HTS for high-power RF applications

Sergio Calatroni, on behalf of the Collaborating Institutes.

Image credits: ESA/Webb, NASA & CSA, H. Dannerbauer

The Universe ☺

- Only a minor fraction of the universe, as we know it, is made of "ordinary matter"

- What are Dark Energy and Dark Matter?
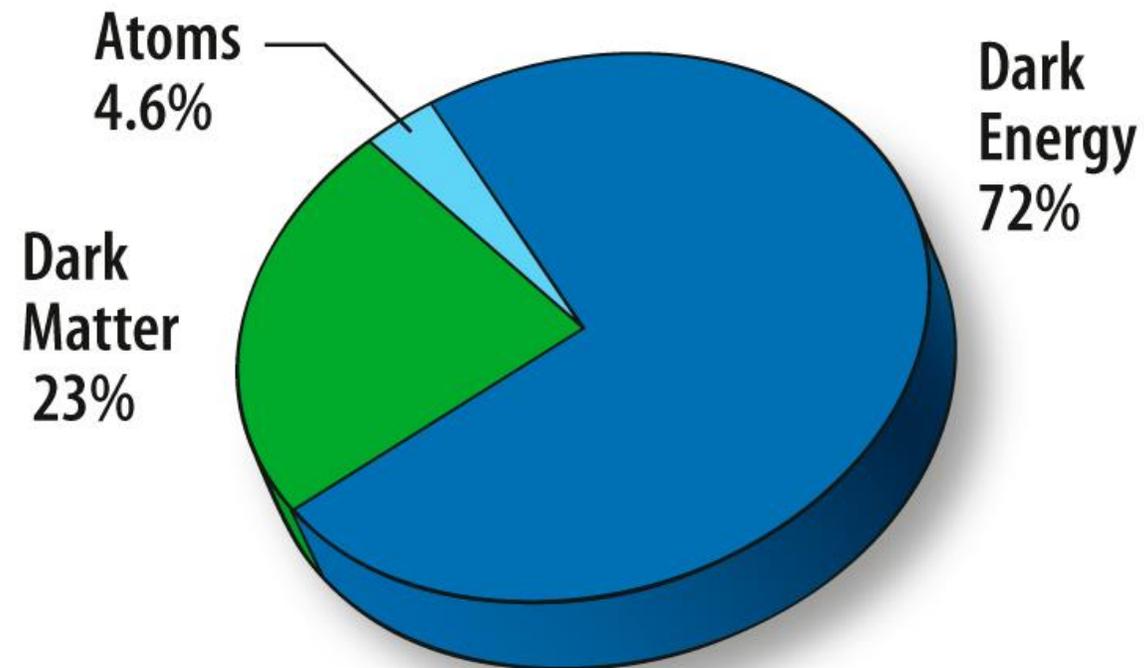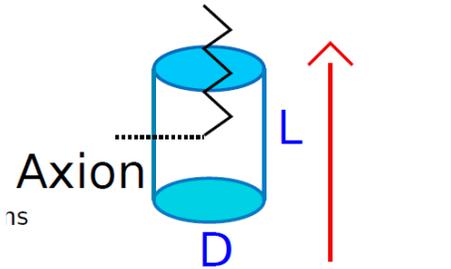

Atoms 4.6%

Dark Matter 23%

Dark Energy 72%

Image source: NASA / WMAP Science Team

Axions as dark matter candidates

Axion detection: a cavity in a magnetic field

microwave photon

L

Axion

D

External B field

Inverse Primakoff Effect

$m_a c^2 \approx h\nu$

Sikivie's haloscope, i.e. with RF cavity

An axion can shift the frequency of a photon, in this case from 0 Hz to ν Hz. Proportional to axion mass m_a

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

Increase Q
copper coating →
superconducting
coating

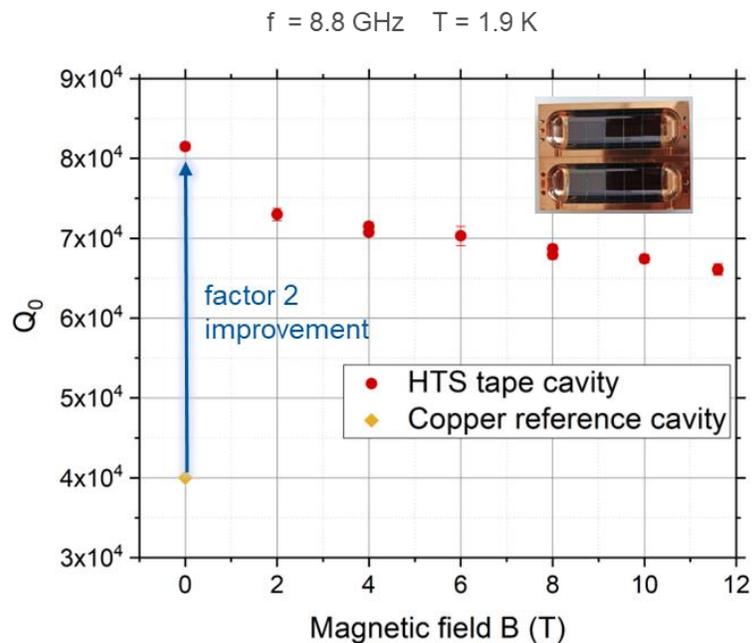**Requirement:** High quality factor in a high magnetic field

Sensitivity is proportional to cavity Q, cavity volume V^2 and to the external magnetic field B^4

HTS for axion searches: RADES

Most sensitive physics results for axion masses around 36.56 μeV

First-generation HTS Cavities - 2021

f = 8.8 GHz   T = 1.9 K

factor 2 improvement

- HTS tape cavity
- Copper reference cavity

Cavity performance, IEEE TAS, Vol. 32, No. 4, (2022) 1500605

Physics results, https://arxiv.org/abs/2403.07790

Second-generation HTS Cavities - 2024

		B = 0 T	B = 11 T
HTS A	Q_0	~ 2.2 x 10^5	~ 1.1 x 10^5
	$Q_{0(HTS)} / Q_{0(Cu)}$	5.5	3
HTS B	Q_0	~ 2 x 10^5	~ 1.4 x 10^5
	$Q_{0(HTS)} / Q_{0(Cu)}$	5	3.5

A new, two-weeks physics measurement run was performed in November 2024 at SM18, with better cavities and better DAQ
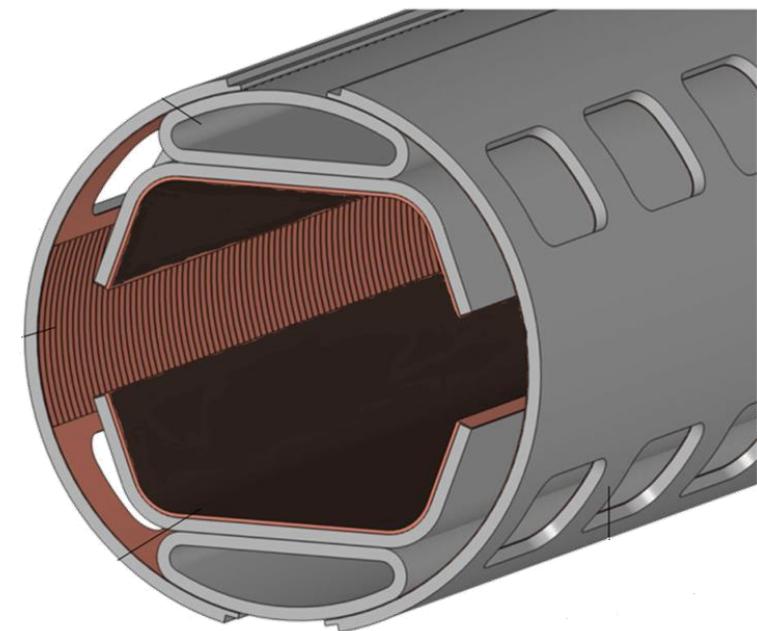
The start: beam screens for the FCC-hh

Link to TE-VSC seminar 2021

Link to TE-VSC seminar 2024

HTS for the FCC-hh beam screen

- Goal: to reduce beam coupling impedance compared to a copper beam screen at 50 K

- Extremely challenging requirements:
  - HTS must operate at 50 K and 14 T
  - Critical fields Hc_2 , H_{irr} >> 14 T
  - J_c > 25 kA/cm^2 (2.5x10^8 A/m^2)
  - Surface resistance R_s better than for copper up to ~1 GHz

- Compatible with accelerator environment
  - Minimize dipole field distortion due to persistent currents
  - UHV compatible, low SEY, lifecycle assessment, etc..

