HIGHEST: high-gradient, high-temperature superconductors

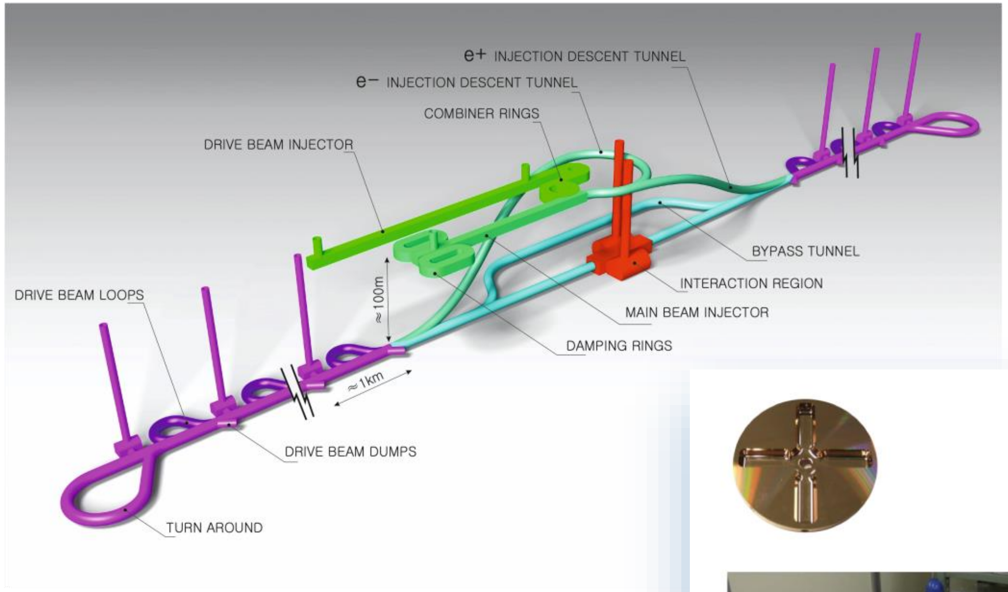
This project has received funding from the European Union's Horizon 2020
Research and Innovation programme under GA No 101004730.

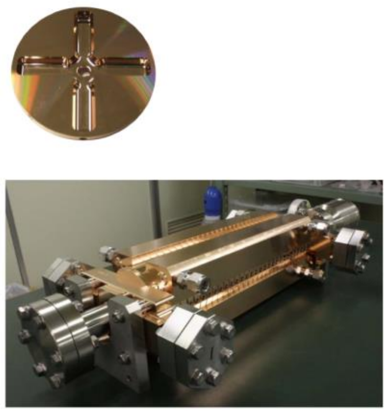
Sergio Calatroni, on behalf of the Collaboration.

A view on Linear Colliders

The Compact Linear Collider (CLIC)

Recent talks: eeFACT-I1 and eeFACTI2





Accelerating structure prototype for CLIC: 12 GHz (L~25 cm)

- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20'500 structures at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)

- CDR in 2012 with focus on 3 TeV. Updated project overview documents in 2018 (Project Implementation Plan) with focus 380 GeV for Higgs and top.

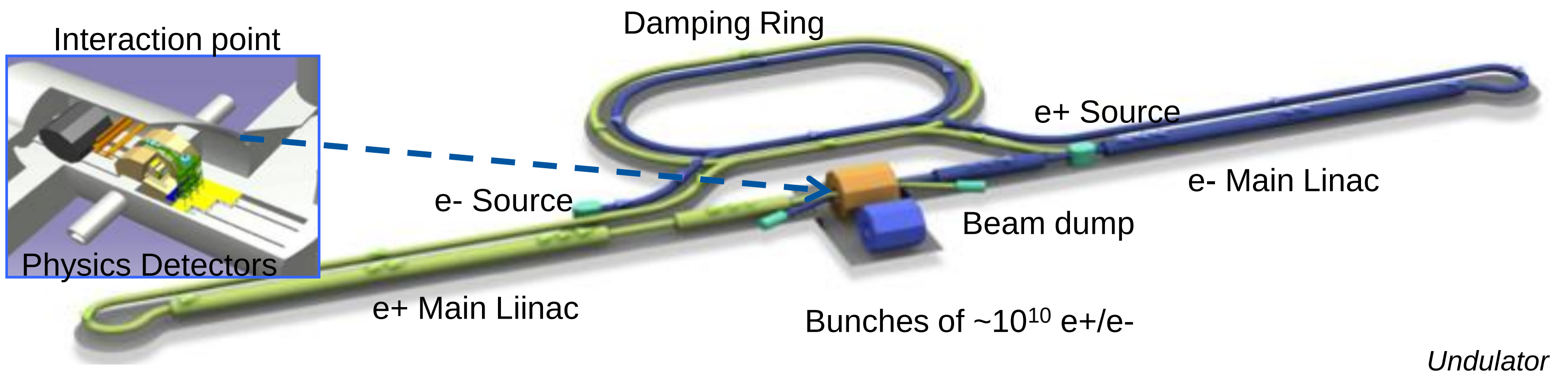
The CLIC accelerator studies are mature:

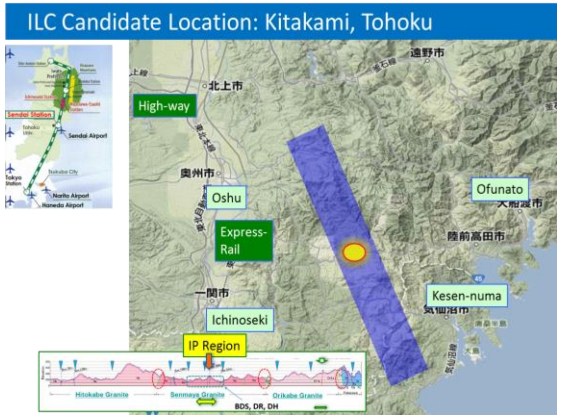
- Optimised design for cost and power
- Many tests in CTF3, FELs, light-sources and test-stands
- Technical developments of "all" key elements

From: Steinar Stapnes

The ILC250 accelerator facility

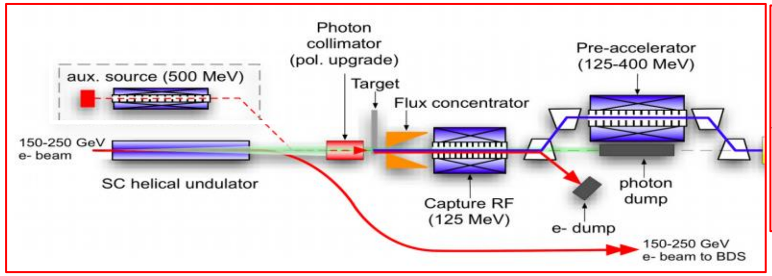
Recent talks: eeFACT-I1 and eeFACTI2

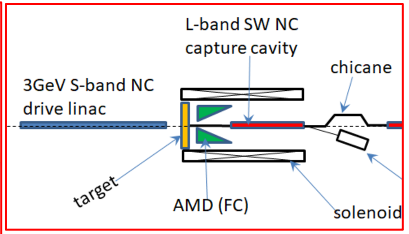




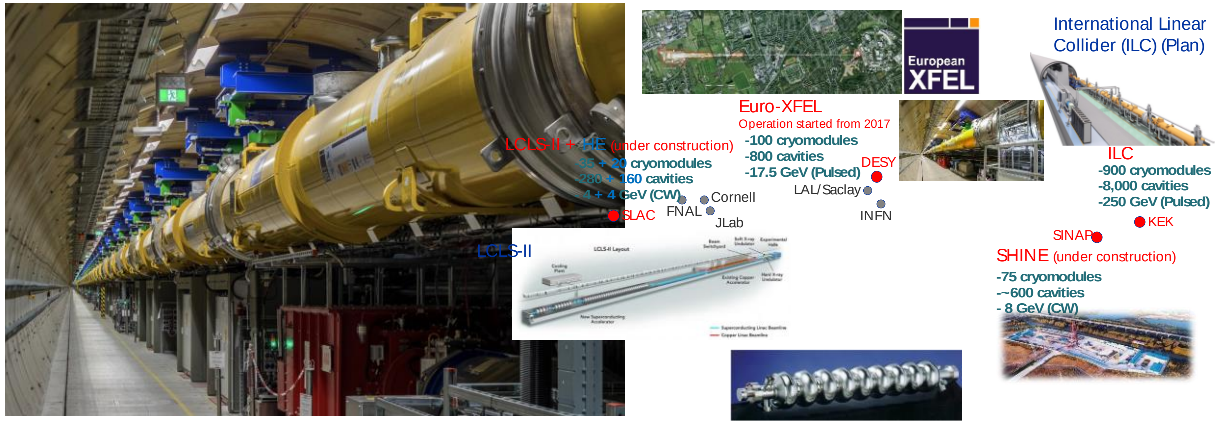
- Creating particles — Sources
  - polarized elections/positrons
- High quality beam — Damping ring
  - low emittance beams
- Acceleration — Main linac
  - superconducting radio frequency (SRF)
- Collide them — Final focus
  - nano-meter beams
- Go to — Beam dumps

Undulator positron source





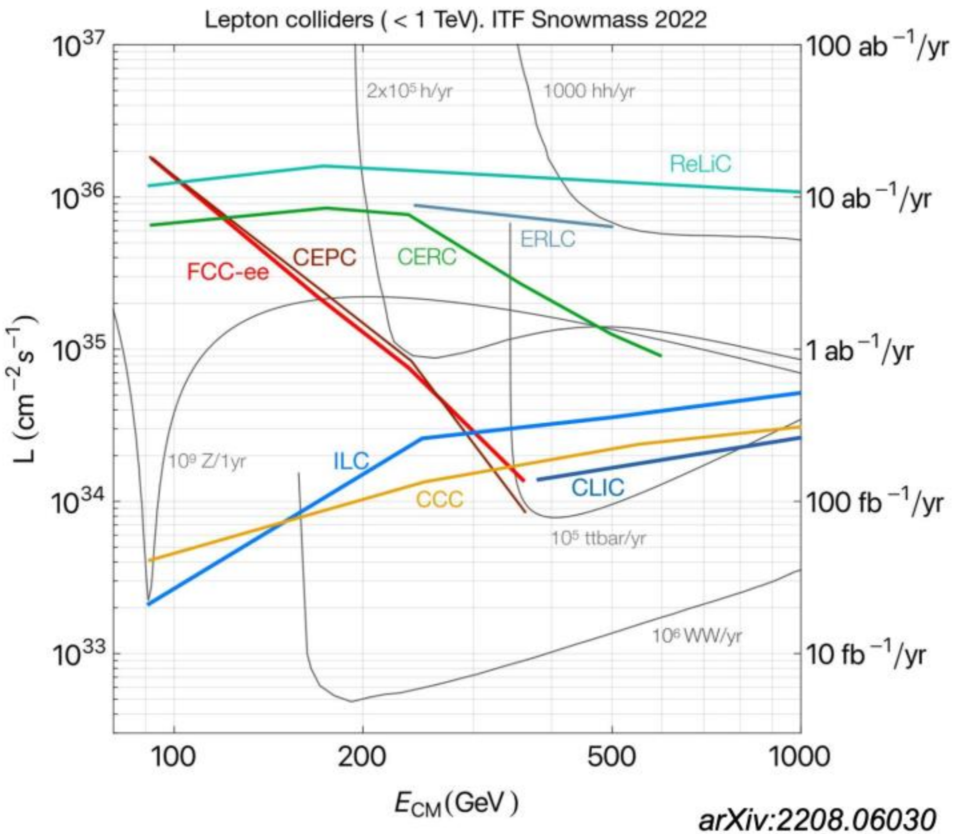
Electron driven positron source



From: Steinar Stapnes

e^+e^- machine comparison: Physics potential

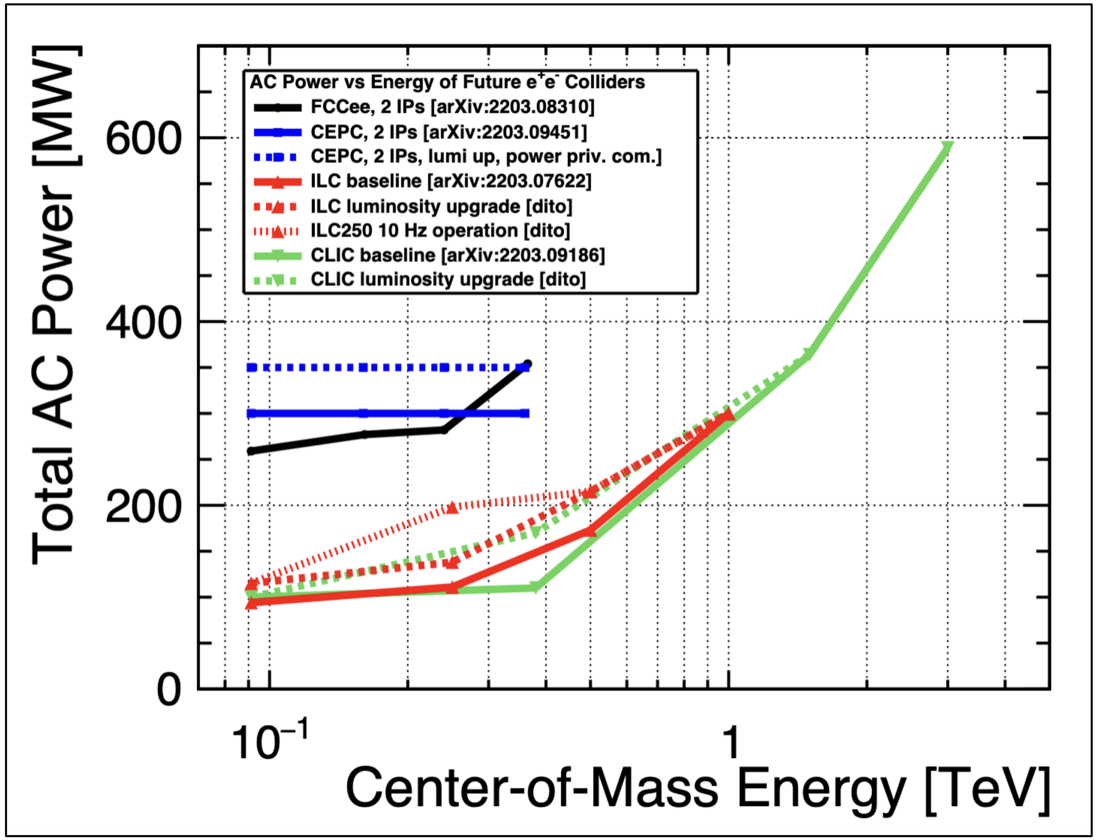
- Roughly equal number of Higgs produced for circular vs linear run plans
- Circular option enables precision EW Z and WW physics program
- Linear option enables extension to higher energies for Higgs self-coupling



arXiv:2208.06030

Which is best?

Power and energy: future colliders



Linear collider studies predict roughly similar power consumption for equivalent machines (ILC vs CLIC)

From: Steinar Stapnes

How can SC and NC have the same power consumption?

- Linear collider RF systems fall in two categories

SC niobium, $Q_0 \approx 10^{10}$, 35 MV/m, CW

$$R_s \propto 1/Q_0 \qquad P = \frac{1}{2} R_s H^2$$

NC copper, $Q_0 \approx 10^4$, 100 MV/m, pulsed

- Despite the ~10^6 difference in quality factor, (~10^3 considering cryo efficiency), pulsing at low duty factor allows reducing the average consumption for NC accelerating structures down to the SC level – which cannot be effectively be pulsed
- We want to verify whether HTS in pulsed RF mode allows a further power gain compared to both Nb and Cu

Cold Copper

Cryogenic temperature elevates performance in gradient

- Material strength is key factor
- Improved conductivity reduces material stress
- Increases rf efficiency

Operation at 77 K with liquid nitrogen is simple and practical

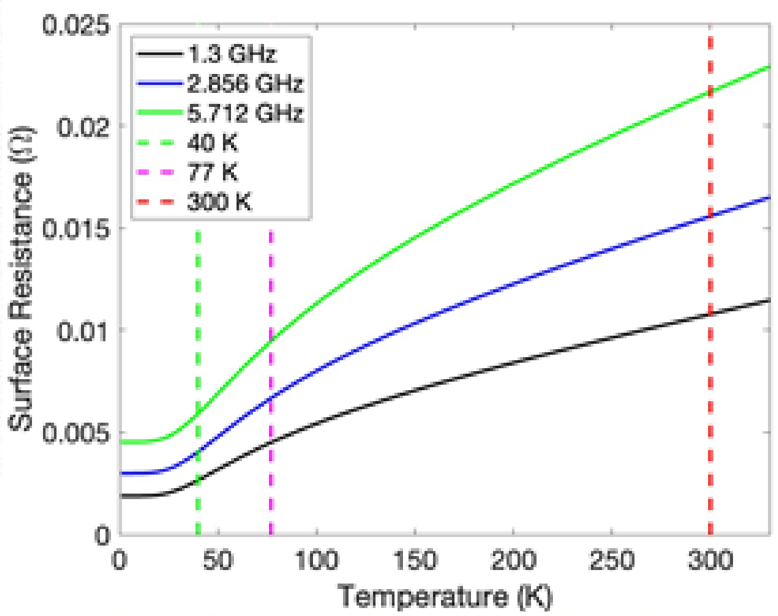
- Large-scale production, large heat capacity, simple handling
- Small impact on electrical efficiency*

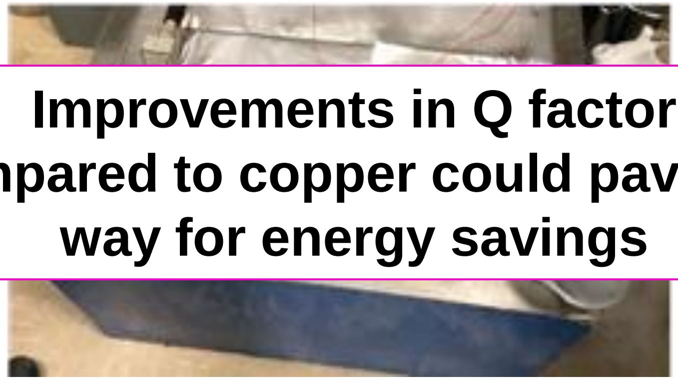
$$\eta_{cp} = LN\ Cryoplant$$
$$\eta_{cs} = Cryogenic\ Structure$$
$$\eta_k = RF\ Source$$

$$\frac{\eta_{cs}}{\eta_k}\eta_{cp} \approx \frac{2.5}{0.5}[0.15] \approx 0.75$$

SLAC

*Assumes long pulse regime, no rf compression





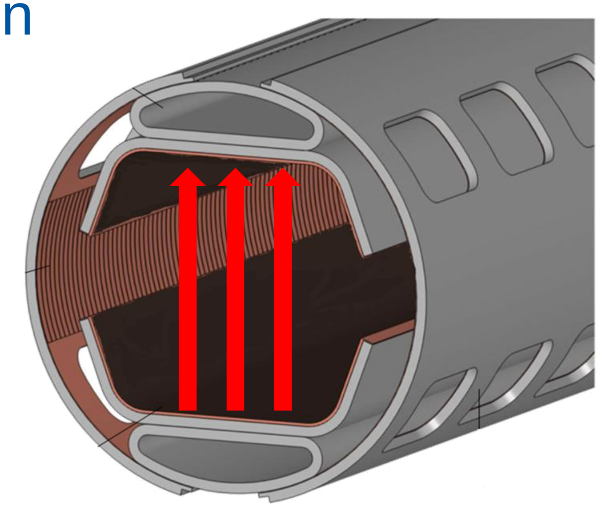
Improvements in Q factor compared to copper could pave the way for energy savings

From: Emilio Nanni

Background of HIGHEST

HTS for the FCC-hh beam screen

- FCC-hh, a proposed 100 TeV p-p collider at CERN, with 16 T dipoles operated at 1.9 K
- A beam screen held at 50 K, to protect the dipoles from synchrotron radiation ~30 W/m/beam (LHC < 0.2 W/m)
- HTS materials instead of copper in the FCC-hh beam screen, to improve beam stability (-> impedance) at 50 K
- Bunched particle beams produces RF fields, up to ~1 GHz
- Extremely challenging requirements:
  - HTS must operate at 50 K and 16 T
  - Critical fields Hc_2 , H_{irr} >> 16T
  - $J_c > 25$ kA/cm^2 (2.5x10^8 A/m^2)
  - Surface resistance R_s better than for copper
- Compatible with accelerator environment
  - Minimize dipole field distortion due to persistent currents
  - UHV compatible, low SEY, lifecycle assessment, etc..



