High temperature superconductor rf cavity development and high power tests

HTS for FCC beam screen

- Beam emits synchrotron radiation at high power levels (~5 MW in total)
- Cannot be absorbed at 1.9 K → Cu beam screen kept at 50 – 60 K
- Cu surface resistance not low enough for stable operation of FCC-hh
- HTS outperforms copper
- Measurement done at 8 GHz
- Extrapolated result at 1 GHz gives a factor 100 improvement

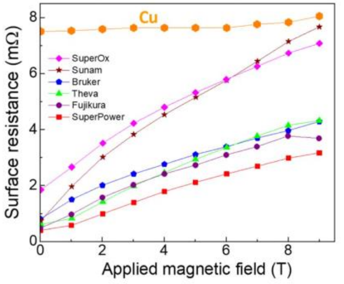
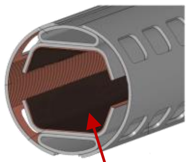
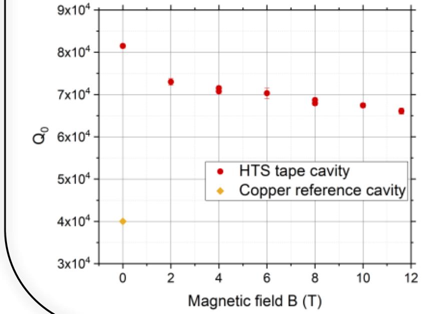


Figure 3. Magnetic field dependence of the surface resistance at 8 GHz and 50 K. Up to 9 T, CCs' R_s outperforms that of copper.



HTS Axion cavity development

- Figure of merit of axion haloscopes scales with Q and B^4
- Conductivity of copper limited by the anomalous skin effect
- Superconductor can increase conductivity further
- REBCO suitable for applications
- Tests with REBCO tape and coating were performed
- REBCO tape at f = 9.0 GHz outperforms copper

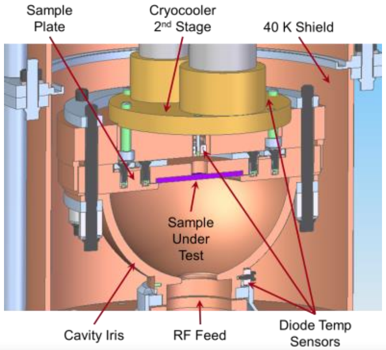


Accelerating HTS cavities

- Could operate at very high gradient
- Require a reduced number of RF power sources
- Could lower overall power consumption than in existing linacs

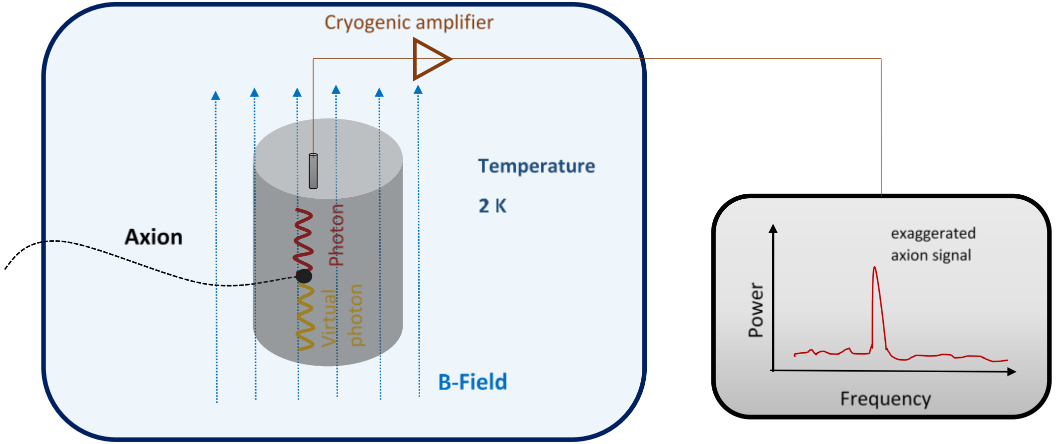
How will HTS behave at high-power?

Tests on a demountable high-power RF cavity (f = 11.4 GHz) at SLAC with HTS discs in July 2022



Axion Cavities

Axion haloscopes



- In the presence of a magnetic field, the conversion of axions into photons is triggered.
- A cavity resonating at the frequency of the expected axion mass will increase its output power.

