HTS for high-power RF applications

Sergio Calatroni, on behalf of the Collaborating Institutes.

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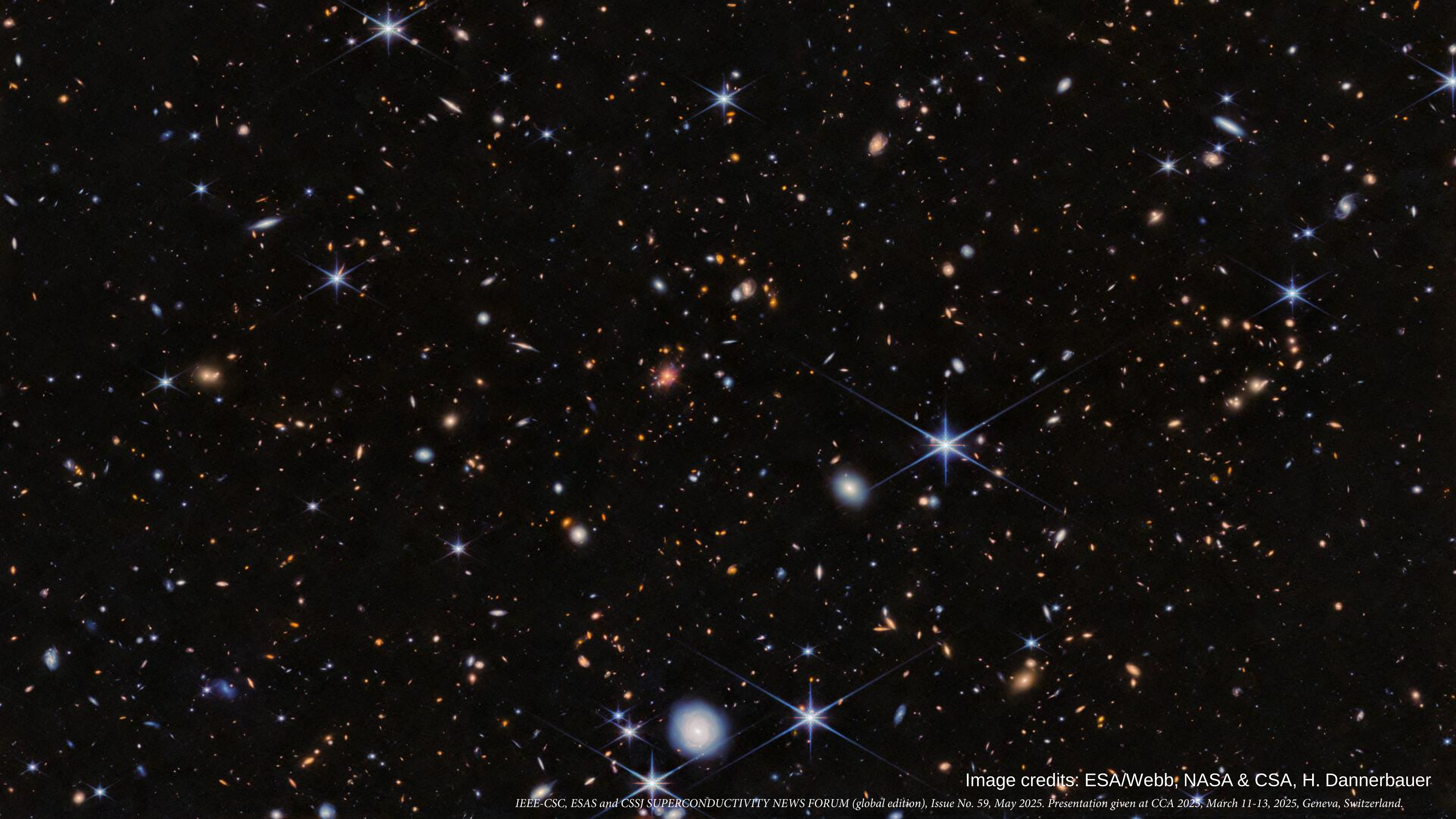
Image credits: ESA/Webb, NASA & CSA, H. Dannerbauer

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?

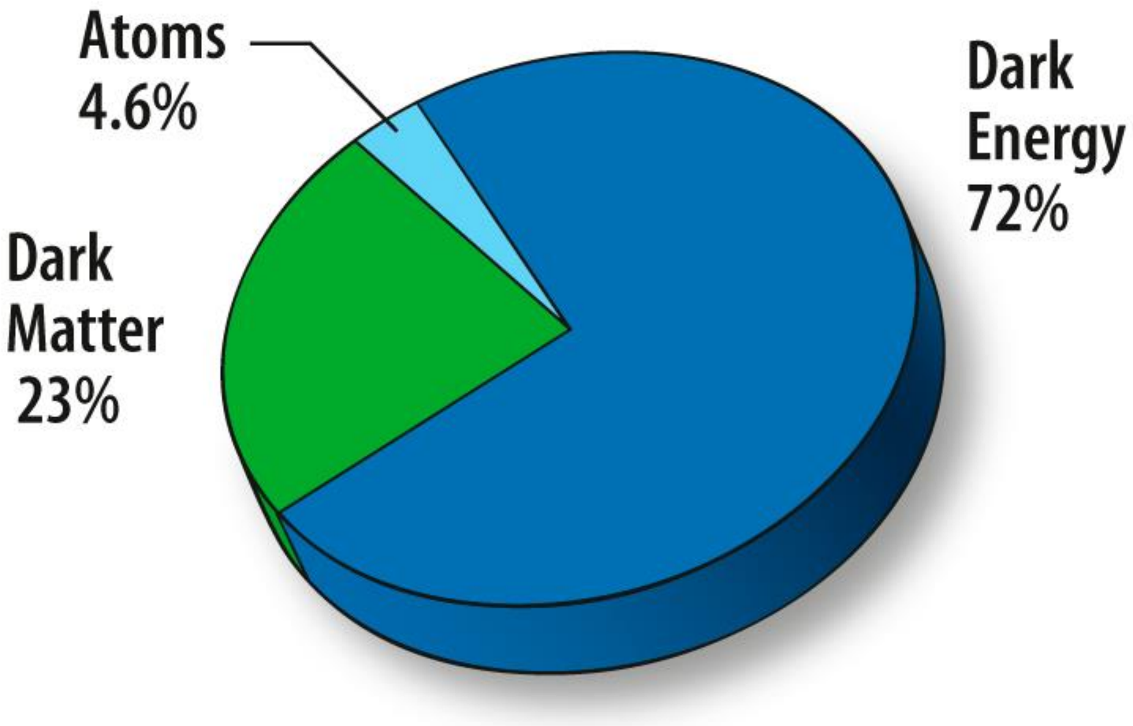

Image source: NASA / WMAP Science Team

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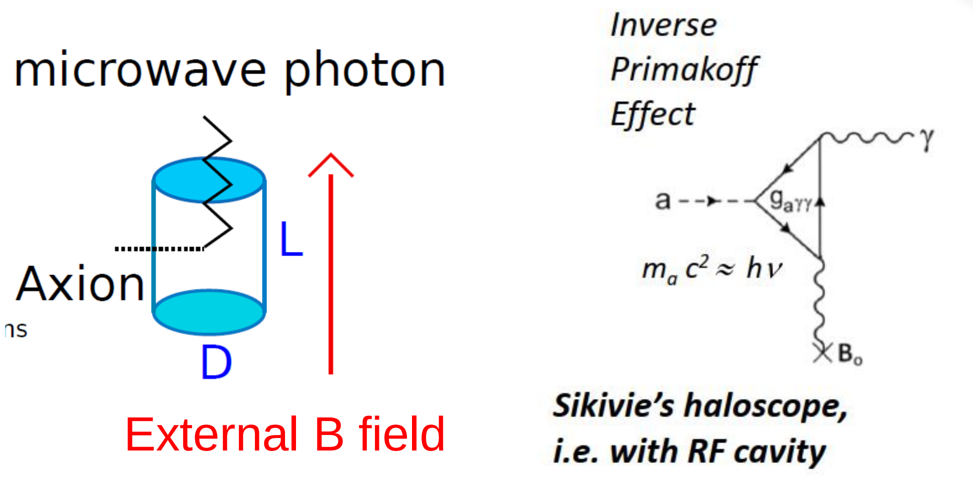
Axions as dark matter candidates

Axion detection: a cavity in a magnetic field



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

Increase Q
copper coating → superconducting coating

Requirement: High quality factor in a high magnetic field

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

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

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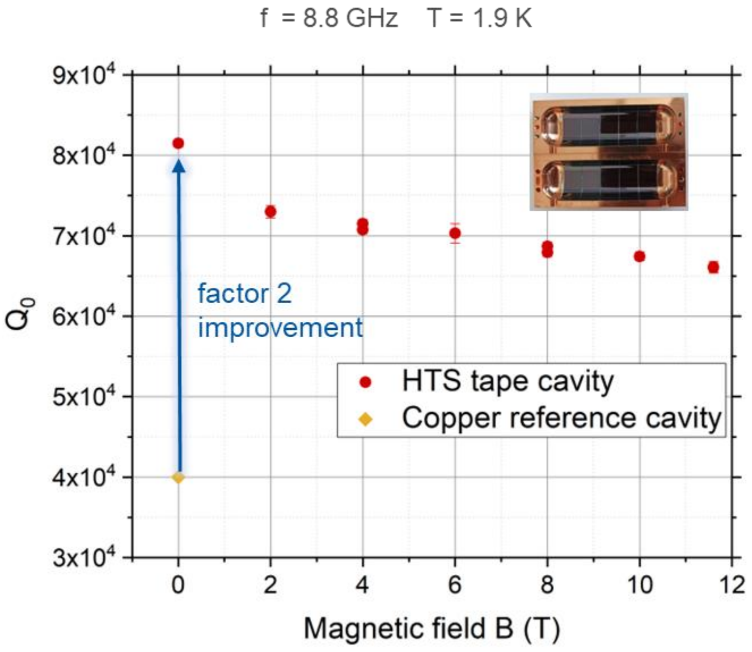
HTS for axion searches: RADES

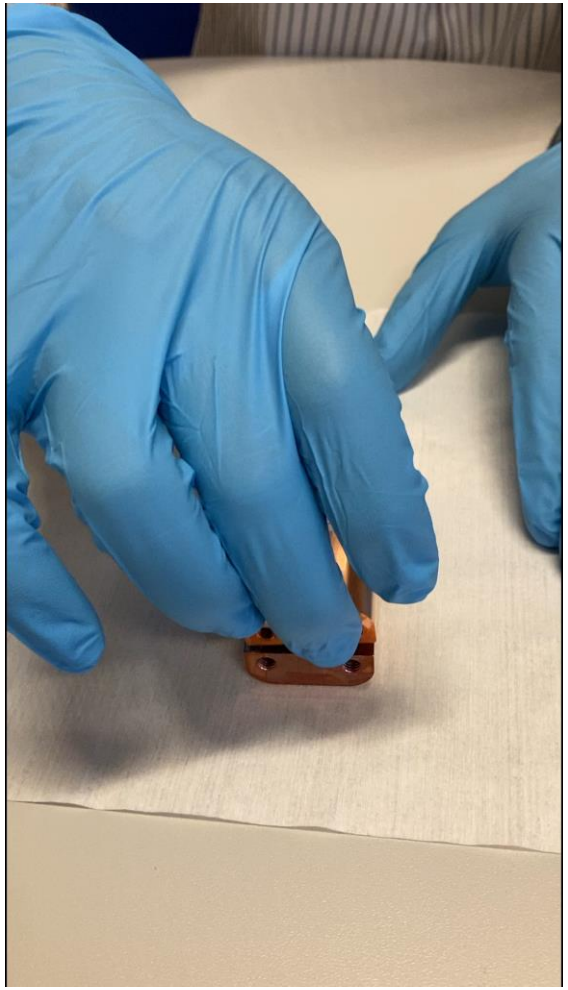
Most sensitive physics results for axion masses around 36.56 µeV

First-generation HTS Cavities - 2021



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 x10^5
	$Q_{0(HTS)}$ / $Q_{0(Cu)}$	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

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The start: beam screens for the FCC-hh

Link to TE-VSC seminar 2021

Link to TE-VSC seminar 2024

FUTURE CIRCULAR COLLIDER
Innovation Study

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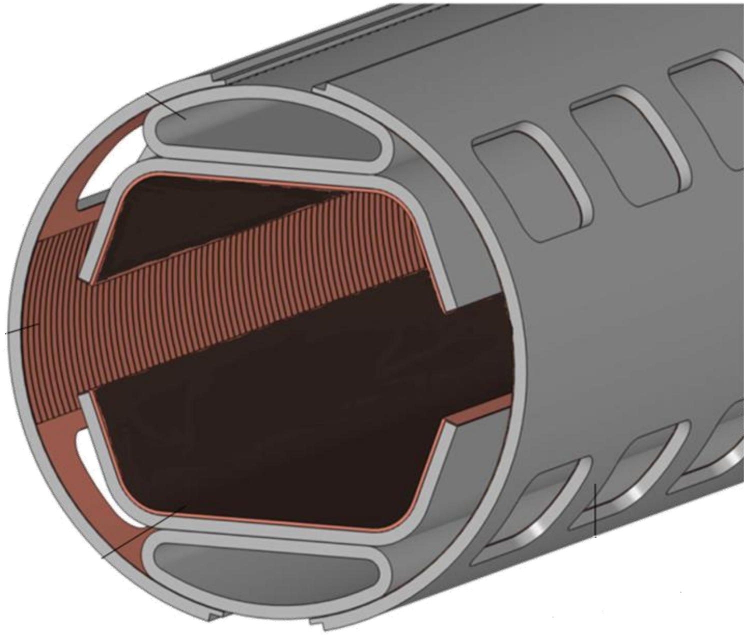
HTS for the FCC-hh beam screen

- 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 (2.5×10^8 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)