16 Tesla !

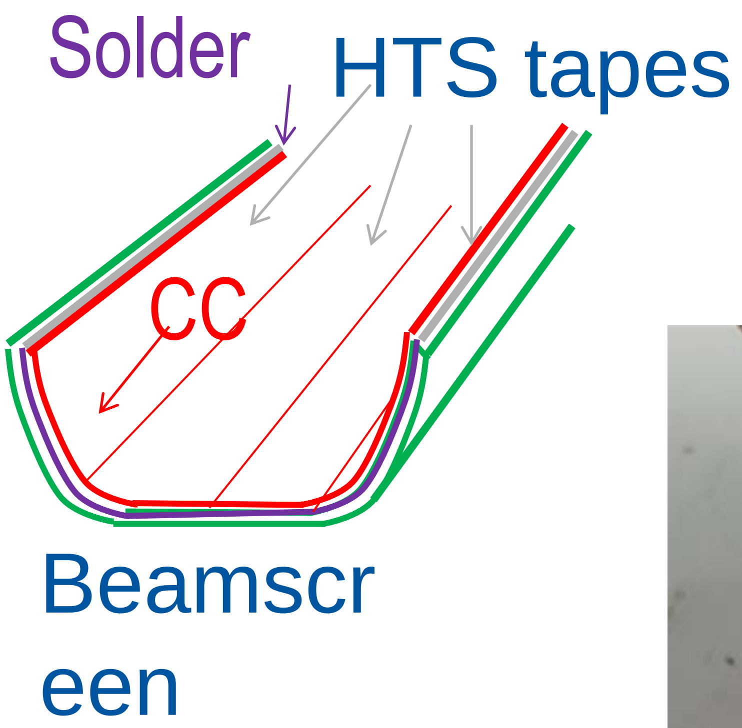
Calatroni, IEEE TAS 26, 3500204 (2016)
Calatroni et al, SuST 30, 075002 (2017)

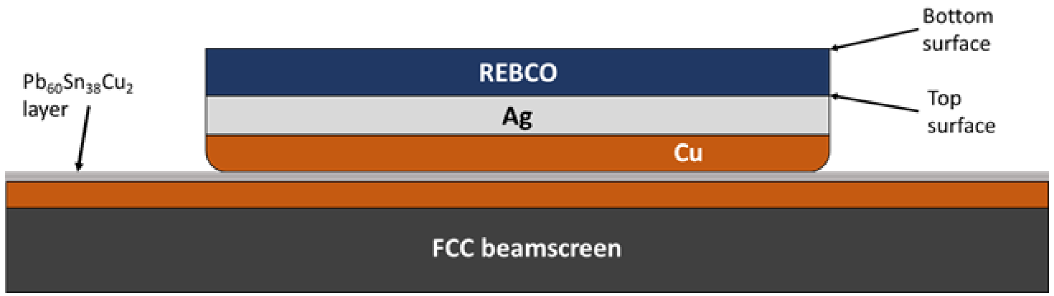
Two material choices

Manufacture the screen using REBCO tapes soldered to the screen

Coat the inside of the screen with Tl-1223 films

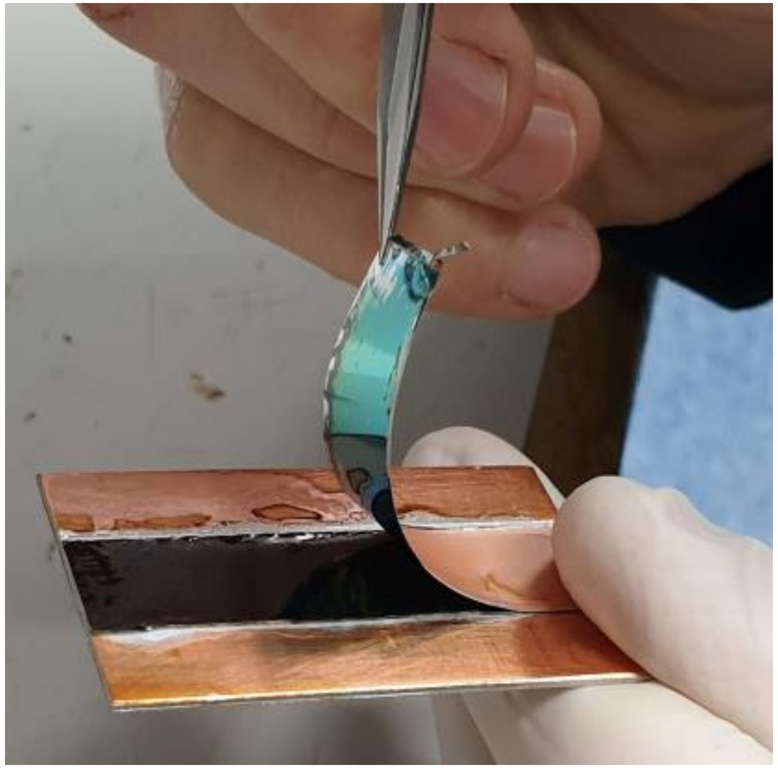
Development of soldering technology

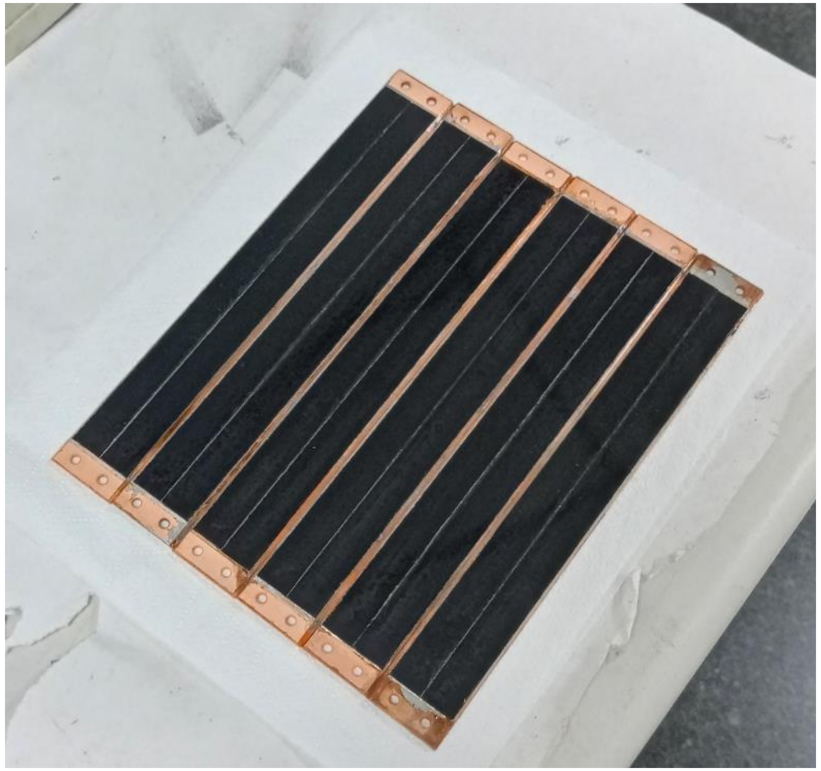




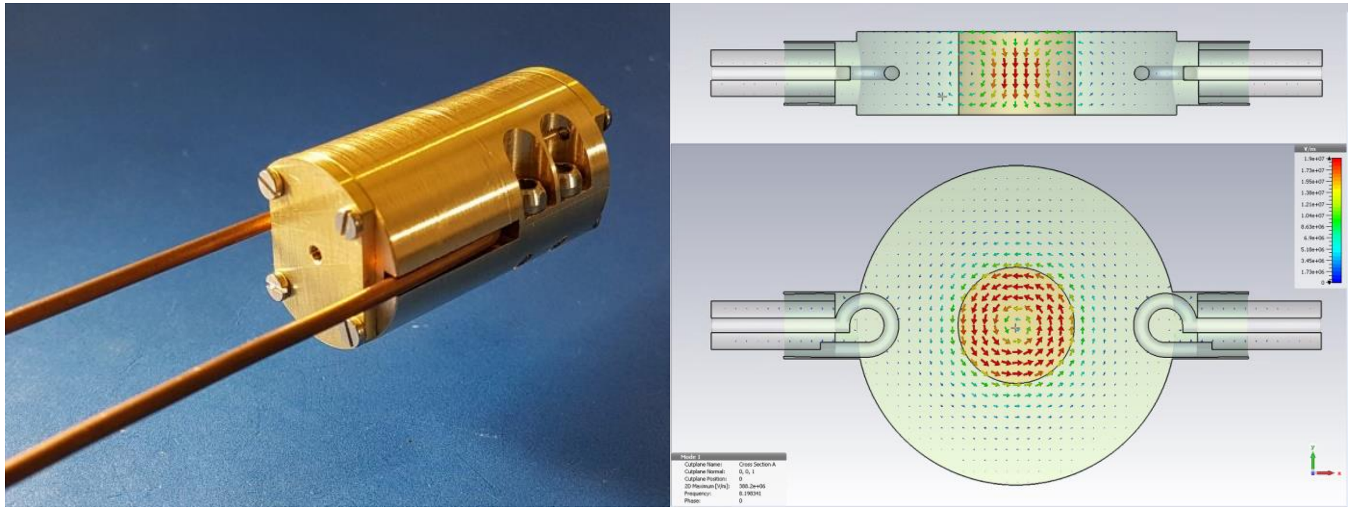
Solders based on Sn / Pb / Cu / Bi & In temperatures < 220ºC

2x80 km of beam screens to be coated with HTS





Validation of RF performance (UPC - ICMAB)



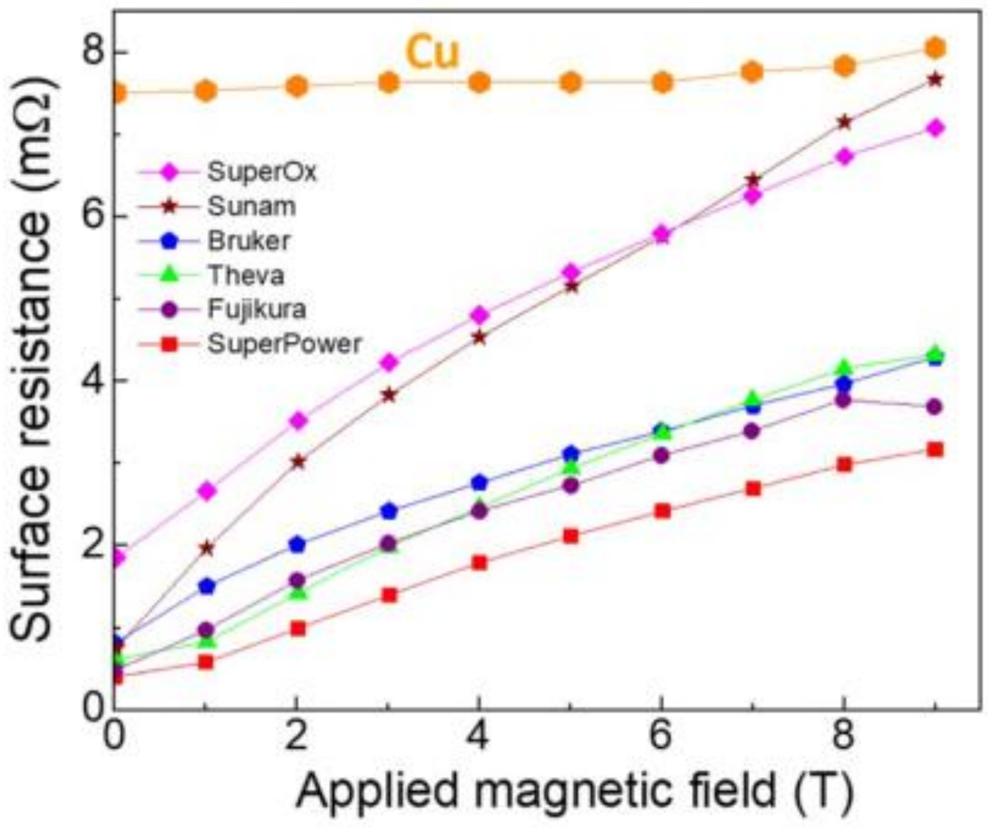


Figure 3. Magnetic field dependence of the surface resistance at 8 GHz and 50 K. Up to 9 T, CCs' R_s outperforms that of copper.

In house developed 8.05 GHz cavity resonator compatible with 25mm bore 9 T magnet at ICMAB

REBCO CCs outperform Cu at 50K and up to 9T
R_S is microstructure dependent

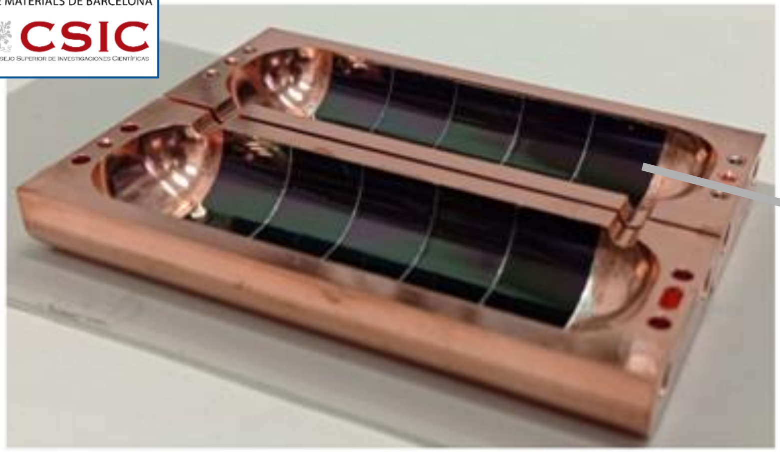
Puig et al, SuST 32, 094006 (2019)

FUTURE CIRCULAR COLLIDER

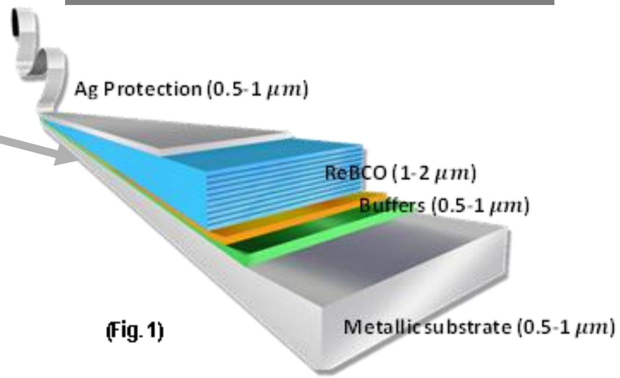
Surface currents equivalent to 0.1 MV/m of a typical accelerating cavity

First real cavity, f≈9 GHz

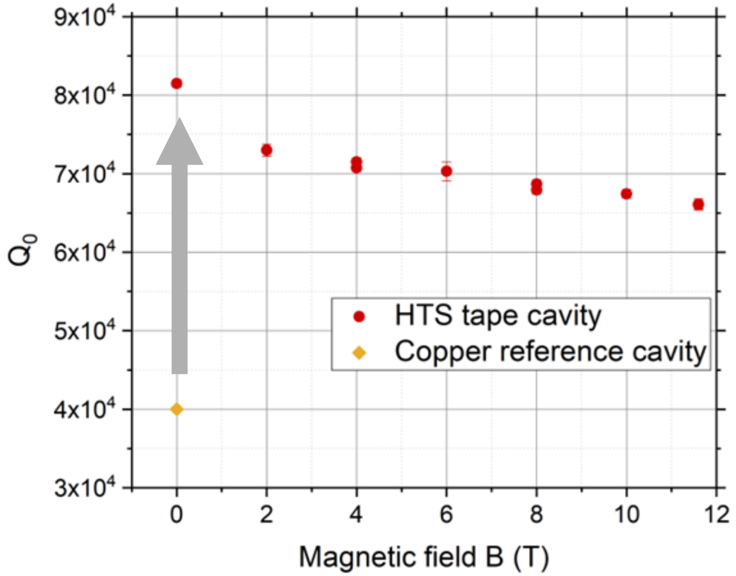
- We have developed a technology for applying 2D HTS tapes to 3D RF "RADES" cavities demonstrating the potential of HTS for RF applications J. Golm et al., IEEE TAS, Vol. 32, No. 4, (2022) 1500605



12 mm-wide HTS tapes



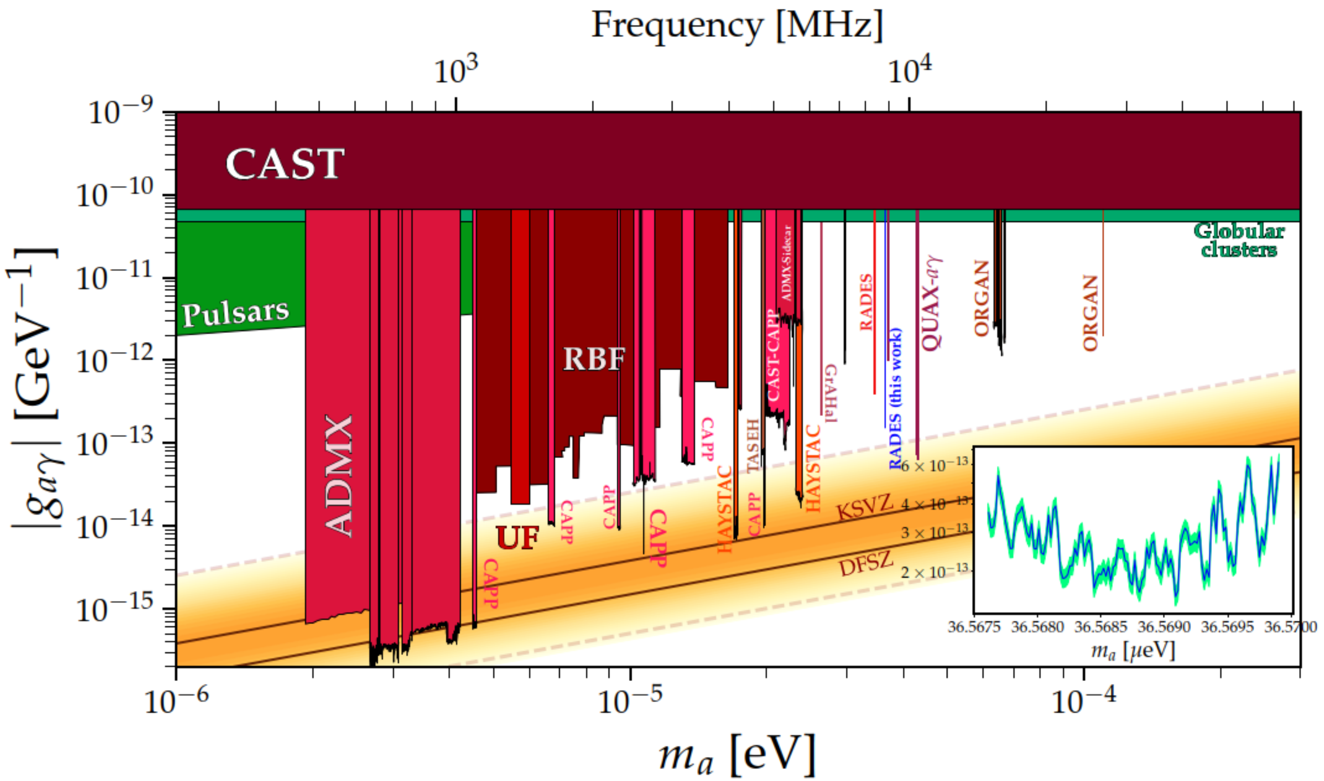
2x improvement of RF quality factor compared to copper
(newer prototype 5x improvement)



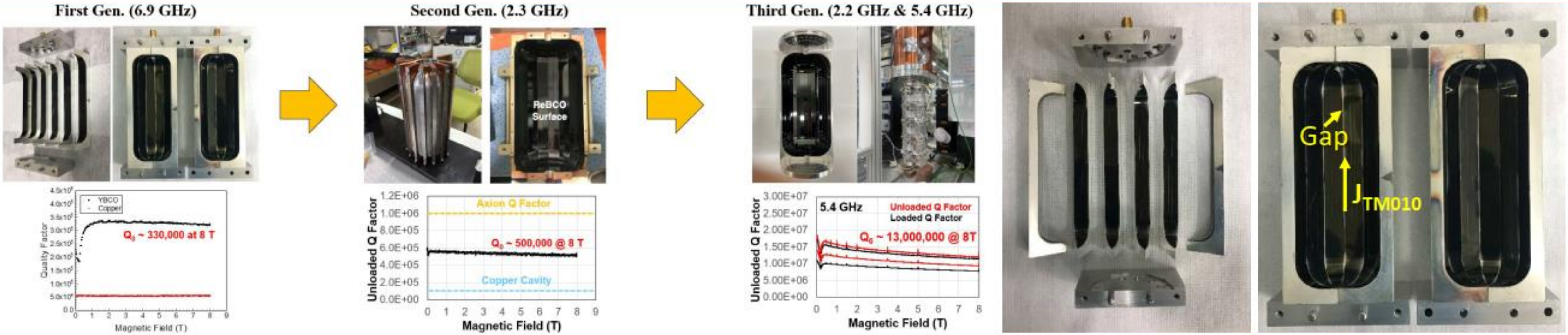
RADES cavity for axion searches

First published physics results with an HTS coated cavity

arXiv:2403.07790



Other results from CAPP



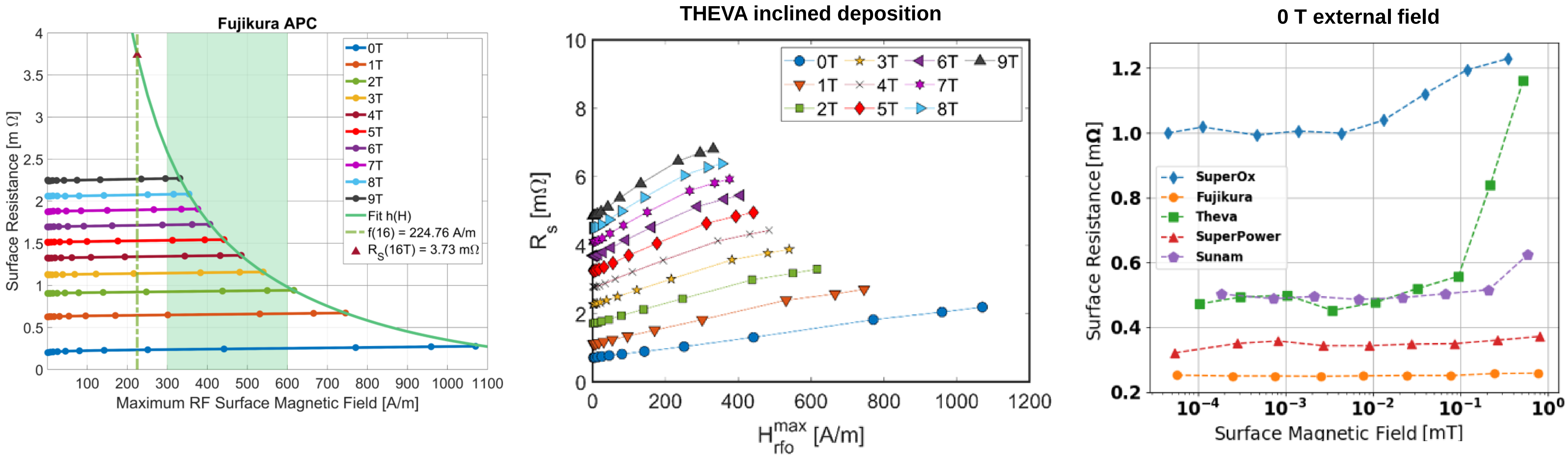
Gen	Tape	f (GHz)	n_{gap}	Q (0 T)	Q (8 T)	Q_{gap}	Experiment
1	YBCO	6.9	12	0.22 M	0.33 M		Prototype
2	GdBCO	2.3	32	0.60 M	0.50 M	3.5x10^{-5} Ω	Axion Haloscope
3-0	GdBCO	2.2x10^{-5} Ω	12	1.1 M	1.2 M		Prototype
3-1	EuBCO+APC	2.3	34	5.0 M	3.5 M	> 10 M	Axion Quark Nugget Search
3-2	EuBCO+APC	5.4	14	20 M	13 M	N Polygonal Structure w/ N Gaps	Axion Haloscope
4	EuBCO+APC	1.5	?	?	?		Axion Haloscope (CAPP-MAX)