Beam image current are RF
This is an SRF problem

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

Manufacture the screen using REBCO tapes soldered to the screen
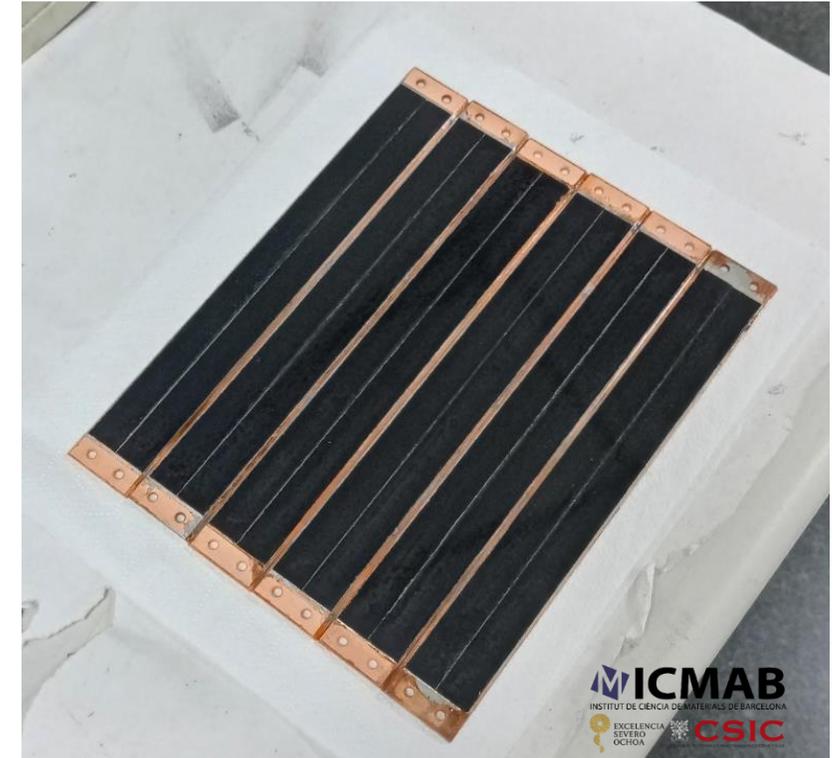
Coat the inside of the screen with TI-1223 films
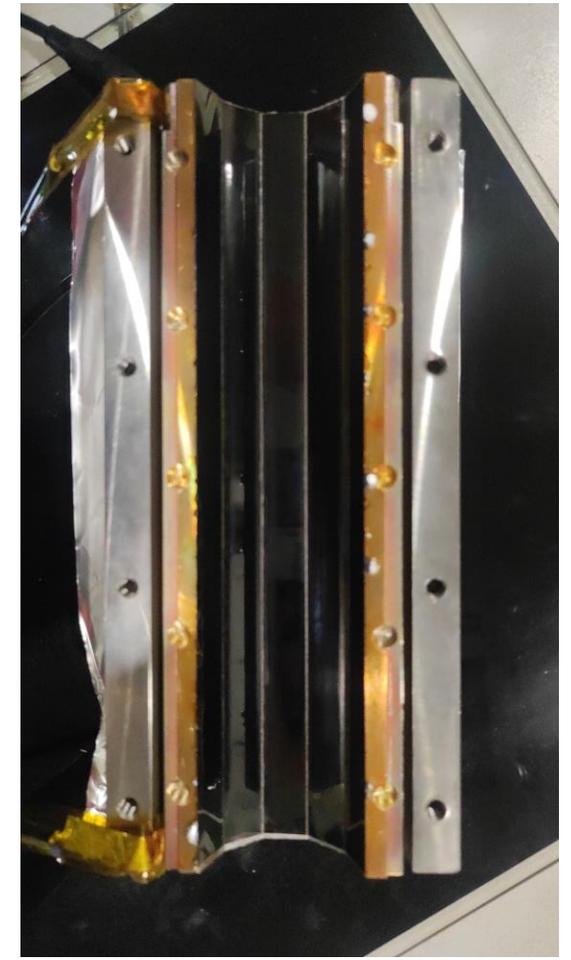
Development of soldering technology