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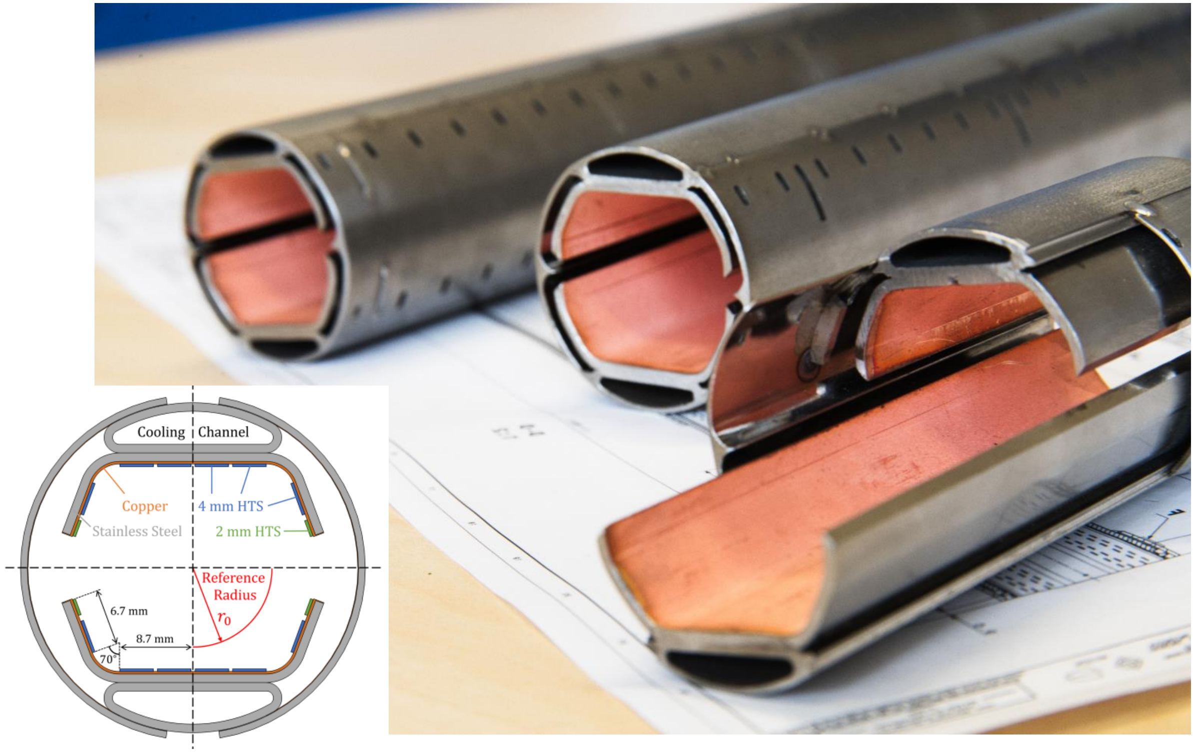
Two material choices

Manufacture the screen using REBCO tapes soldered to the screen

Coat the inside of the screen with Tl-1223 films



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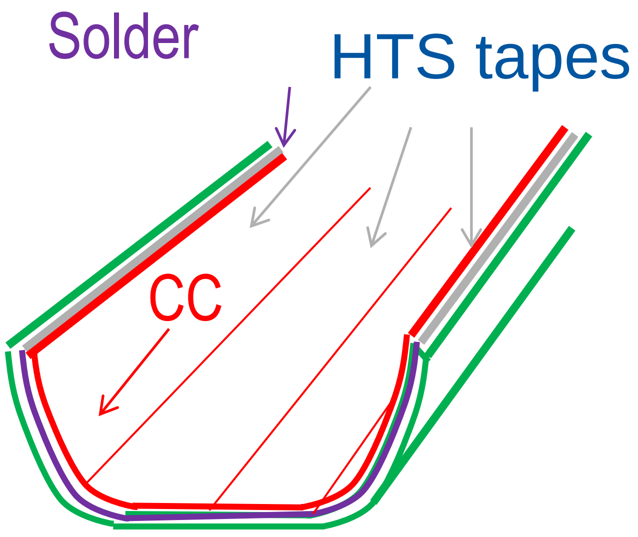
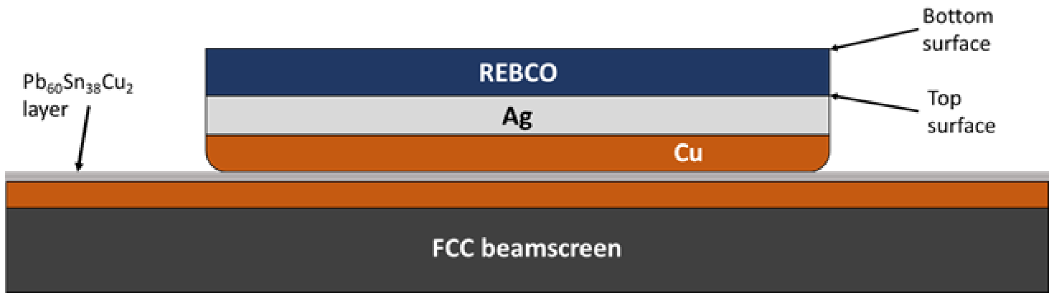
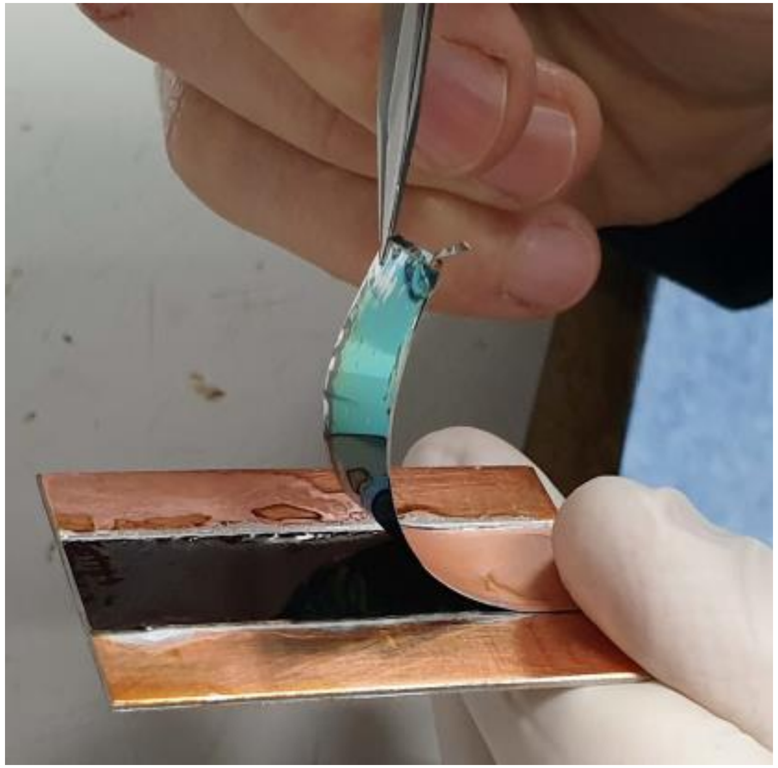
Development of soldering technology

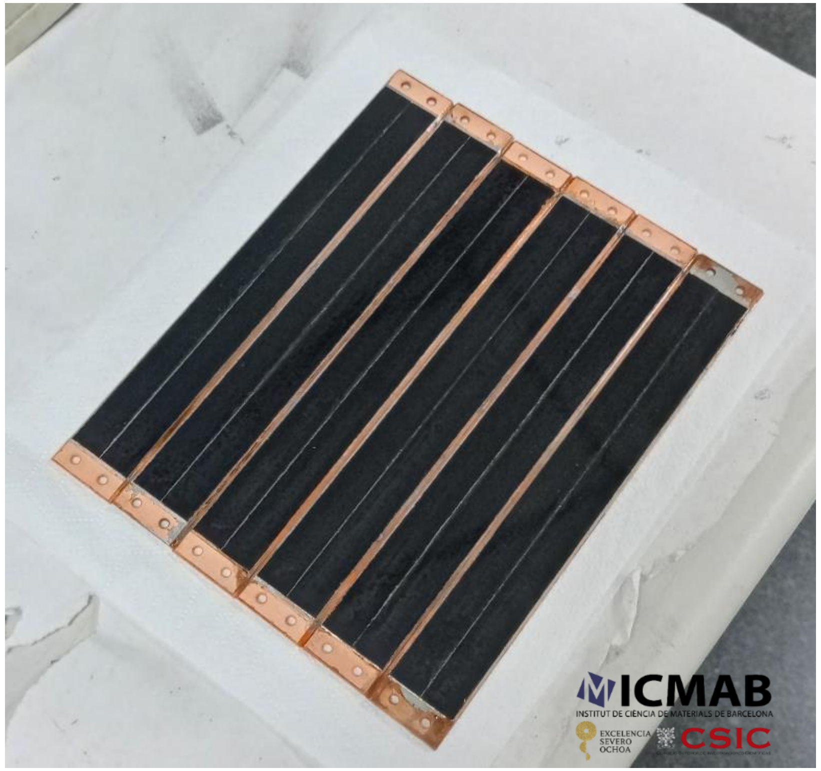




Solders based on Sn / Pb / Cu / Bi & In temperatures < 220ºC

Technical feasibility is demonstrated





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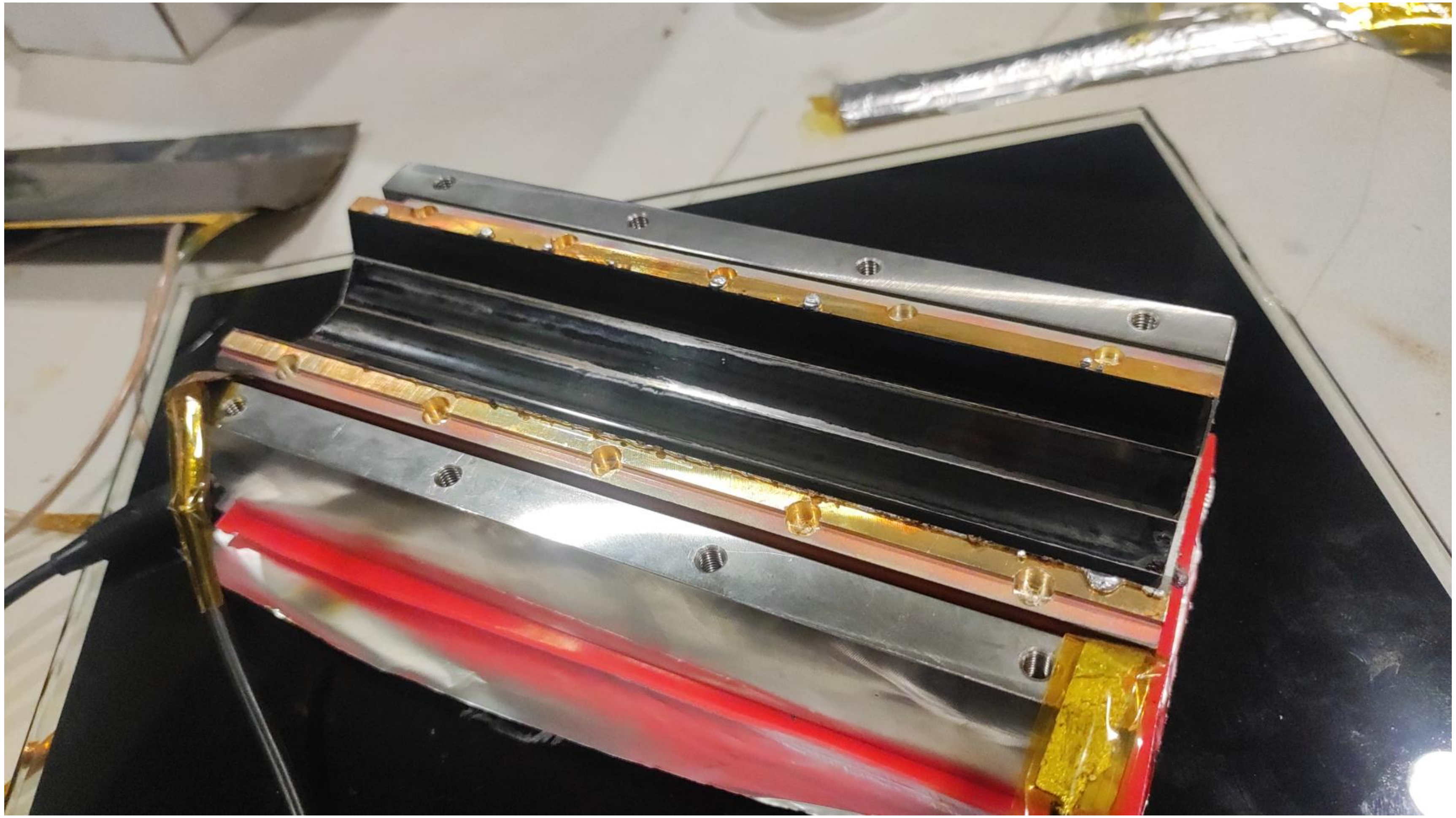
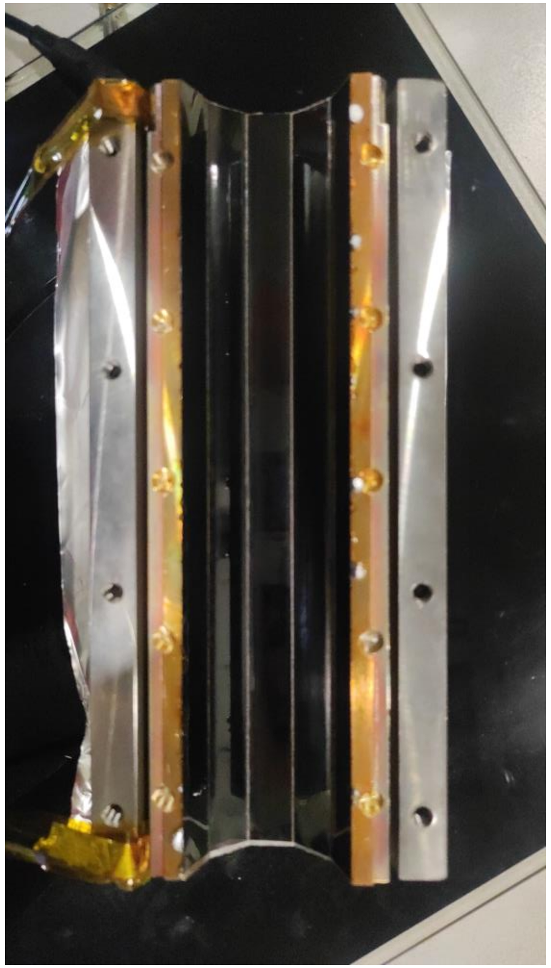
Decagons coated with HTS: PSD being measured at KEK