18TH PATRAS WORKSHOP

From: D. Ahn, CAPP. More info at Patras Workshop 31

Goals of HIGHEST

ICMAB – UPC: testing at higher RF power

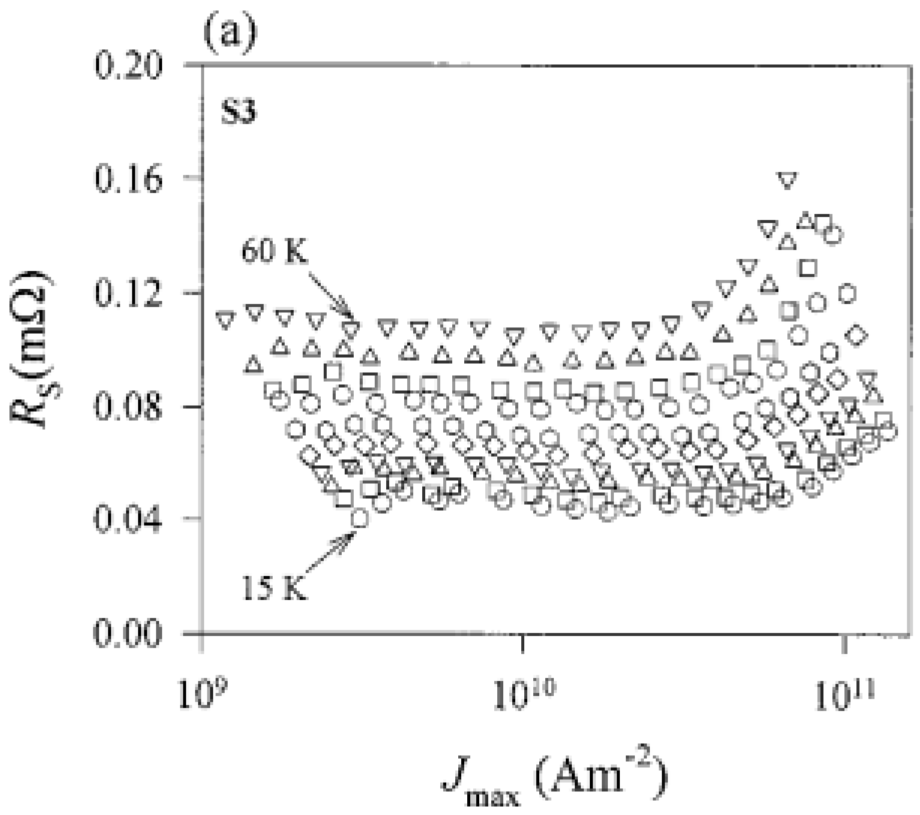


HTS coated conductors at 8 GHz (dielectric resonator) and 50 K

Patrick Krkotic, PhD dissertation, UPC Barcelona 2022

Literature review

- There are very few measurements on HTS at high RF currents (mostly microstrip resonators). But physics is proven.



~10^{11} A/m^2 RF current (microstrip resonator, 200 µm, 350 nm thick, 8 GHz)

Powell et al. Journal of Applied Physics 86, 2137 (1999)

For 1 µm thickness this is equivalent to 10^5 A/m (≅ 0.1 T ≅ 25 MV/m)

Entering the "high-gradient" range

Literature review - II

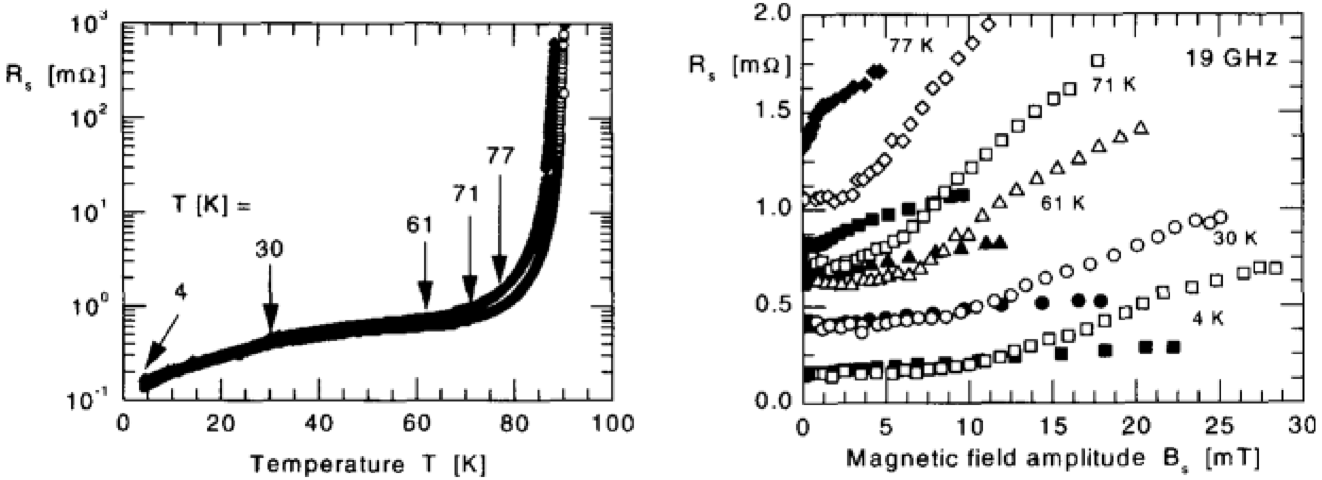


Fig. 4.1. Temperature dependence at 19 GHz (*left part*) of the surface resistance a ⌀2″ laser-ablated film (*diamonds*, "L49", [23]) and a ⌀1″ DC-sputtered film (*circles*, "S145", [24]). The *right part* displays the field dependences $R_s(B_s)$ of both films at the temperatures indicated by *arrows* in the left part. *Filled (open) symbols* refer to the laser-ablated (sputtered) films.

23. T. Kaiser: Dissertation, University of Wuppertal, Report WUB-DIS 98-13 (1998).
24. T. Bollmeier, W. Biegel, B. Schey, B. Stritzker, W. Diete, T. Kaiser, G. Müller:

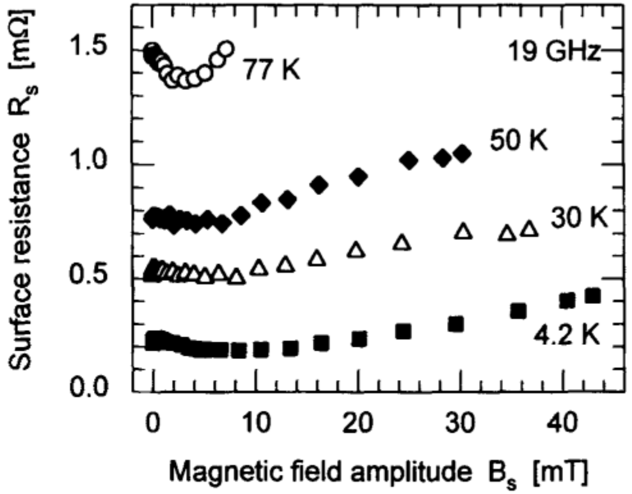
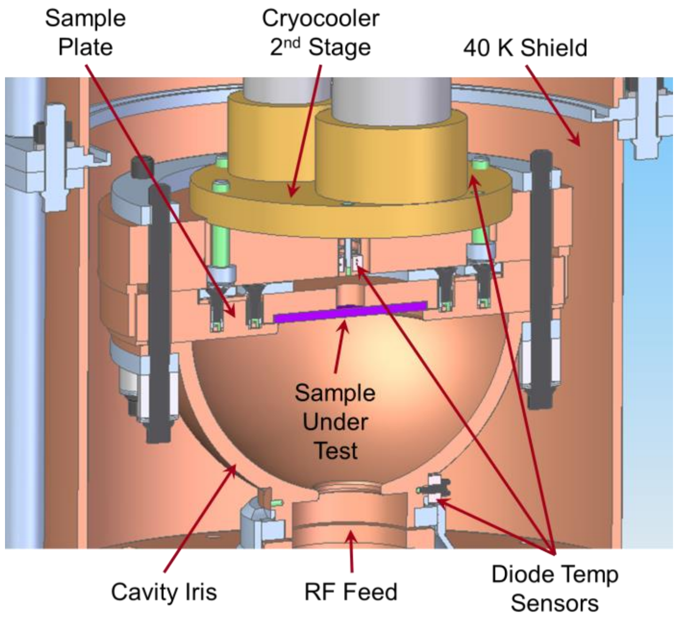


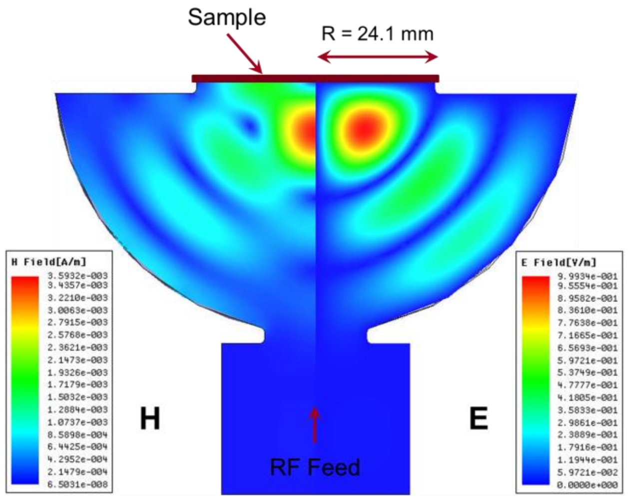
Fig. 4.31. Anomalous microwave field dependences $R_s(B_s)$ at 19 GHz for the two DC-sputtered films S178 (T = 77 K, *circles*) and S373 (T = 4.2 K (*squares*), 30 K (*triangles*) and 50 K (*diamonds*)) [23].

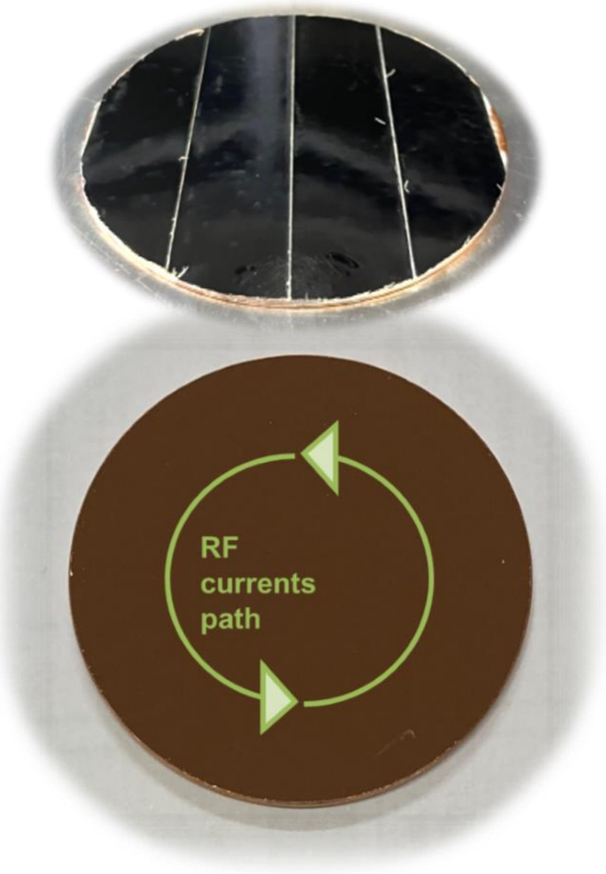
From: M. Hein, "High-Temperature-Superconductor Thin Films at Microwave Frequencies" (Springer Tracts in Modern Physics, 155)

High-gradient testing at SLAC – supported by I.FAST IIF

- "Mushroom" cavity. Can achieve H_{peak} of about 360 mT – 2.9×10^5 A/m (equivalent to ~80 MV/m in a standard accelerating cavity) using 50 MW XL-4 Klystron at 11.4 GHz.
- Zero E-field on the sample
- Maximum H-field on the sample
- Sample accounts for ⅓ of total cavity loss







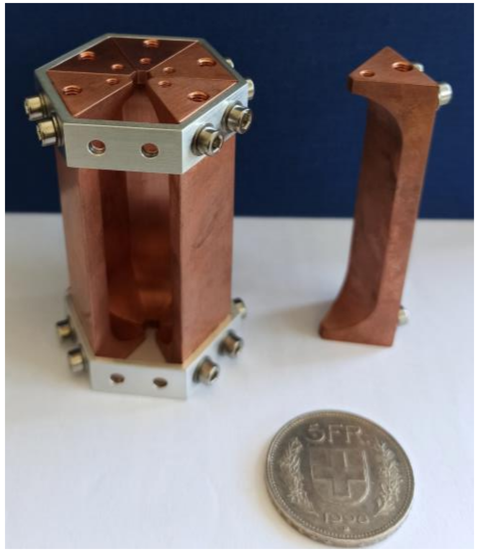
Goal: demonstrate and qualify high-gradient pulsed operation of HTS, at cryo-temperatures

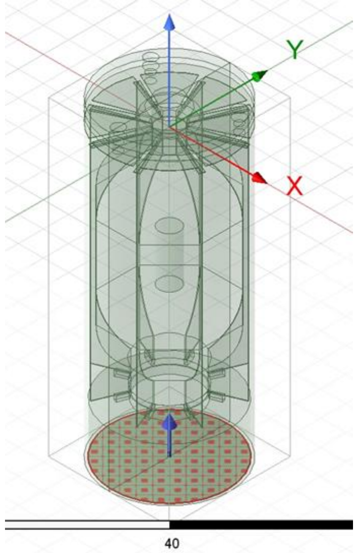
Work plan from 4/2023 to 4/2025

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
WP 1 (CERN)								
Coordination activities								
Samples and substrates procurement		M1						
RF low power characterization of segmented cavities (small tapes)					D1			
Final report								D2
WP 2 (KCT)								
Design and fabrication of sample holder system				M1				
HTS coating of large samples								D1
WP3 (CSIC-ICMAB)								
Coating on discs and segmented cavities for benchmarking (small tapes)				D1				
Measurement of superconducting properties of large size tapes								D2
SLAC supporting partner								
RF high power characterization of 3D coated HTS discs in their mushroom cavity								

Segmented cavities

CERN Segmented cavity for axion detection

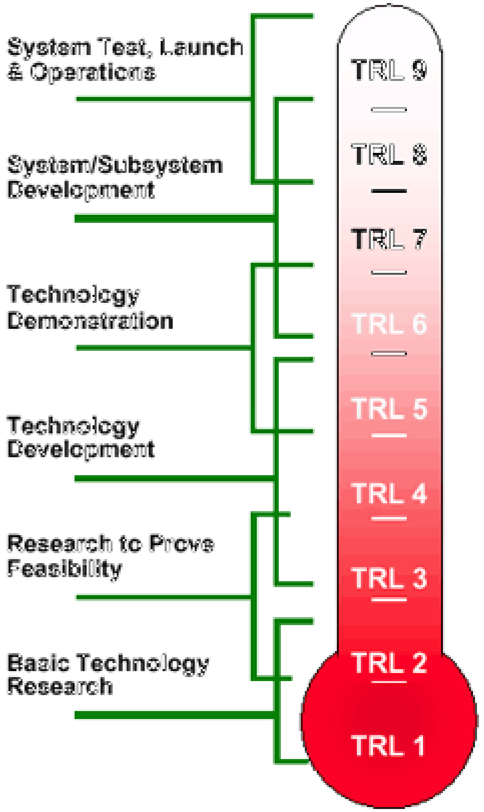




SLAC Segmented cavity for RF pulse compressor

Industrial application prospect

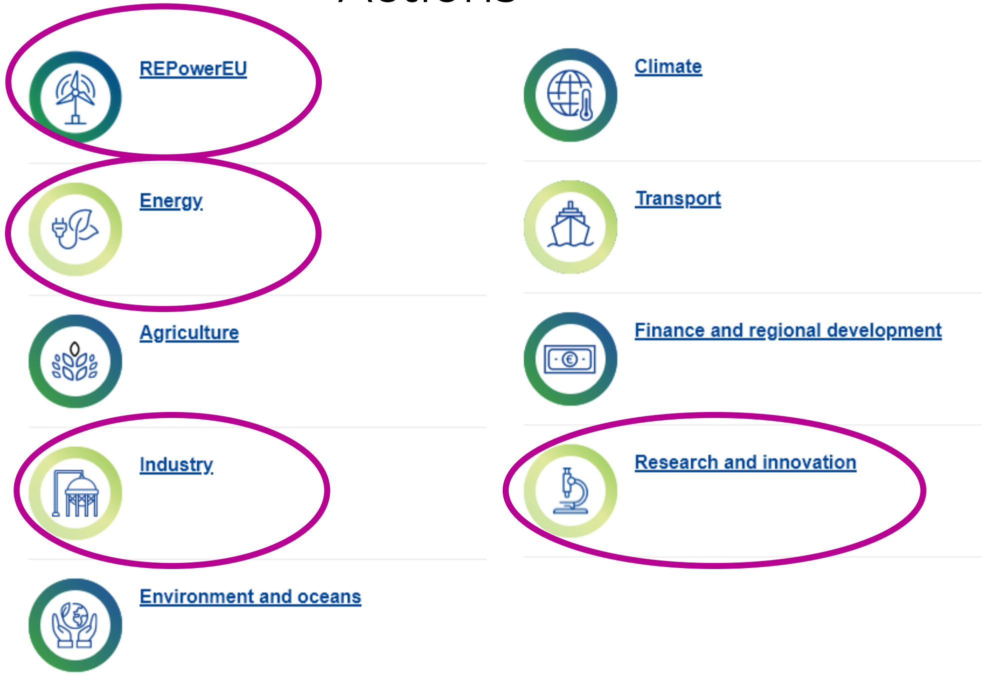
- At the end of this study, we aim at consolidating TRL4.
- Prototype pulse compressor with SLAC will demonstrate TRL6.
  - Timescale: 2-3 years after completion of this study
  - Need a further round of funding
  - This will include the design, fabrication and coating, and its validation in a high-power RF bench test bench.
- Future accelerator projects will drive achieving further TRLs and drive commercialization.
  - Industry will be involved for construction of devices
  - Other companies may be involved for hardware manufacturing



Addressing the European Green Deal

Benefits

Actions



- New-generation collider linacs are expected to use hundreds of MW of electricity
- Energy savings from HTS are in line with current policies of societal impact minimization

Resources and budget

- CERN:
  - Provided resources: two senior physicist (scientific coordination, 0.2 FTE) and one senior Fellow (follow up, measurements, 0.5 FTE)
  - Requested resources: 10 kEUR (sample manufacturing)
- KCT:
  - Provided resources: one senior scientist (design, procurement, coating, 1 FTE)
  - Requested resources: 100 kEUR (80 kEUR manpower for coating operations, 20 kEUR sample holder manufacturing)
- CSIC-ICMAB:
  - Provided resources: one senior scientist (0.2 FTE), and one PhD student (0.5 FTE)
  - Requested resources: 50 kEUR (40 kEUR PhD student and manpower for coating and characterization work, 10 kEUR consumable)

Ratio for the requested IIF funds: 120 kEUR personnel and labour / 40 kEUR material

- Final deliverable is a report on the demonstrated achieved performance, and on the prospects for scalability to accelerator-scale RF devices.

Budget table

	Manpower	Materials	Total
CERN		10 kEUR	10 kEUR
KCT	80 kEUR	20 kEUR	100 kEUR
CSIC-ICMAB	40 kEUR	10 kEUR	50 kEUR
			160 kEUR

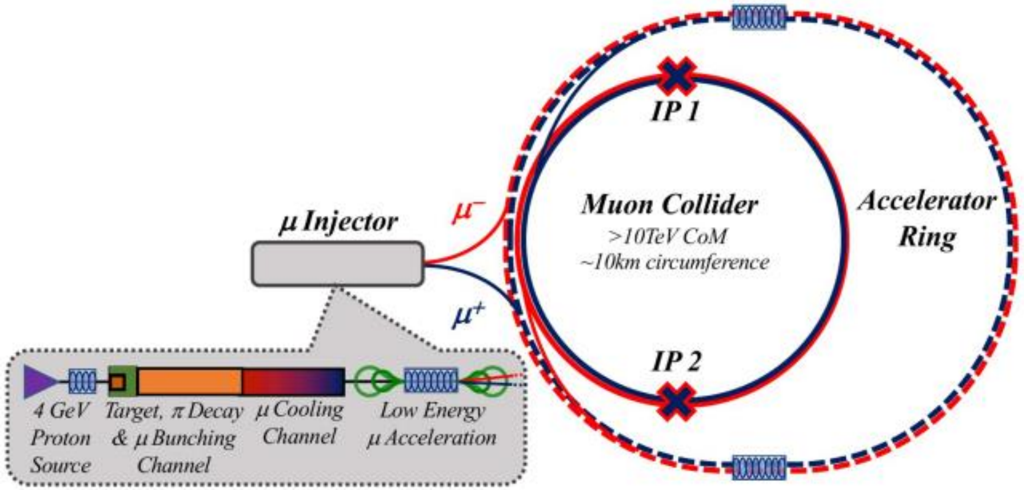
A possible future ?

