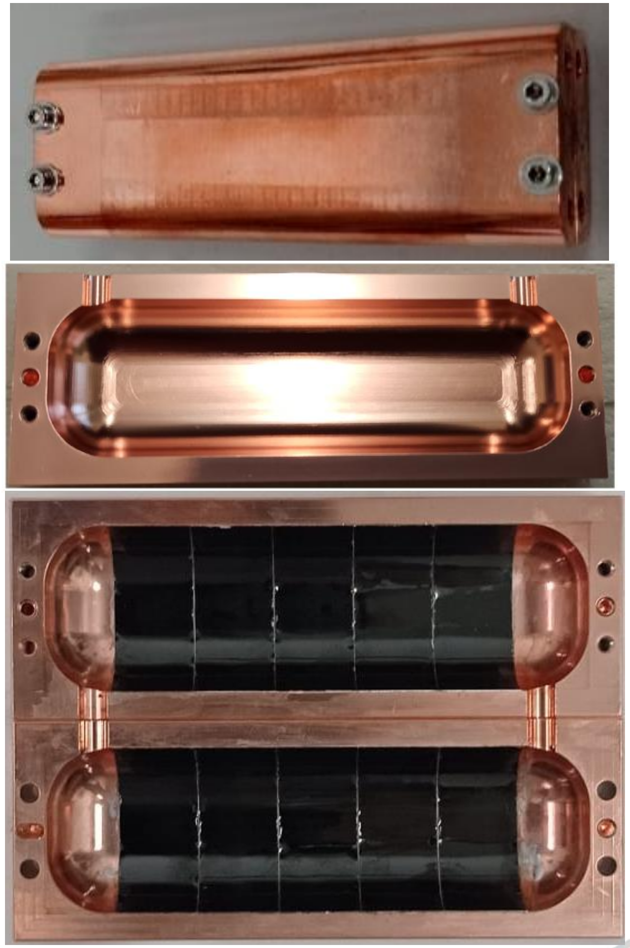
HTS coating of RADES cavity for Dark Matter Axions search

RAD.ES

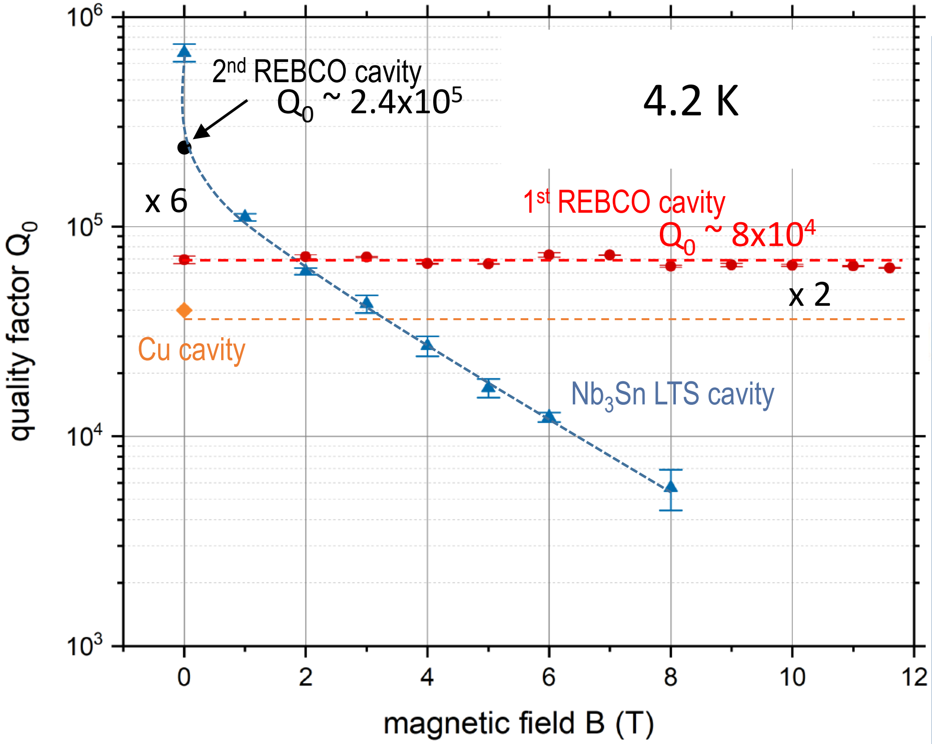
ICMAB EXCELENCIA SEVERO OCHOA — INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

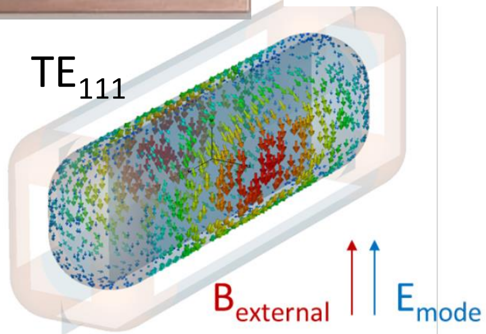
CSIC — CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

MINISTERIO DE CIENCIA E INNOVACIÓN — Plan de Recuperación, Transformación y Resiliencia — CERN — IFAE