Solder

HTS tapes

CC

Beamscreen

Technical feasibility is demonstrated

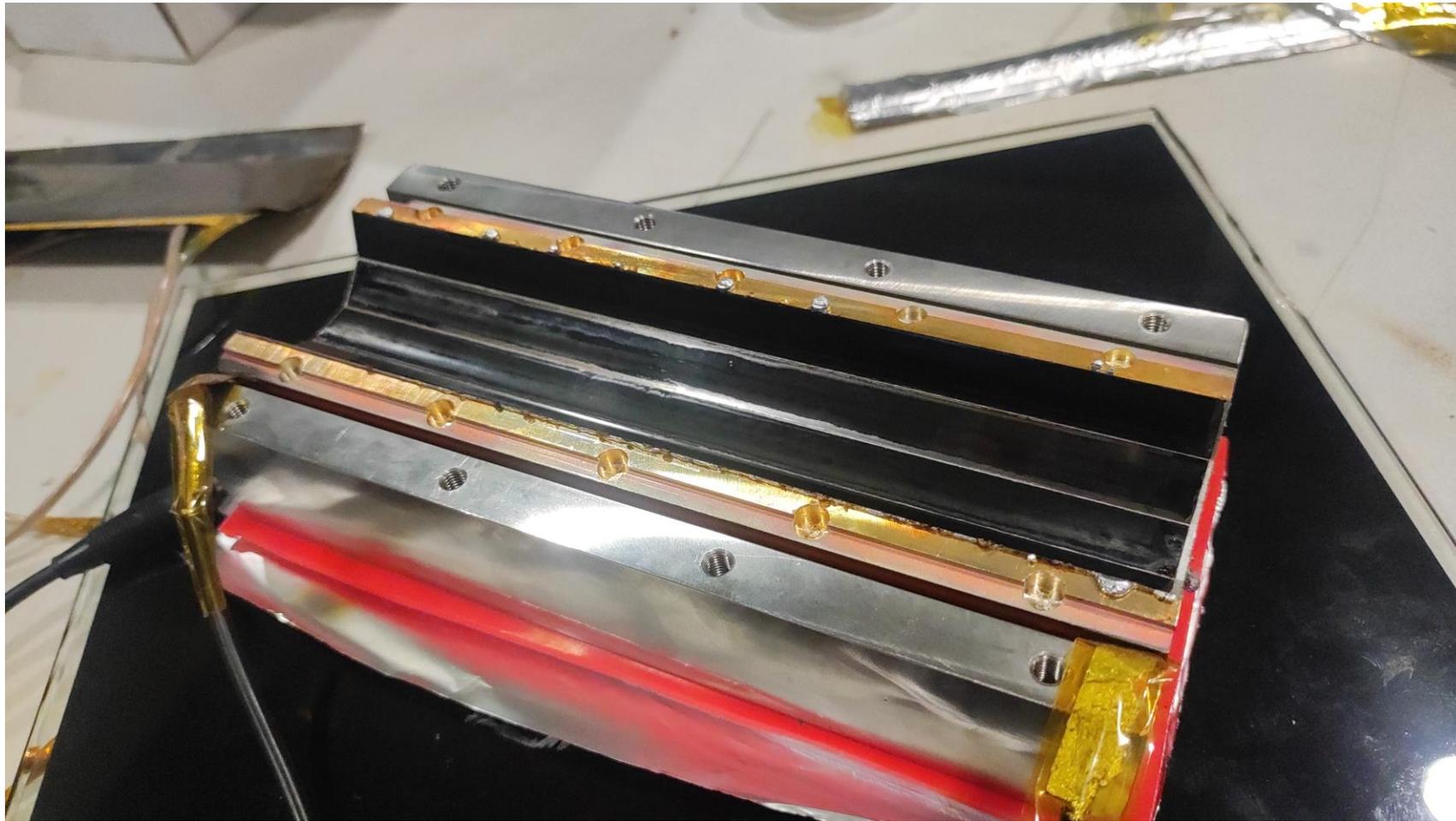Pb$_{60}$Sn$_{38}$Cu$_2$ layer

Bottom surface

REBCO

Top surface

Ag

Cu

FCC beamscreen

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

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

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)

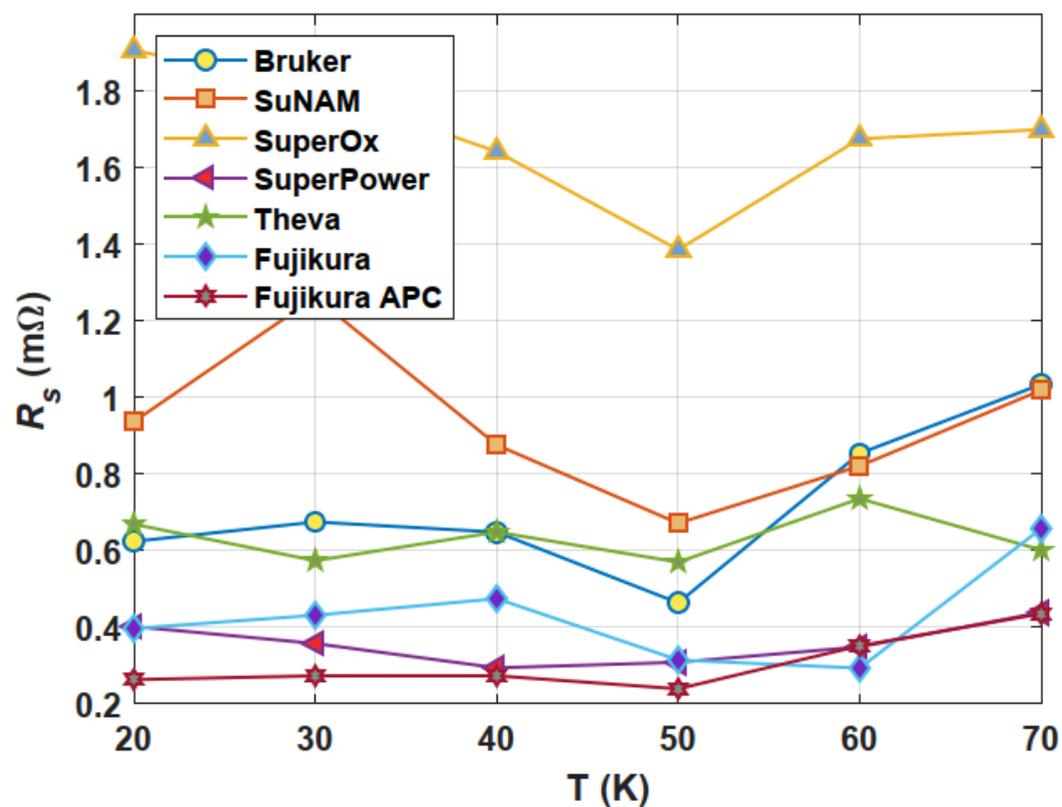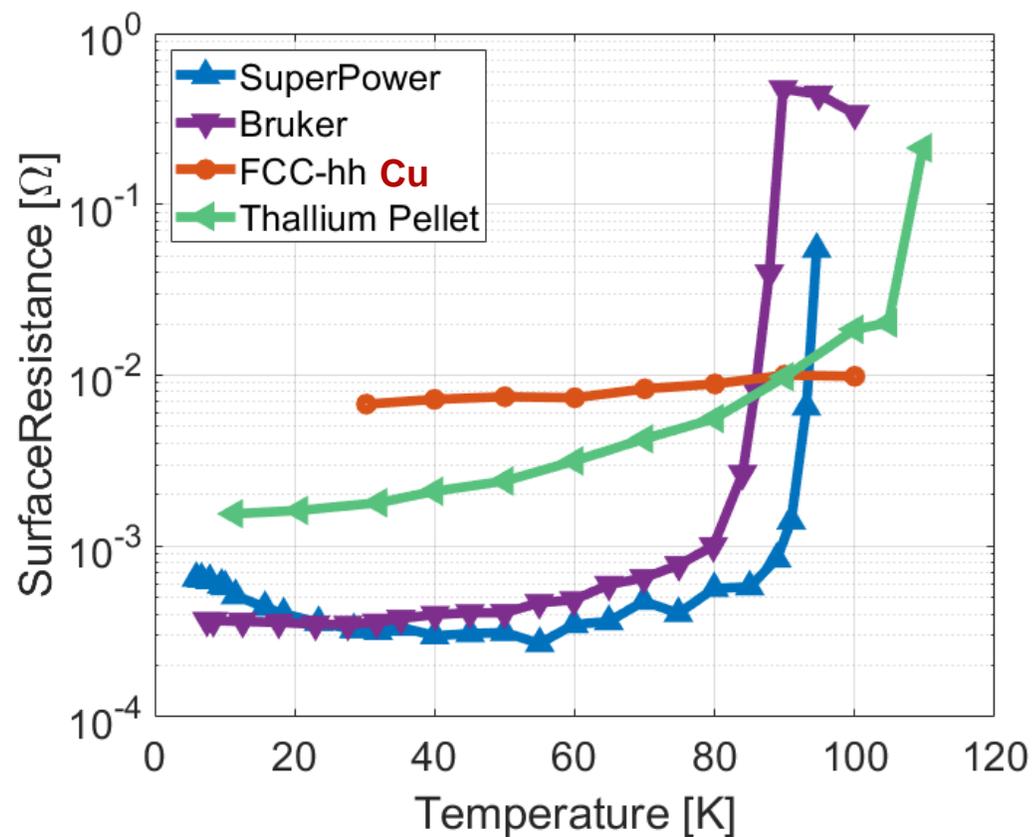For HTS Rs scales as f^2
For Cu Rs scales as $f^{1/2}$

New developments: HTS in high power RF – "HIGHEST"