Motivation

The figure of merit for our experiment is given by:

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

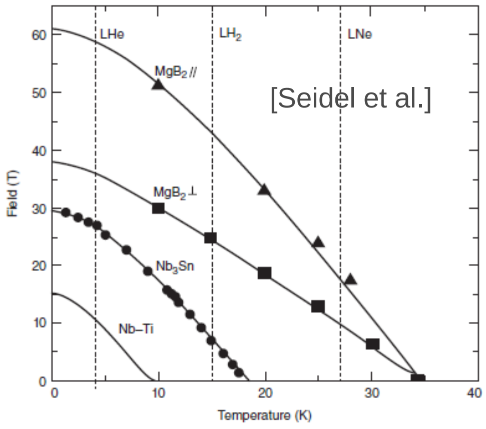
11 T short
model dipole
magnet

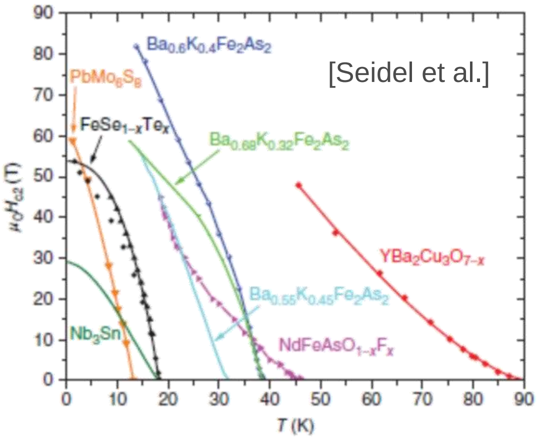
increase Q
copper coating
→ superconducting coating

T_{sys}	detection noise temperature
G	geometrical form factor
Q	Quality factor
$g_{A\gamma}$	axion-photon coupling
B	magnetic field
V	cavity volume

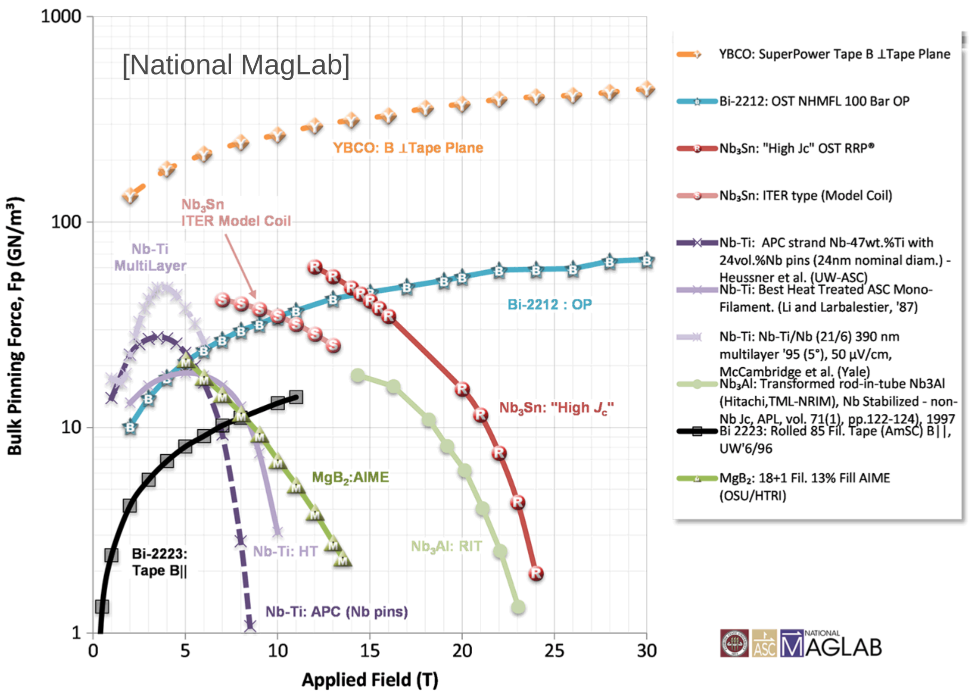
requirement: high quality factor
in a high magnetic field

What kind of superconductor can be used?


[Seidel et al.]


[Seidel et al.]

Superconductor with critical magnetic field at 4 K above 11 T and strong pinning force.

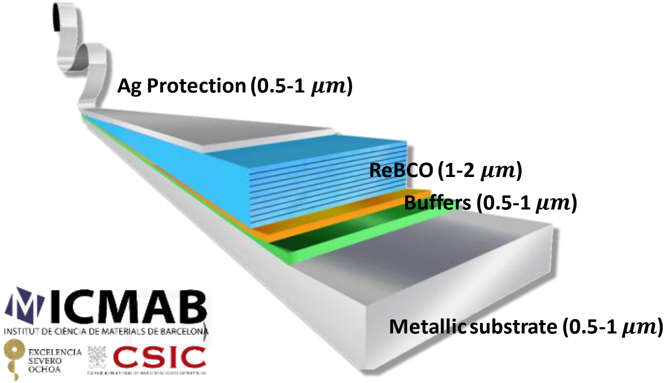

[National MagLab]