Muon Collider

- Muon collider → potential short cut to the energy frontier
  - Multi-TeV collisions in next generation facility
  - Combine precision potential of e^+e^- with discovery potential of pp
  - High-flux, TeV-scale neutrino beams for nuclear & BSM physics
- Bright muon beams are required
  - Protons onto a target to make pions
  - Pions are captured and decay to muons
  - Muon beam is cooled to get to high brightness
- Cooling time must be competitive with muon lifetime
  - Ionisation cooling

International MUON Collider Collaboration

MuCol

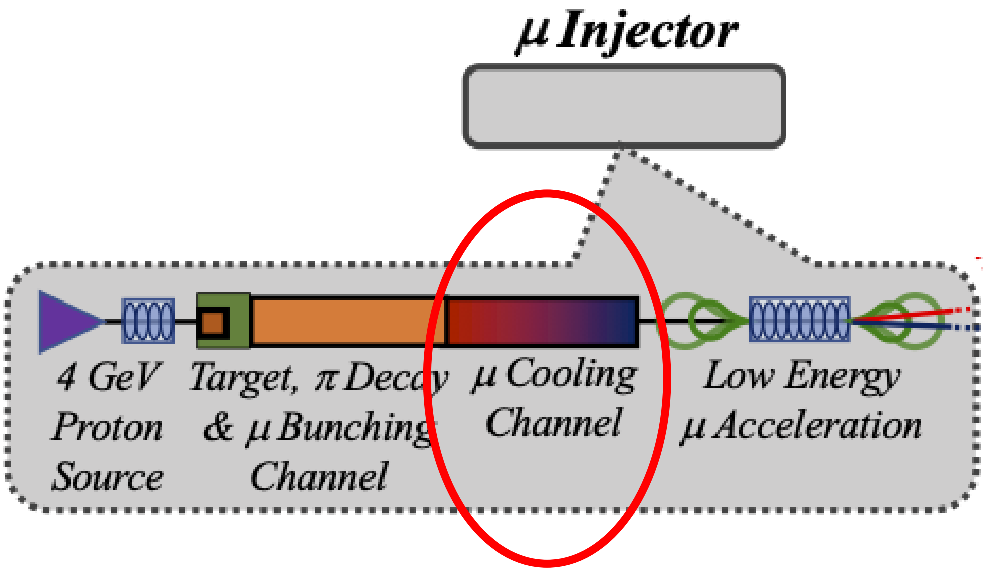


Muons/bunch	N	10^{12}	2.2
Repetition rate	f_r	Hz	5
Beam power	P_{coll}	MW	5.3
RMS longitudinal emittance	$\varepsilon_{\parallel}$	eVs	0.025
Norm. RMS transverse emittance	$\varepsilon_{\perp}$	μm	25

From: Chris Rogers

Muon collider

- Muon cooling system requires RF cavities operating at high-gradient AND in a strong magnetic field.



- Normal conducting copper, possibly cryo: baseline option
- A dream: High-Temperature Superconductors ?

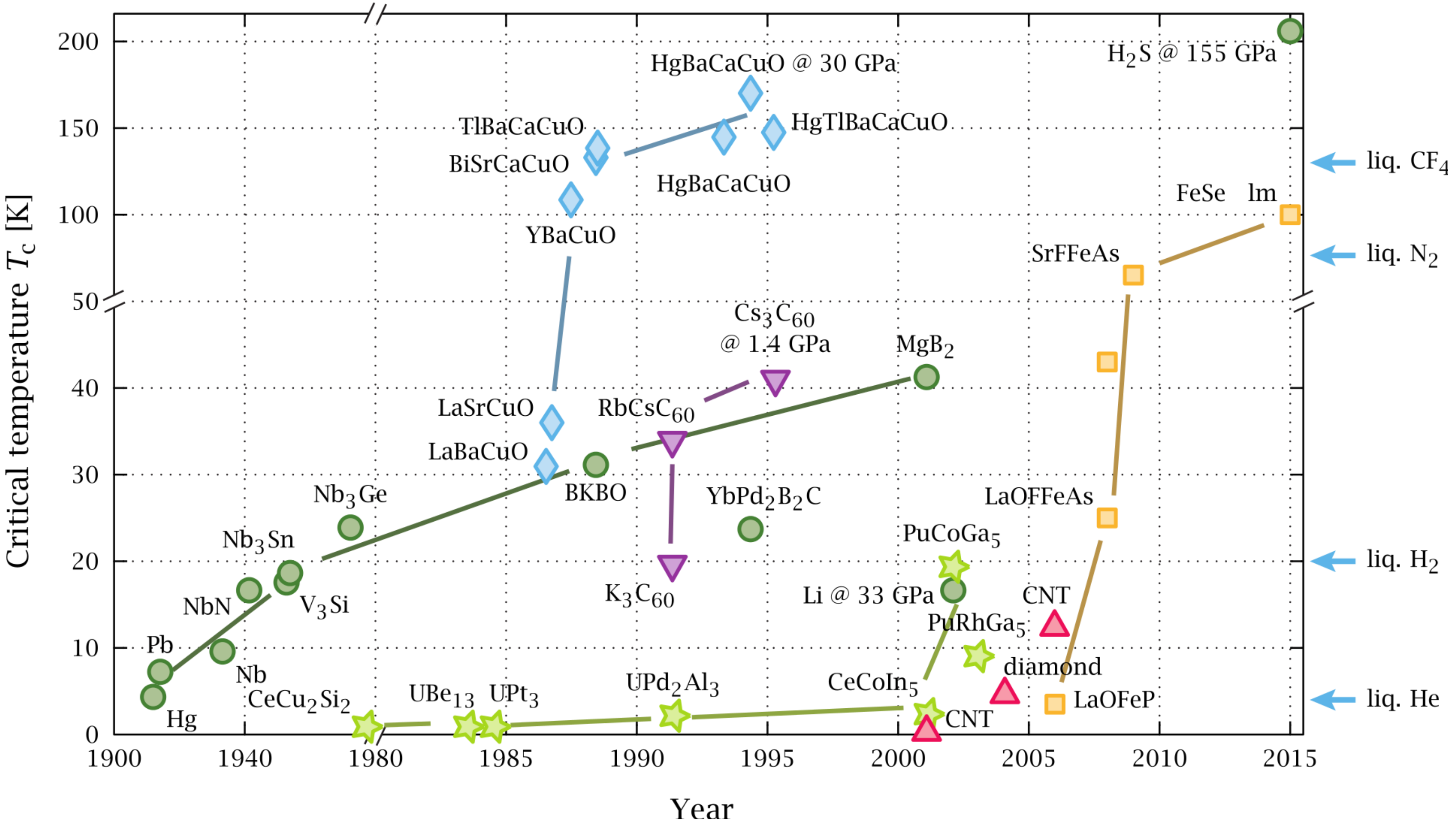
Final remarks

- No data exist for modern HTS at high-gradient RF (either samples or cavities): experiments needed
- Fabrication technologies for real cavities must be developed: wider soldered tapes within the iFAST collaboration “HIGHEST”
- Eventually, develop a direct HTS coating technique on copper

CERN

High-temperature Superconductors

Superconductors zoo



By PJRay - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=46193149

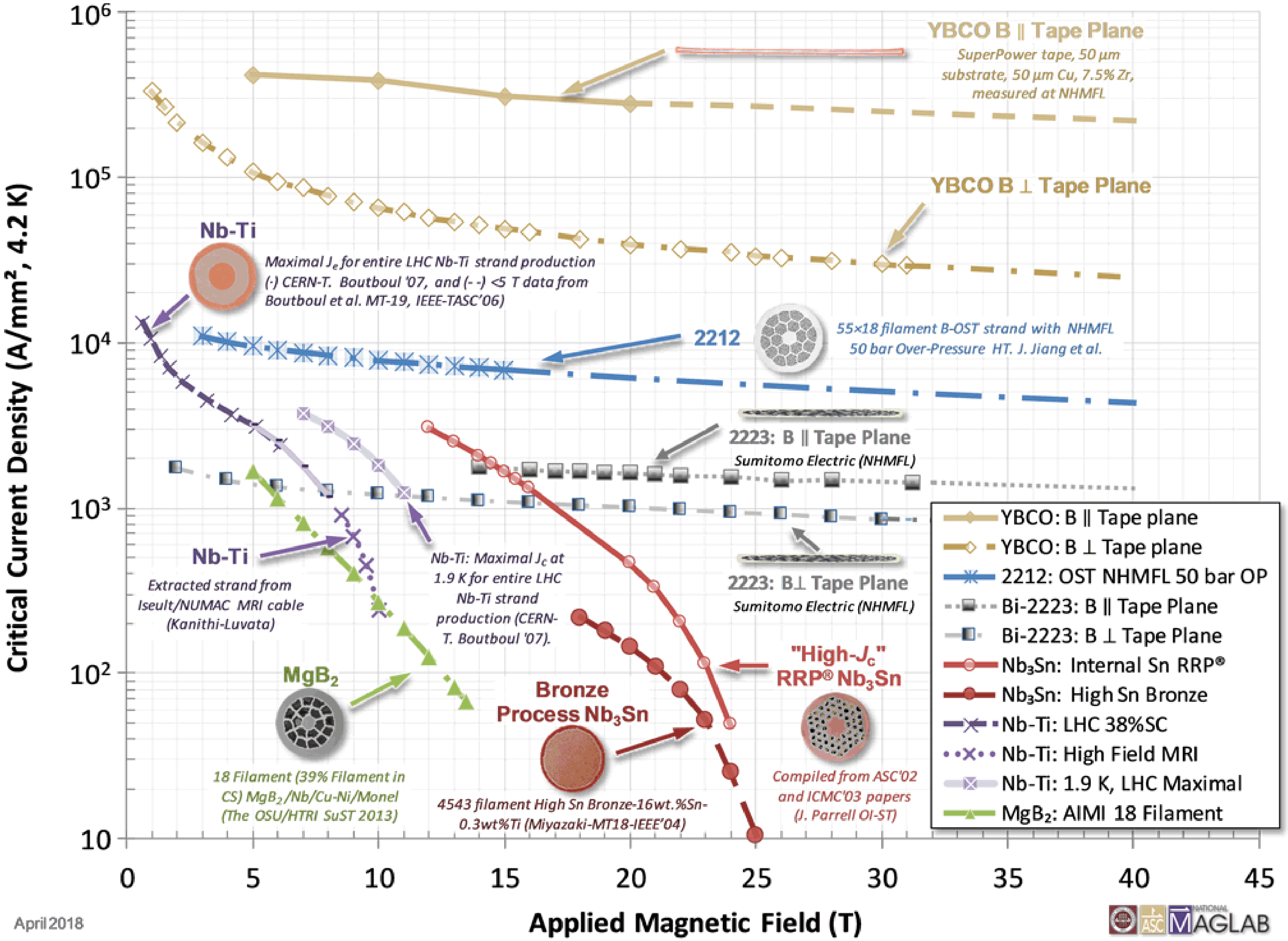
Zoo of superconductors

J_c may vary of orders of magnitude.
H_{c2} has much smaller variation.

YBCO most promising candidate

NbTi – NbTiN possible candidates at B < 10T

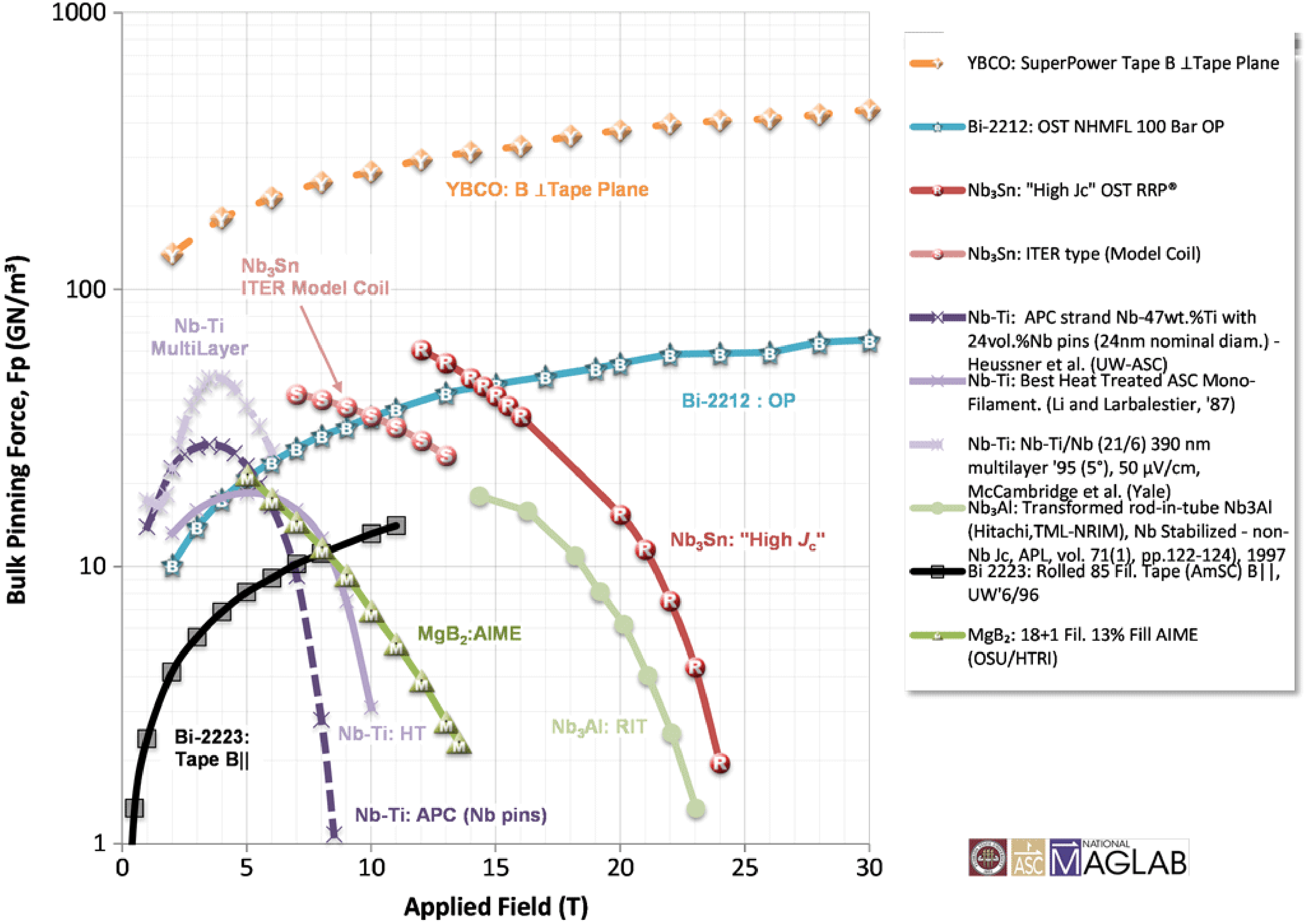
Nb_3Sn for B < 15 T



https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

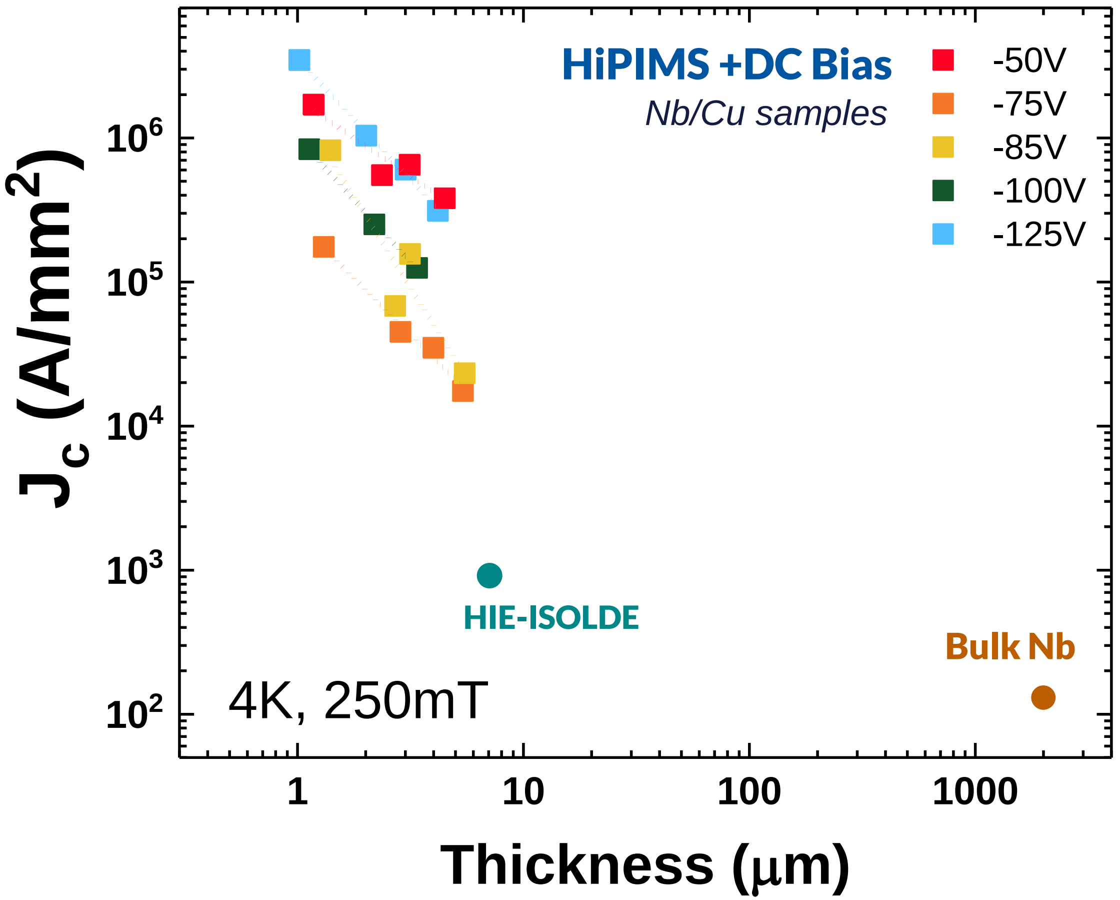
Zoo of superconductors

Pinning force



https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

First: a caveat



J_C decrease is guiding the development of Nb/Cu films

Rationale:

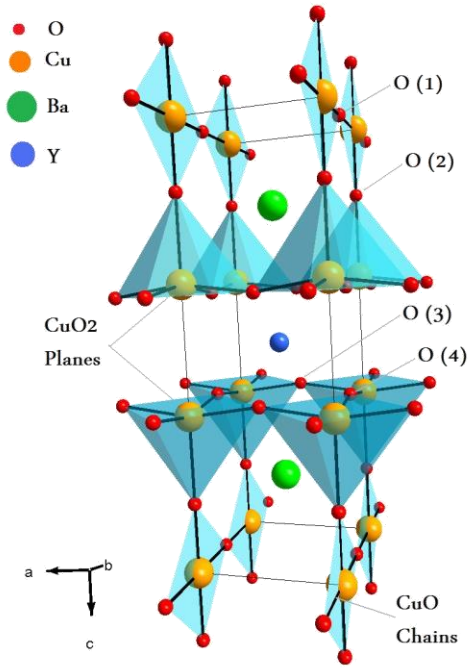
- Results from HIE-ISOLDE and bulk Nb
- Modelling of losses as hysteretic losses from RF fluxons penetration

Existing HTS Coated Conductors might not be the best choice at high-gradient RF, being optimized for flux pinning

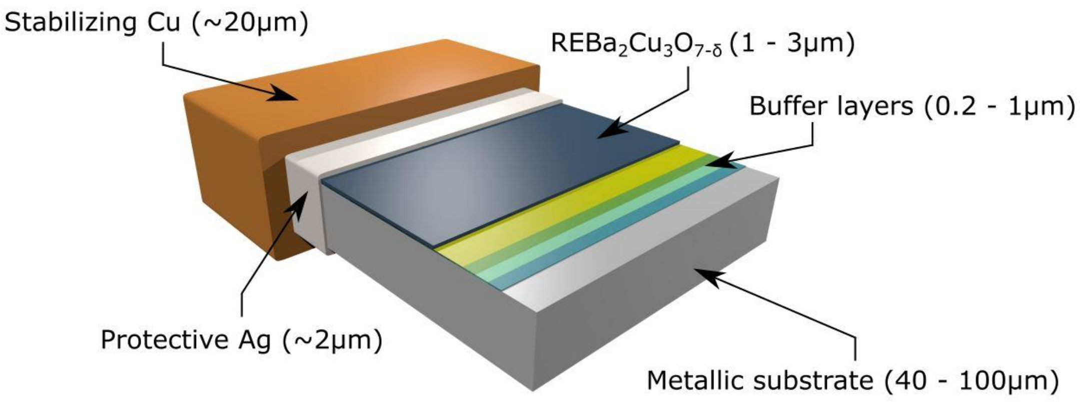
From: Carlota Pereira Carlos

REBCO coated conductors

REBCO crystal structure



Scheme of Coated Conductor (CC)



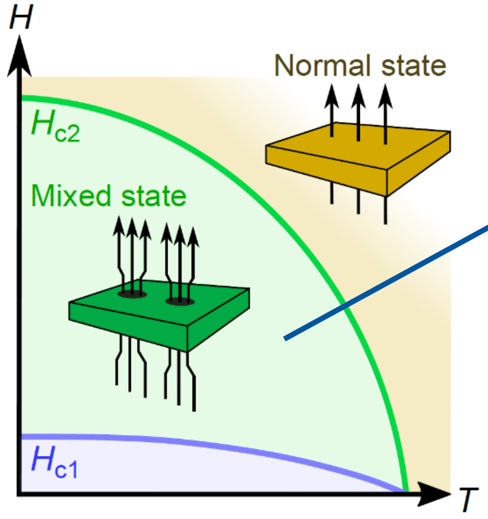
- Buffer layers allow biaxial epitaxial REBCO growth
- Metallic substrate makes tape ductile

Electronic features:

- Charge transport in CuO_2 planes
- High anisotropy
- Extreme sensitivity to oxygen content
- Large $\lambda_L(0K) \approx 150\ nm$ and small $\xi(0K) \approx 2\ nm$

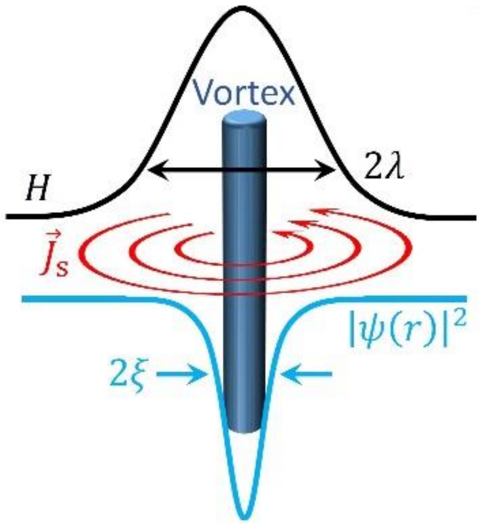
Artur Romanov, PhD dissertation, UA Barcelona 2022

Magnetic phase diagram for type II SC



Characterized by mixed phase with vortex penetration.