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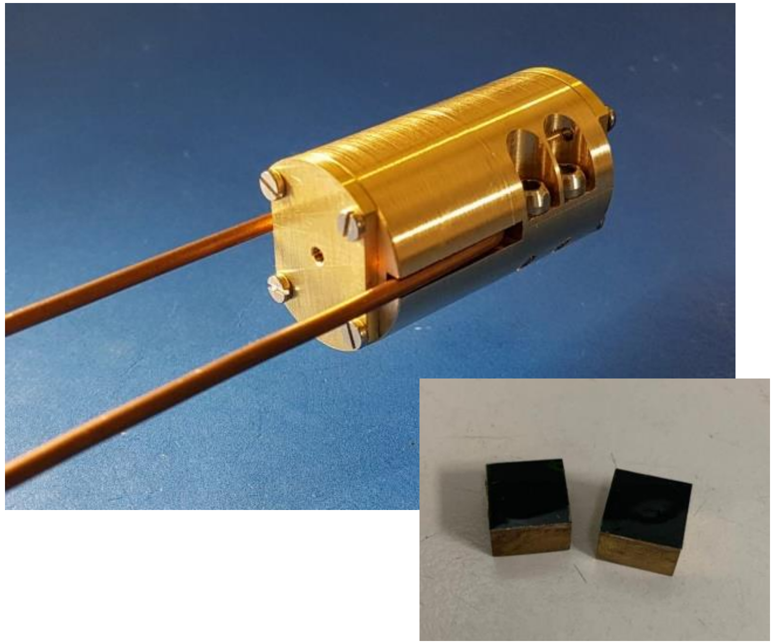
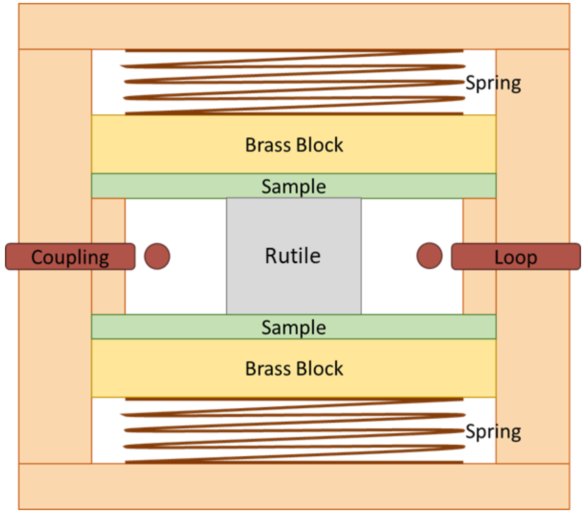
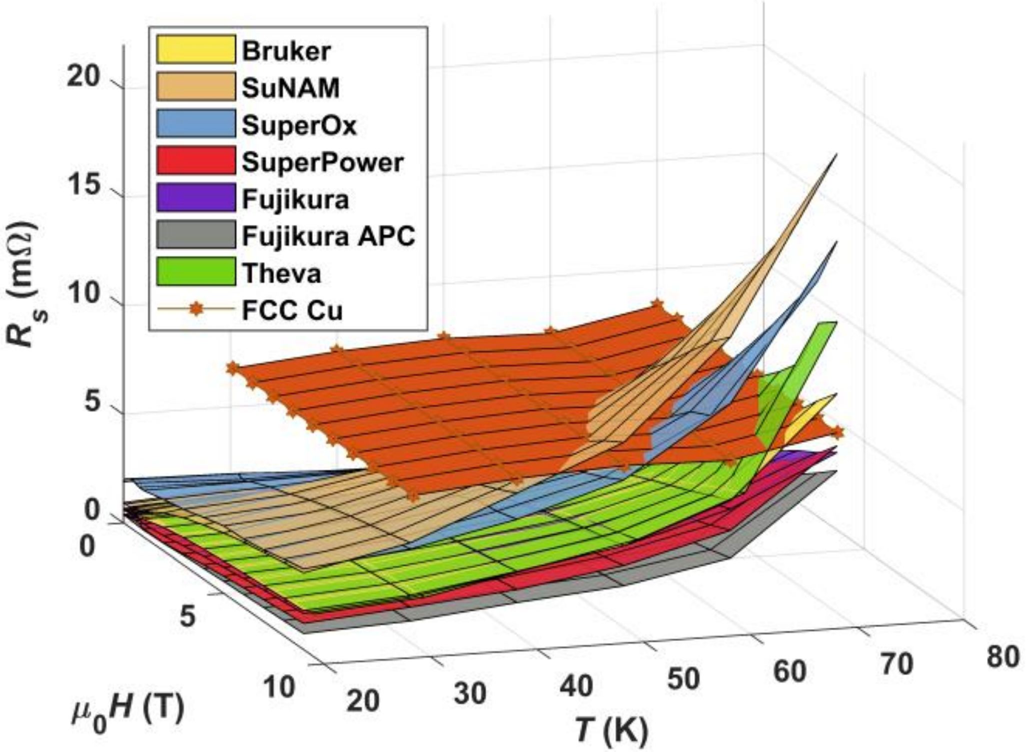
Validation of RF performance (UPC - ICMAB)







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

Puig et al, SuST 32, 094006 (2019)

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

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New developments: HTS in high power RF – “HIGHEST”

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

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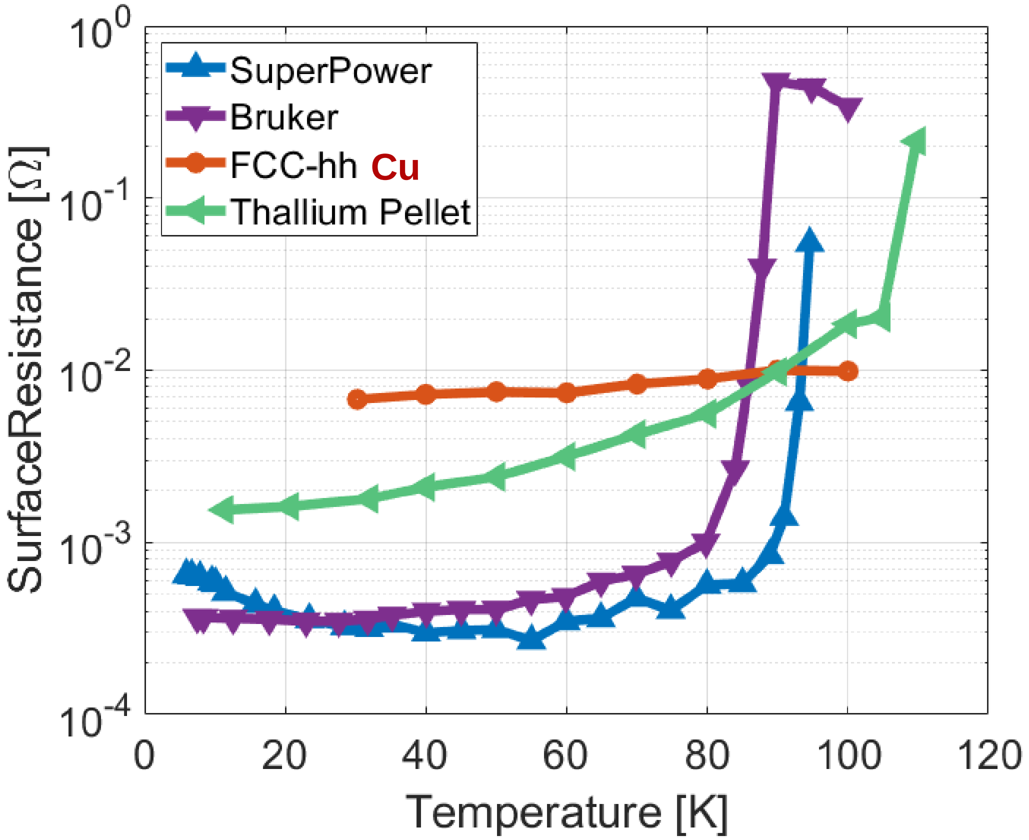
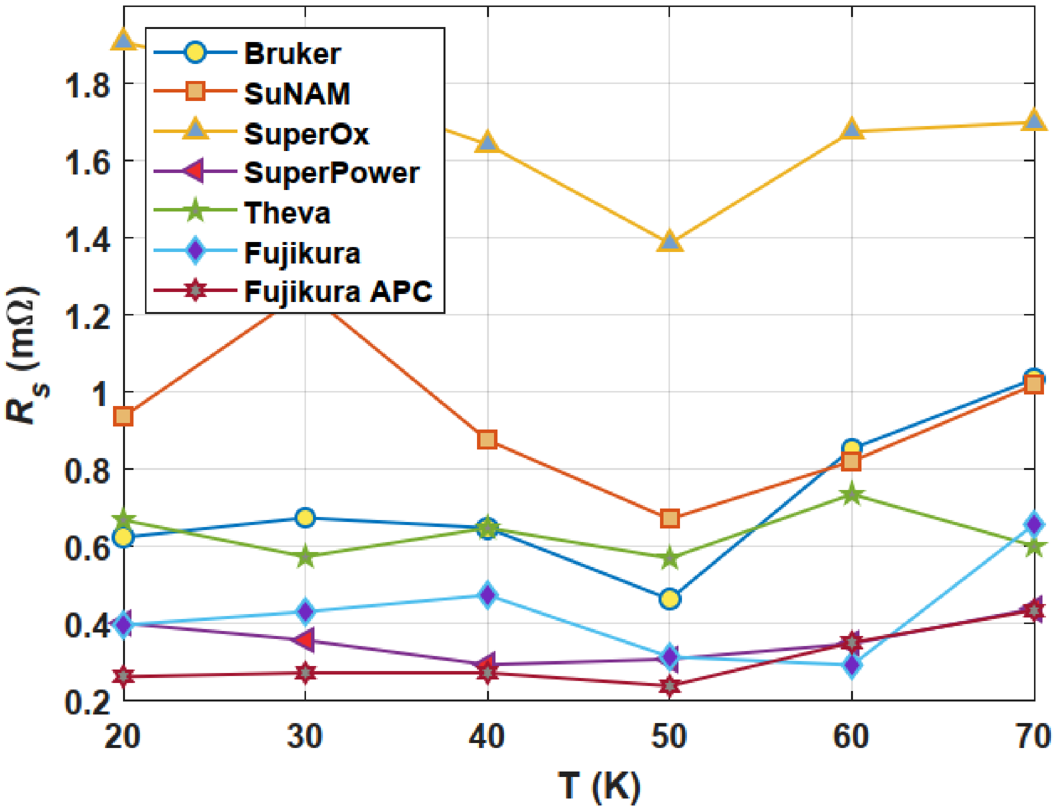
Low-power RF measurements of HTS – zero magnetic field

- 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

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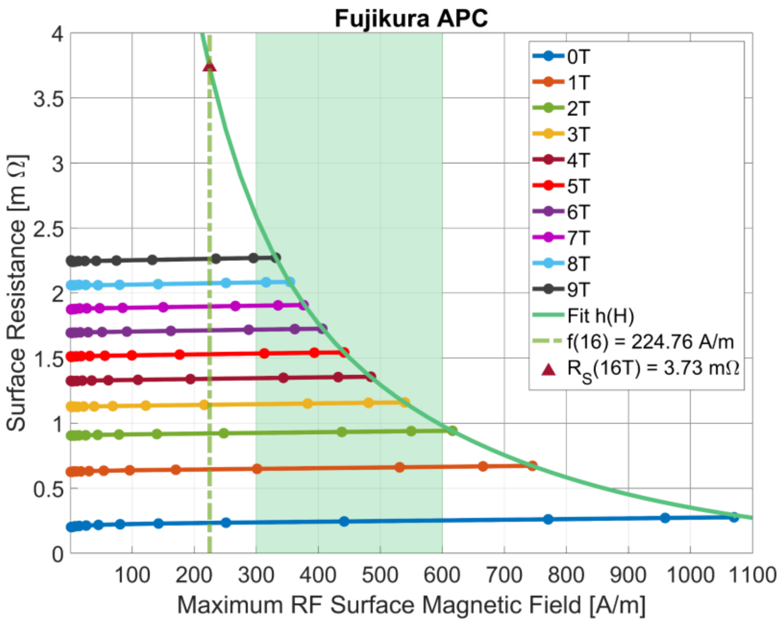
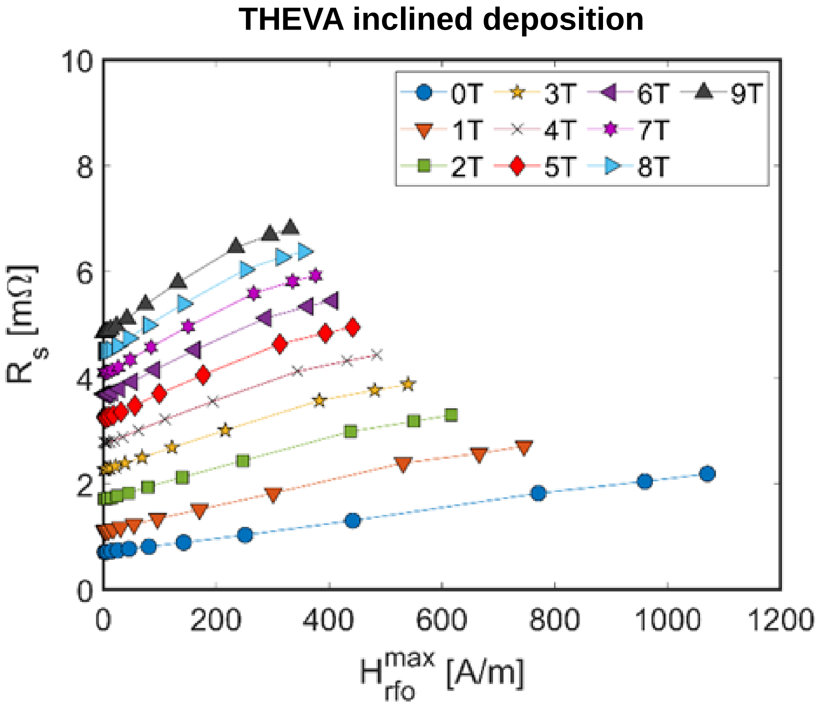
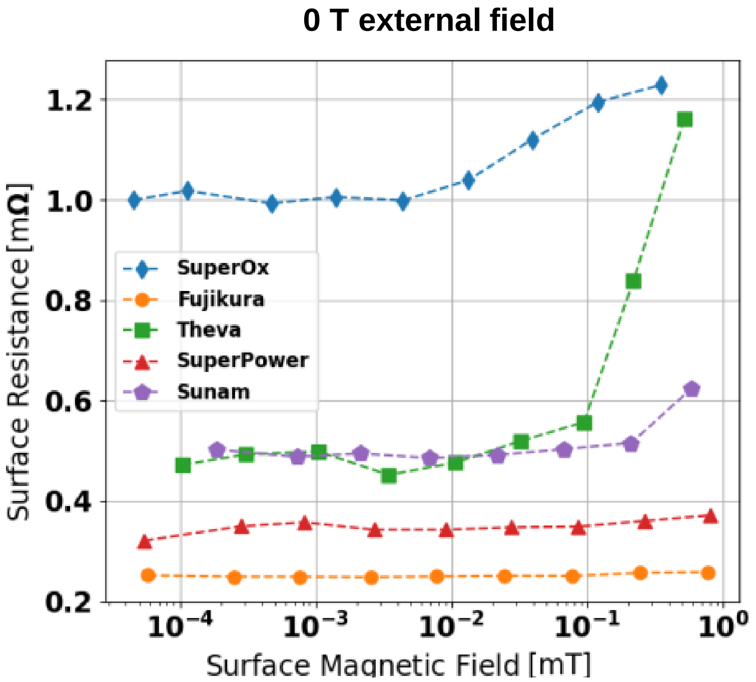
Testing HTS at higher RF power