RADES coatings and cavity design

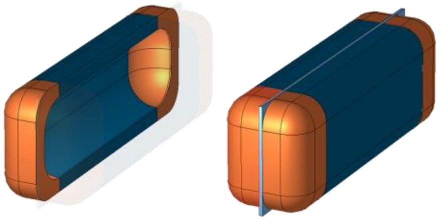
coating material

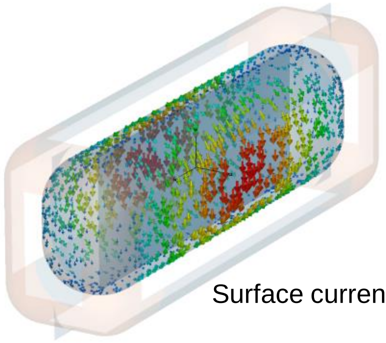
- ReBCO tape → scalable
  ICMAB technology to strip of Cu and Ag layers
  REBCO layer is exposed to the RF fields

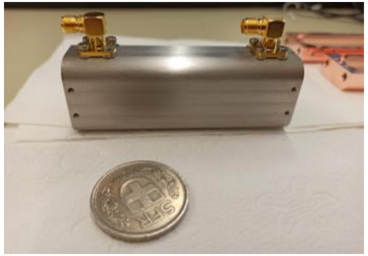
- Nb_3Sn coating



optimized design for coating



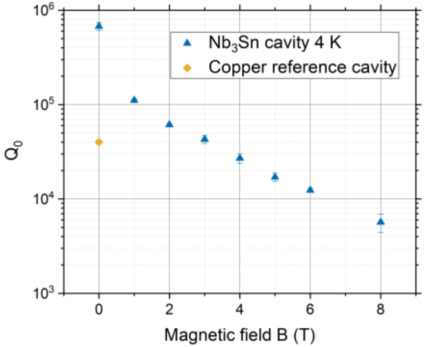

Surface currents



Coatings

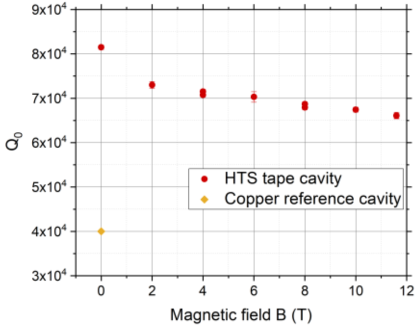
Nb_3Sn

Coated at CERN by G. Rosaz & C. Pereira Carlos



HTS tape

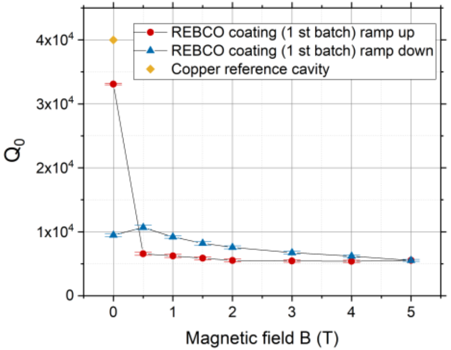
ICMAB
(G. Telles, N. Lamas, X. Granados, T. Puig, J. Gutierrez)



HTS coating

Coated by THEVA and Ceraco.