9 GHz - $m_a \sim 36\ \mu eV$
V=0.03 L

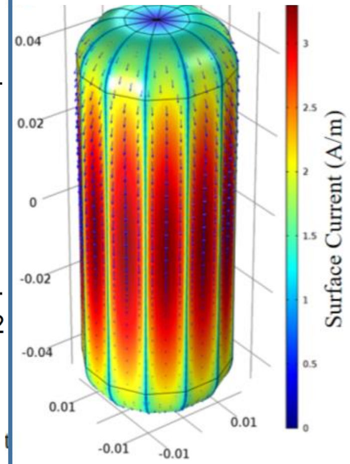


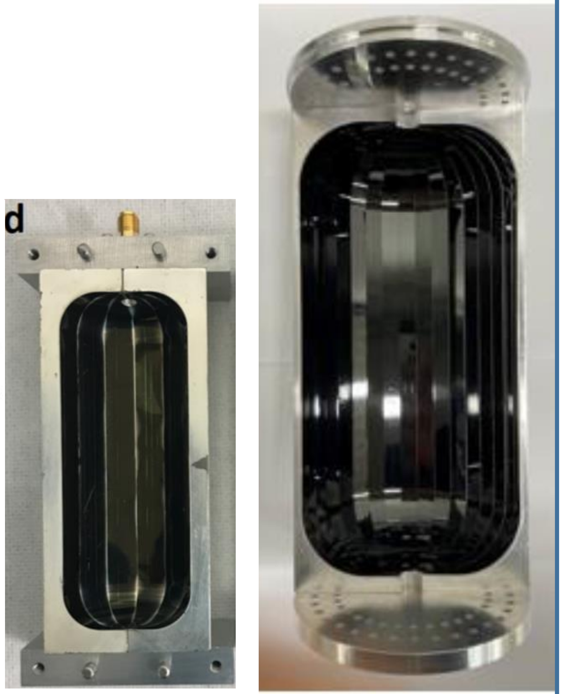


Continue adaptation to curved surfaces
Critical bending radius for CC
Choice of CC w/ APC
Design of a cavity for HTS coating

J. Golm et al, IEEE TAS 32 (2022)

CAPP
Center for Axion and Precision Physics Research

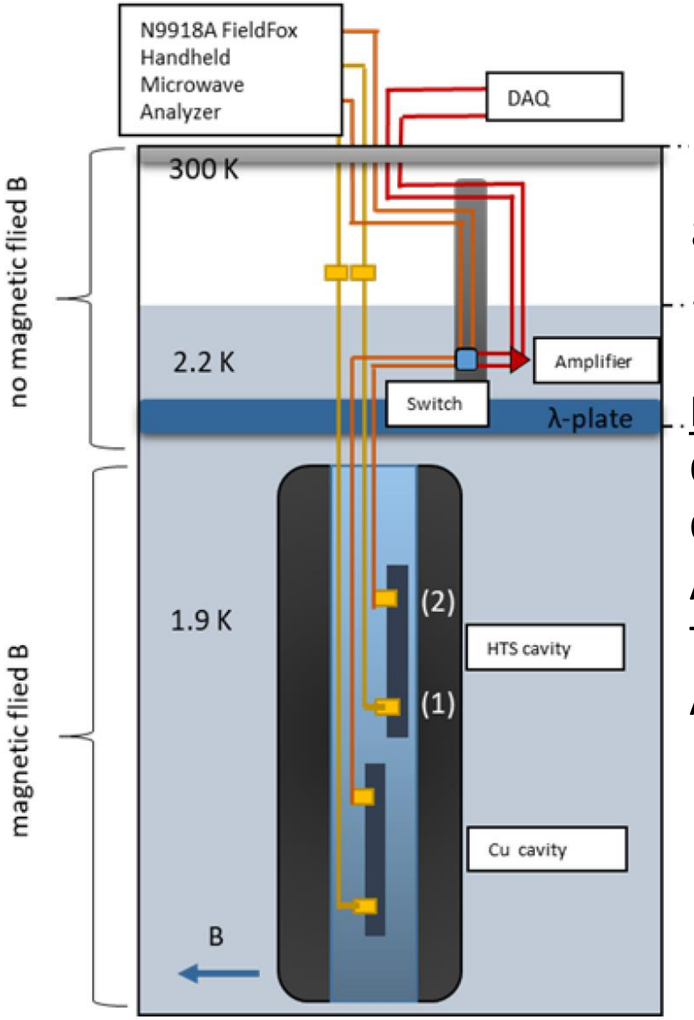




$Q_0 \sim 3.3\times10^5$ @ 8T, 4.2 K (6.9 GHz) -8 x Q_{cu}
$Q_0 \sim 1.3\times10^7$ @ 8 T, 150 mK (5.4 GHz) -200 x Q_{cu}

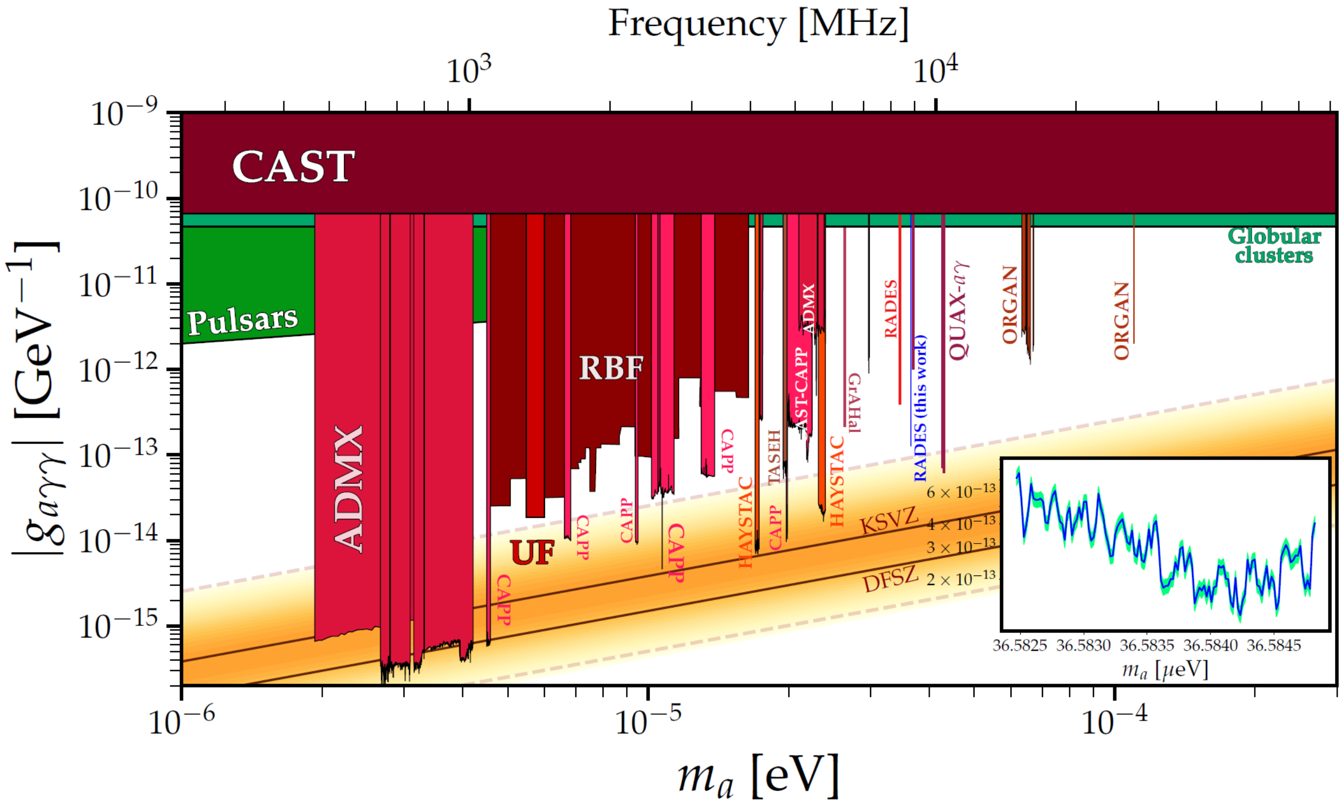
D. Ahn et al, Phys Rev Appl 17 (2022)