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

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

Patrick Krkotic, PhD dissertation, UPC Barcelona 2022

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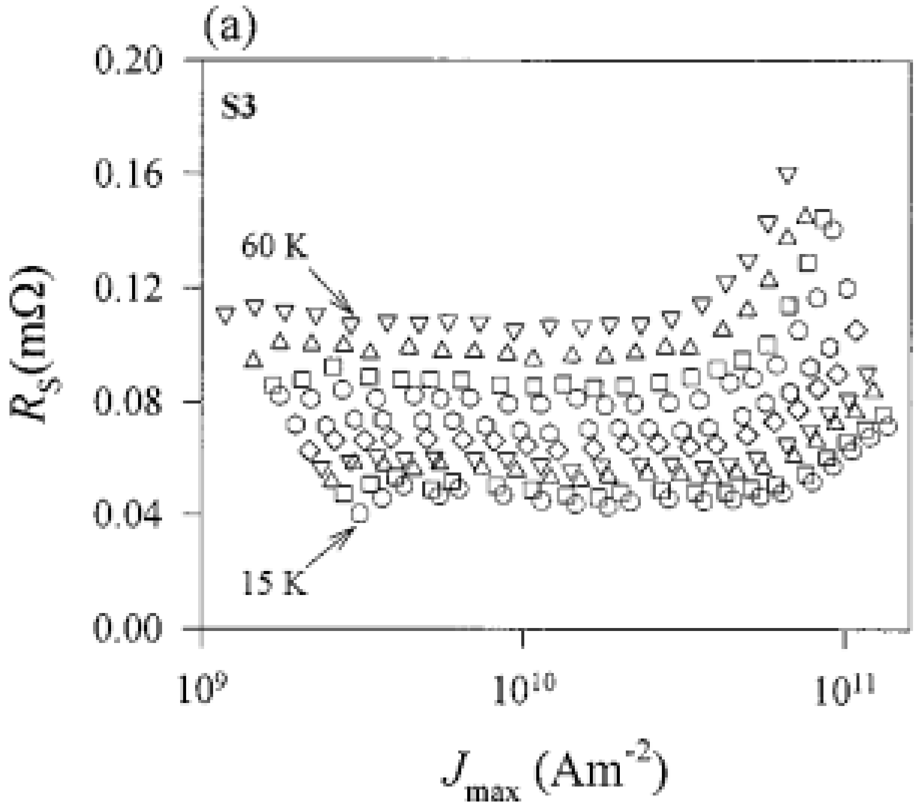
Literature review

- 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

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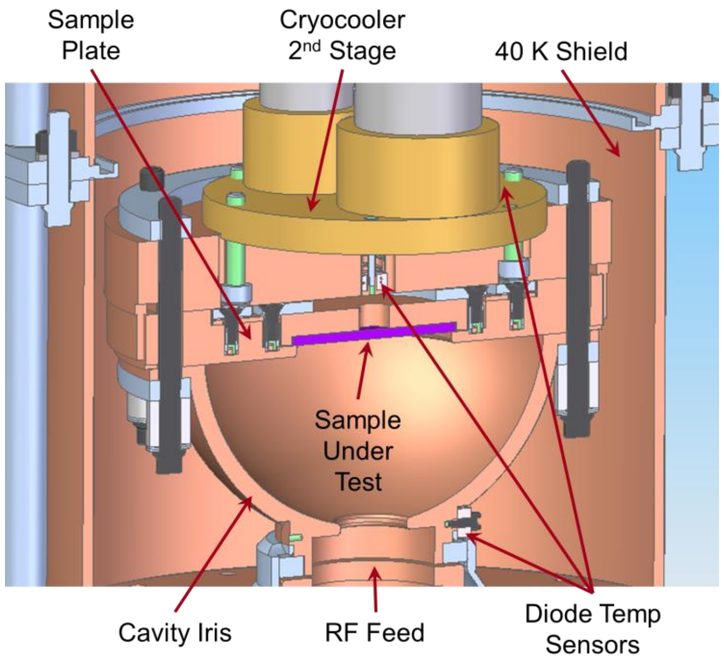
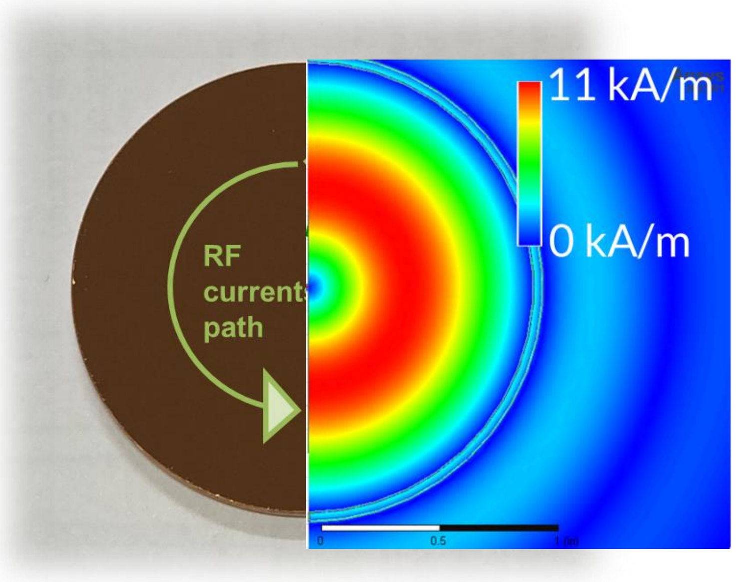
High-gradient testing at SLAC

- "Mushroom" cavity. Can achieve H_{peak} of about 360 mT – 2.9x10^5 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





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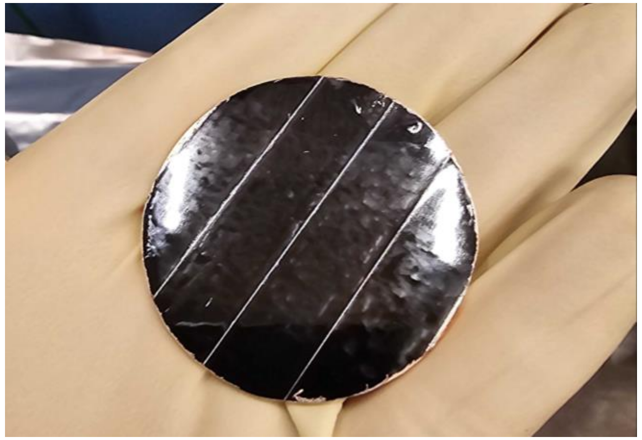
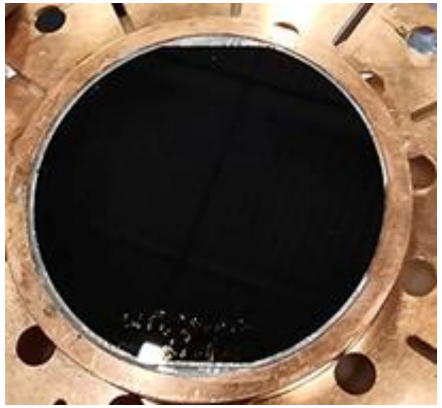
First results at SLAC, at low gradient

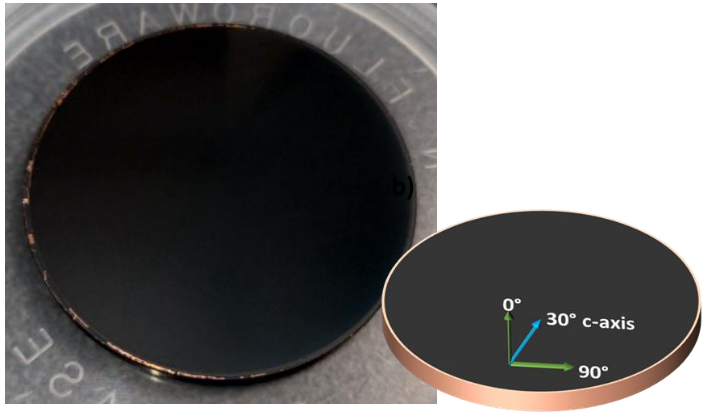
Two HTS measurements, after calibration measurements with Cu and Nb

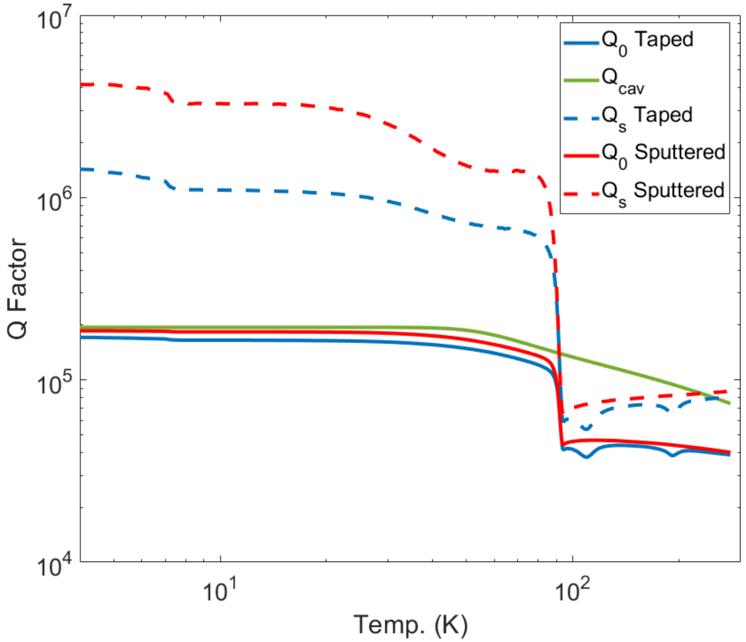
Soldered REBCO-CCs on copper (Fujikura by CSIC-ICMAB)



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







R_s Cu ≅ 17 mΩ
R_s REBCO Fujkura tapes ≅ 3 mΩ
R_s REBCO on Cu PVD/CERACO ≅ 1 mΩ
(R_s REBCO on MgO PVD/CERACO ≅ 0.5 mΩ)

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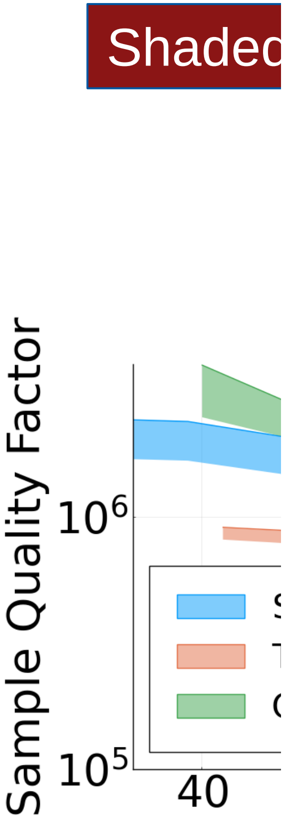
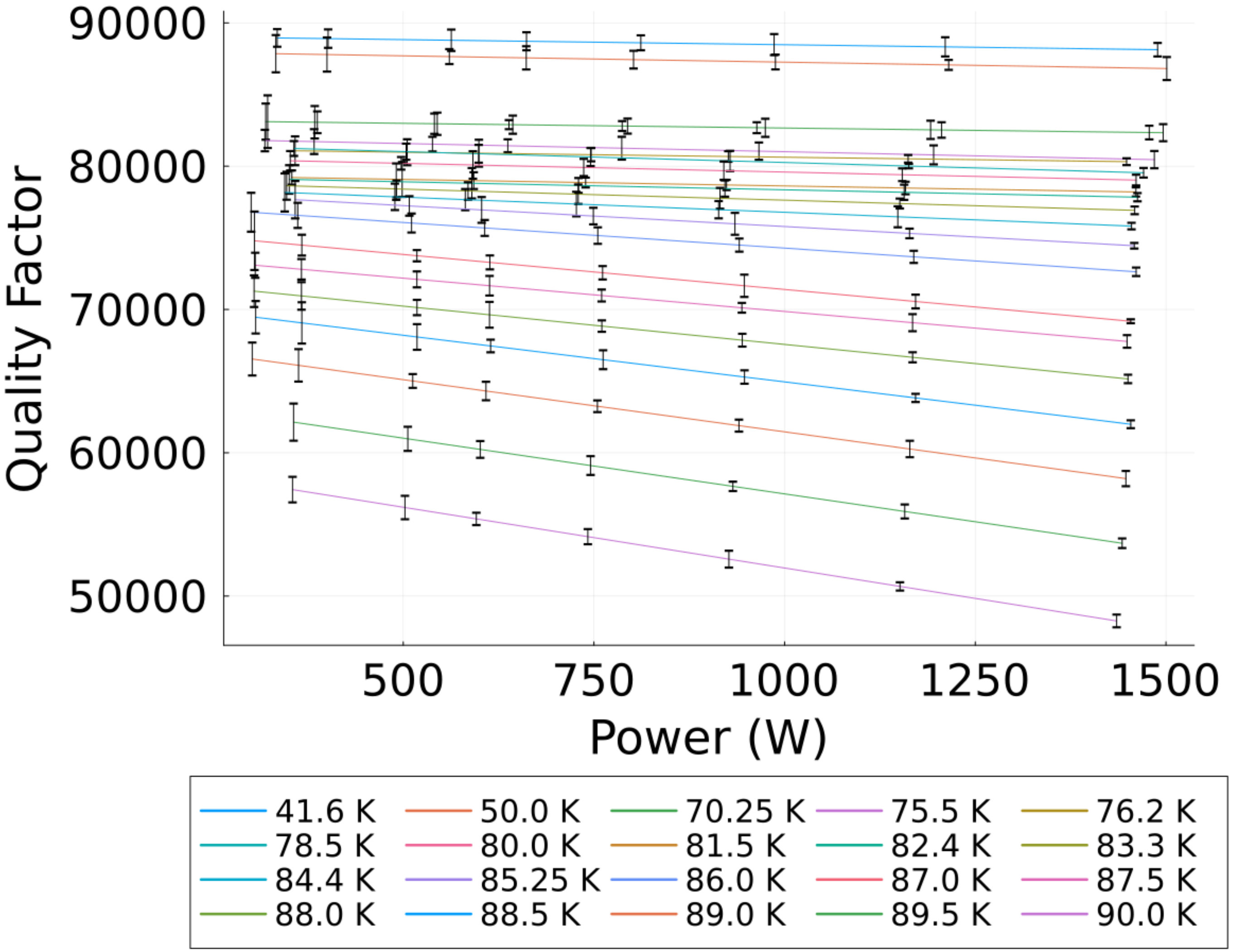
Preliminary SLAC results at high-gradient I