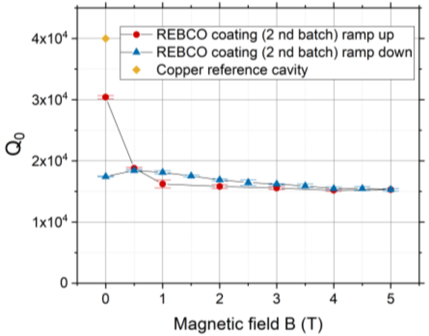
1.4 um



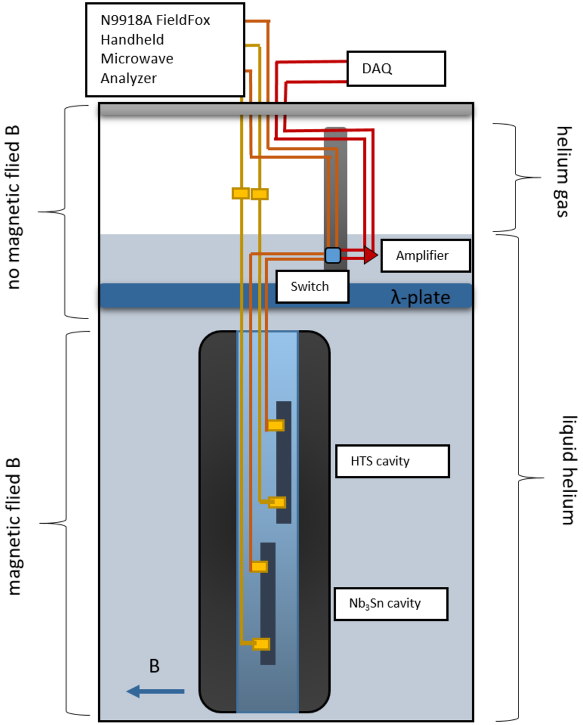
HTS coating

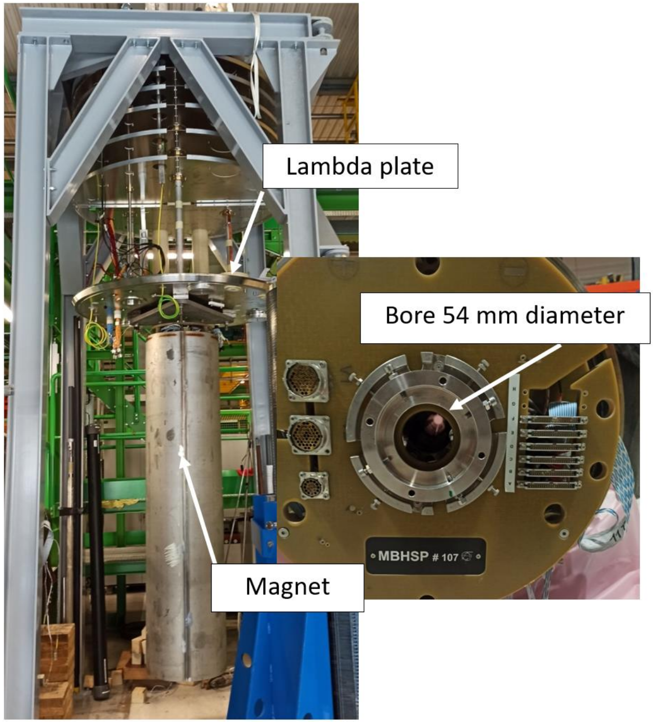
Coated by THEVA and Ceraco.