RADES results on Axion search with HTS coating in a 11 T magnet



11.7 T dipole magnet
1.9 K
8.84 GHz ± 573 kHz
27h

Essential aspects:
Quality factor
Coupling
Amplification
Temperature stability
Analysis procedure



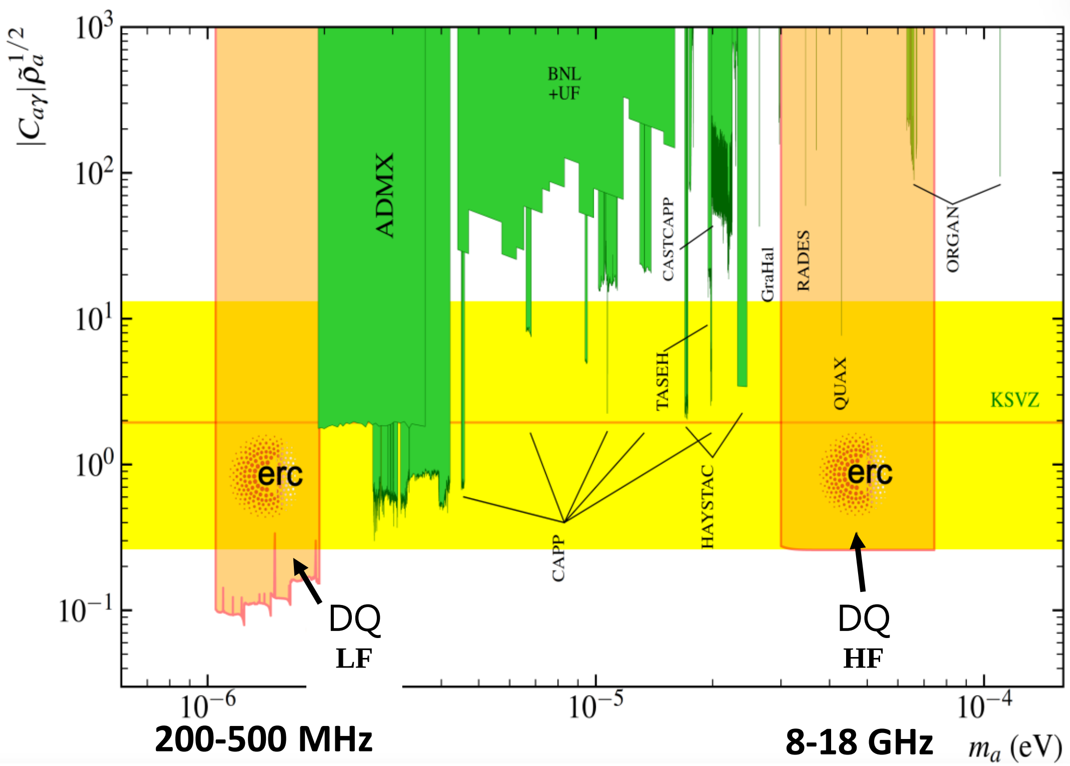
Measurements at SM18 at CERN

- Axion-photon coupling outperforms CAST limit x 100 and previous RADES results x 3
- An Axion-photon coupling strength limit, $g_{a\gamma} \geq 1.27 \times 10^{-13}$ GeV^{-1} is set
- No excess in the signal hinting to an Axion-like particle was found at 36.5824 μeV < m_a < 36.5848 μeV
- Next experiments schedule for Sept. 24 with new HTS cavities

S. Ahyoune et al, submitted to JHEP

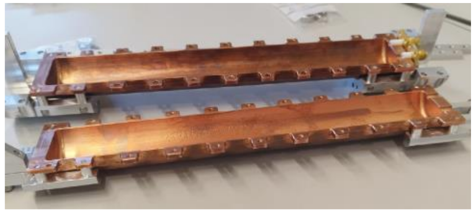
DarkQuantum

Synergy Grant, Starting Sept. 24
Coord. I.G. Irastorza (CAPA)