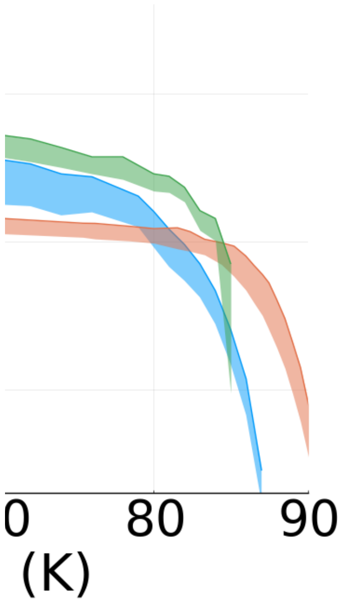
TWT is 1.6 kW @ 11.7 µs

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: Ankur Dhar

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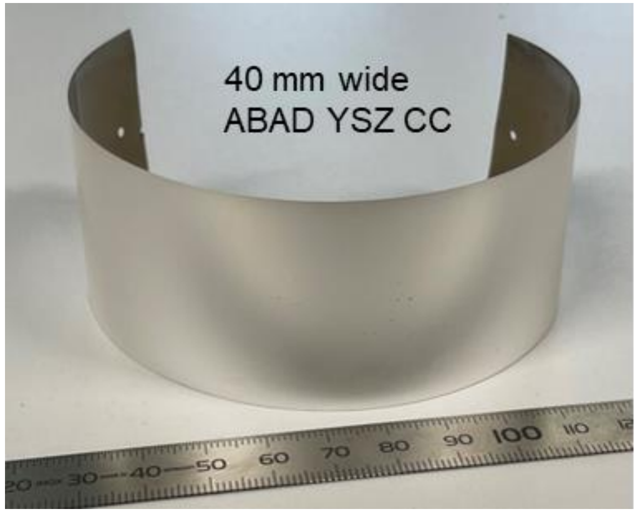
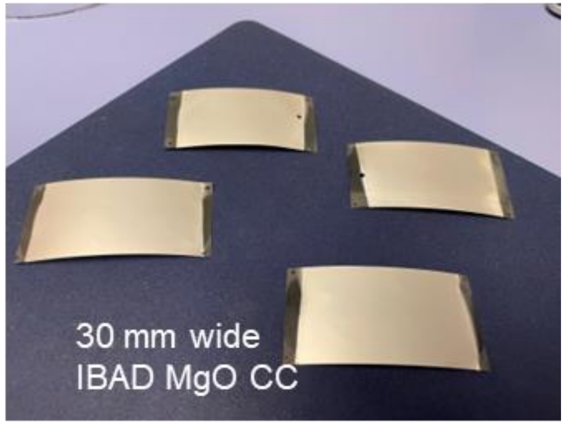
Key enabler for future lower frequency applications: wider tapes I

- Development of large tapes pursued at KCT/KIT.
- Buffer layer deposition is key technological hurdle

Roll to roll coater for HTS tapes





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

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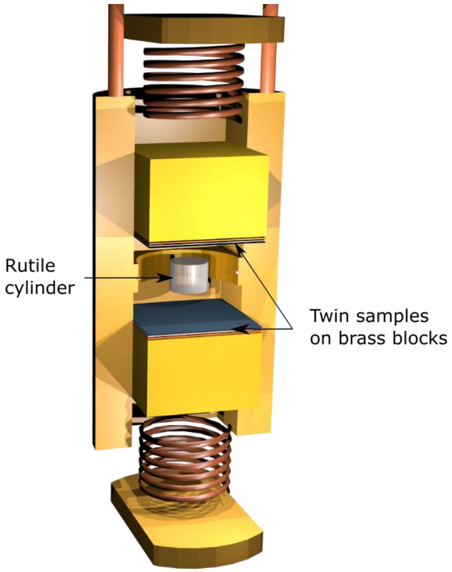
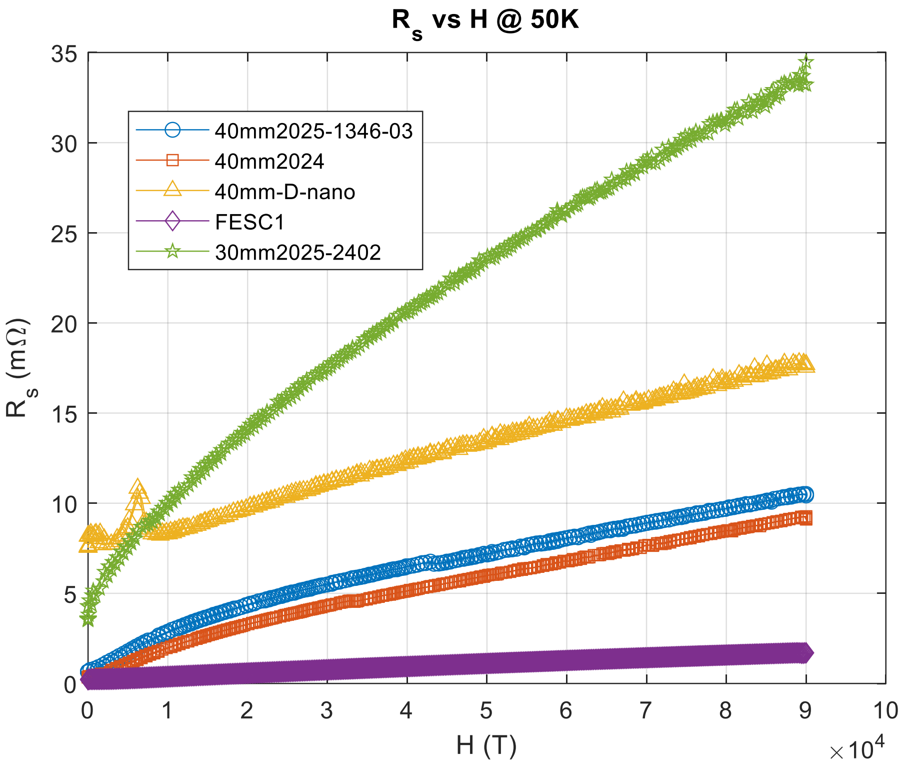
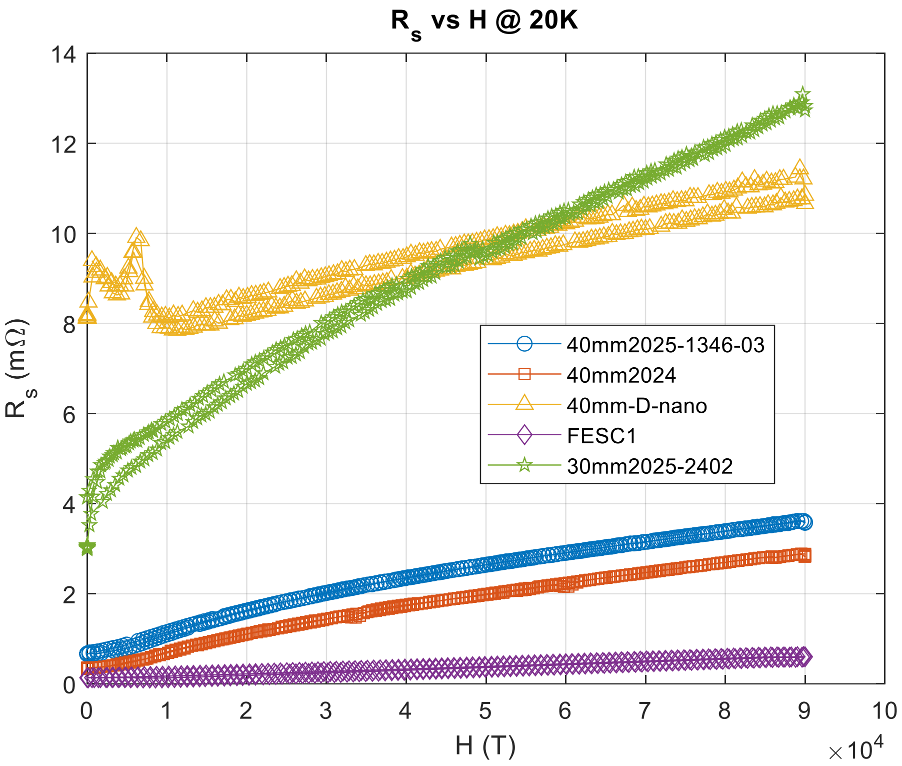
Key enabler for future lower frequency applications: wider tapes II



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

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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

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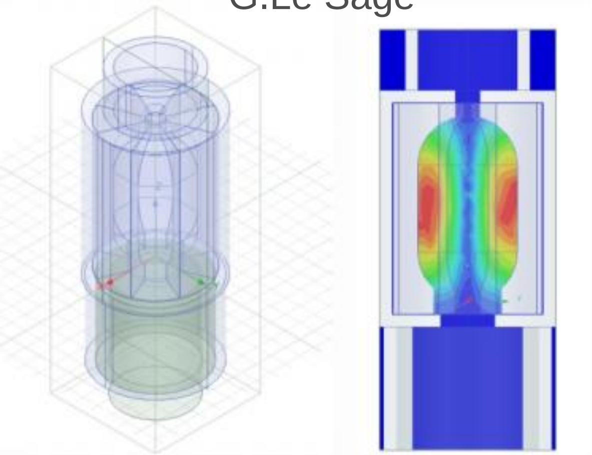
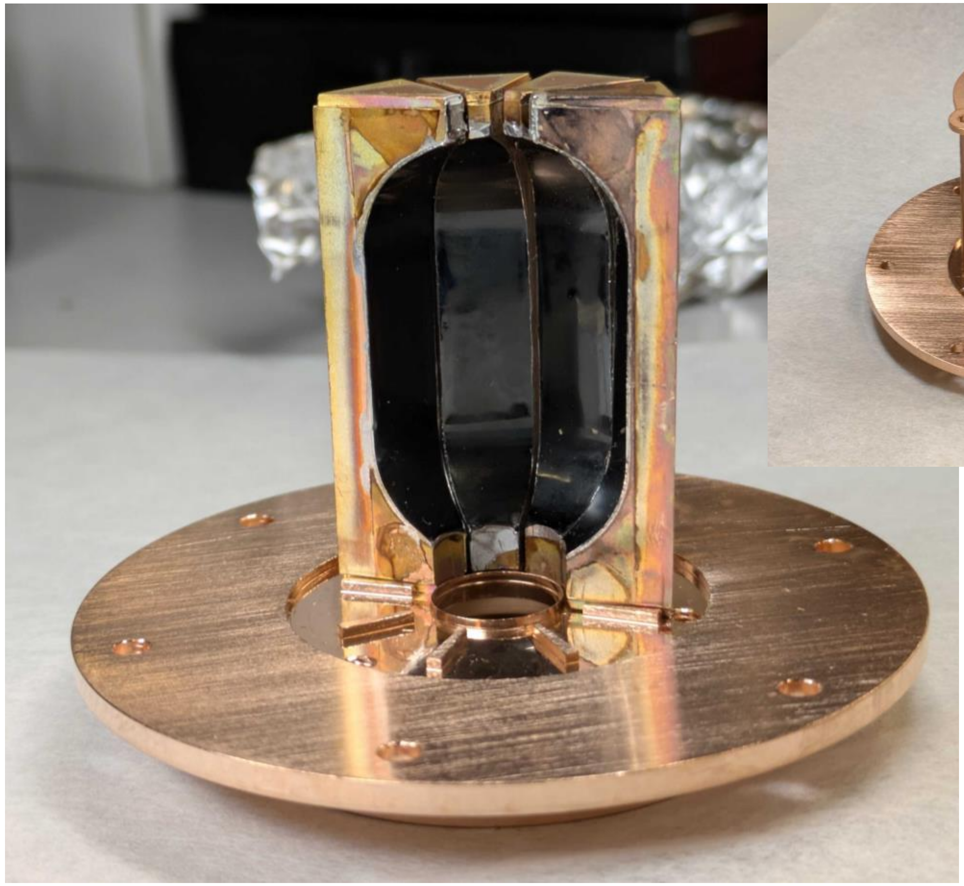
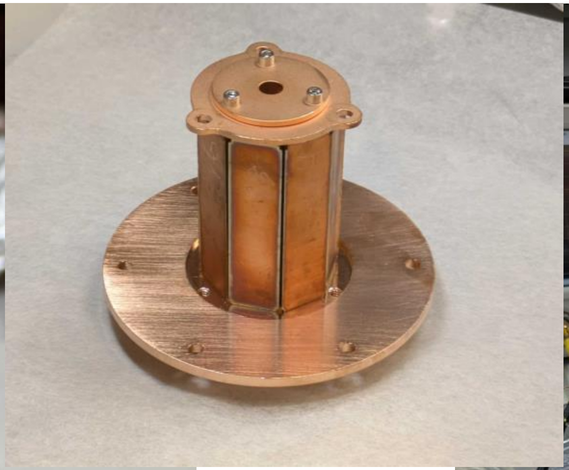
Pulse compressor tests with HTS tape at SLAC

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

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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

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And why not? The muon collider

Or: HTS in high magnetic field AND high RF power

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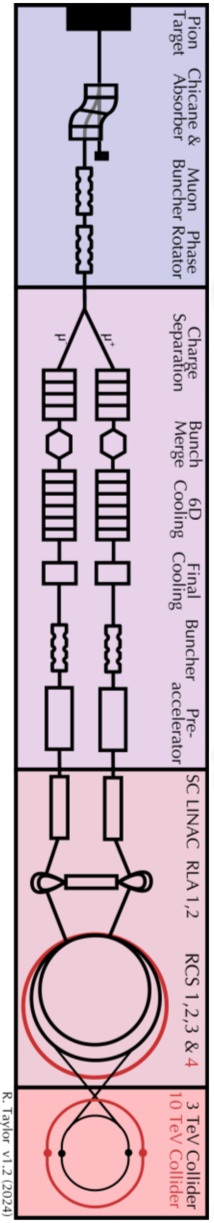
Muon Collider