2.1 um

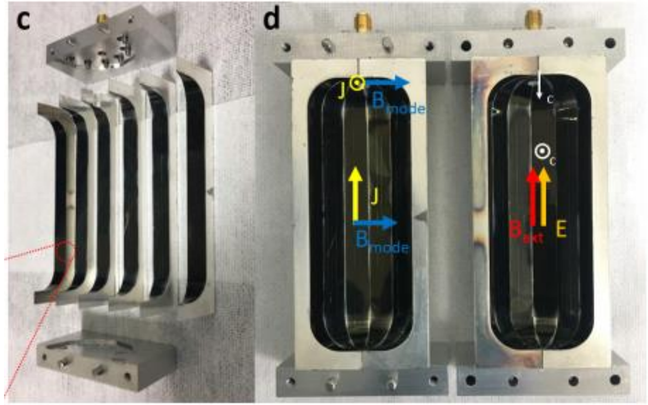


Experimental set-up

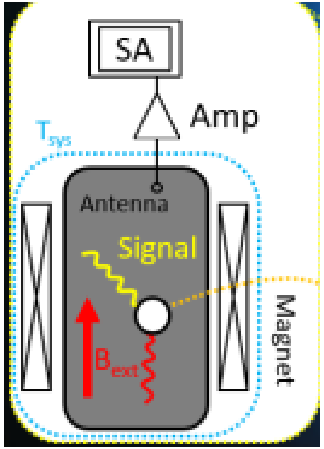




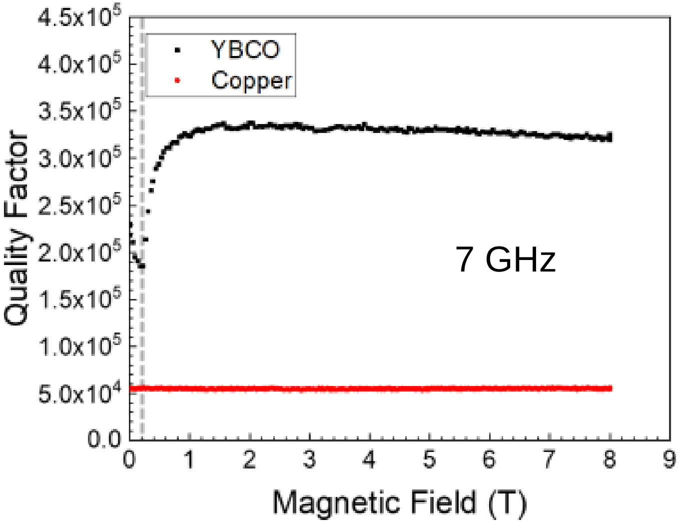
CAPP HTS tape cavity



CAPP, arXiv:2103.14515v1



REBCO tape glued on Al segmented cavity @ 7 GHz

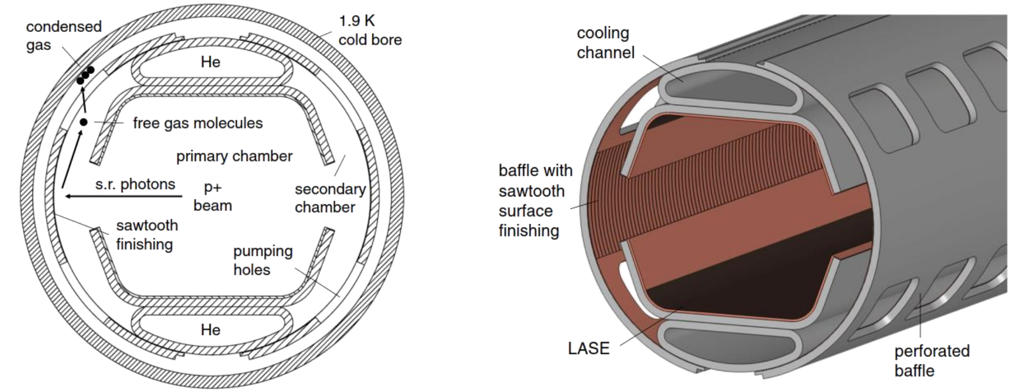


J_{RF} parallel to B

FCC Beam screen

Need for a beam screen in a p-p collider

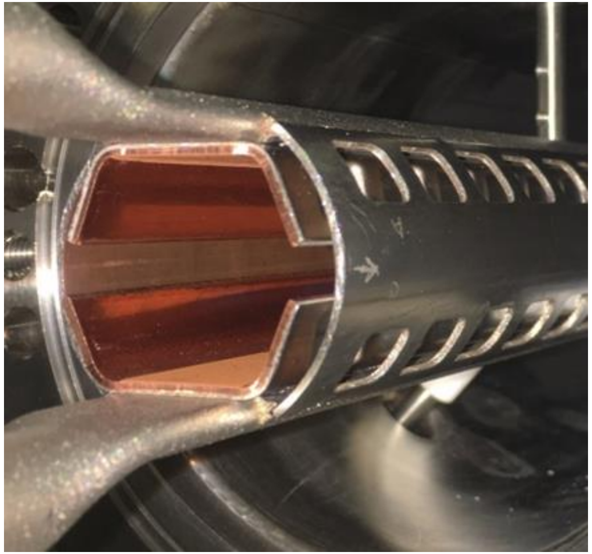
I. BELLAFONT *et al.* PHYS. REV. ACCEL. BEAMS **23,** 033201 (2020)



(a) Cross section of the FCC-hh beam screen inside the cold bore

(b) View of the FCC-hh beam screen with the sawtooth surface finishing applied on the irradiated baffle

FIG. 4. FCC-hh beam screen for bending magnets, featuring LASE treatment on the upper and lower flat areas of the inner chamber.



Synchrotron radiation load:

→ ~30 W/m/beam (@16 T) (LHC < 0.2 W/m)

→ ~5 MW total in arcs + Image currents, + electron cloud, + …

The synchrotron radiation cannot be dumped on the cold bore at 1.9 K: considering cryo efficiency, this would require almost 5 GW of electrical power

In the LHC, the beam screen is held in the 4÷20 K interval

Slides by Sergio Calatroni
- 1.11.2021
HTS for RF applications

Surface impedance: the key

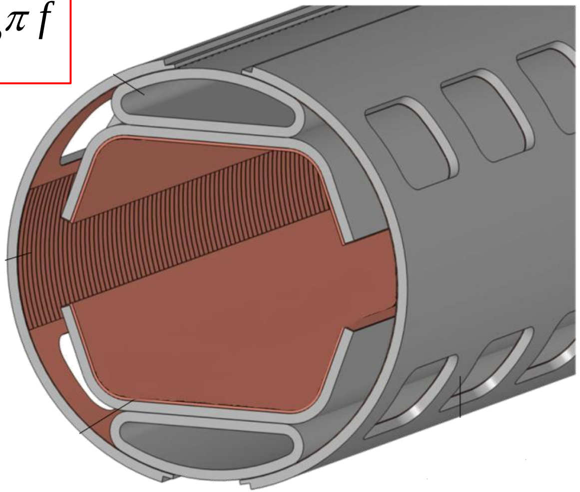
τ Risetime of beam instabilities

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

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

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

The lower the resistivity ρ, the higher the time τ it takes for developing beam instabilities