RADES

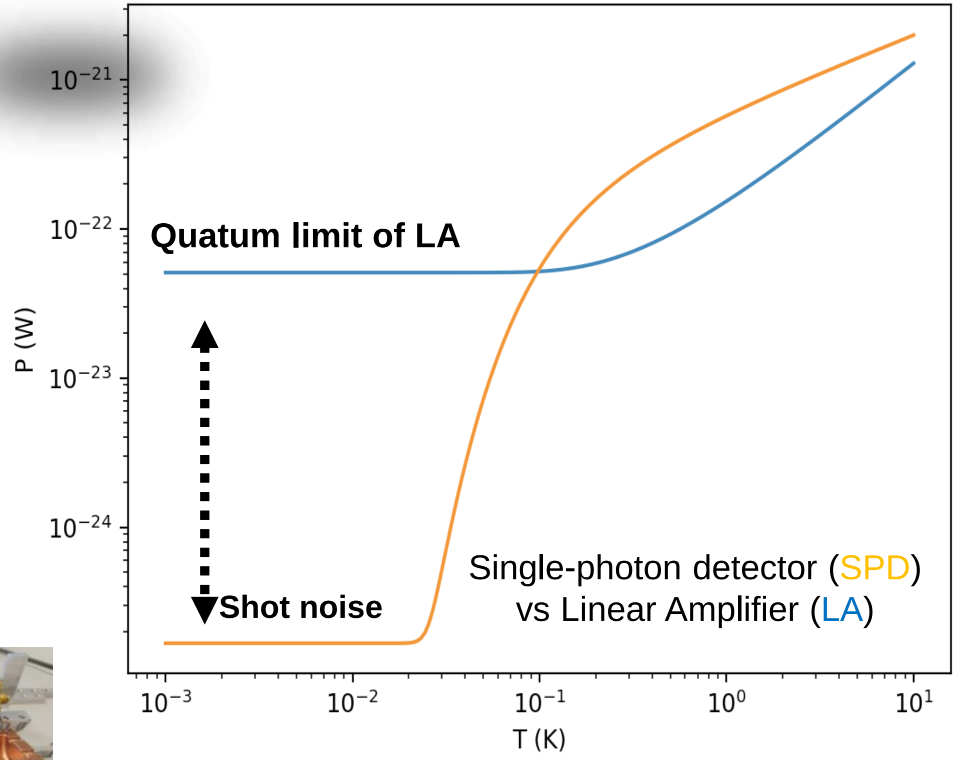
(9 GHz / 36 μeV)



(8-9 GHz)

BabyIAXO
(250 – 450 MHz/ 1 – 2 μeV)

Minimum detectable power vs. Temperature



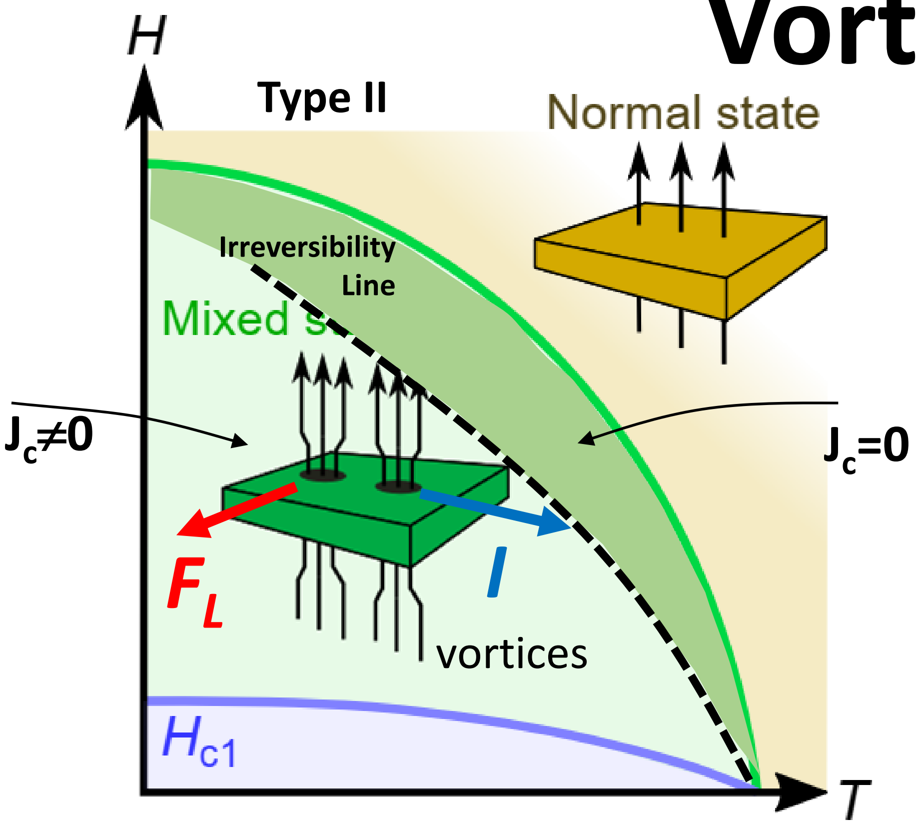
- Single-photon detectors
- Ultra-cryogenics
- HTS coating
- Magnonics for tuning
- Machine learning for quantum sensing

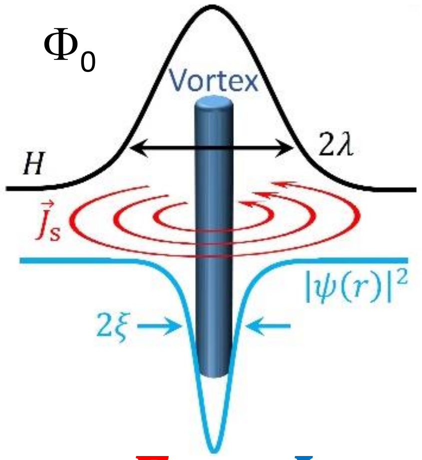
CONCLUSIONS

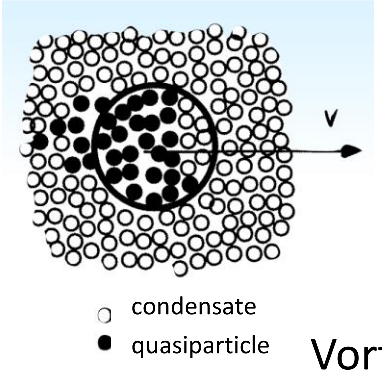
- The search for Dark Matter Axions is a challenging study but halloscope cavities operating at high magnetic fields can help
- HTS enhances the sensitivity (Q factor) of resonant cavities at high magnetic fields
- A robust coating technology adapted to complex surface is being developed
- Cooperation between HEP and HTS may lead to new leaps in technology