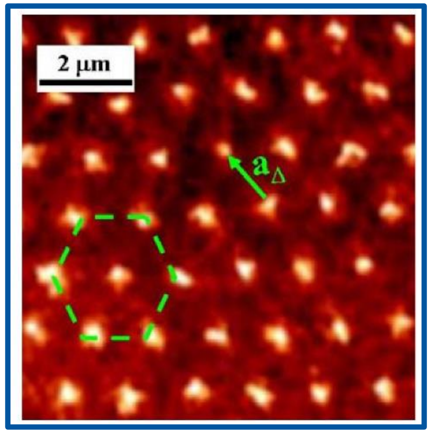
Vortex in type II SC



Vortex length scales:

1. $\lambda_L \doteq$ Distance upon which magnetic field decays.
2. $\xi \doteq$ Distance upon which the order parameter decays.

Abrikosov lattice



Distribution into hexagonal lattice in homogenous material.

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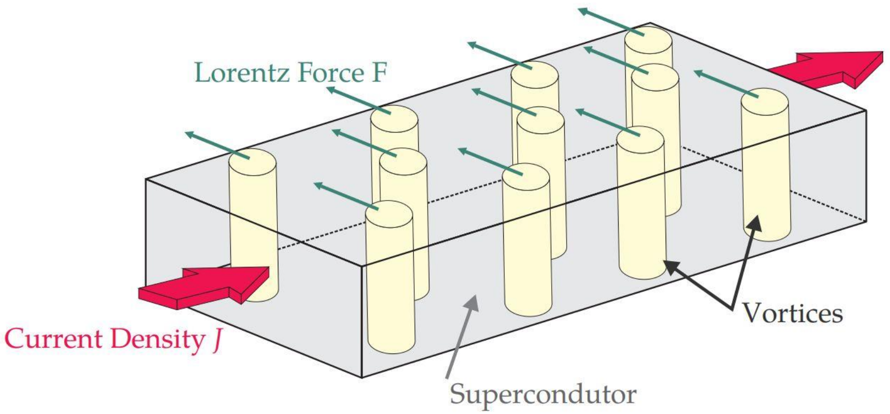
Vortex pinning

Lorentz-like force provokes vortex movement



Scales with current density and magnetic field:

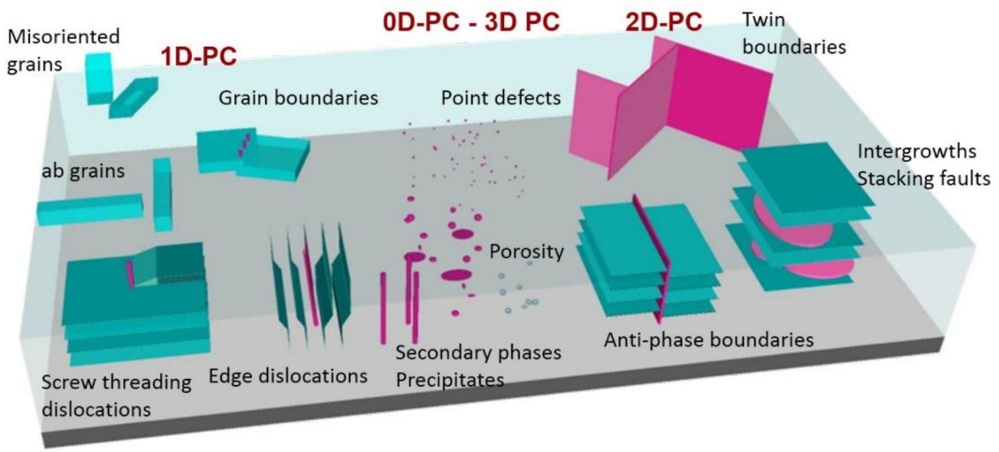
$$\vec{F}_L = \vec{J} \times \vec{B}$$

Critical current density $\vec{J}_c$:

$$\vec{F}_P = \vec{J}_c \times \vec{B}$$

The maximum value of J without moving the lattice, without presenting resistance.

Defects: Strategy to pin vortices



Defect landscape:

- 0D: Impurity atoms, interchanged atoms
- 1D: Dislocations, columnar defects
- 2D: Twin boundaries, grain boundaries
- 3D: Nanoparticles, associated strained regions

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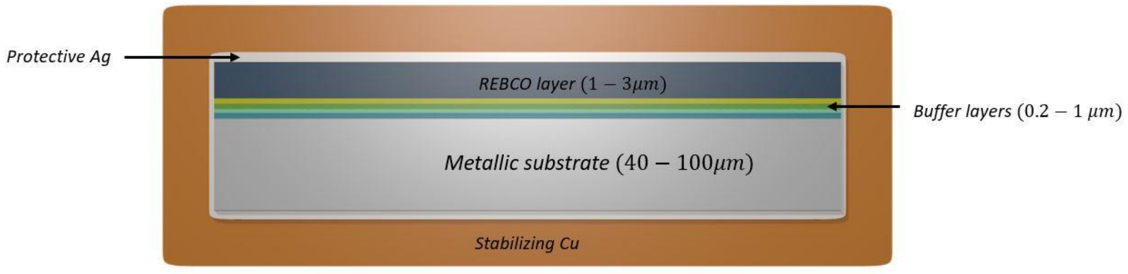
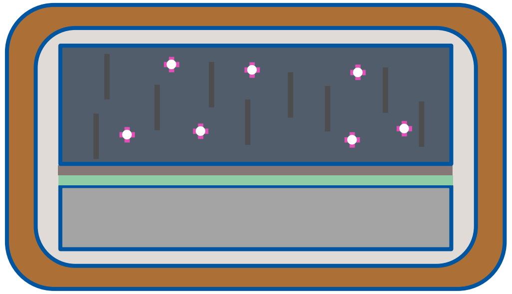
Various producers of CCs

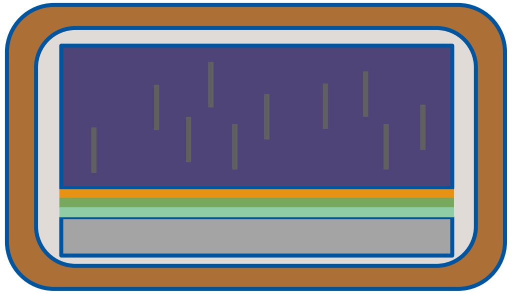


Bruker



YBCO $(1.6\ \mu m)$ + BZO nanorods

Fujikura APC

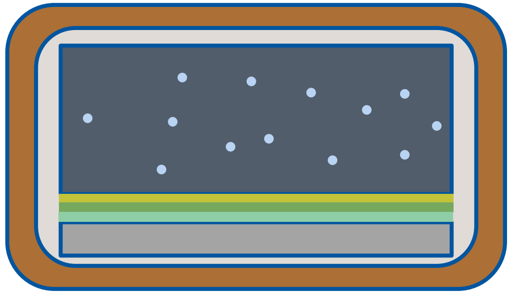


EuBCO $(2.5\ \mu m)$ + BHO nanorods

SuNAM

GdBCO $(1.5\ \mu m)$

SuperOx 2



YBCO $(3\ \mu m)$ + Y_2O_3 nanodots

CCs differ in architecture and REBCO microstructure.

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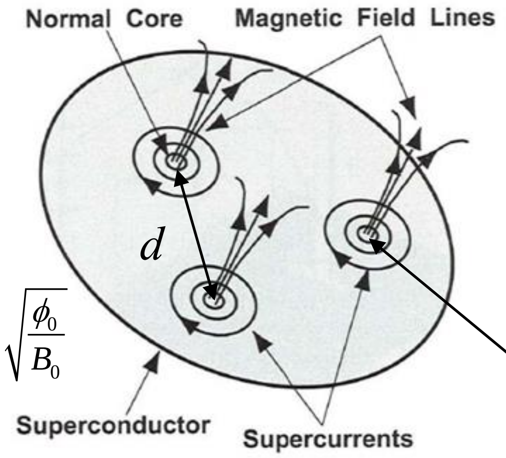
HTS coating technologies

	BRUKER	Fujikura	SuNAM	SuperOx	SuperPower Inc.	THEVA
$Re\mathrm{Ba_2Cu_3O_7}$	Y	Gd | Eu	Gd	Gd | Y	{ Y,Gd }	Gd
Thickness [µm]	1.6	1.8 | 2.5	1.6	0.9 | 3.0	1.5	3.0
Nano-inclusion	$BaZrO_3$	none | $BaHfO_3$	none	none | Y_2O_3	$BaZrO_3$	none
Technology	PLD	PLD	RCE	PLD	MOVCD	EB-PVD
Substrate	Stainless Steel	Hastelloy C276	Hastelloy C276	Hastelloy C276	Hastelloy C276	Hastelloy C276
Thickness [µm]	100	75 | 50	100	60 | 40	50	100
Stabilizer [µm]	e.p. 25	lam. 75	e.p 20	e.p. 10	e.p 20	e.p. 20
T_C [K]	85	94 | 92	94	94	91	92

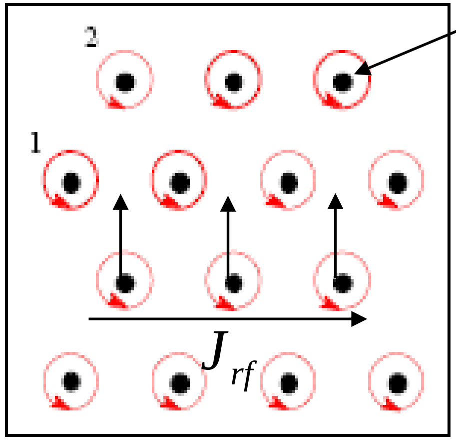
Patrick Krkotic, PhD dissertation, UPC Barcelona 2022

Some theory background: fluxon motion in RF



$$d \propto \sqrt{\frac{\phi_0}{B_0}}$$

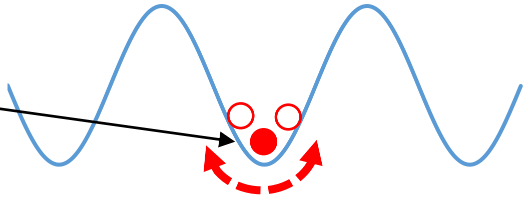
Pinning centers



B field is normal to surface: worst case

The motion of the rigid fluxon lattice behaves as a harmonic damped oscillator (neglecting thermal creep)

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



$$\eta = \frac{\phi_o B_{c2}}{\rho_n} \qquad k = \frac{2\pi J_c \phi_0}{d} \qquad \omega_o = \frac{k}{\eta}$$

The "depinning frequency"

$$f_o(B_o) = \frac{\omega_o(B_o)}{2\pi} = \frac{\rho_n \sqrt{B_o}\, J_c(B_o)}{\sqrt{\varphi_o}\, B_{c2}}$$

Surface resistance

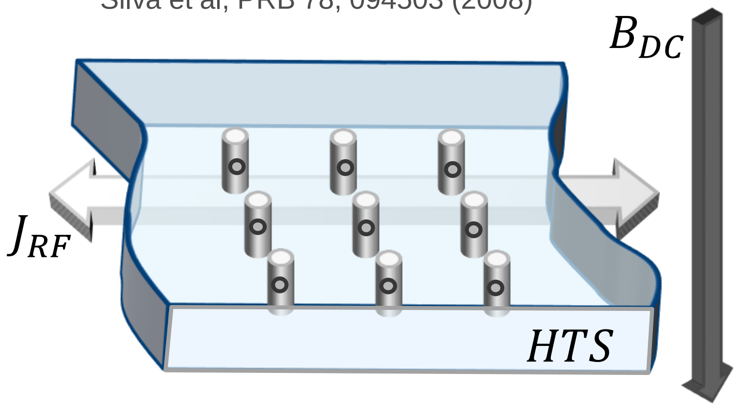
$$R_f = \frac{\rho_n}{2\lambda} \frac{B_o}{B_{c2}} \frac{f^2}{f_0^2}$$

Gittleman and Rosenblum: Phys Rev. Lett. 16, 734 (1966)
Calatroni and Vaglio, IEEE Trans. Appl. Supercond. 27 (2017) 3500506
Coffey, Clem PRL 67, 386 (1991)
Brandt PRL 67 2219 (1991)
Silva et al, PRB 78, 094503 (2008)

RF when an external magnetic field is present

Gittleman and Rosenblum: Phys Rev. Lett. 16, 734 (1966)
Calatroni and Vaglio, IEEE Trans. Appl. Supercond. 27 (2017) 3500506
Coffey, Clem PRL 67, 386 (1991)
Brandt PRL 67 2219 (1991)
Silva et al, PRB 78, 094503 (2008)

- Vortex lattice
  - cylindrical normal conducting regions
    ≈ tens of nm diameter
  - Each vortex carries one flux quantum



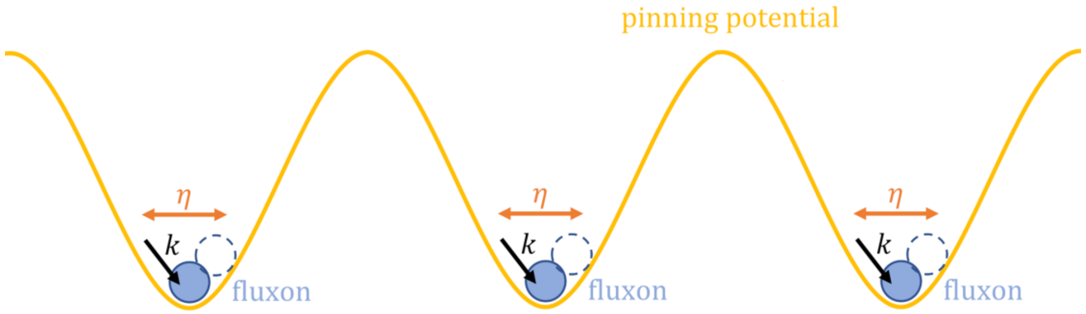
- Apply RF Current
  - Motion of vortices → dissipation

$$m\ddot{x} + \eta\dot{x} + kx = J_{RF}\Phi_o$$

  - The motion of the rigid vortex lattice behaves as an harmonic damped oscillator with quadratic potential

$$\eta = \frac{\phi_o B_{c2}}{\rho_n} \qquad k = \frac{2\pi J_c \phi_0}{d} \qquad \omega_o = \frac{k}{\eta}$$

- Vortex pinning
  - Artificial pinning centres

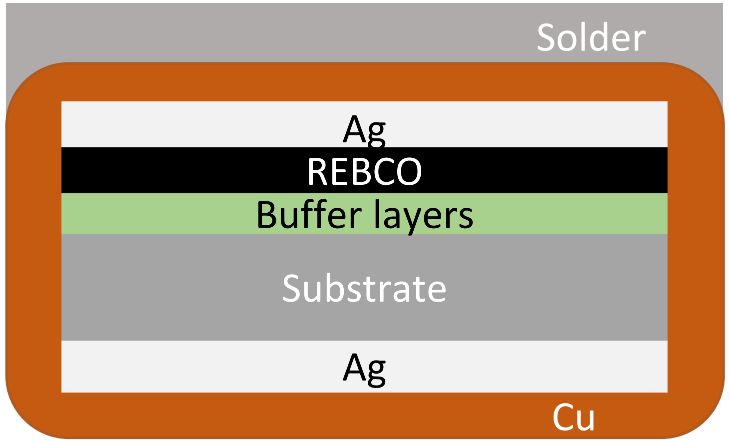


Simplified model valid for estimates and scaling

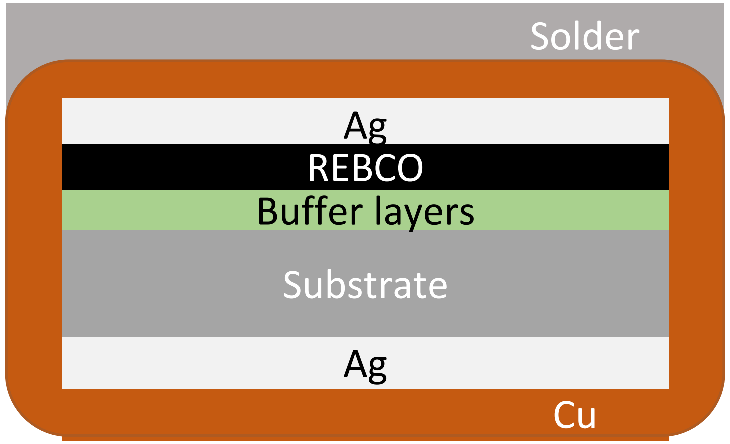
Patrick Krkotic, PhD dissertation, UPC Barcelona 2022

Coating process I

1) Pre-tinning

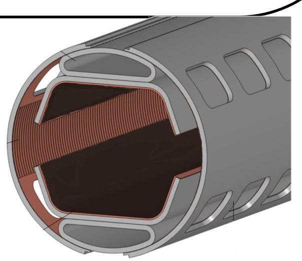


2) Edge removal



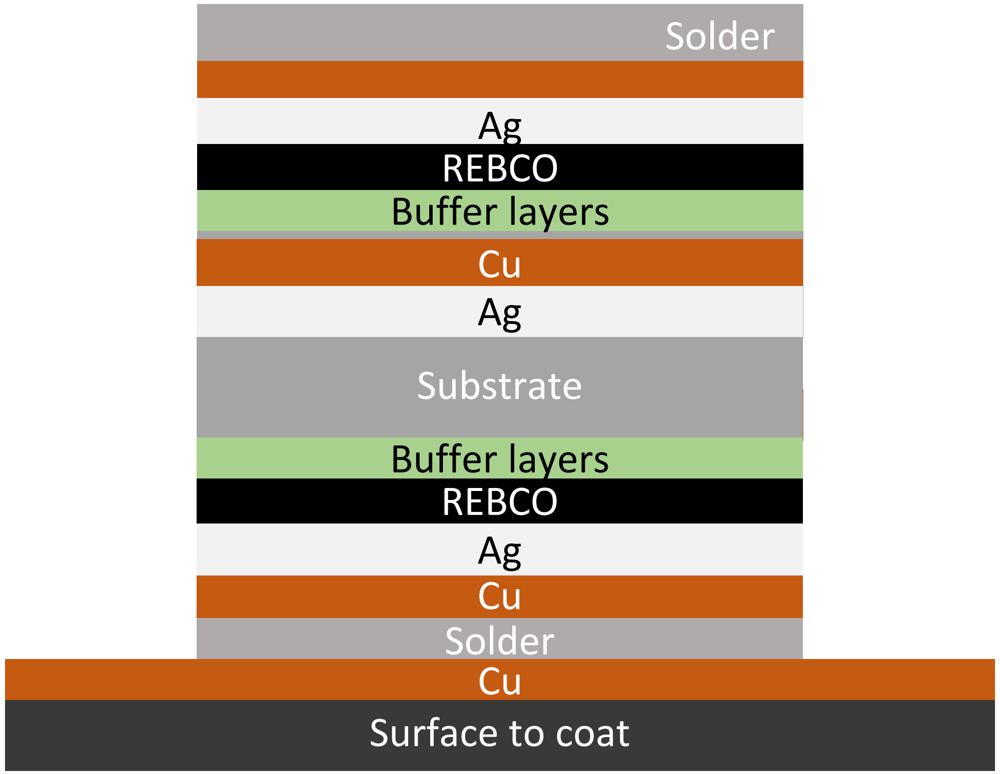
FUTURE CIRCULAR COLLIDER

Developed in the context of FCC-hh impedance reduction by coating the beam screen with HTS tapes