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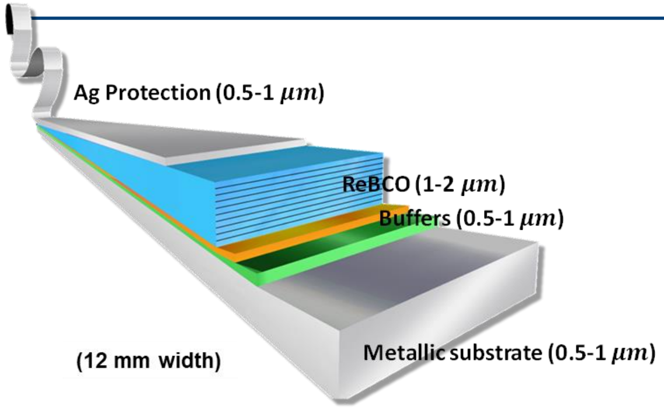
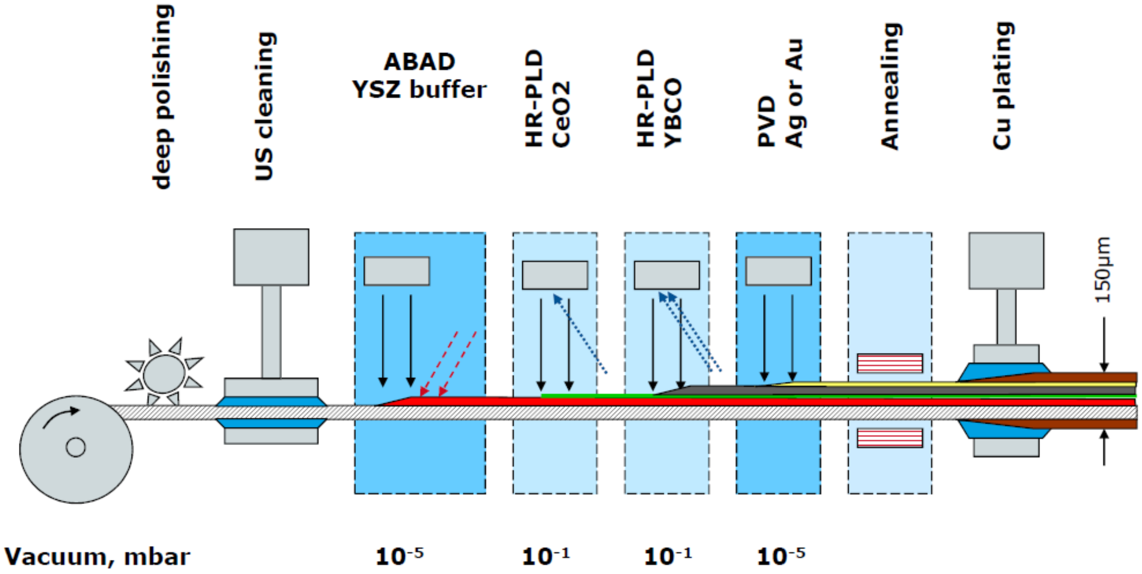
HTS for RF applications

HTS Coated Conductor (Y, Nd, Sm, Gd, Dy)Ba$_2$Cu$_3$O$_{7-\delta}$





Bruker HTS GmbH

Scalable technology for growing km-length REBCO CC

Presently produced by

American Superconductor
BRUKER
Fujikura
SuNAM
SuperOx
SuperPower Inc. A Furukawa Company
STI
THEVA
Shanghai 上海超导
OXOLUTIA
deutsche nanoschicht
MetOx

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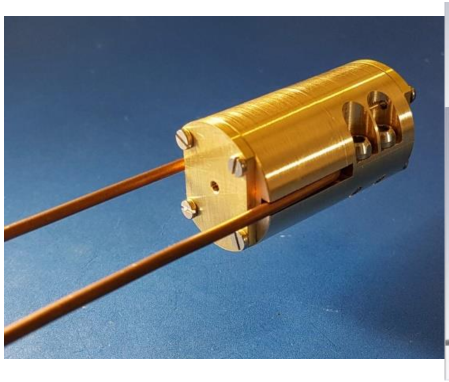
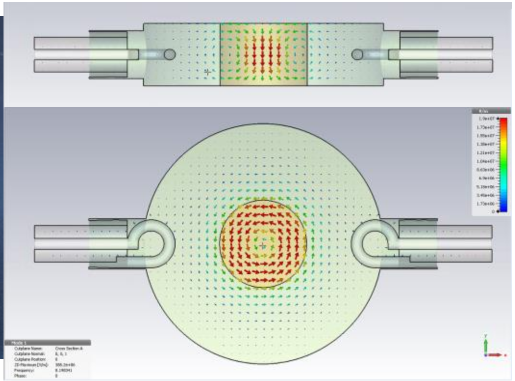
HTS for RF applications