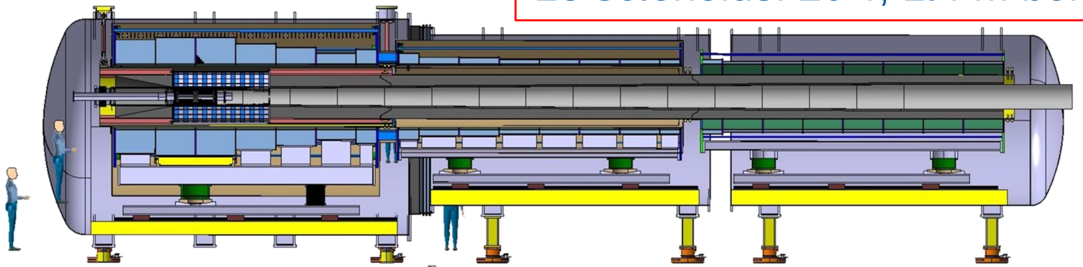
Target and capture solenoid

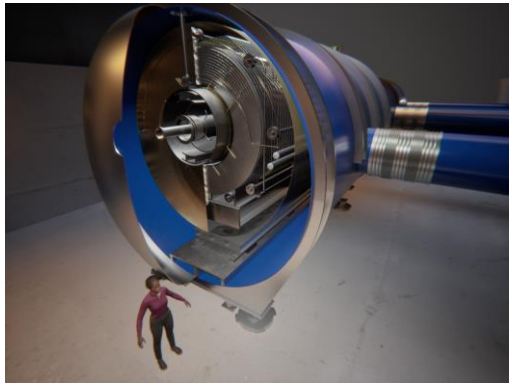
Muon beam cooling solenoids

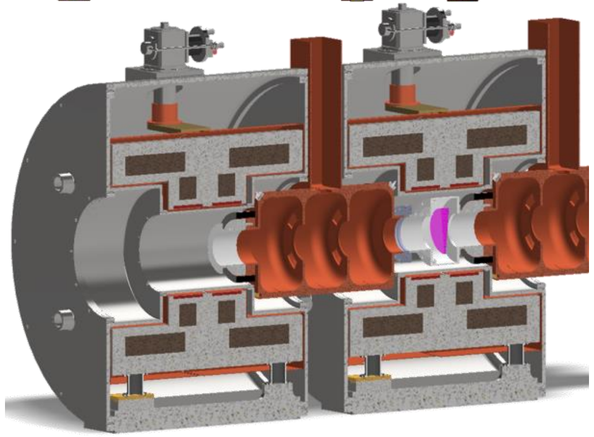
Accelerator and collider magnets

L. Bottura HFM Meeting 2025

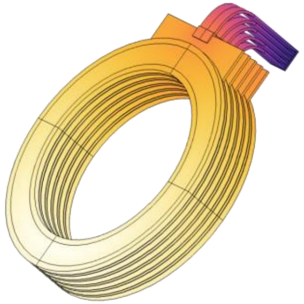
23 solenoids: 20 T, 1.4 m bore

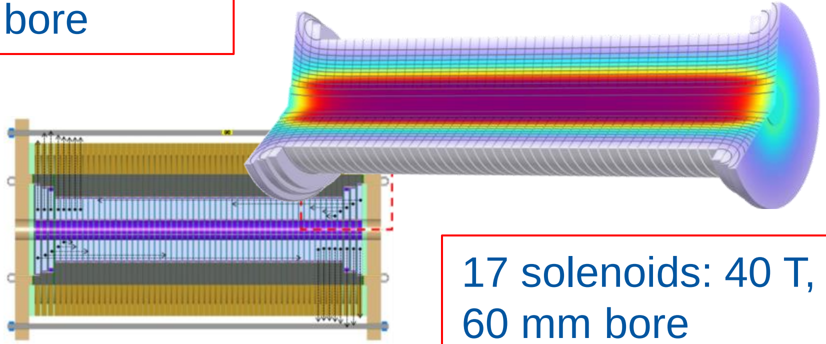




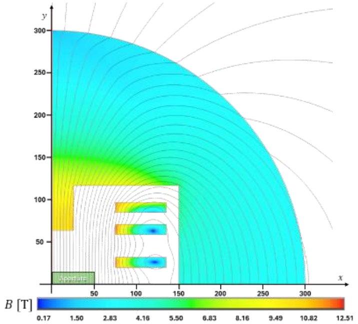


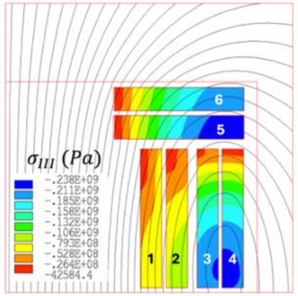
3000 solenoids: 2 to 14 T, 90 mm to 1.5 m bore



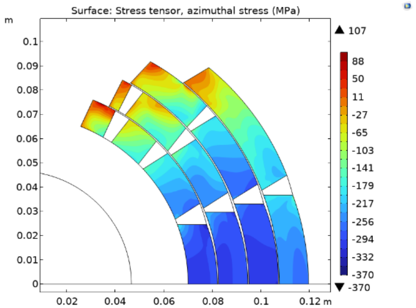


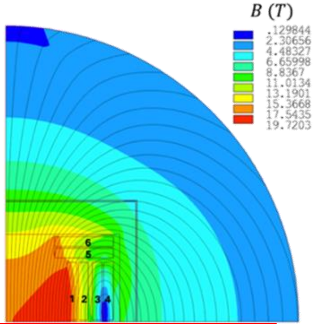
17 solenoids: 40 T, 60 mm bore





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





10 km 14 T, 140 mm bore dipoles

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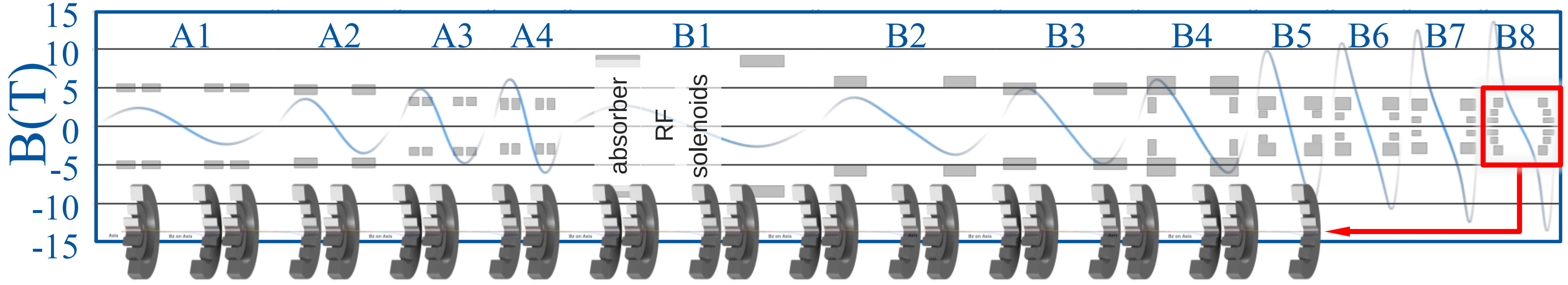
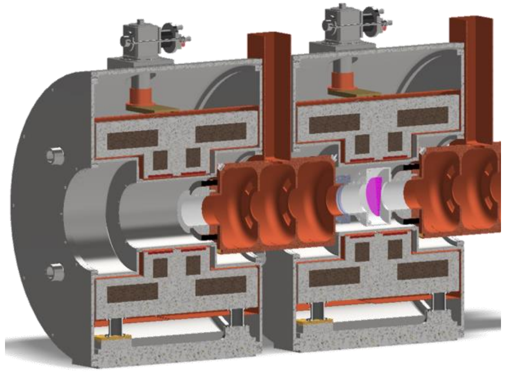
Muon collider

- 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 ?

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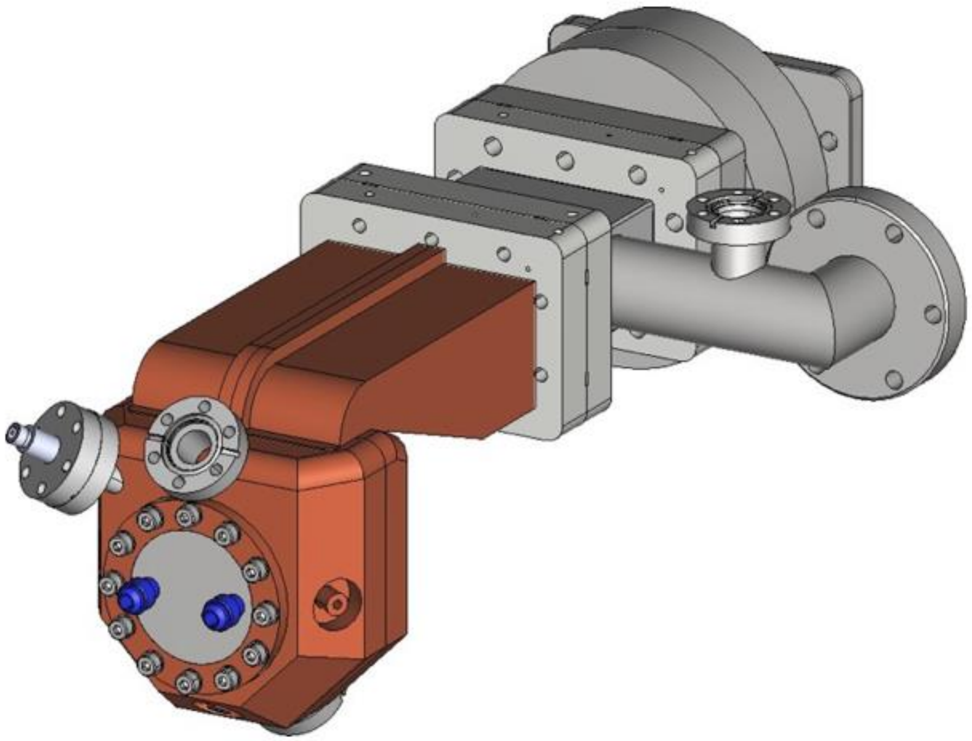
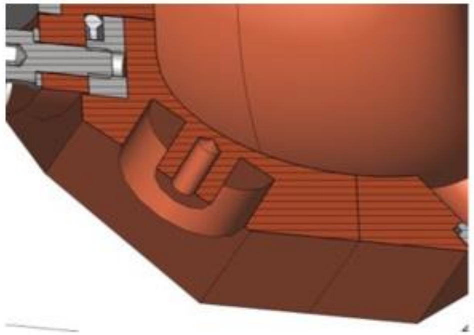
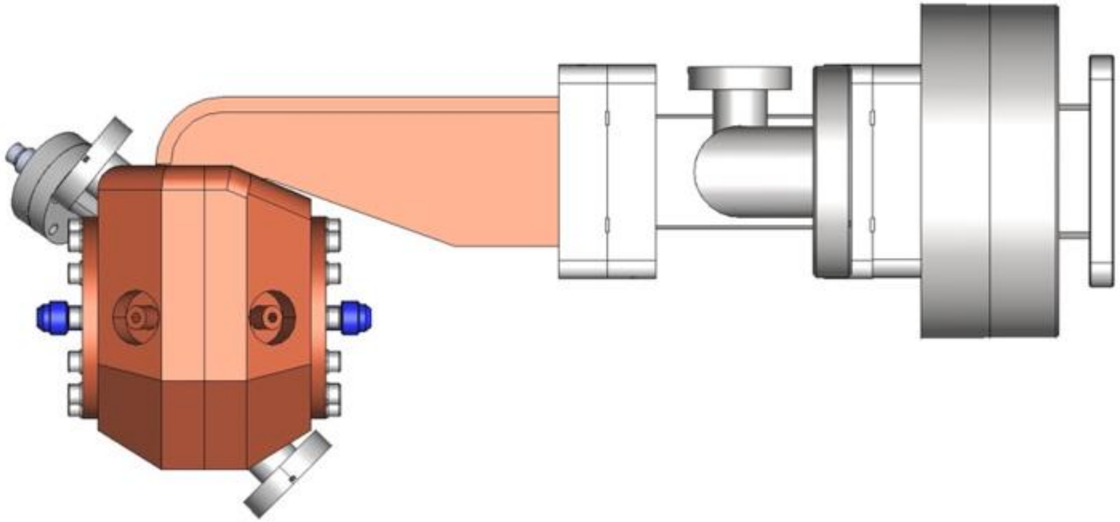
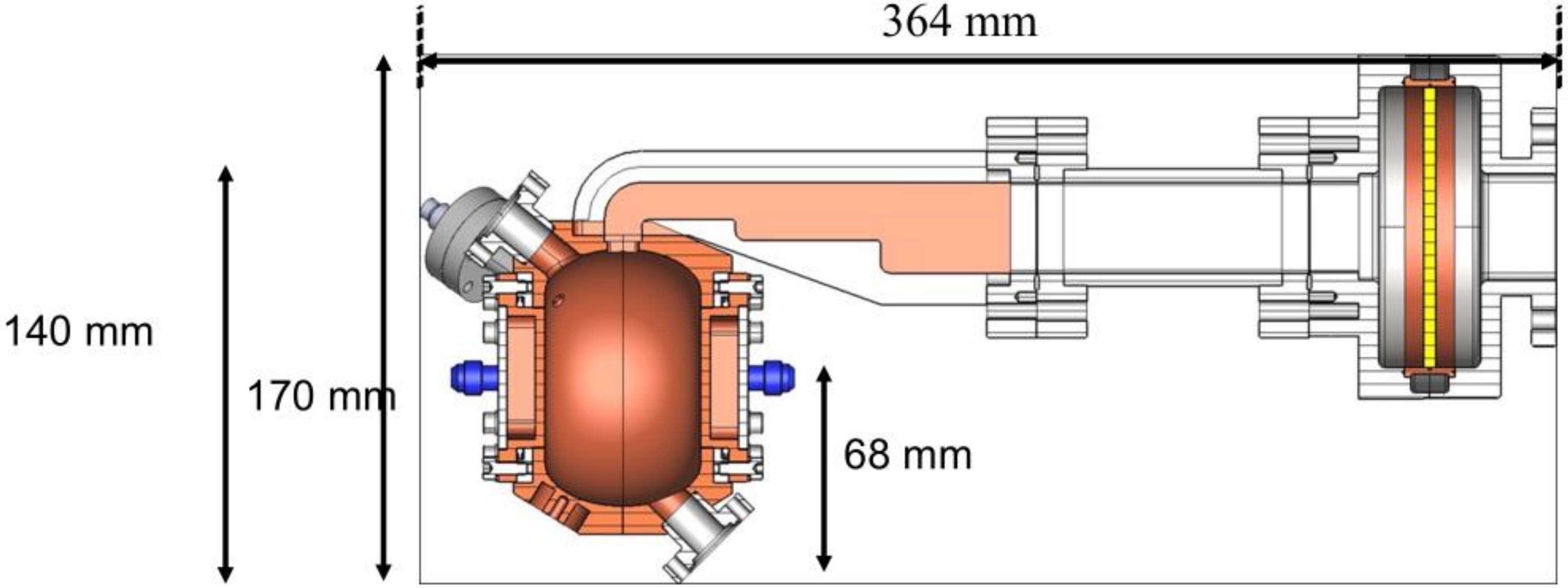
A 3 GHz Proposal for a INFN LASA Test Facility