MPP-Garching, GE, May 2024

Vortex mixed state

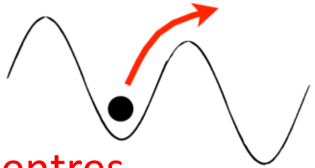






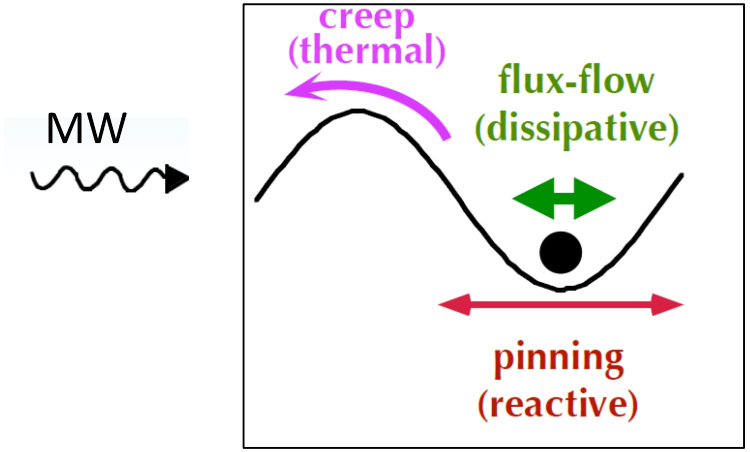
$$\boldsymbol{F_L} = \boldsymbol{J_c} \times \vec{\boldsymbol{B}} = \vec{\boldsymbol{F}}_{\boldsymbol{P}}$$

Vortices are pinned in defects



Nanoengineering Artificial Pinning Centres (APC)

Vortices under Microwave radiation



$$R_s(H_{MW}, B, T) = R_{BCS}(H_{MW}, 0, T) + R_{res}(H_{rf}, 0,0) + \boldsymbol{R_{vm}(H_{MW}, B, T)}$$

Surface Resistance

R_{BCS} ≅ Deduced from BCS formalism

R_{res} ≅ Contribution from impurities and defects

$\boldsymbol{R_{vm}}$ ≅ **Losses induced by vortices**

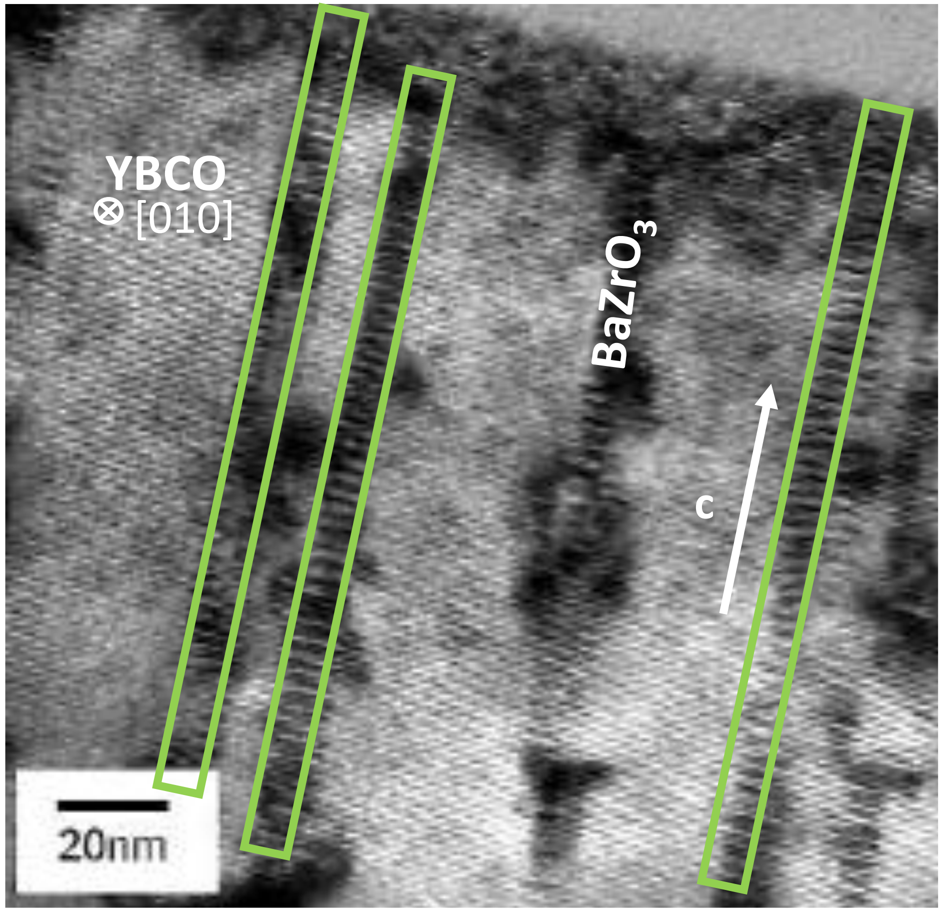
$\boldsymbol{v_{MW}} < \boldsymbol{v_{depining}}$ → APC modulate dissipation

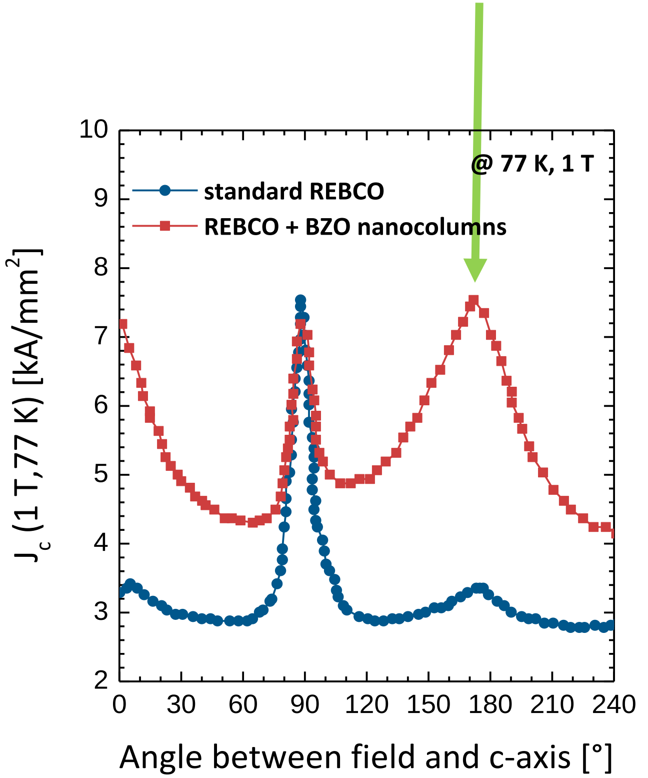
$\boldsymbol{v_{MW}} > \boldsymbol{v_{depining}}$ → APC cannot mitigate dissipation