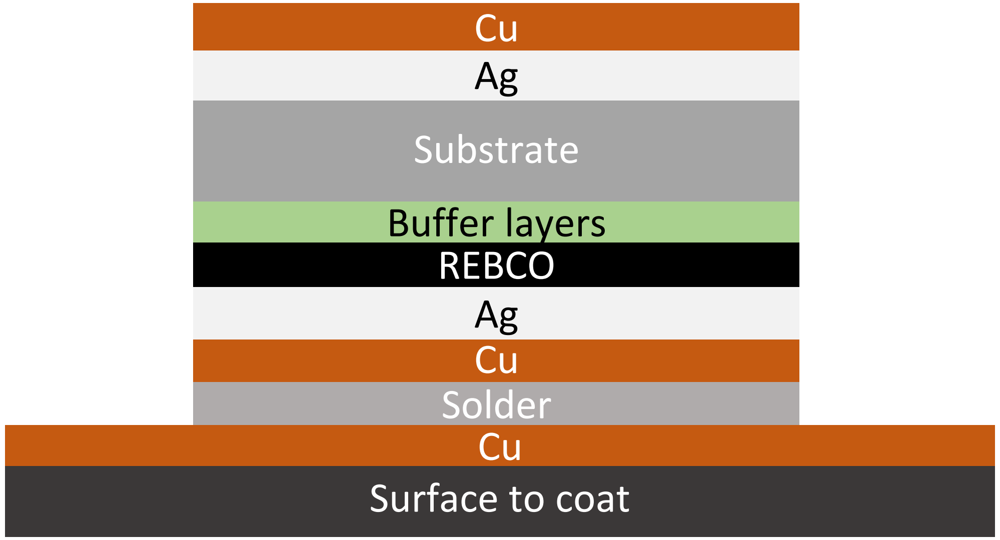


Coating process II

3) Soldering



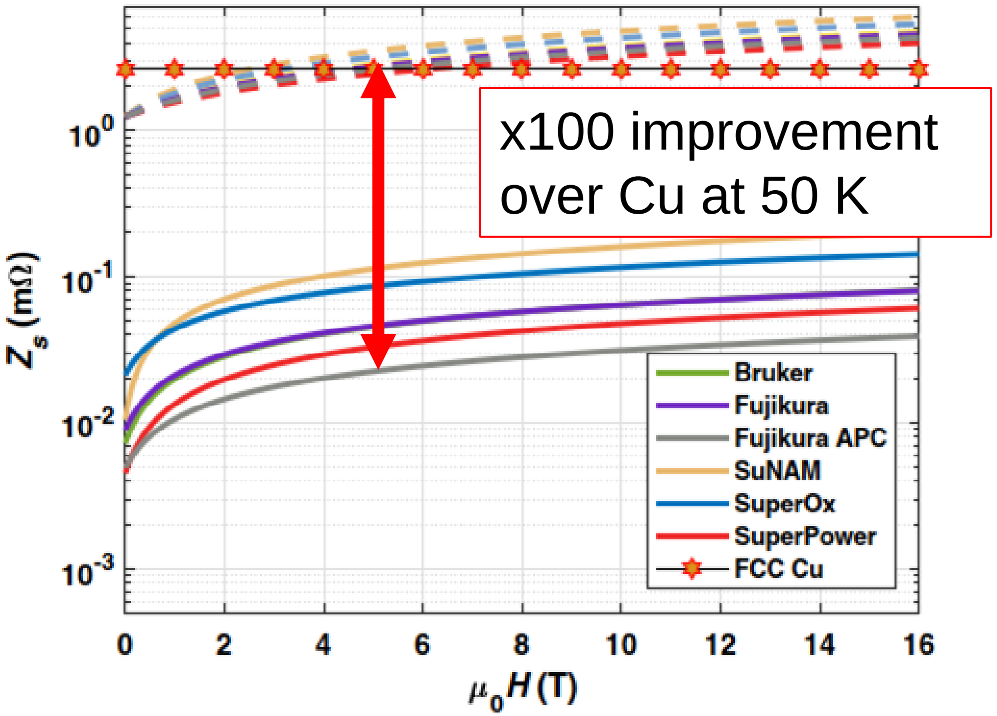
4) Substrate extraction



N. Lamas et al., to be published

Scaling to lower frequency

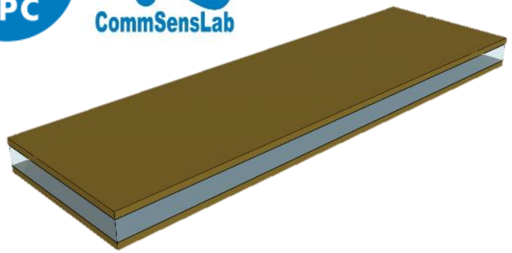
REBCO scaled to 1 GHz at 50 K



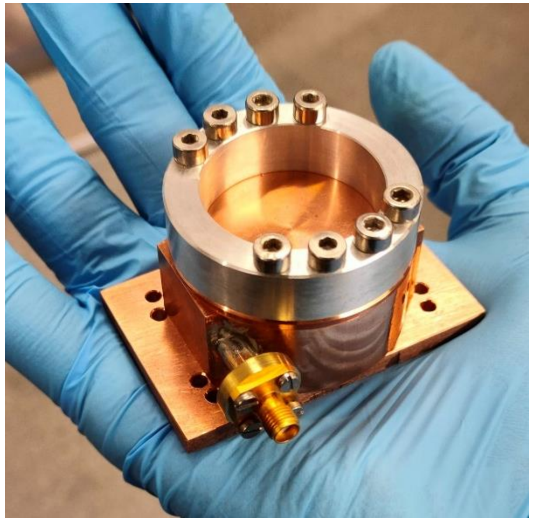
Romanov et al, SciRep 10:12325 (2020)

For HTS Rs scales as f^2
For Cu Rs scales as $f^{1/2}$

A parallel-plate resonator is being commissioned to test samples at ~1 GHz



38x12 mm samples
50 mm bore
16 T
$X_s(T)$ at all frequencies



Will demonstrate real experimental frequency scaling on samples

Surface impedance: the key

τ Risetime of beam instabilities

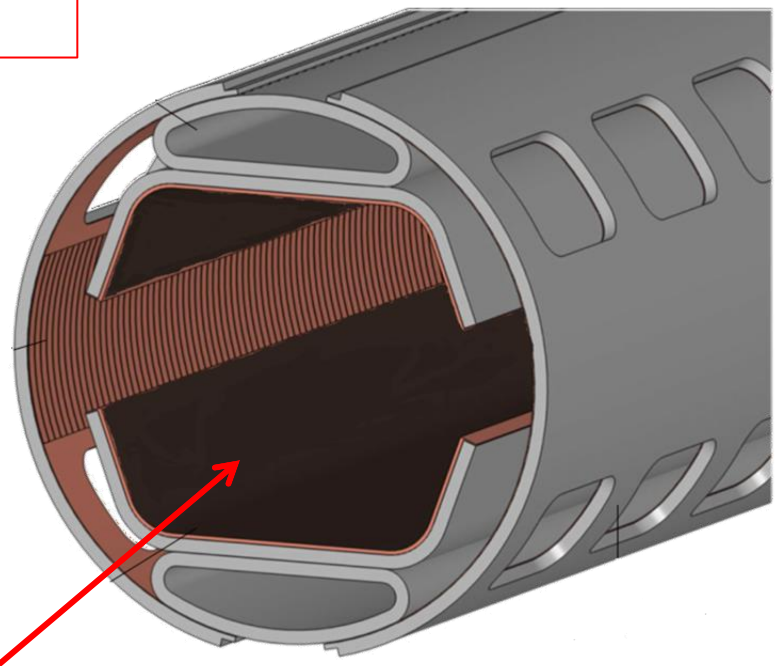
$$\frac{1}{\tau} \propto -\mathrm{Im}|\Delta\omega| \propto \frac{I_b M}{EL} \mathrm{Re}(Z_T)$$

$$\mathrm{Re}(Z_T) = \frac{R\,c}{\pi b^3\, f} R_S = \frac{R\,c}{\pi b^3\, f} \sqrt{\rho \mu_o \pi f}$$

Z_T Transverse impedance (property of the beam)

R_S Surface resistance (property of the surface)

τ: instabilities rise-time
$\Delta\omega$: betatron tune-shift
I_b: bunch current
M: number of bunches
E: beam energy
L: bunch length
R: accelerator radius
c: speed of light
b: vacuum chamber radius
f: wakefields frequency
ρ: electrical resistivity



What could be better than copper at 50 K?

High-Temperature Superconductors (HTS)

New kid on the blocks: the C3 study @ SLAC

More info here

8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

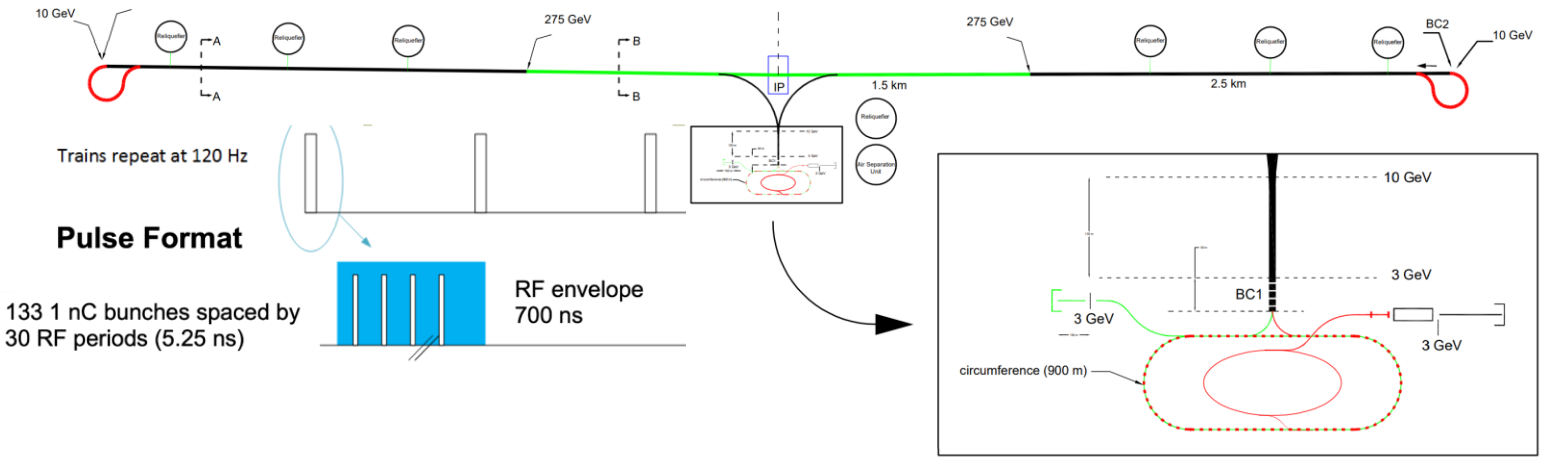
Large portions of accelerator complex compatible between LC technologies

- Beam delivery / IP modified from ILC (1.5 km for 550 GeV CoM), compatible w/ ILC-like detector
- Damping rings and injectors to be optimized with CLIC as baseline
- Cryogenically cooled – 77 K (liquid nitrogen)

C^3 Parameters

Collider	C^3	C^3
CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	~150	~175
Design Maturity	pre-CDR	pre-CDR

C^3 - 8 km Footprint for 250/550 GeV (to scale)



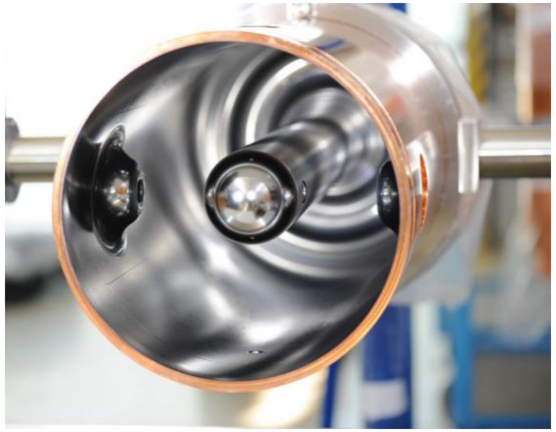
Cooling allows for increase in accelerating gradient, and savings in RF power infrastructure

From: Emilio Nanni

Flux pinning

- Typical SRF accelerator cavities are made of niobium

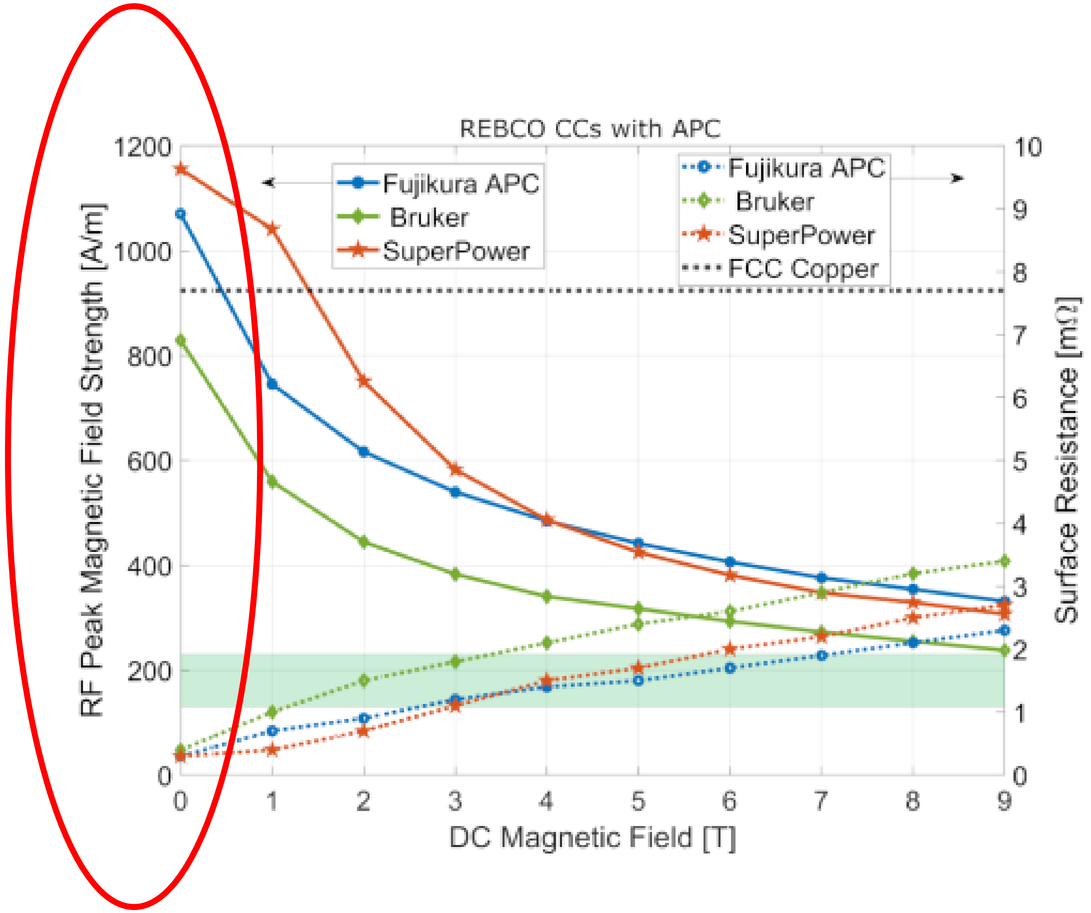
Strong magnetic shielding needed

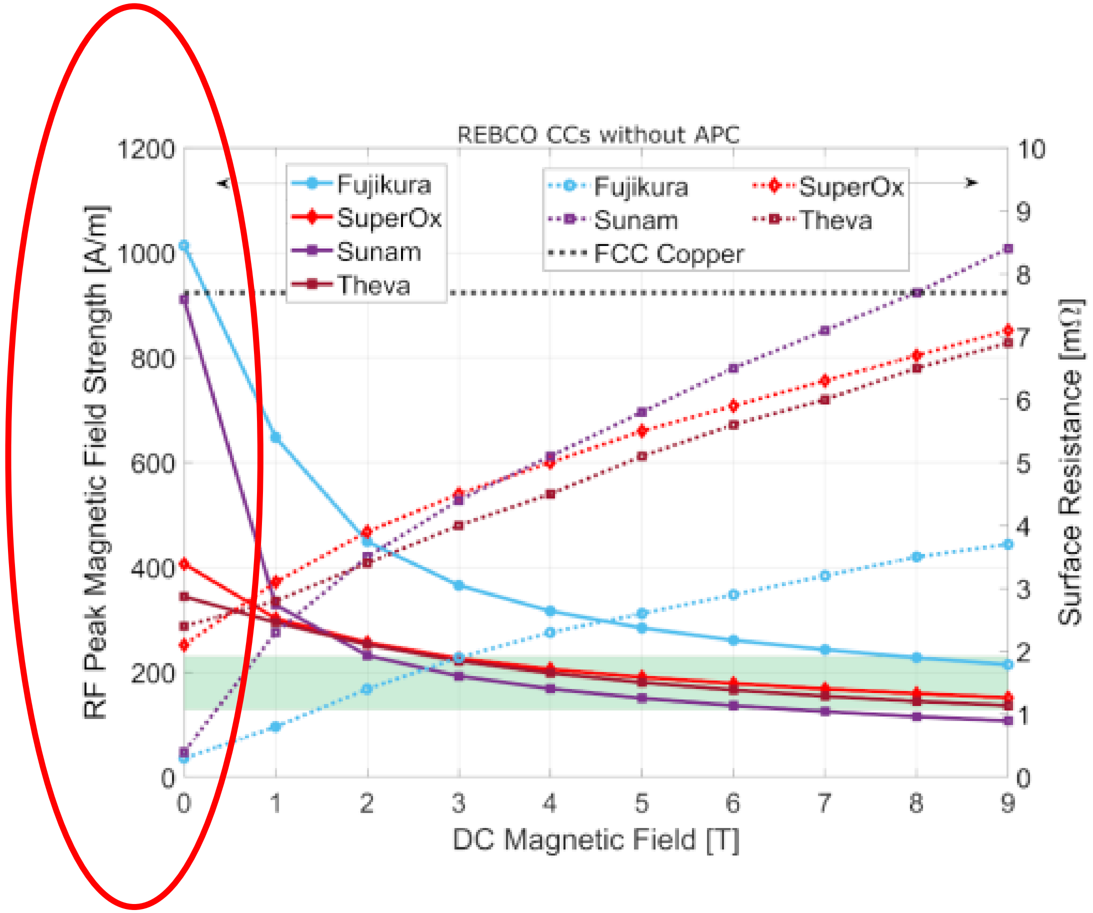


Limited or no magnetic shielding

- Effect of external magnetic field on SRF accelerating cavities is mostly due to flux pinning, weak pinning in bulk Nb and strong in Nb/Cu
- Earth magnetic field should not be an issue for HTS (to be verified)

HTS tape at 8 GHz (dielectric resonator) and 50 K

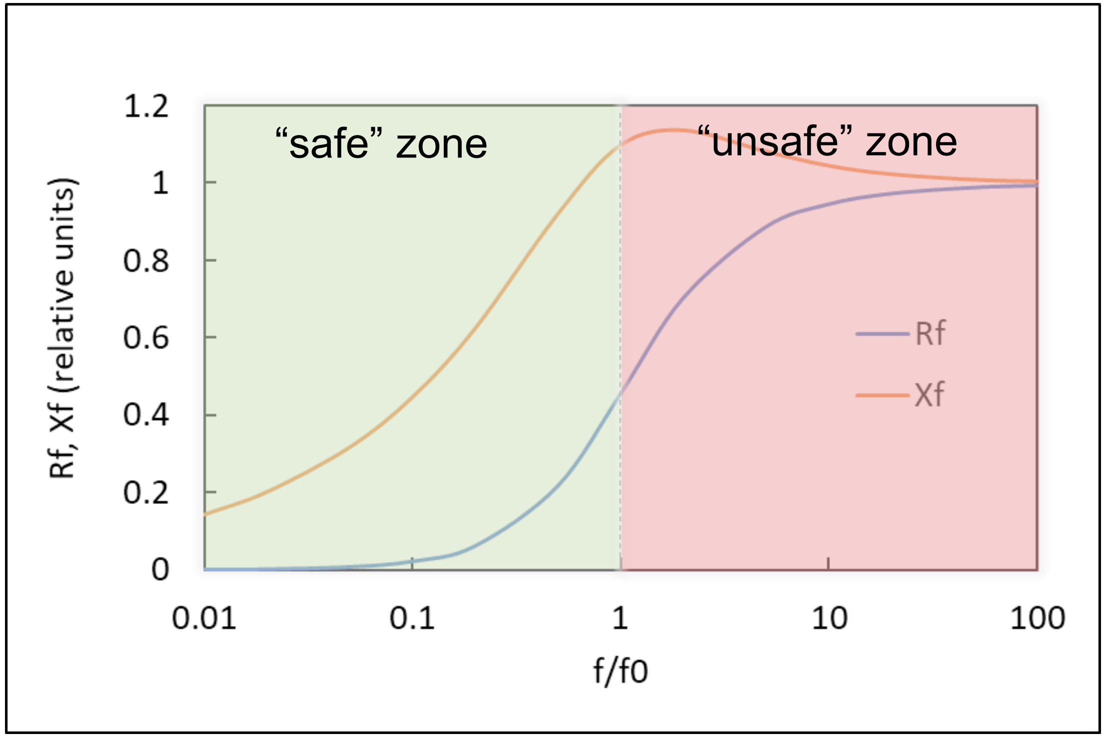




Patrick Krkotic, PhD dissertation, UPC Barcelona 2022

Effect of magnetic field: fluxon losses in RF

Surface resistance, reactance due to vortex motion



Case $f < f_o$

$$R_f = \frac{\rho_n}{2\lambda}\frac{B_o}{B_{c2}}\frac{f^2}{f_0^2} \qquad B_0 \ll B_{c2}$$