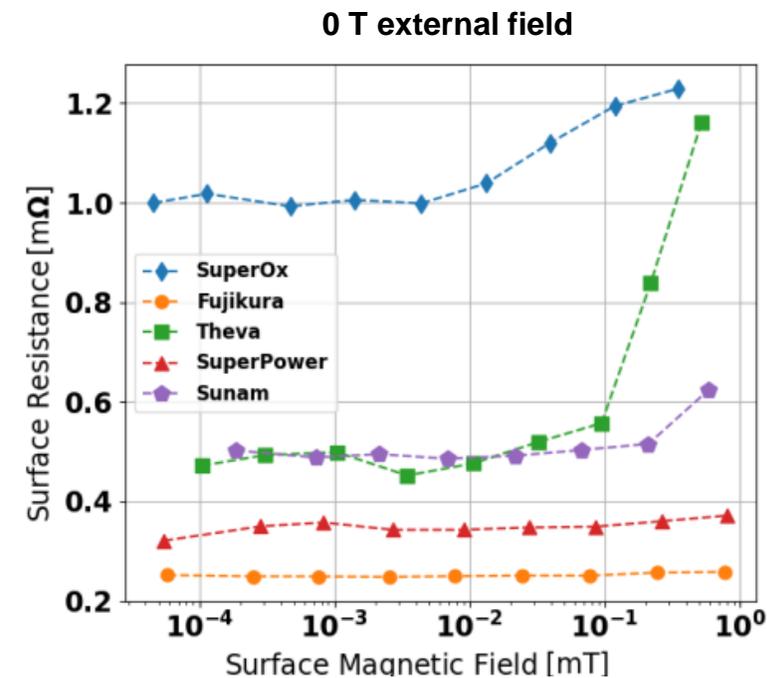Or: we have a technology, let's push it to the limits

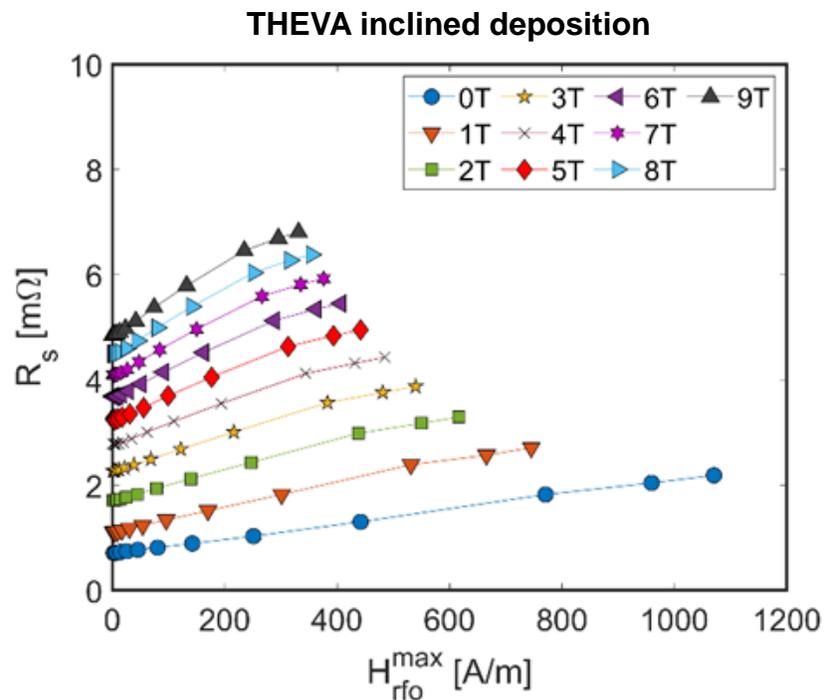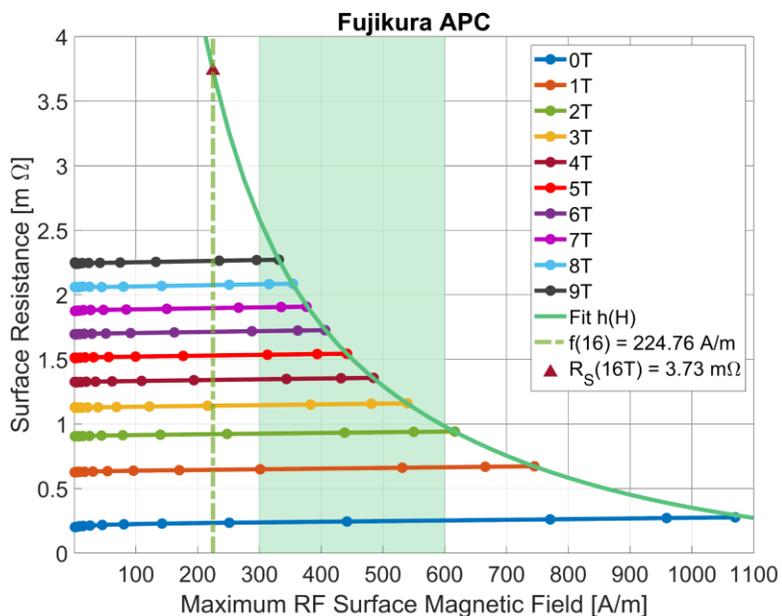# Low-power RF measurements of HTS – zero magnetic field

- An **improvement up to x25** compared to copper (Rs=8mΩ) has been **measured on samples of tapes** (8 GHz) at extremely **low RF power**

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

Fujikura APC

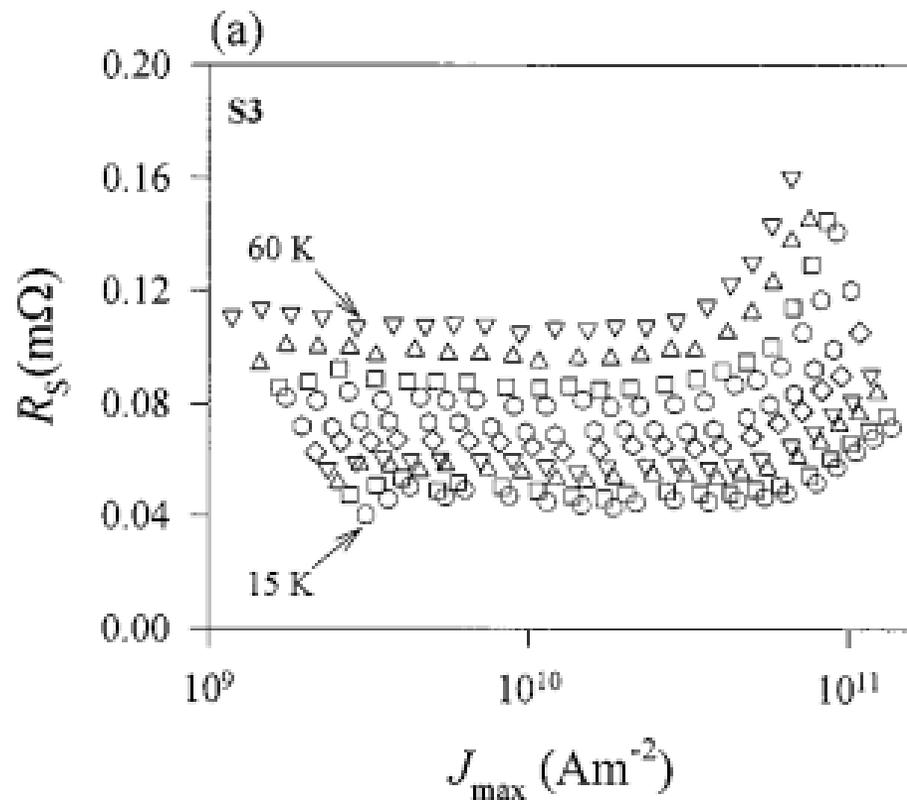**THEVA inclined deposition**

0 T external field

HTS coated conductors at 8 GHz (dielectric resonator) and 50 K, up to $\cong$ 0.3 MV/m