APC in HTS CC: Thick epitaxial Nanocomposites

Self-assembled nanorods induced by the strain

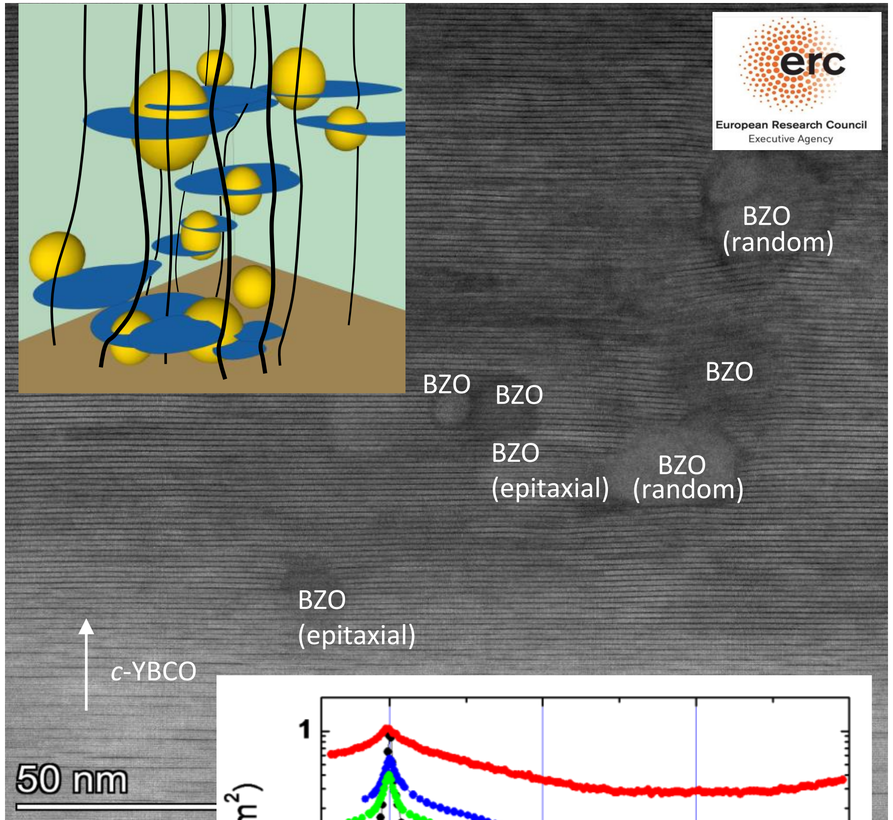
Epitaxial YBCO films even up to 3-4 μm thick

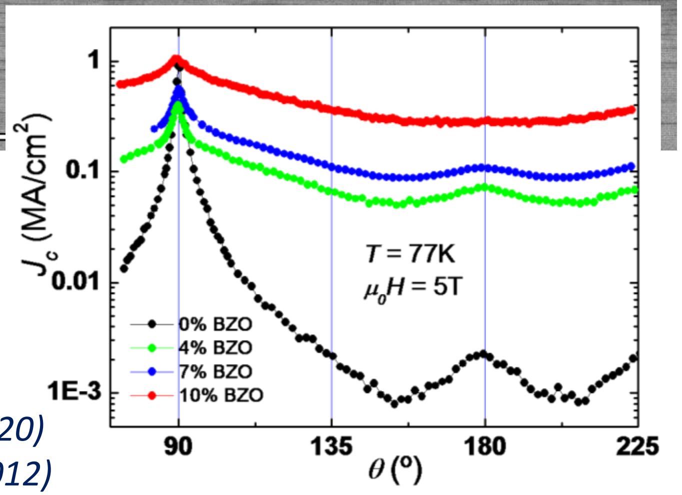




Selvamanickam et al., IEEE TAS 21 (2011)<

Majkic, G. et al. SUST 33 (2020)