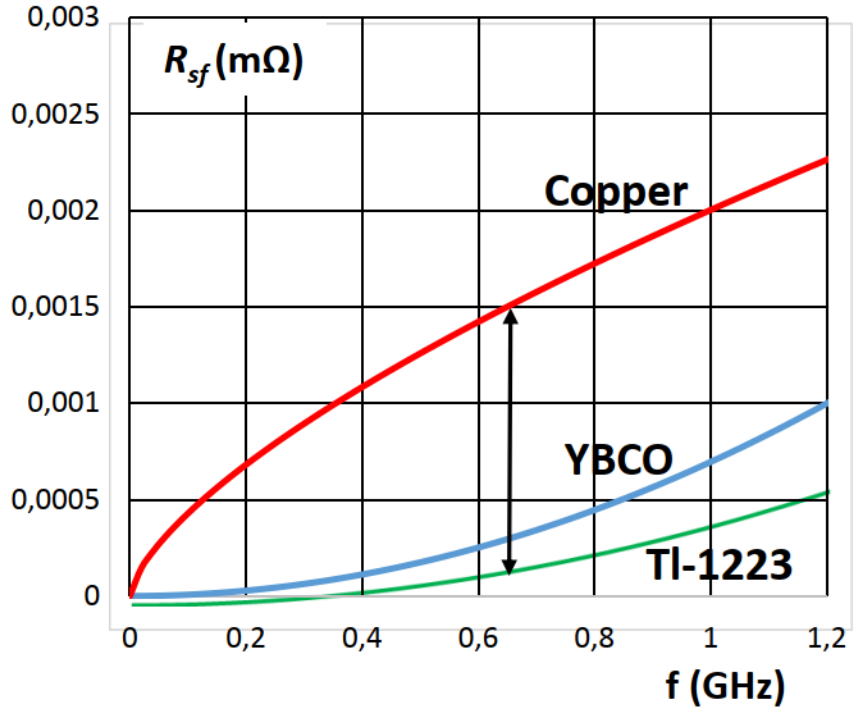
$$R_f = \frac{R_n}{\sqrt{2}}\sqrt{\frac{B_o}{B_{c2}}}\left(\frac{f}{f_0}\right)^{3/2} \qquad B_0 \gg B_{c2}$$

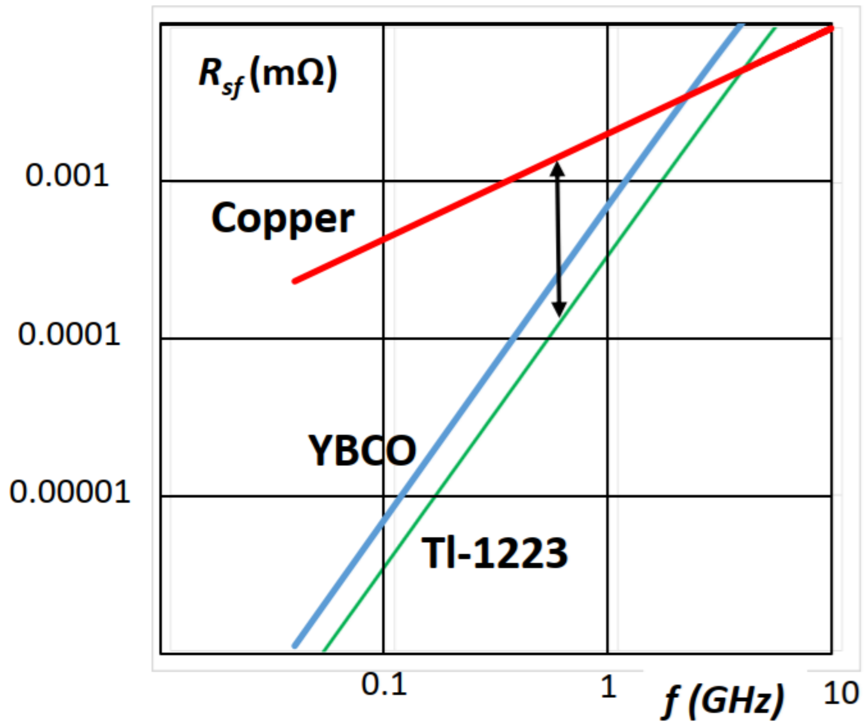
$$f_o(B_o) = \frac{\omega_o(B_o)}{2\pi} = \frac{\rho_n\sqrt{B_o}\,J_c(B_o)}{\sqrt{\varphi_o}\,B_{c2}}$$

To maximize f_0 and minimize fluxon losses we need high J_c materials

Predicted surface resistance of HTS in 16 T field

YBCO	T_c=92K	T=50K	B_0=16T	$J_c(50,16)=7.5\times10^9 Am^{-2}$	$B_{c2}(50)$=40T	$\rho_n=60\mu\Omega cm$	f_0=10GHz
Tl-1223	T_c=125K	T=50K	B_0=16T	$J_c(50,16)=1\times10^{10} Am^{-2}$	$B_{c2}(50)$=80T	$\rho_n=80\mu\Omega cm$	f_0=14GHz

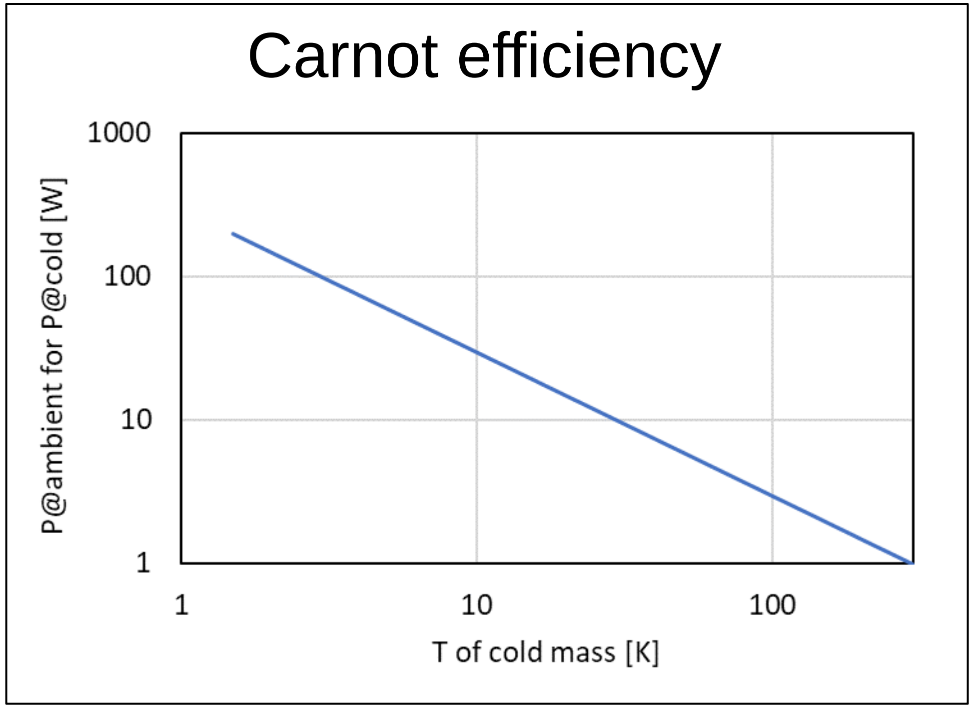


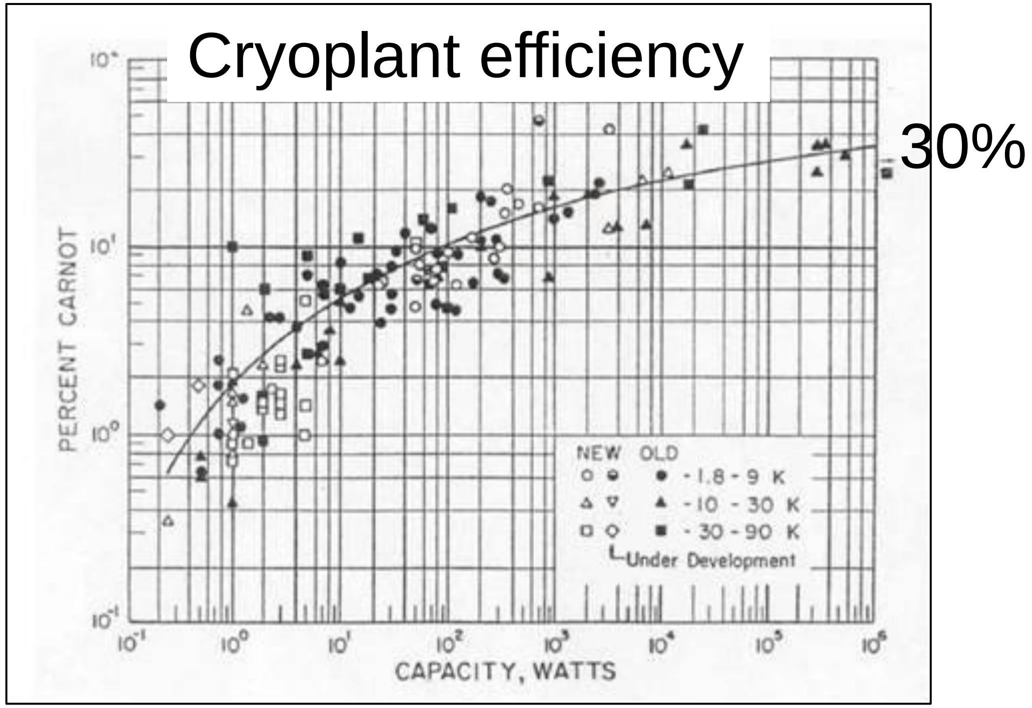


For HTS the Rs scales as f^2

For Cu the Rs scales as $f^{1/2}$

Cryogenic losses: SRF aimed at energy saving compared to NRF



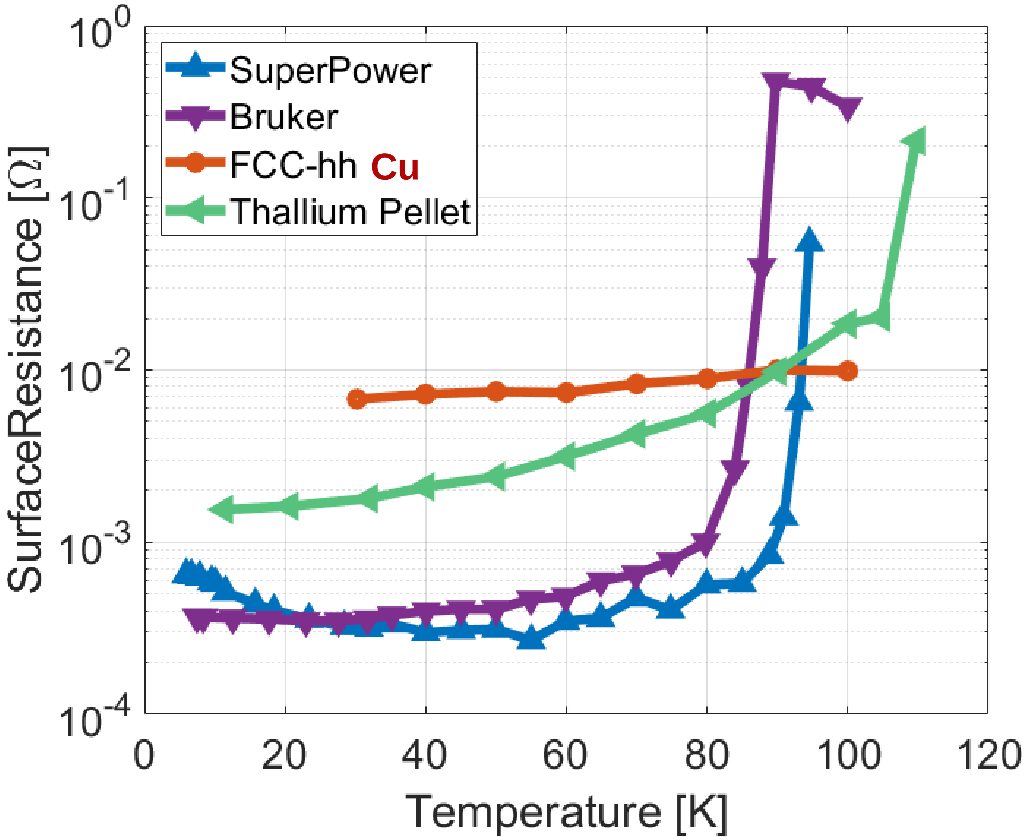


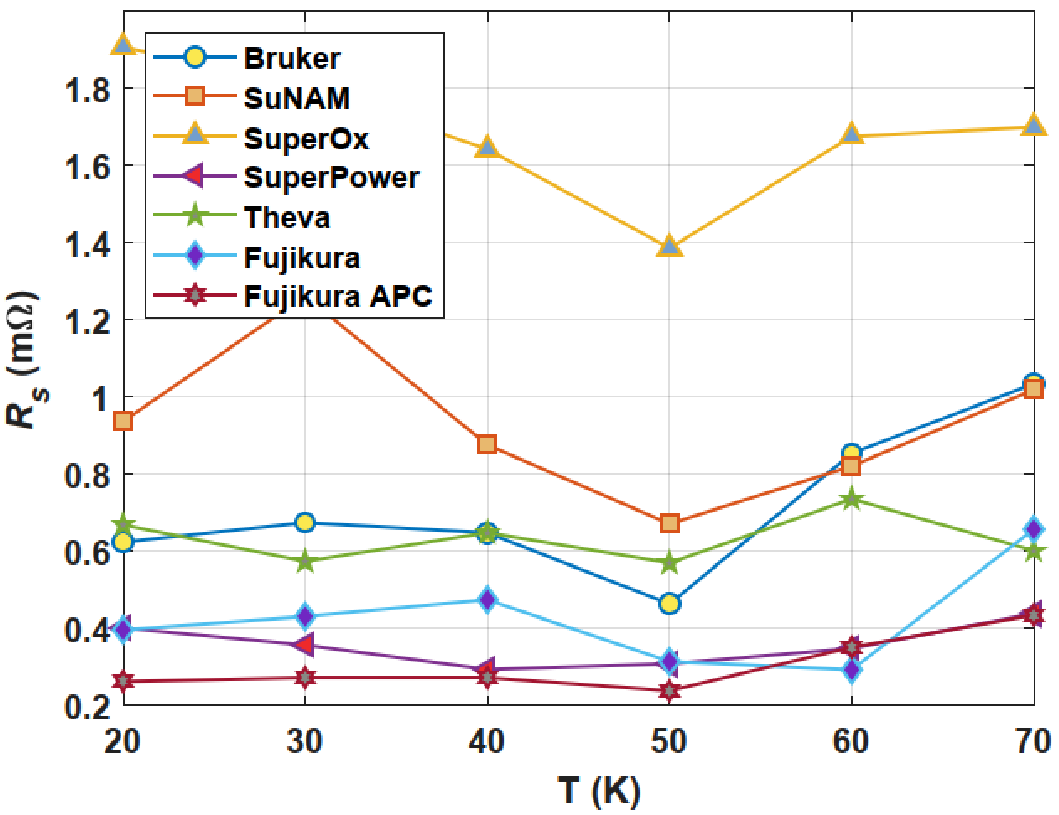
Power consumption for 1 W @ 77 K	13 W
Power consumption for 1 W @ 20 K	50 W
Power consumption for 1 W @ 4.2 K	230 W
Power consumption for 1 W @ 1.9 K	920 W

Thanks to T. Koettig, CERN

Low-power RF measurements

- An improvement larger than x10 compared to copper (Rs=8mΩ) has been measured on samples of tapes (8 GHz) at low RF power



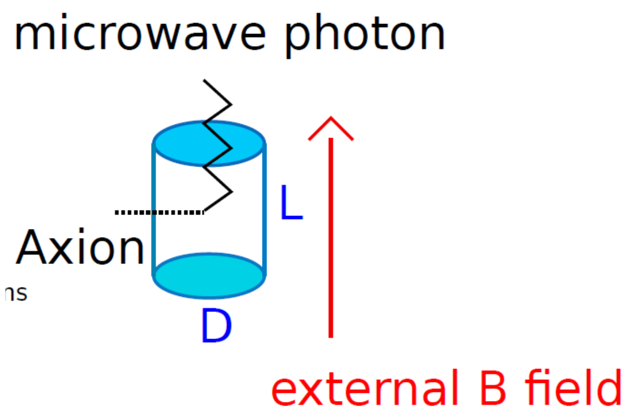


Adapted from Romanov et al, Sci. Rep. (2020) 10:12325

HTS for axion searches

Motivation:

Axion haloscope



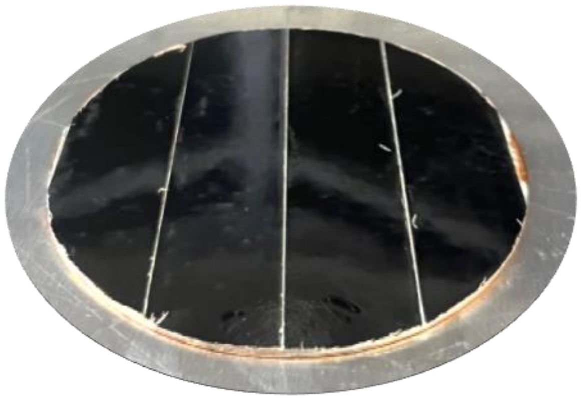
$$\mathcal{F} \sim g_{A\gamma}^4 \, \boldsymbol{Q} \, T_{sys}^{-2} V^2 G^4 m_A^2 \, \boldsymbol{B^4}$$

Increase Q
copper coating → superconducting coating

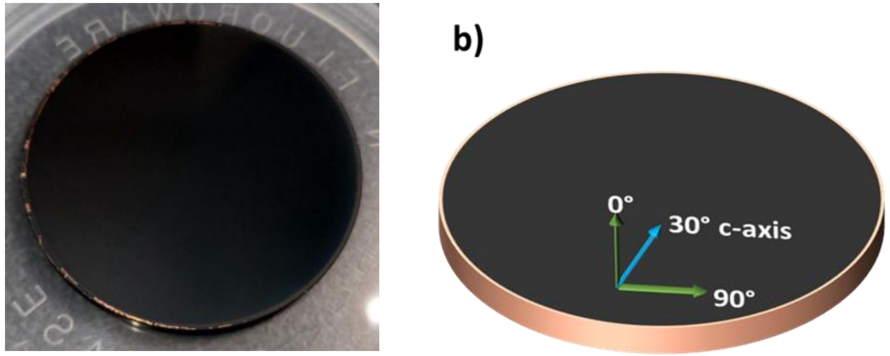
Requirement: High quality factor in a high magnetic field

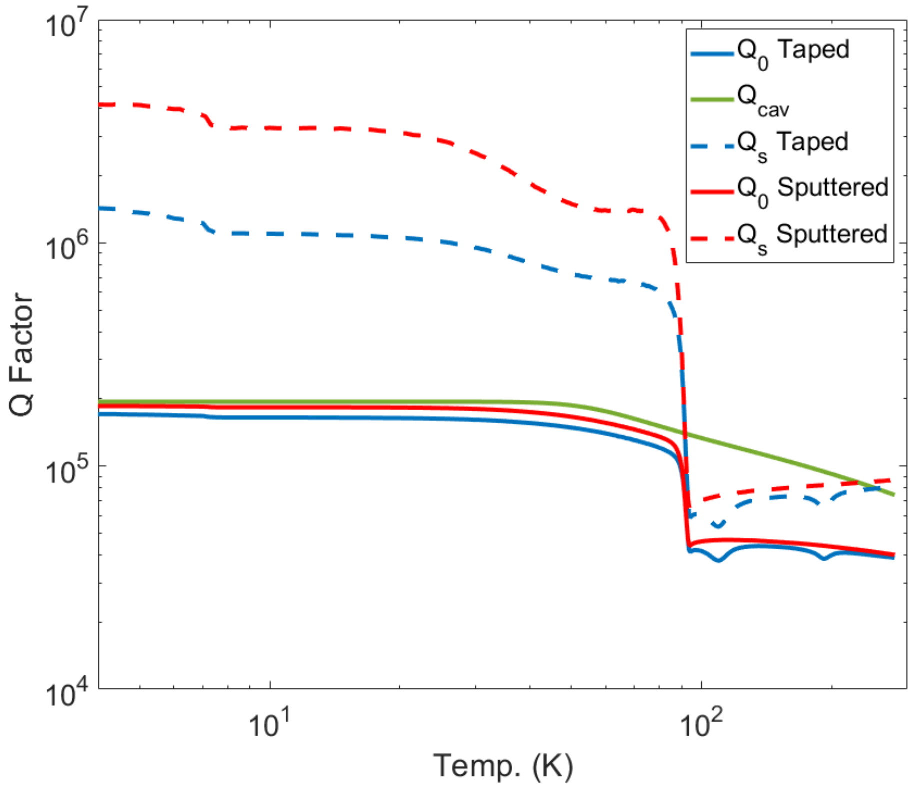
Two HTS measurements, after calibration measurements with Cu and Nb

Soldered REBCO-CCs on copper (Fujikura by CSIC-ICMAB)



Directly grown REBCO on MgO and on copper+MgO (CERACO)