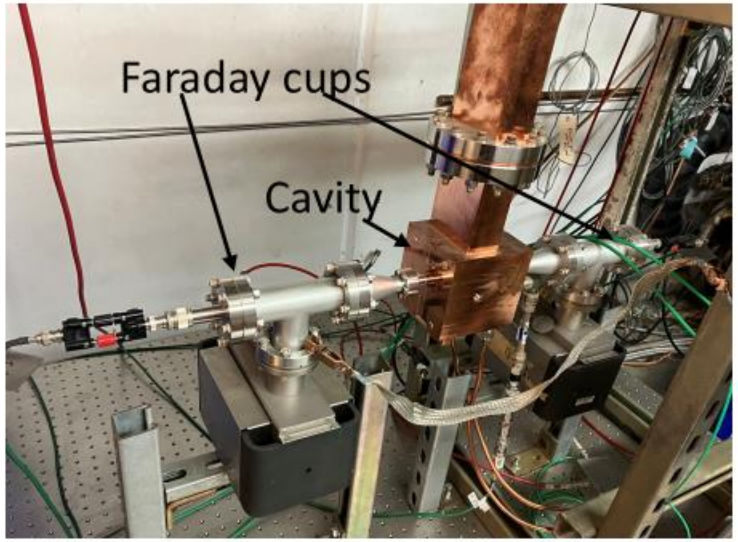
Extending to new frequencies

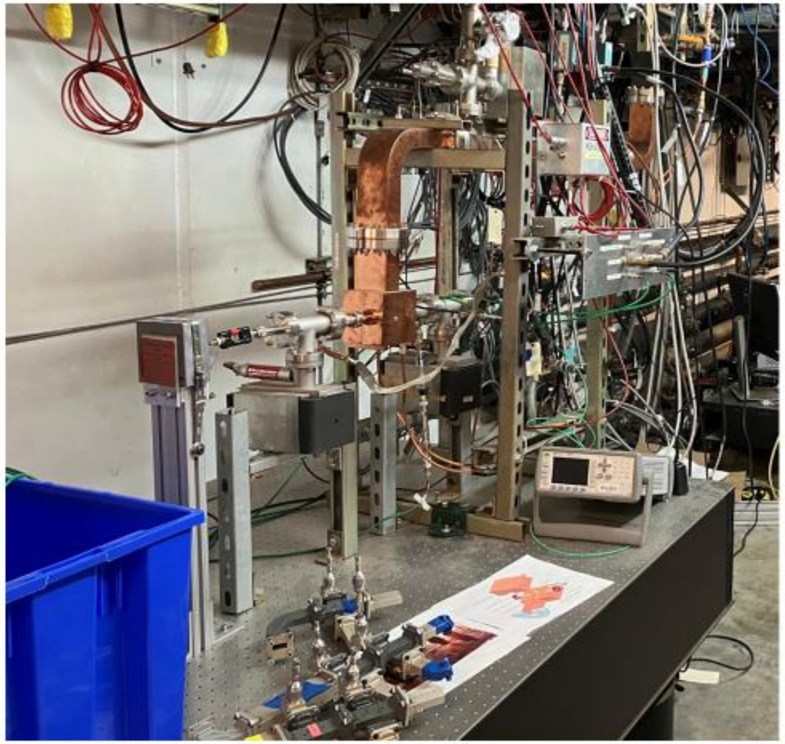
Our existing designs were centered on X-band frequencies, however our test facilities also extend to S-band

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

High field magnet





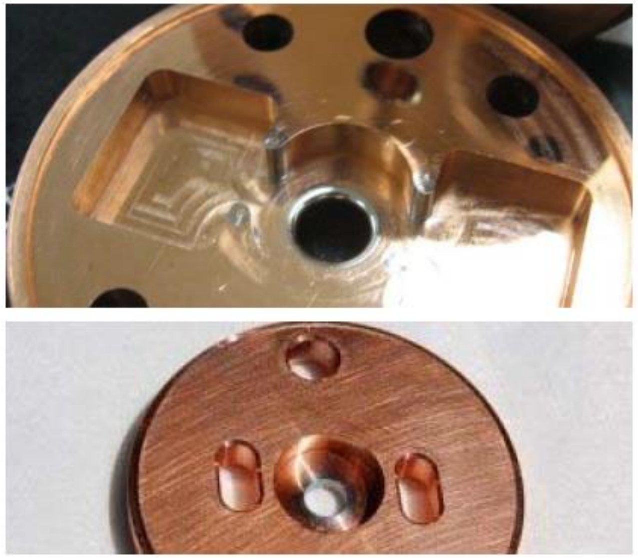
S-band test stand

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.

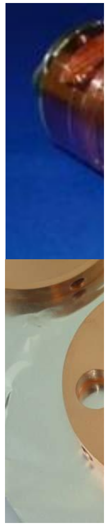
CERN

Possible practical implementation of HTS tape-coated cavities

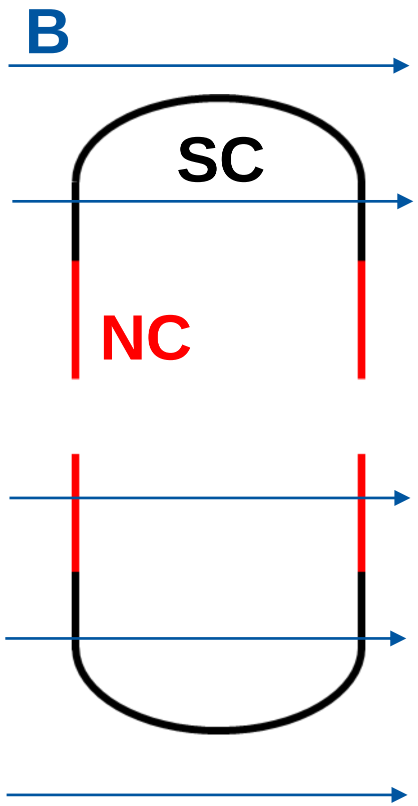
- How could a future cavity look like? Bimetallic cavities

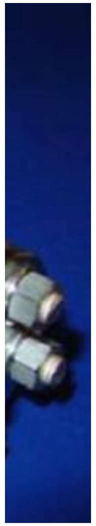


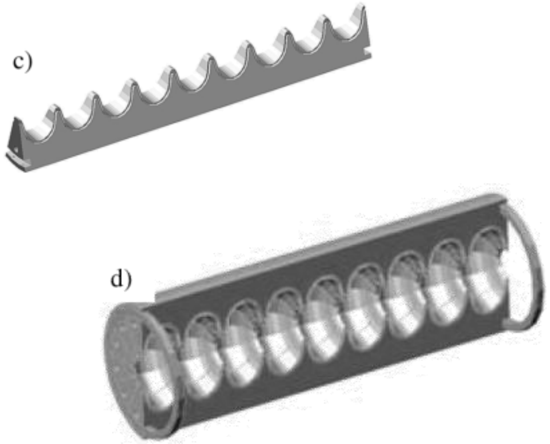
J. Haimson, WEPMS085, PAC07 (s.steel inserts)



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

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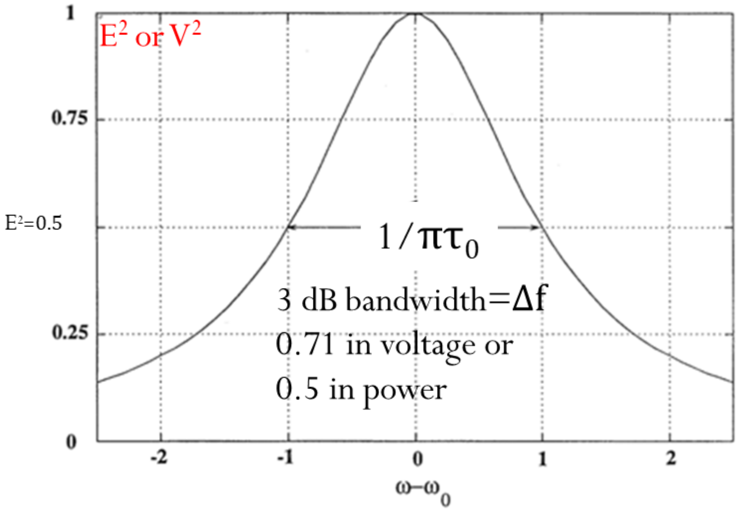
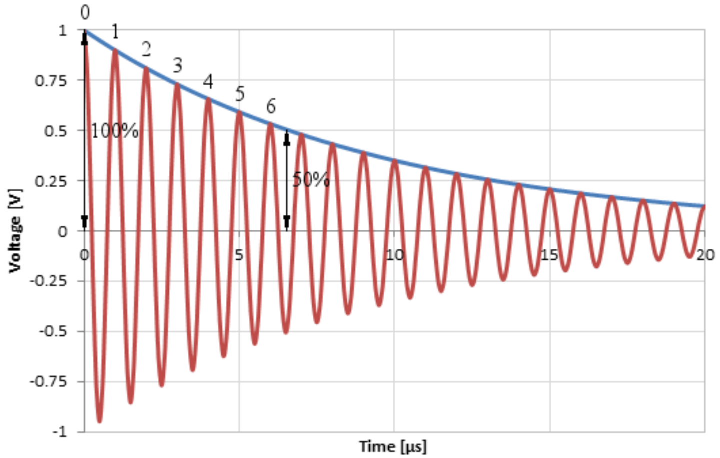
Quality factor, etc.

- Cavity power losses: $P_c = \frac{1}{2} R_s H^2$
  - Where R_s is the surface resistance and H the magnetic field at the cavity surface

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

- Decay time τ_0:
  - It is $\tau_0 = \frac{Q_0}{\pi f_0} = \frac{1}{\pi \Delta f}$
  - Giving $E(t) = E_0 \exp(-t/\tau_0)$ for the field envelope E





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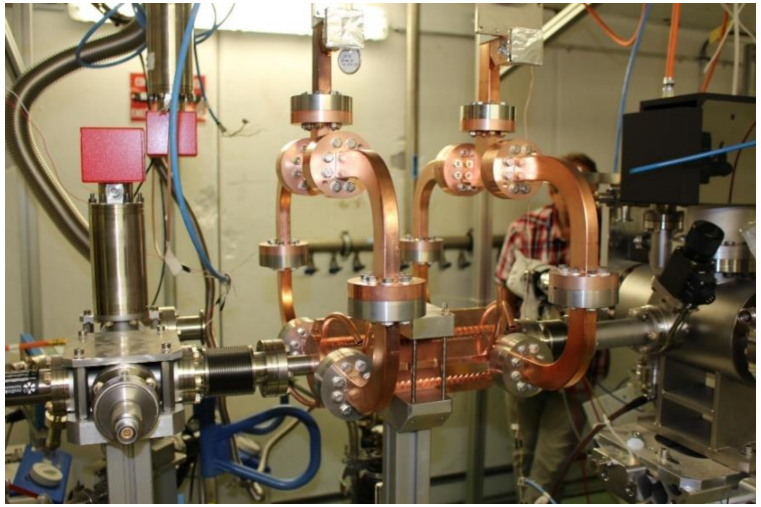
SC vs NC cavities

- 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 $\sim 10^6$ difference in quality factor, ($\sim 10^3$ 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

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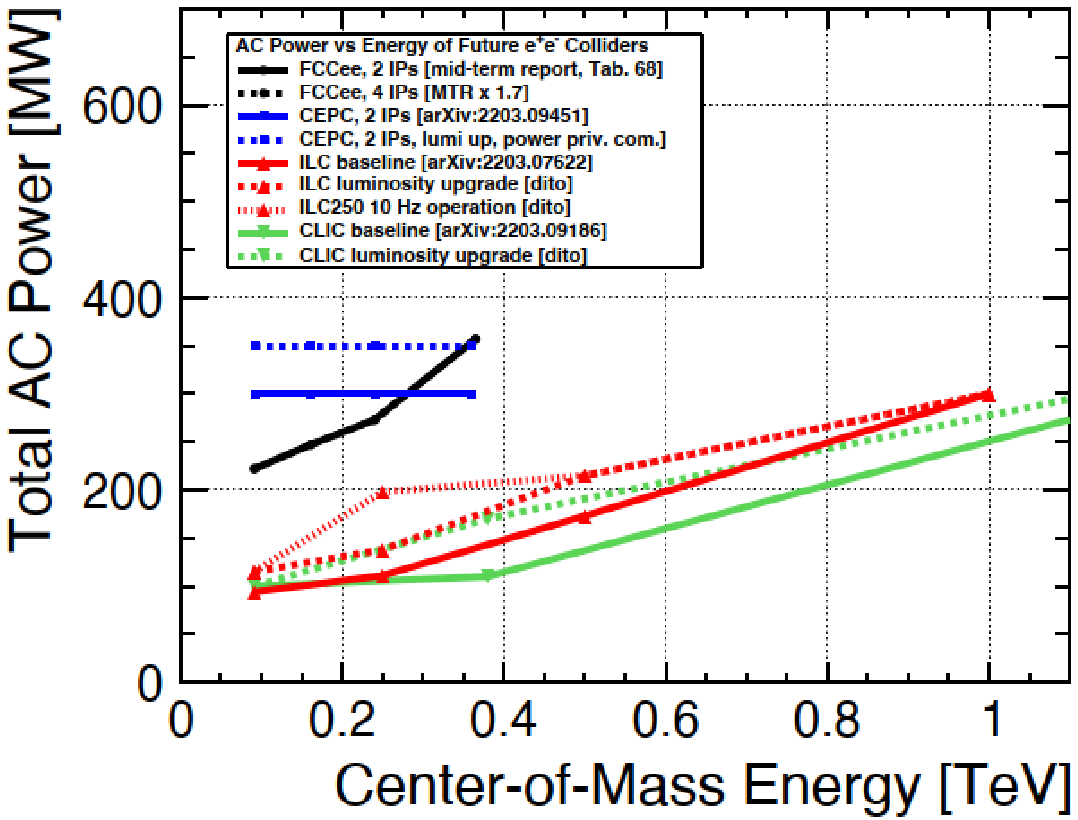
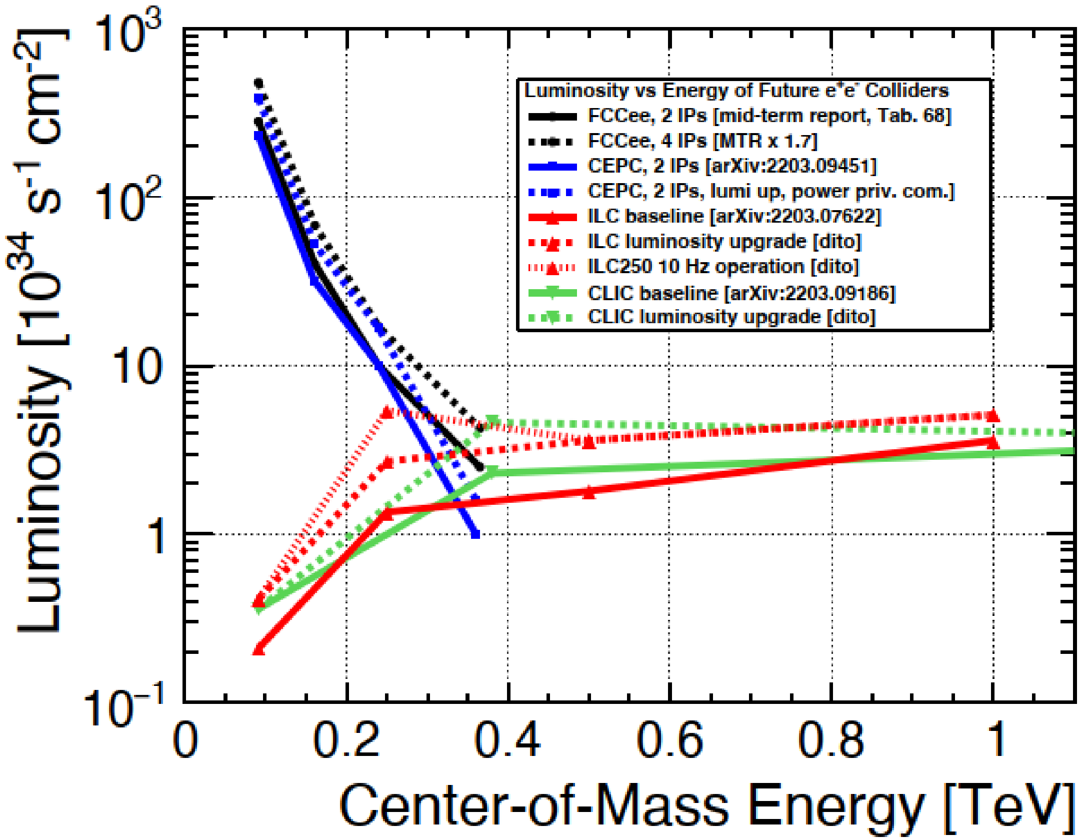
Power consumption and luminosity of future colliders