J. McManus-Driscoll, Nat. Mat. 3, 439(2004)

Y. Yamada, APL 87(2005)

S. Kang, Science 311 (2006)

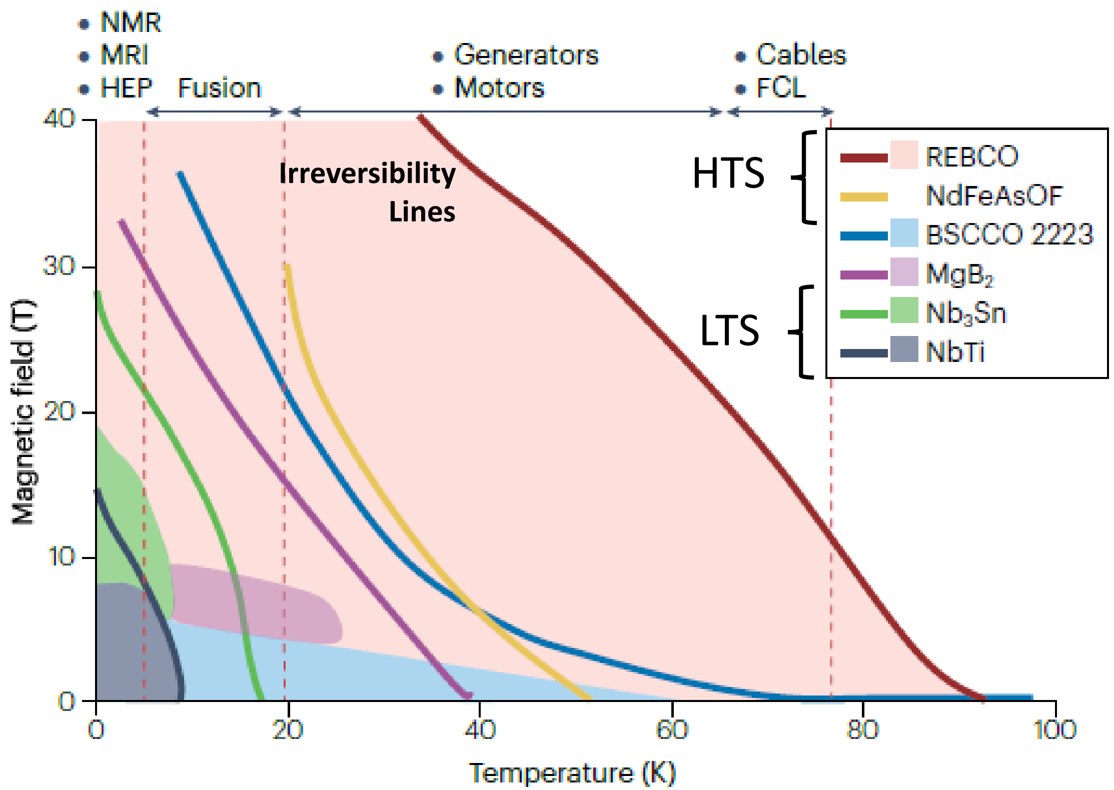
T. Puig et al, Nat Rev Phys (2024)

L. Soler, T. Puig et al, Nat Comm (2020)

A. Llordes, T. Puig et al, Nat Mat (2012)

J. Gutierrez,T. Puig et al, Nat Mat (2007)

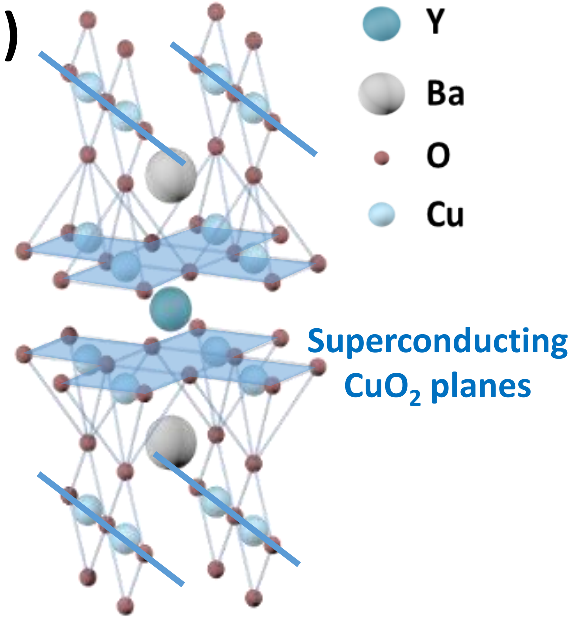
Superconducting materials operational limits



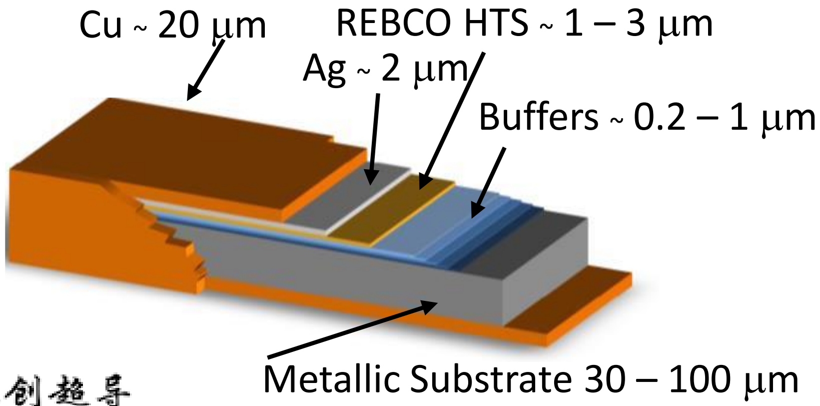
T. Puig et al, Nature Reviews Physics (2024)

$REBa_2Cu_3O_{7-x}$ RE (Y, Rare Earth)

- Oxide material, brittle
- Critical doping levels
- Heavily anisotropic ($\rho_c/\rho_{ab} \approx 10^2$-$10^4$)
- Single crystal type growth
- 20 years R&D