Validation of RF performance (UPC - ICMAB)





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

T. Puig et al., Supercond. Sci. Technol. 32 (2019) 094006 (8pp)

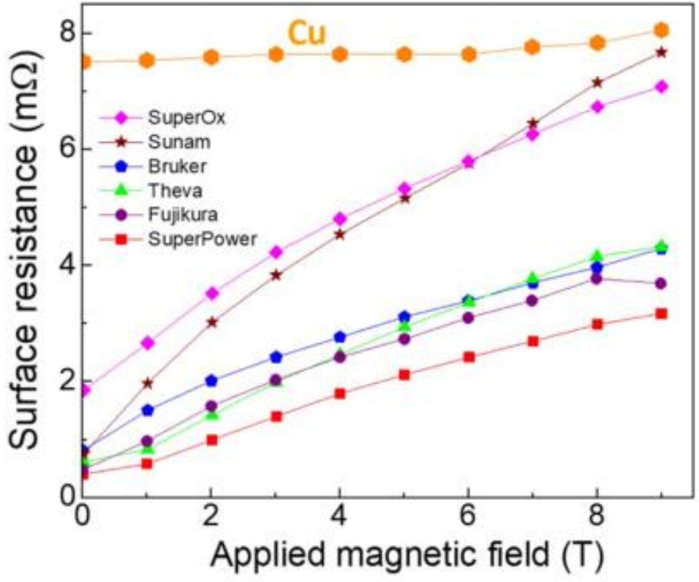


Figure 3. Magnetic field dependence of the surface resistance at 8 GHz and 50 K. Up to 9 T, CCs' R_s outperforms that of copper.

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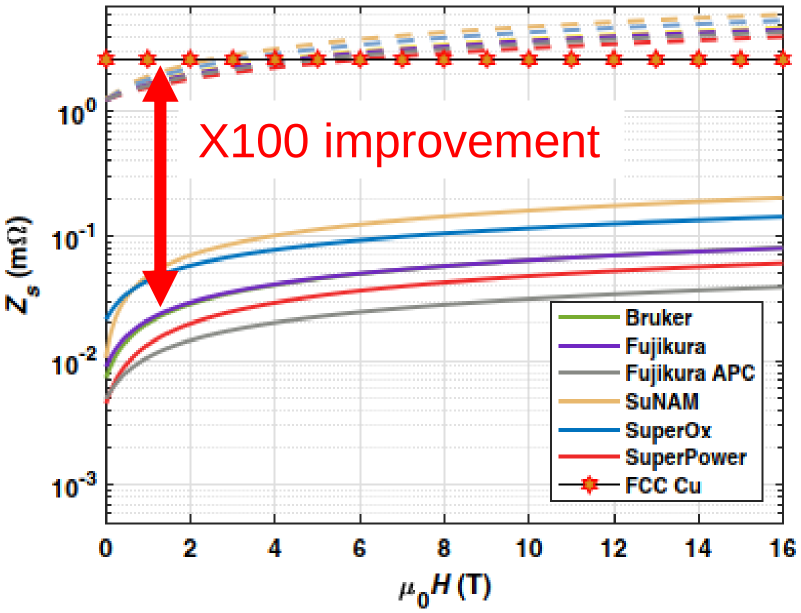
HTS for RF applications

Depinning frequency, and frequency scaling

Rs scaling to 1 GHz



X100 improvement

For HTS the Rs scales as f^2

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

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HTS for RF applications

A. Romanov et al., Scientific Reports | (2020) 10:12325 | https://doi.org/10.1038/s41598-020-69004-z

HTS accelerating cavity

Synthesis 1

- Copper accelerating structures cooled in the range temperatures of temperatures of 50-70 °K show an increase in gradient of 20 to 50 % compared to room temperature. Excellent!
- Cryo also show an increase in *Q* of around 2.5 for GHz-range cavities (anomalous skin effect). This reduces the number of RF power sources by the same factor (in a low beam loaded linac). Excellent!
- But overall power consumption higher due to Carnot efficiency (power factor of a bit over 10 for 80 °K system, 2.5 improvement in *Q* and about 30 % RF power production efficiency).

Slides by Walter Wuensch
PBC SRF miniworkshop
21 September 2021

Synthesis 2

- Implementation of an HTS coating has the potential to give an additional factor in efficiency – would be reflected in a reduced the number of power sources and make the system more efficient than at room temperature!
- Existing HTS axion and accelerating cavity fabrication layouts (halves and quadrants) are the same, although the latter has a somewhat more complicated geometry. Discussion with company required.