Conversion factor for equivalent TESLA-shape cavities: 1 MV/m $\cong$ 3.6 kA/m $\cong$ 4.55 mT

Patrick Krkotic, PhD dissertation, UPC Barcelona 2022

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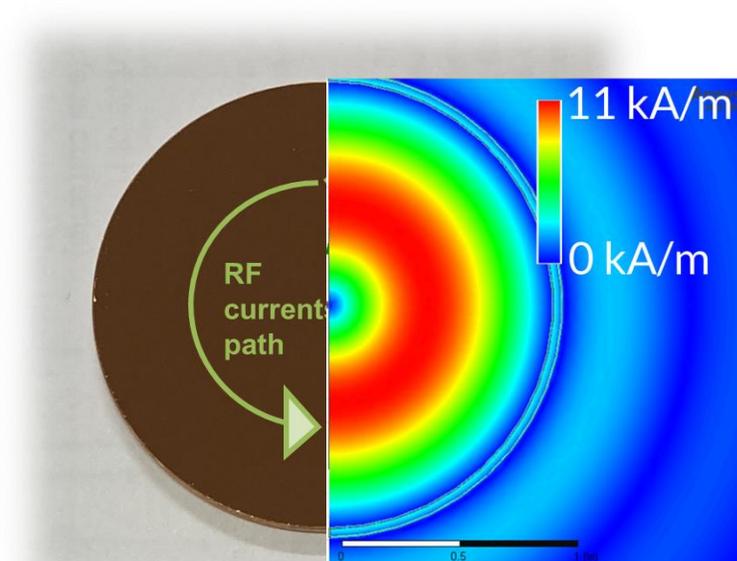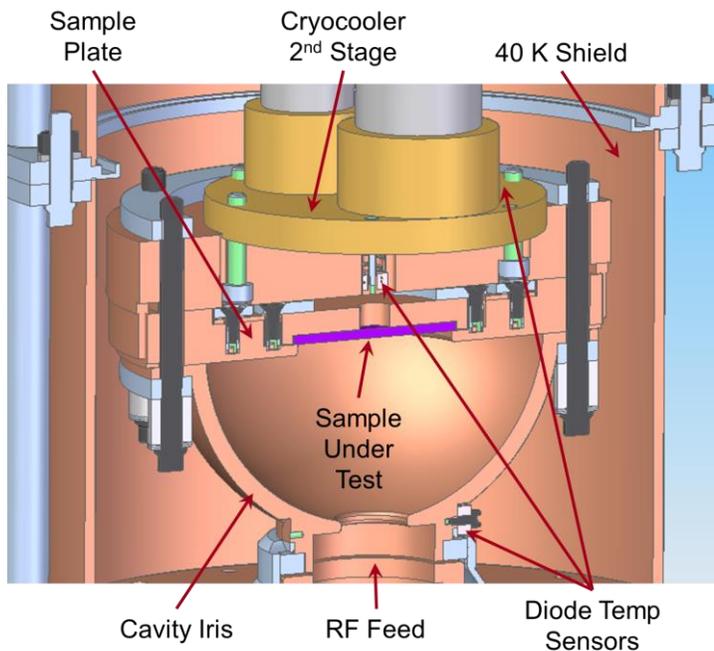
Powell et al. Journal of Applied Physics 86, 2137 (1999)

For 1 µm thickness this is equivalent to 10^5 A/m ($\cong$ 0.1 T $\cong$ 25 MV/m)
Entering the "high-gradient" range
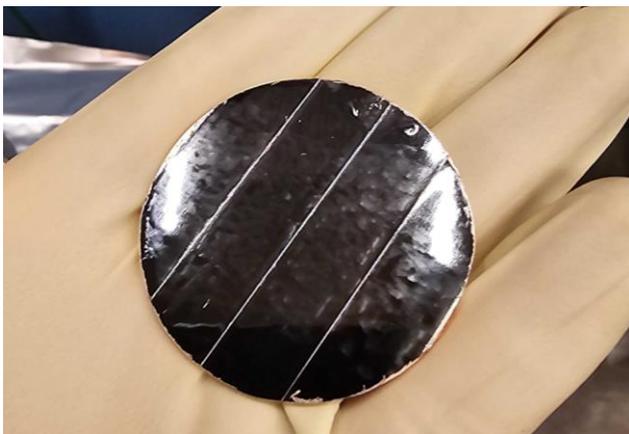
High-gradient testing at SLAC

- "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 11.424 GHz.
- Maximum H-field on the sample
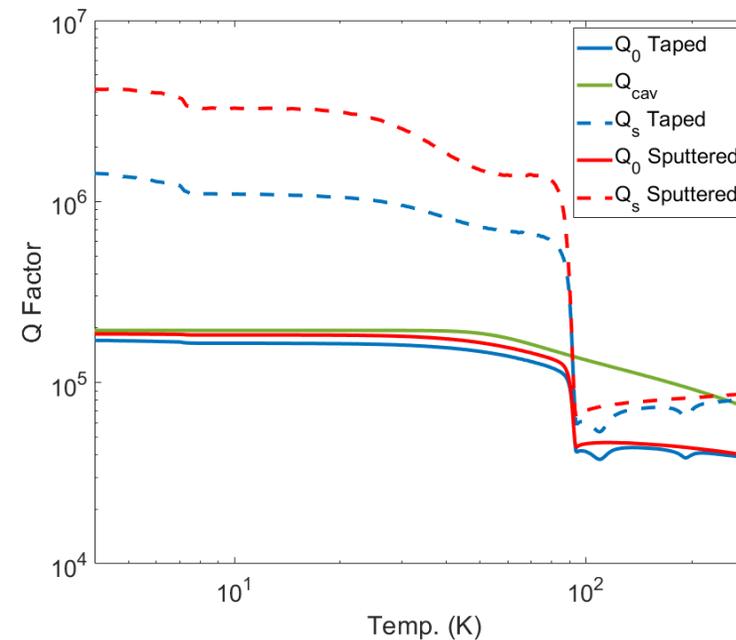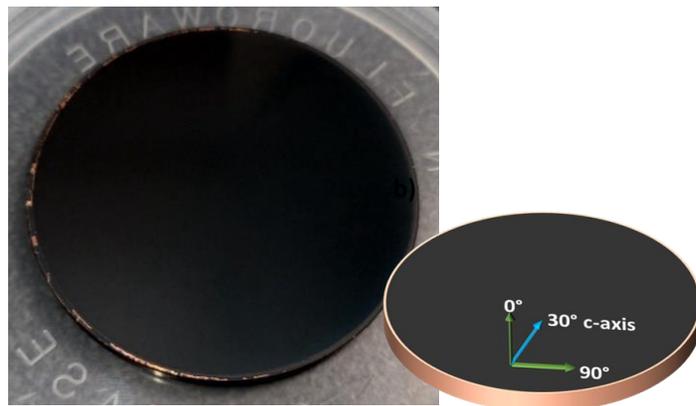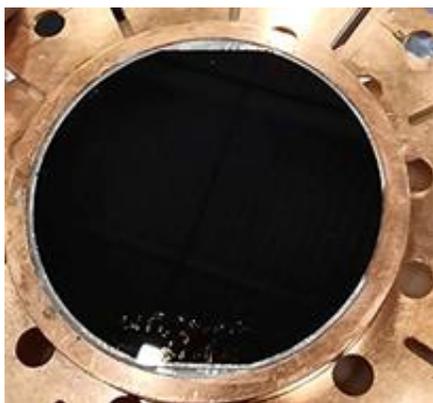- Zero E-field on the sample
- Sample accounts for ⅓ of total cavity loss