Coated Conductors *(in km length)*

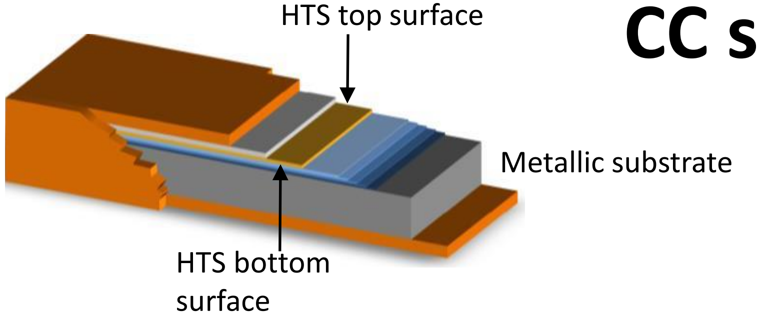


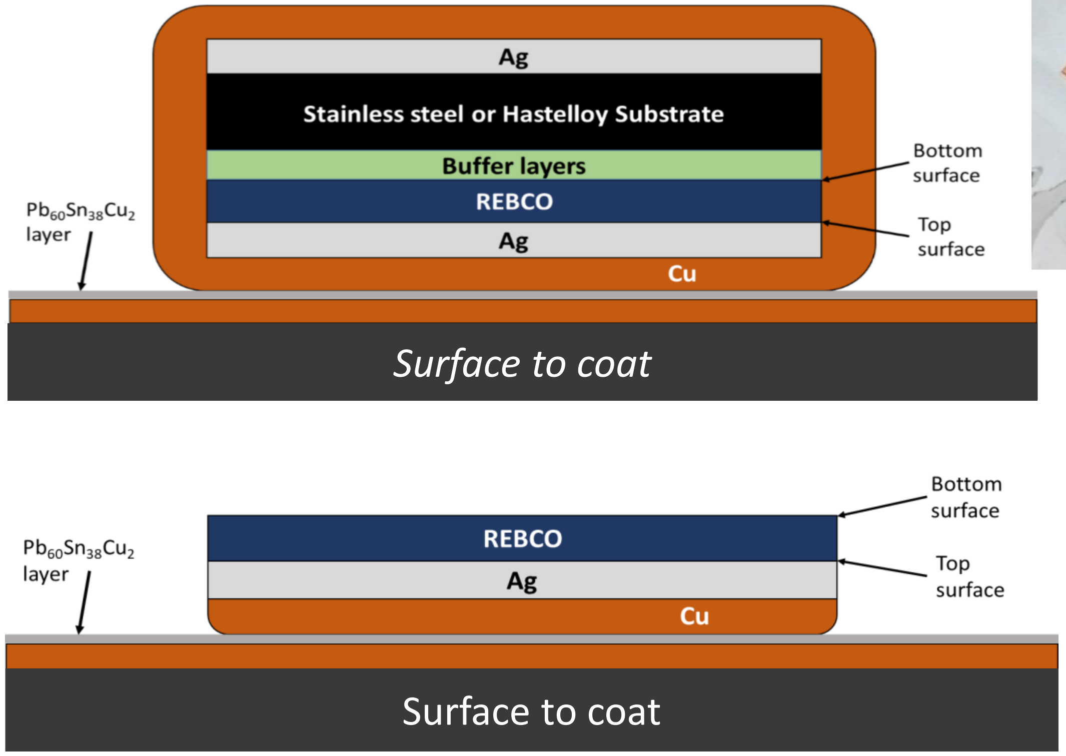
$T_c \approx 92$ K , H_{c2} (4.2K) > 100 T, H_{irr} (4.2K) > 60 T

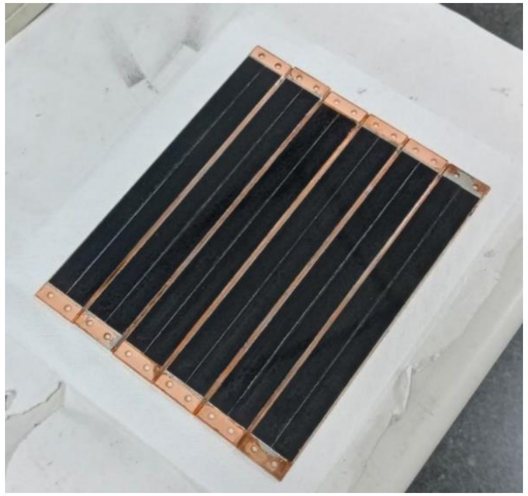
I_c(0T,77K)= 350-750 A/cm-w, I_c(20T,4.2K)= 1000-1600 A/cm-w

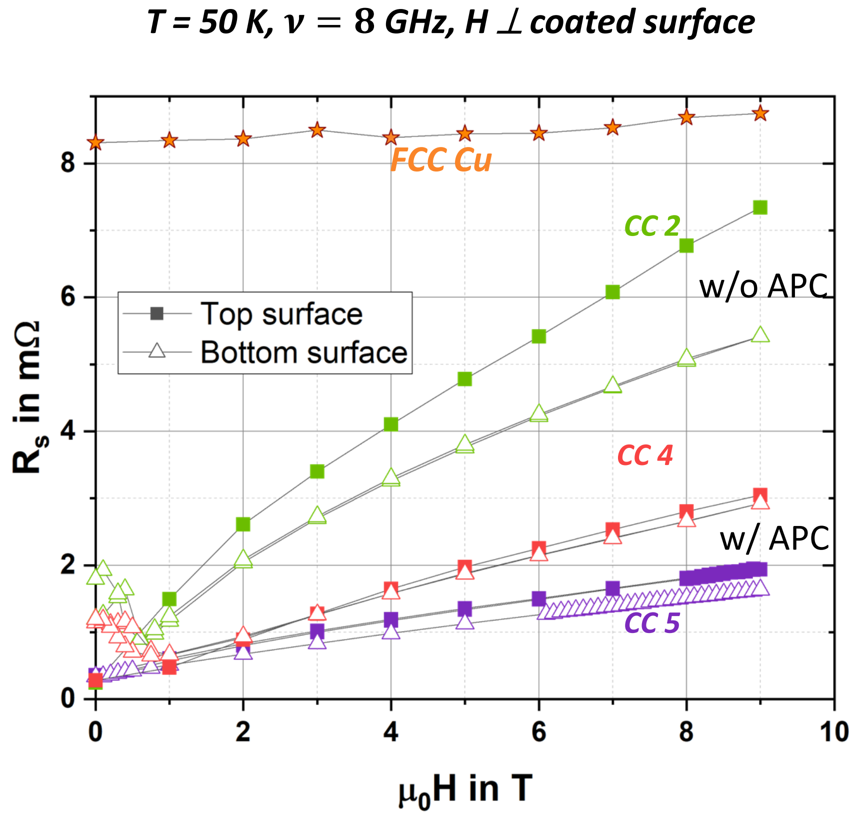
FARADAY FACTORY JAPAN THEVA 上海超导 SHANGHAI SUPERCONDUCTOR SuperPower Inc. "Tsunagu" Technology Fujikura SuNAM 上创超导

Scalable HTS coating technique based on CC soldering and substrate delamination









Properties retained

G. Telles et al, Supercond. Sci. Technol 36 (2023)
N. Lamas, et al. (to be submitted)