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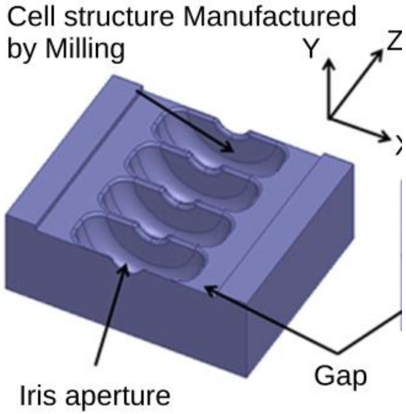
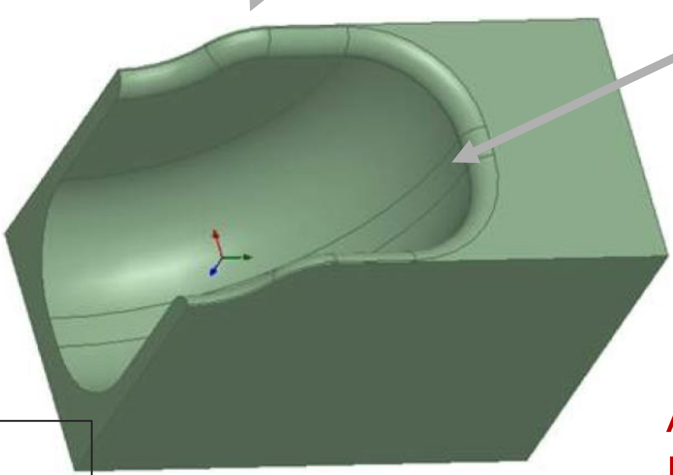
Possible implementation in an accelerating cavity



Copper in high electric field region

HTS in high magnetic field regio



(a) Elliptical Rounding

3 or 12 GHz for high power test in CLIC test stands.

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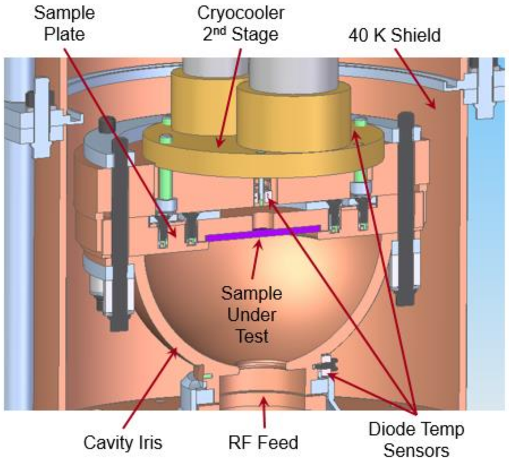
A key open question is how the HTS will behave at high-power. Can it be even put in the high electric field region?

Test set-up at SLAC

Cryostat Design

- Built around a pulse-tube cryorefrigerator from Cryomech w/ 3.6 K base temp.
  - 1.35 W cooling power at 4.2 K.

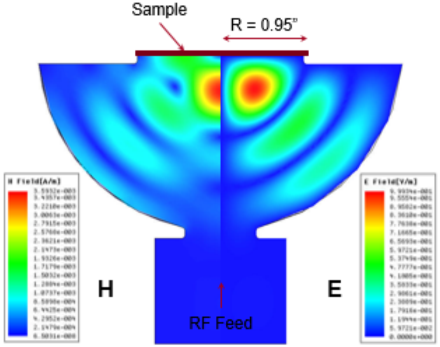


- X-band operation (11.4 GHz) permits a compact design and small sample size.
  - Sample size = 2.0 in. (50.8 mm)
  - Cavity O.D. = 5.6 in. (142 mm)
- Can achieve H_{peak} of about 360 mT using our 50 MW XL-4 Klystron.

HFSS Modeling

- High-*Q* X-band hemispheric cavity with a TE_{032}-like mode at 11.4 GHz.
  - Zero **E**-field on the sample
  - Maximum **H**-field on the sample (2.5x the peak **H**-field on the cavity iris)
  - Sample accounts for ⅓ of total cavity loss
  - No radial current on the cavity bottom

HFSS modeling of high-*Q* Cu cavity under TE_{032}-like mode



- Cavity geometrical factors calculated with HFSS EM simulator.
  - Relate Q_0 to R_s through single *G*-factor
  - Determine participation ratio, *α*, for both the cavity body (Cu/Nb) and sample, *s*

Information provided by Mitch Schneider. Pictures taken from poster by Paul Welander, Matt Franzi, Sami Tantawi.