Two HTS measurements, after calibration measurements with Cu and Nb

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

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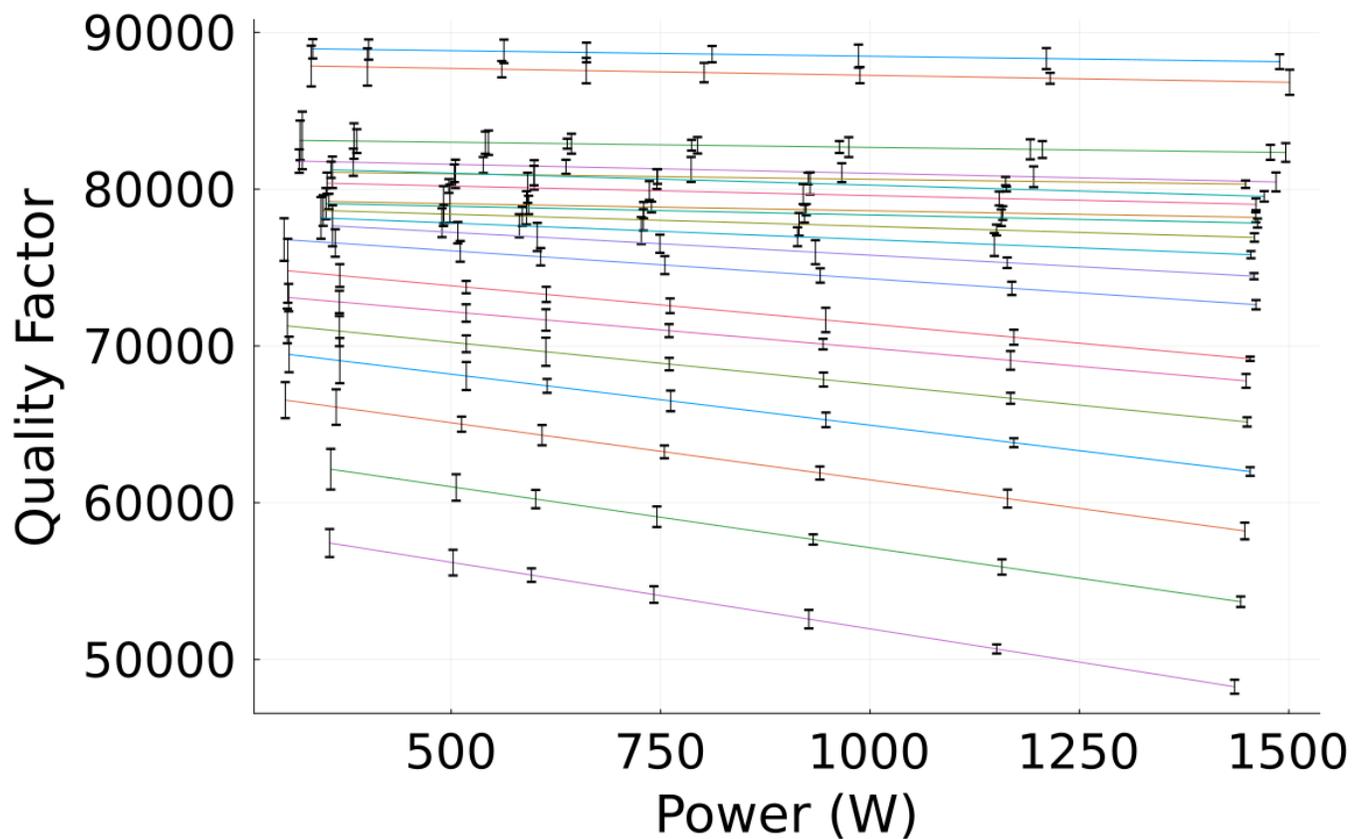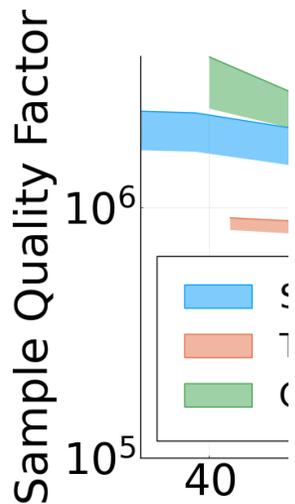

R_s Cu $\cong$ 17 mΩ

R_s REBCO Fujkura tapes $\cong$ 3 mΩ

R_s REBCO on Cu PVD/CERACO $\cong$ 1 mΩ

(R_s REBCO on MgO PVD/CERACO $\cong$ 0.5 mΩ)

Shaded

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

Legend:
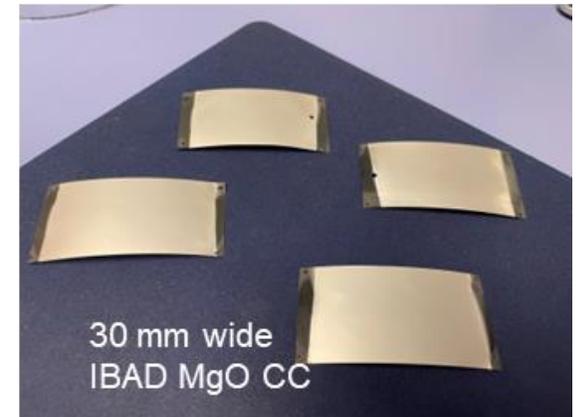| 41.6 K | 50.0 K | 70.25 K | 75.5 K | 76.2 K |
78.5 K	80.0 K	81.5 K	82.4 K	83.3 K
84.4 K	85.25 K	86.0 K	87.0 K	87.5 K
88.0 K	88.5 K	89.0 K	89.5 K	90.0 K

From: Ankur Dhar

- Development of large tapes pursued at KCT/KIT.

- Buffer layer deposition is key technological hurdle

Roll to roll coater for HTS tapes

40 mm wide ABAD YSZ CC

30 mm wide IBAD MgO CC

Further info: talk by Nadja Bagrets at CCA workshop, Wednesday 13.3 at 8:30

Samples of large-size HTS tapes, prepared at ICMAB for RF characterization with the 8 GHz dielectric resonator
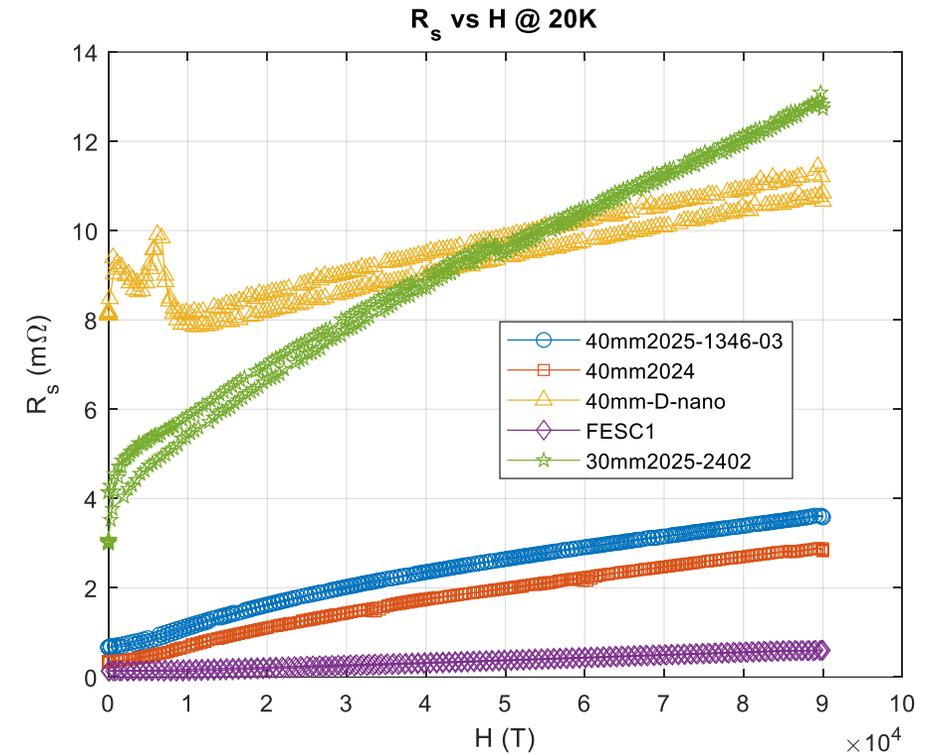