R_s Cu ≅ 17 mΩ
R_s REBCO tapes ≅ 1.7 mΩ
R_s REBCO PVD ≅ 1.0 mΩ

Preliminary SLAC results at high-gradient I

YBCO RF from TWT

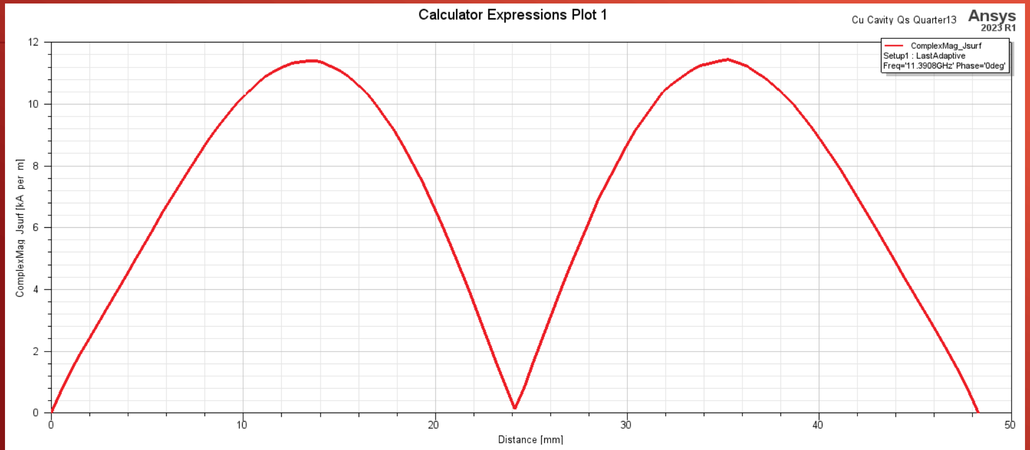
TWT is 1.6 kW @ 11.7 µs

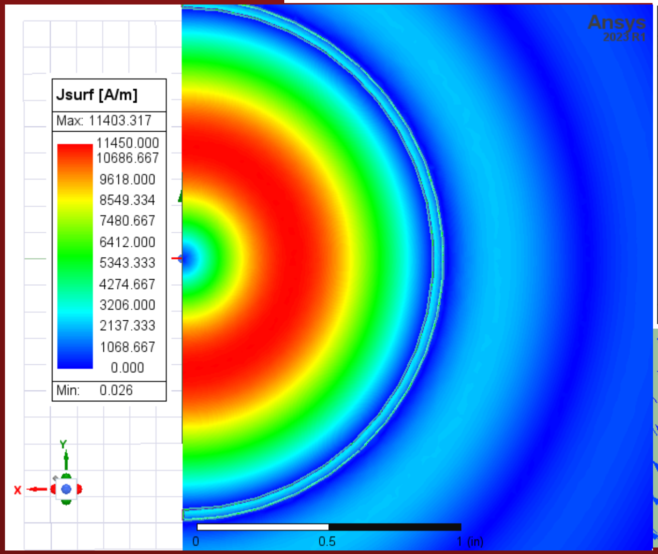
Q_{tot} is 75k and f_0=11.43 GHz

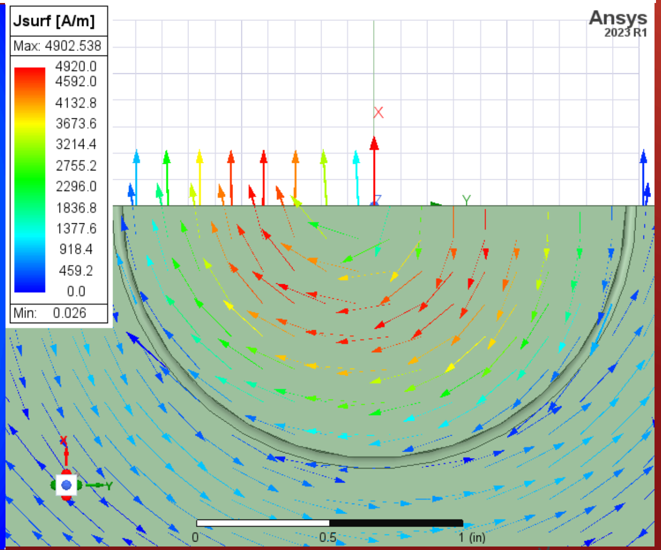
=> fill time is 13.4 µs

Tape sample has surface currents of 10 kA/m

Equivalent to ~3 MV/m





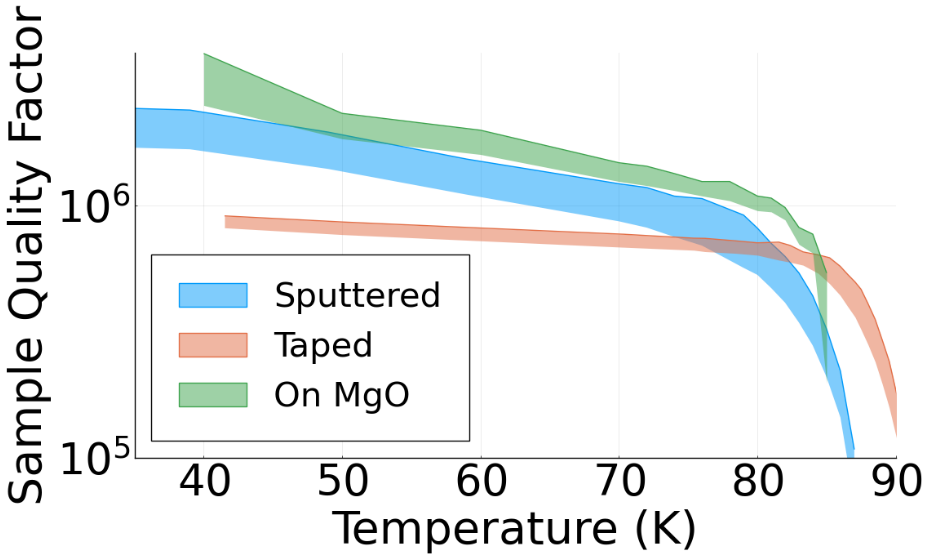


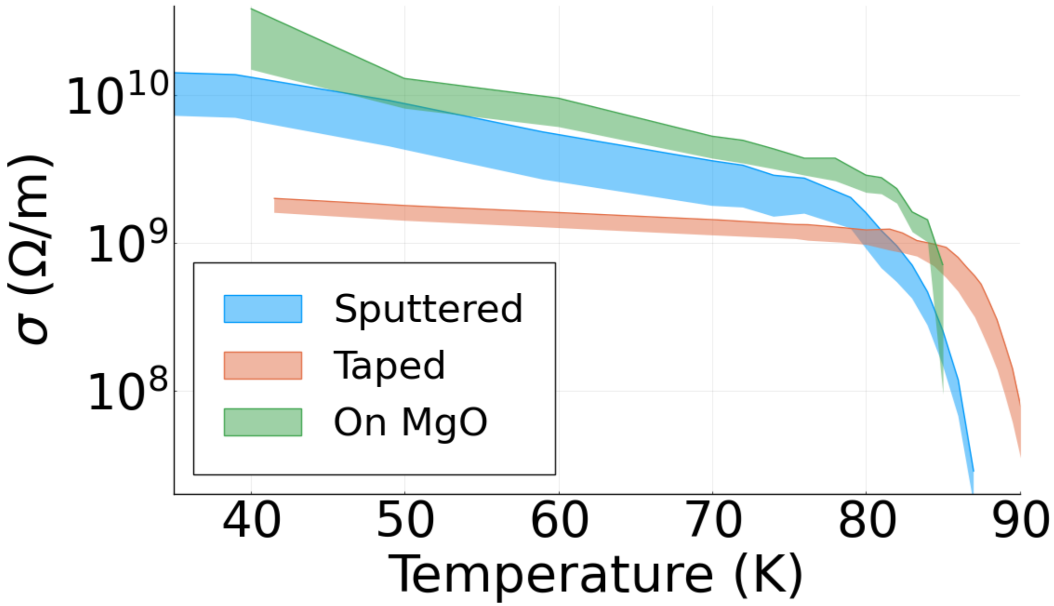
From: Mitch Schneider

Preliminary SLAC results at high-gradient II

Measurements of YBCO on MgO

Tested YBCO on MgO sample for comparison, appeared to reach quench limit sooner





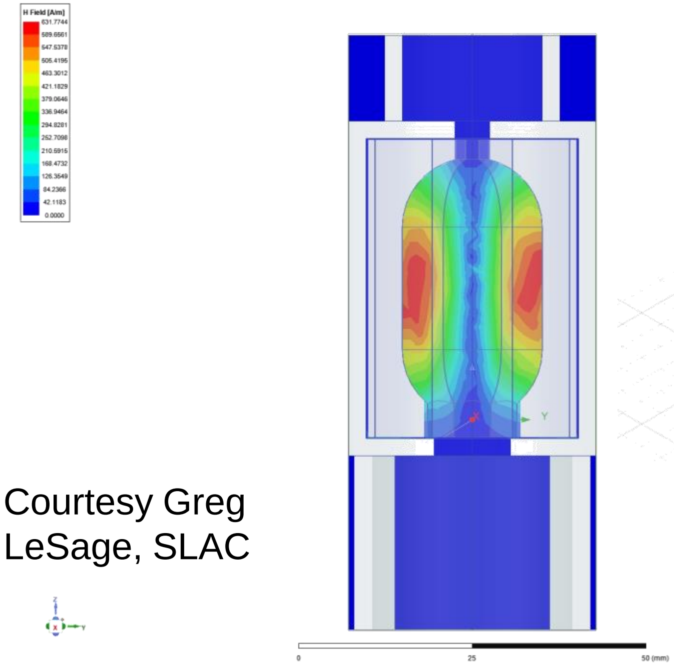
SLAC

Shaded area: change from 100 W to 1.6 kW of forward power

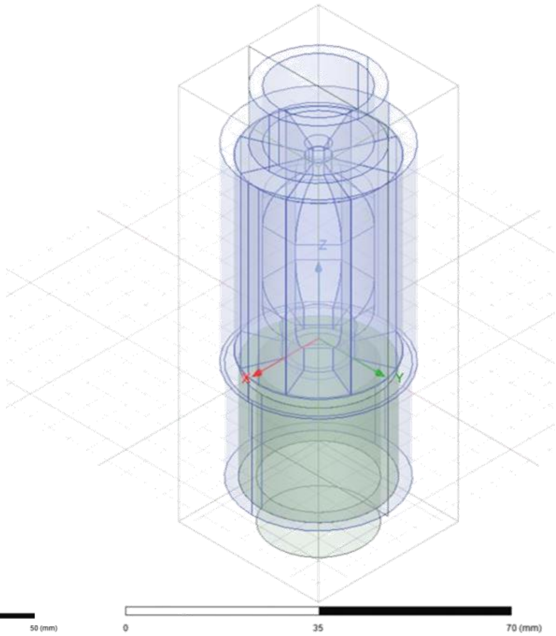
From: Ankur Dhar

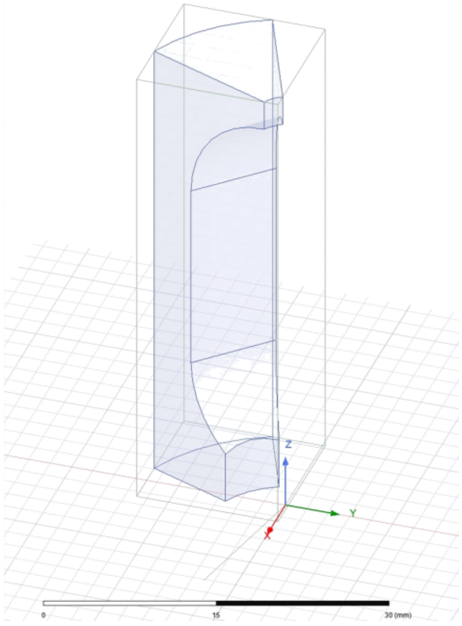
First device validation – supported by I.FAST Innovation Fund

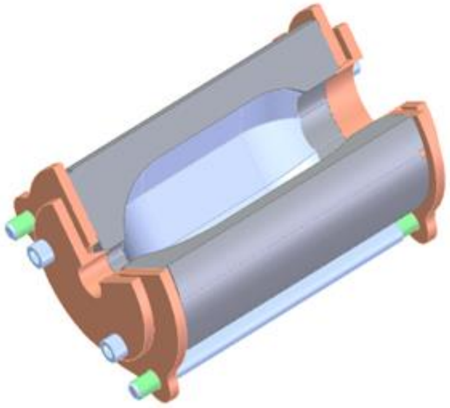
- Next goals: develop large-size tapes (50 mm wide) in collaboration with KCT, to be first tested on discs at SLAC. Two-years plan funded by IIF
- (Ideally: REBCO coating directly on 3D objects)
- Device validation: X-band pulse compressor (SLAC) as first “real” RF device



Courtesy Greg LeSage, SLAC





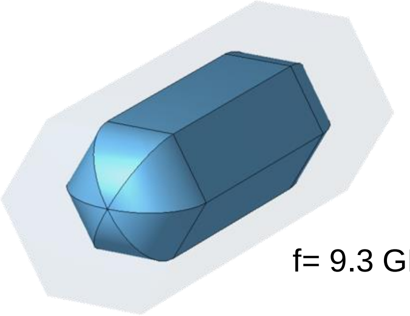


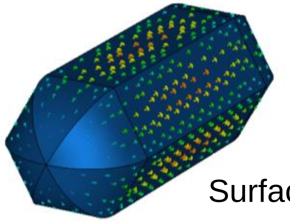
Pulse compressor

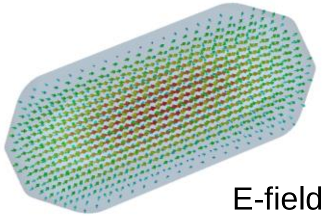
- Coating will be performed by CSIC-ICMAB

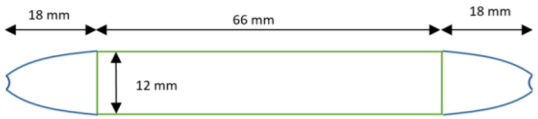
Axion cavity as earlier demonstrator

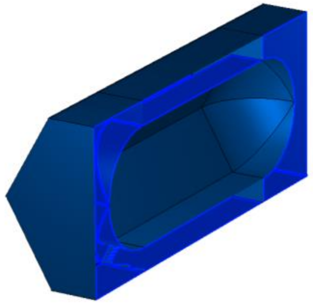
- Approach being validated also for axion detection cavities in RADES collaboration having a similar geometry
- Copper body manufactured at Mainz University, adapted to 12 mm wide coated conductors, coated by CSIC-ICMAB

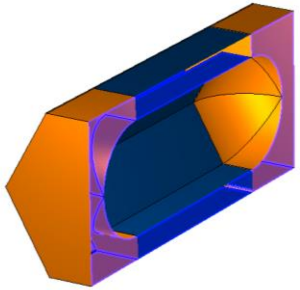

f= 9.3 GHz


Surface currents


E-field




Q_0 = 356 070


Q_0 = 268 520 (75%)

Summary of milestones and deliverables: WP2 KCT

- M1 - Design and fabrication of sample holder system (due 3/2024). Achieved well in advance
- D1 - HTS coating of large samples (due 3/2025). On track and well under way, first 40 mm wide tape already coated (final goal is 50 mm, but 40 mm is enough for our final goal)

Roll to roll coater for HTS tapes

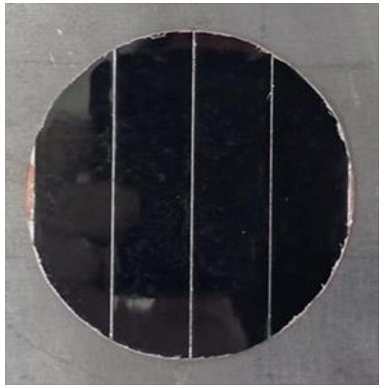
KCT confidential
Do not disclose

40 mm wide HTS tape

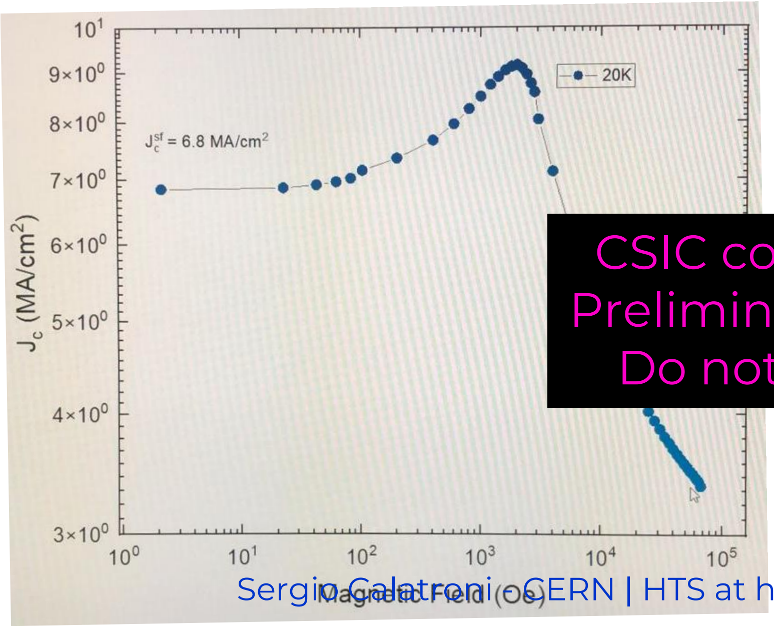
Summary of milestones and deliverables: WP3 CSIC

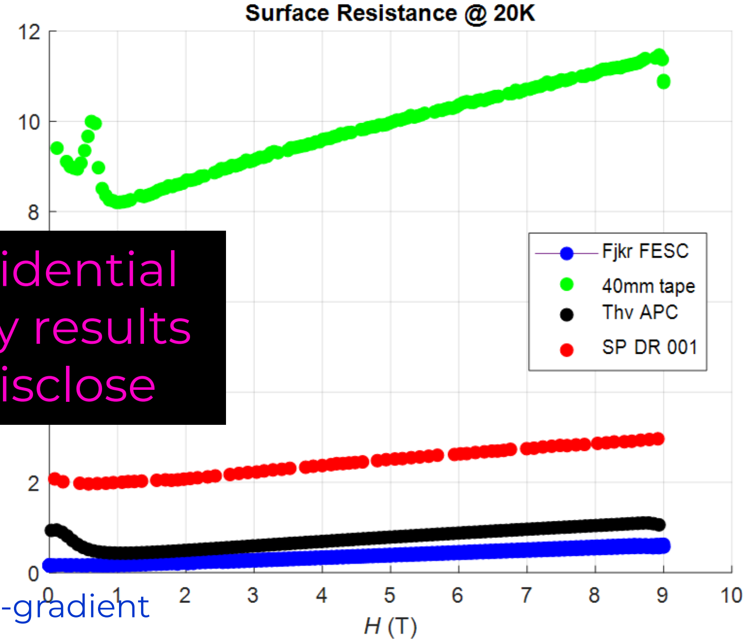
- D1 - Coating on discs and segmented cavities for benchmarking (small tapes) (due 3/2024). Achieved for discs, already high-power tested at SLAC (presented at EUCAS 2023 / IPAC 2024) waiting for readiness of segmented cavity
- D2 - Measurement of superconducting properties of large size tapes (due 3/2025). On track and well under way, first 40 mm wide tape already characterized

Copper disc coated with 12 mm tapes



First tests of 40 mm tape

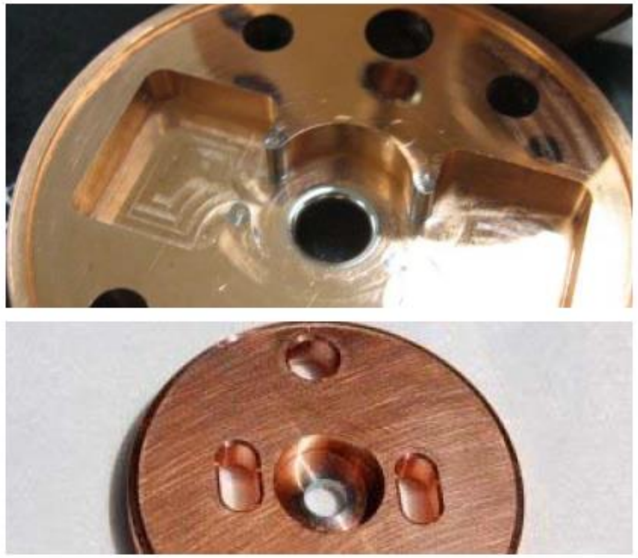




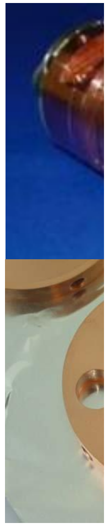
CSIC confidential
Preliminary results
Do not disclose

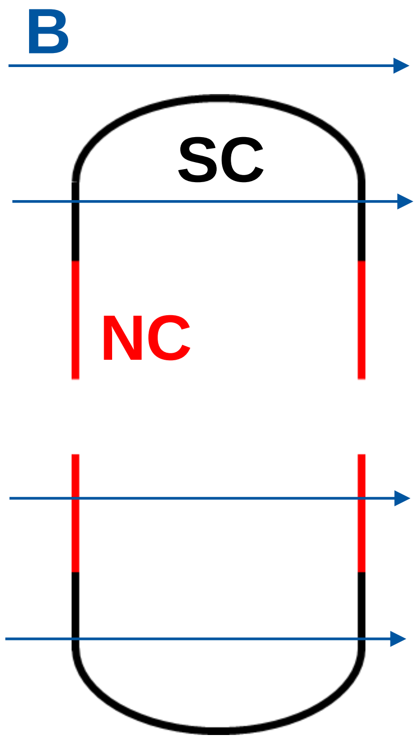
Possible practical implementation of HTS tape-coated cavities

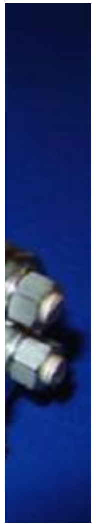
- How could a future cavity look like? Bimetallic cavities



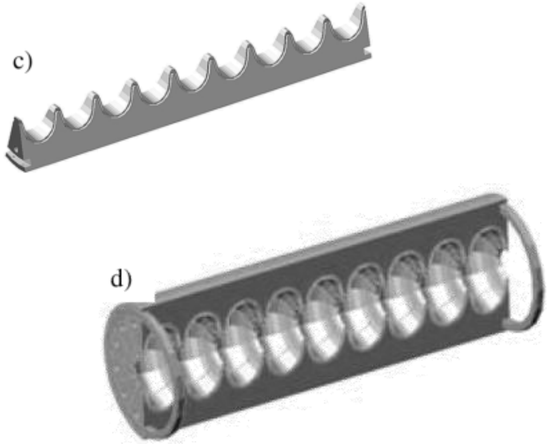
J. Haimson, WEPMS085, PAC07 (s.steel inserts)







C



P. McIntyre et al., IEEE TAS 19 (2009) 1380

Composite cavities exist and have ed.
Joints at low-current regions are standard practice even in SRF cavities (ie QWRs)
Segmentation at zero-current region is possible, see device being designed at SLAC