- 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

See also A. Miyazaki, IEEE TASC 34 (2024) 0601106

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

New kid on the blocks: the C^3 study @ SLAC

More info here

8 km footprint for 250/550 GeV CoM $\Longrightarrow$ 70/120 MeV/m

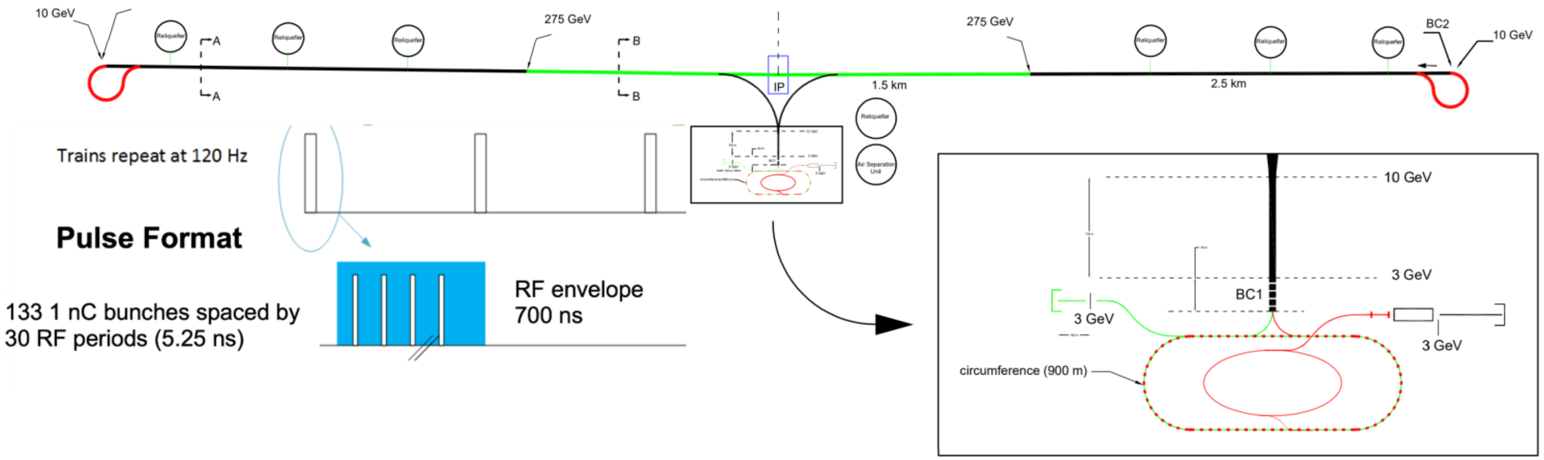
Large portions of accelerator complex compatible between LC technologies

- 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

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

C^3, wall-plug power efficiency

More info on C^3 here

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

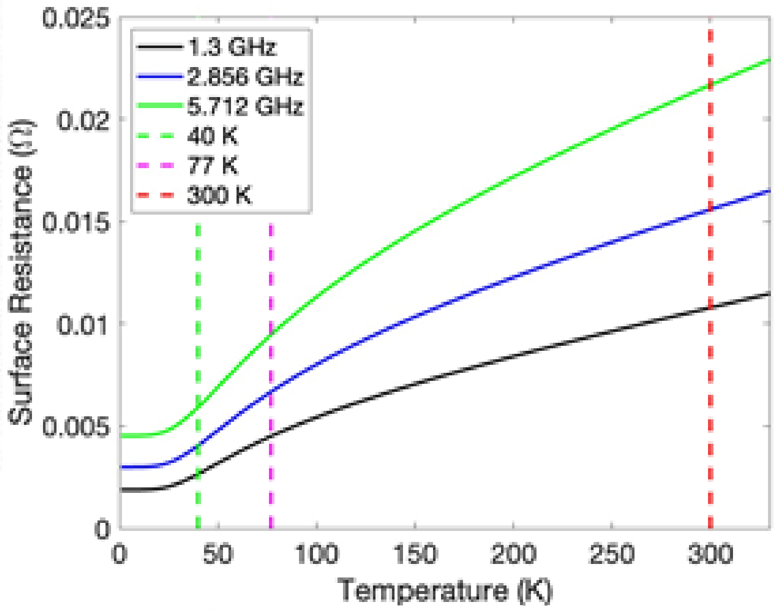
- Large-scale production, large heat capacity, simple handling
- Small impact on electrical efficiency*

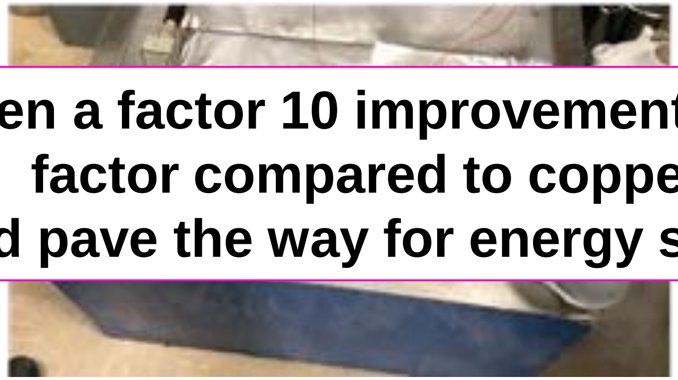
$$\eta_{cp} = LN\ Cryoplant$$
$$\eta_{cs} = Cryogenic\ Structure$$
$$\eta_k = RF\ Source$$

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

SLAC

*Assumes long pulse regime, no rf compression





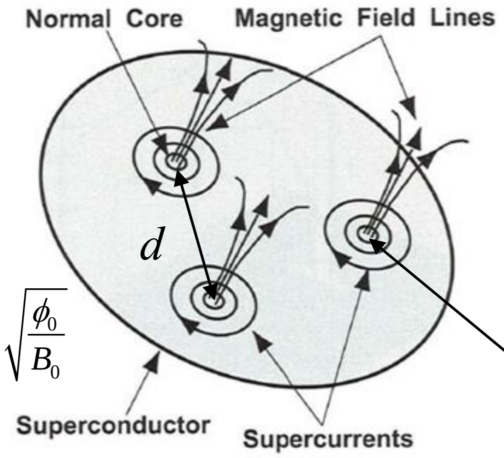
Even a factor 10 improvement in Q factor compared to copper could pave the way for energy savings

From: Emilio Nanni

Fluxon motion

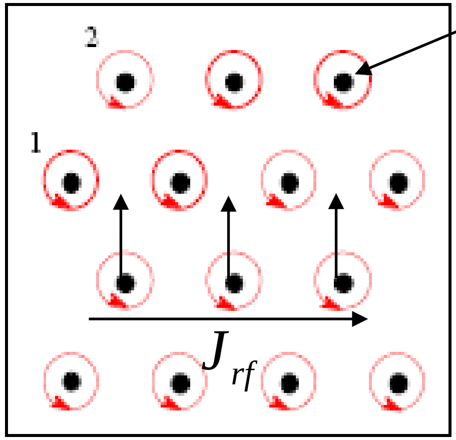
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

Some theory background: fluxon motion in RF



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

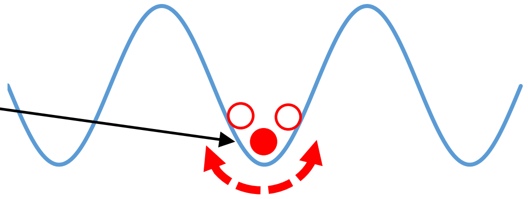
Pinning centers



B field is normal to surface: worst case

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

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



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

The "depinning frequency"

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

Surface resistance

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

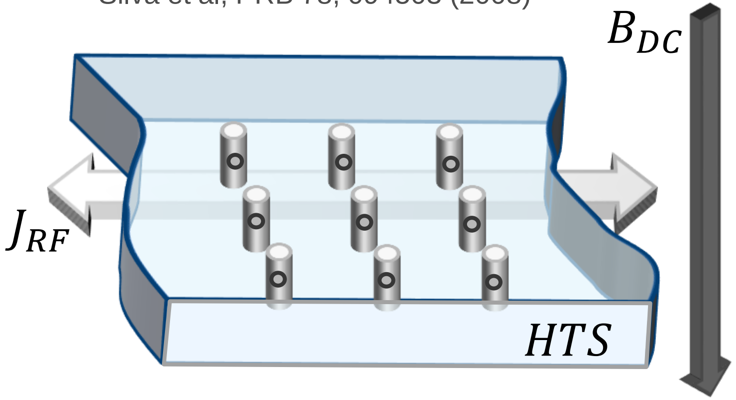
Gittleman and Rosenblum: Phys Rev. Lett. 16, 734 (1966)
Calatroni and Vaglio, IEEE Trans. Appl. Supercond. 27 (2017) 3500506
Coffey, Clem PRL 67, 386 (1991)
Brandt PRL 67 2219 (1991)
Silva et al, PRB 78, 094503 (2008)

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

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



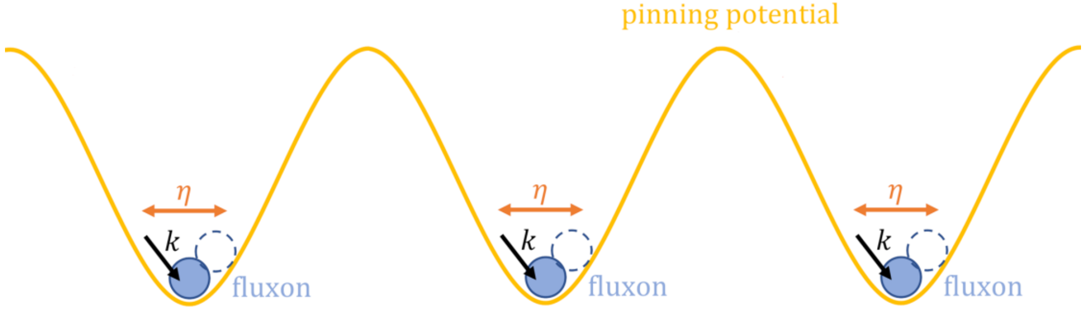
- Apply RF Current
  - Motion of vortices → dissipation

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

  – 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

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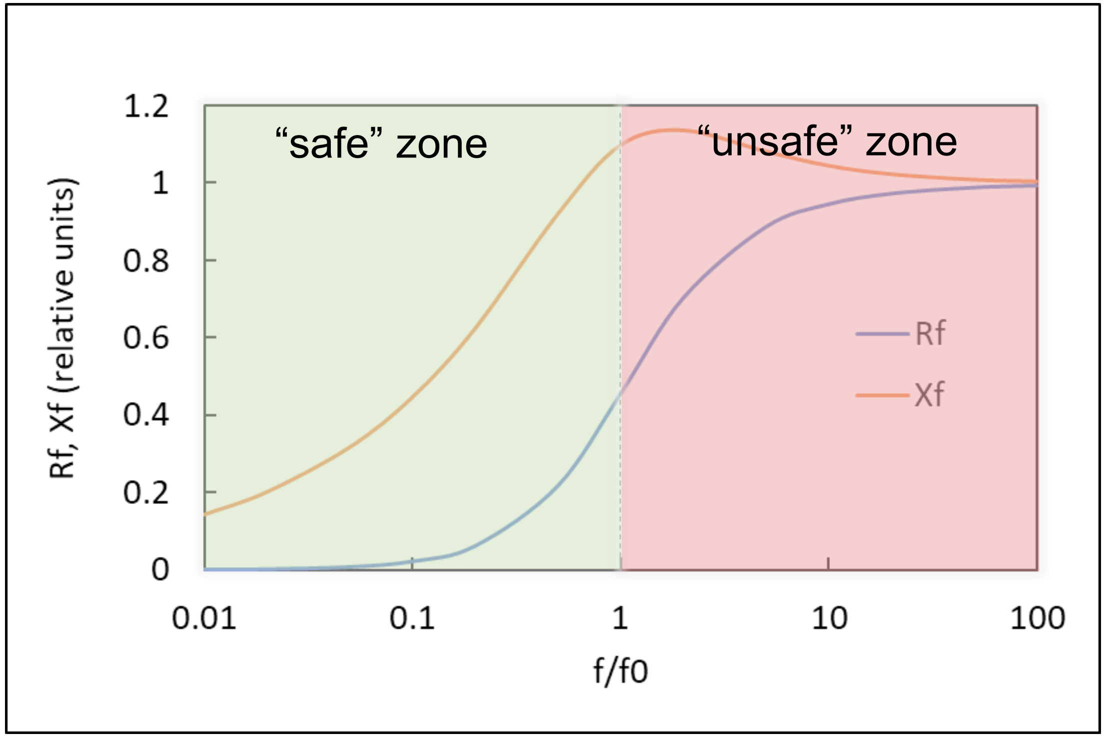
Surface resistance, reactance due to vortex motion



Case $f < f_o$

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

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

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

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

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