Surface resistance at 50 K and 20 K. State-of-the art reference commercial tapes (with APC, Artificial Pinning Centres) are indicated for comparison. Various 30 mm and 40 mm KCT coatings without APC. Zero-field performance is very promising

HIGHEST: High-power, high temperature superconducting tapes

- Two-years plan funded by IIF – I.FAST Innovation Fund

- Goals of HIGHEST:
  - Coating with tapes on discs and on segmented cavities for benchmarking of the HTS material and of the technology.
  - Develop large-size tapes (up to 50 mm wide) in collaboration with KCT, to be first validated at ICMAB, then tested on discs at SLAC.
  - Device validation: X-band pulse compressor (SLAC) as first "real" RF device

G.Le Sage

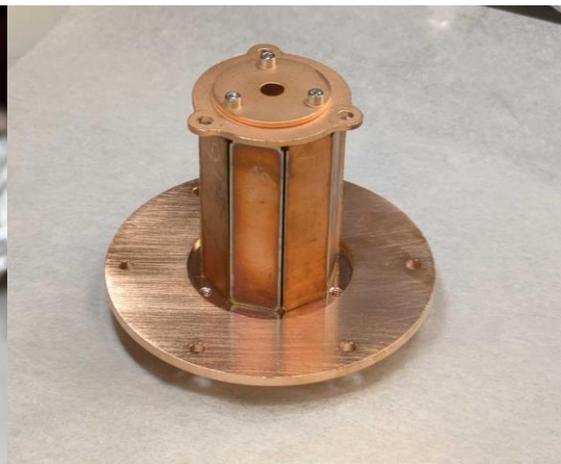Octagonal cavity exciting the TM010 mode was designed. This allows currents to run longitudinally.

Photos by
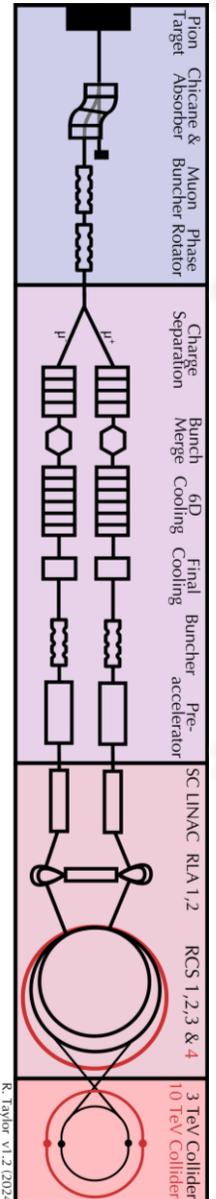Ankur Dhar

Cryo test coming in April

Final remarks

- A fruitful international collaboration has developed a robust technology for using HTS tapes

- This technology is now being reused in novel applications:
    - RF cavities at low power (Axion detection – RADES): excellent first results
    - RF cavities at high power. No data exist for HTS at high-gradient (either samples or cavities): experiments needed, and are being performed

- Wider soldered tapes (iFAST collaboration "HIGHEST") are being developed – key for applications at lower frequency / larger size

- For future large-scale applications, we should eventually consider developing a direct HTS coating technique on large 3D objects

- We are looking for companies and partners able to rise to the challenge…
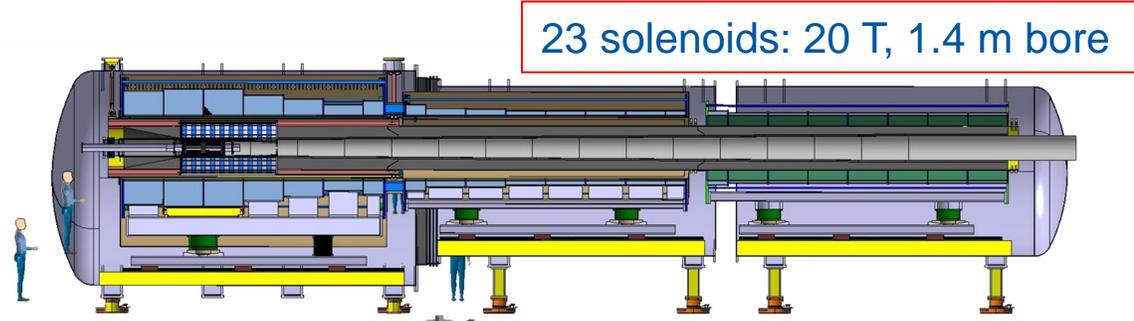
- … and we are looking for new challenges as well

And why not? The muon collider
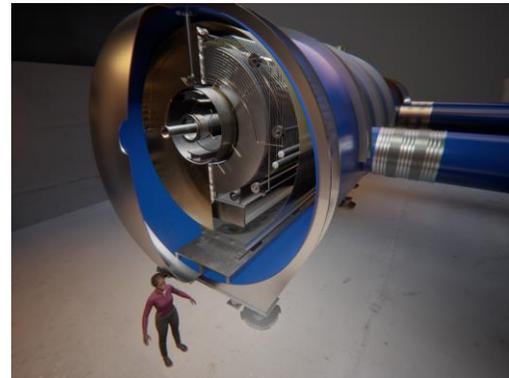
Or: HTS in high magnetic field AND high RF power

Muon Collider

Target and capture solenoid

Muon beam cooling solenoids

Accelerator and collider magnets

23 solenoids: 20 T, 1.4 m bore

3000 solenoids: 2 to 14 T, 90 mm to 1.5 m bore

17 solenoids: 40 T, 60 mm bore

5 km: 10 T, 30(V) x 100 mm (H) dipoles

10 km 14 T, 140 mm bore dipoles

L. Bottura HFM Meeting 2025

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 ?

A 3 GHz Proposal for a INFN LASA Test Facility

Extending to new frequencies

Our existing designs were centered on X-band frequencies, however our test facilities also extend to S-band

L-band capabilities will hopefully revived in the near future.

Procurement has begun for a 5 Tesla magnet with a 24 cm bore for testing S-band and L-band cavities in high magnetic fields

Faraday cups

Cavity

High field magnet

S-band test stand

RF Source:
S-band 5045 klystron at 2.856 GHz
Typically operates with a peak power of
10 MW in a 2 us pulse length, up to 60 Hz.

- How could a future cavity look like? Bimetallic cavities

B

SC

NC

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

- Cavity power losses: $P_c = \frac{1}{2} R_s H^2$

  o Where R_s is the surface resistance and H the magnetic field at the cavity surface

- Quality factor Q_0:

  o It is $Q_0 = \frac{2\pi f_0 W}{P_c} = \frac{\Gamma}{R_s}$ where W is the stored energy, f_0 the resonant frequency and Γ a geometry factor

  o Also it is $Q_0 = \frac{f_0}{\Delta f}$ where Δf is the bandwidth (FWHM)

- Decay time τ_0:

  o It is $\tau_0 = \frac{Q_0}{\pi f_0} = \frac{1}{\pi \Delta f}$

  o Giving $E(t) = E_0 \exp(-t/\tau_0)$ for the field envelope E

SC vs NC cavities

- RF systems fall in two categories

SC niobium, $Q_0 \approx 10^{10}$, 35 MV/m, $R_s \propto \omega^2$ NC copper, $Q_0 \approx 10^4$, 100 MV/m, $R_s \propto \sqrt{\omega}$

- 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 level of SC structures – which cannot be effectively pulsed due to high Q_0

Power consumption and luminosity of future colliders

- In our study, we want ultimately to verify whether HTS in pulsed RF mode allow a further power gain compared to both Nb and Cu

8 km footprint for 250/550 GeV CoM $\Rightarrow$ 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)

C³ Parameters

Collider	C³	C³
CM Energy [GeV]	250	550
Luminosity [$\times 10^{34}$]	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

C³ - 8 km Footprint for 250/550 GeV (to scale)

Trains repeat at 120 Hz

Pulse Format

133 1 nC bunches spaced by
30 RF periods (5.25 ns)

RF envelope
700 ns

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

From: Emilio Nanni

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

Even a factor 10 improvement in Q factor compared to copper could pave the way for energy savings

From: Emilio Nanni

Fluxon motion

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

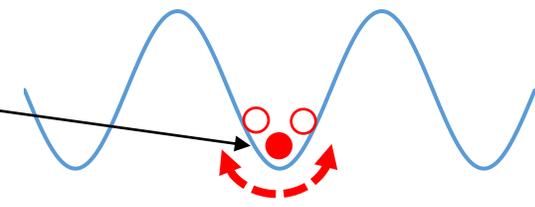Normal Core   Magnetic Field Lines

d

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

Superconductor   Supercurrents

Pinning centers

B field is normal to surface: worst case

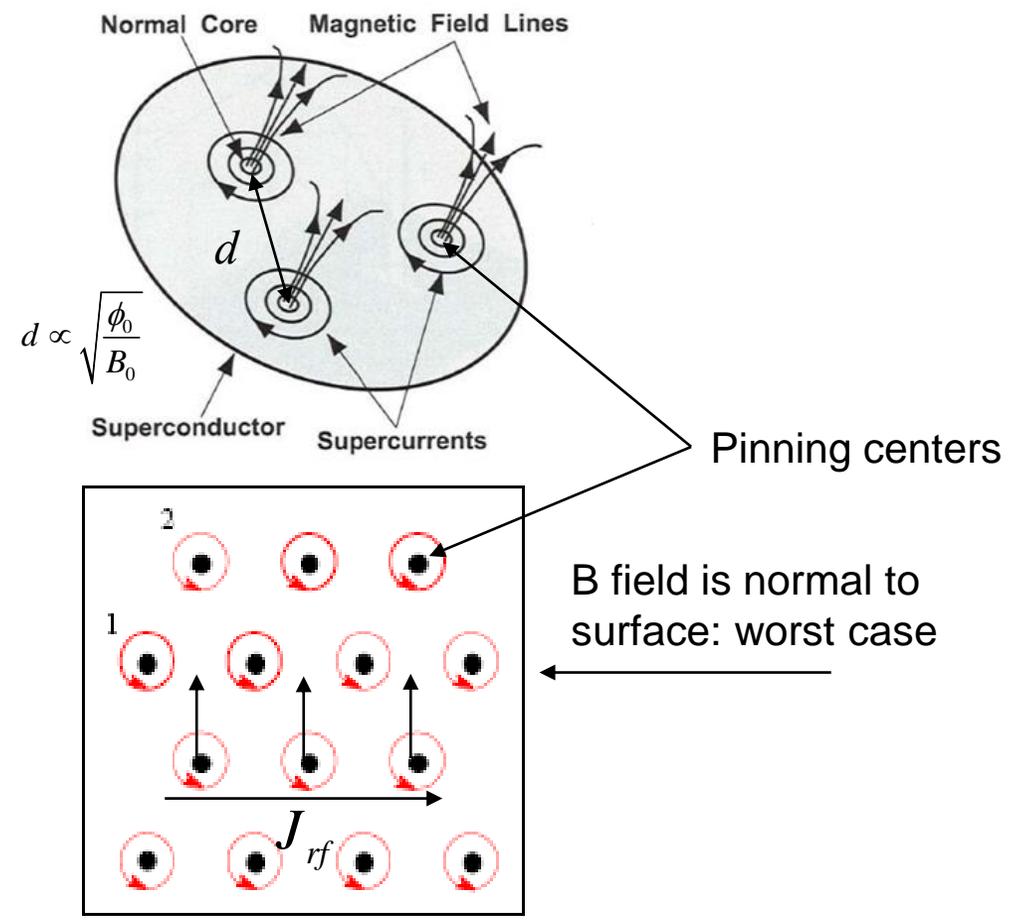J_{rf}

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

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

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

    $\approx$ tens of nm diameter

  - Each vortex carries one flux quantum

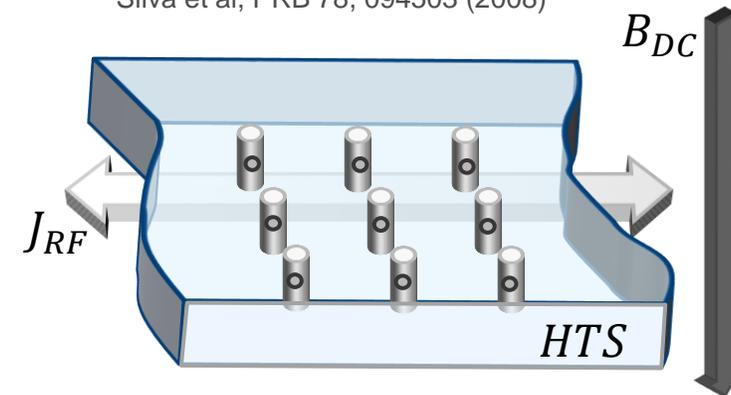- ## Apply RF Current

  - Motion of vortices $\rightarrow$ 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
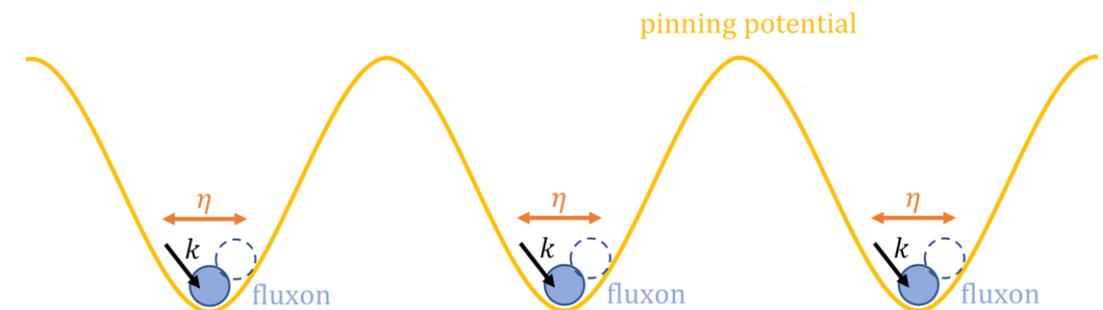
$$\eta = \frac{\phi_o B_{c2}}{\rho_n} \qquad k = \frac{2\pi J_c \phi_0}{d} \qquad \omega_o = \frac{k}{\eta}$$

Patrick Krkotic, PhD dissertation, UPC Barcelona 2022

- ## Vortex pinning

  - Artificial pinning centres

Simplified model valid for estimates and scaling

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