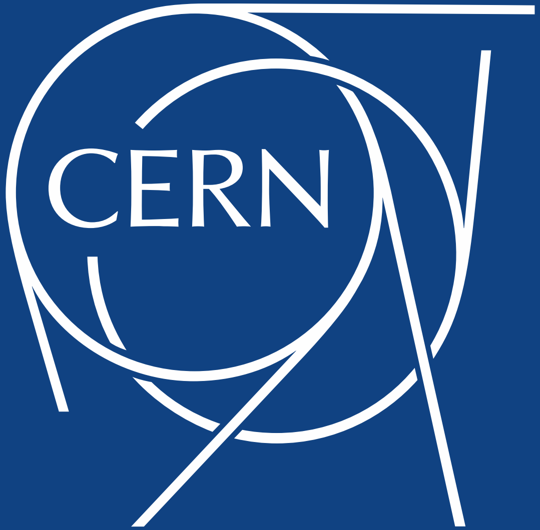

CERN

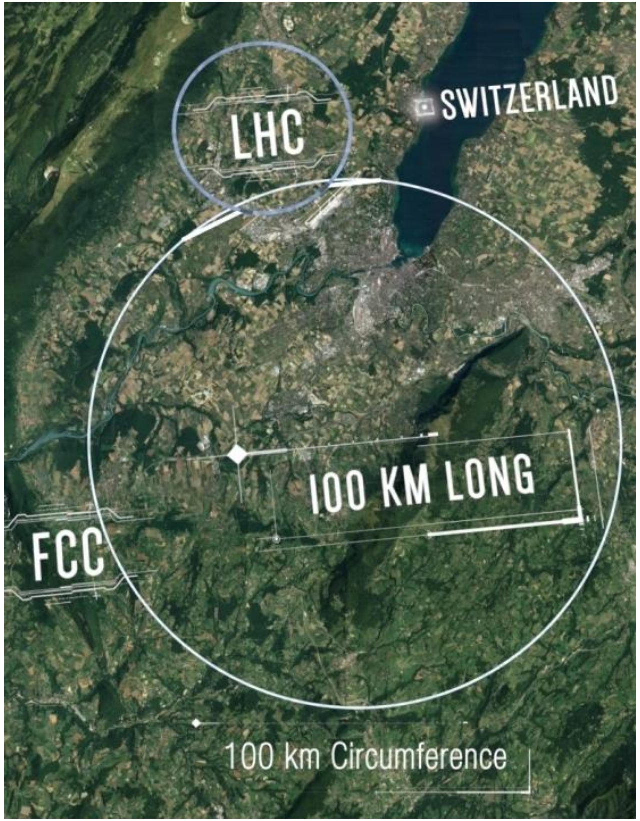
FUTURE
CIRCULAR
COLLIDER

High-Temperature Superconducting (HTS) materials for the Future Circular Collider (FCC-hh) beam screen. And beyond.

Sergio Calatroni – CERN

Outline

- The FCC-hh at CERN
- Why a beam screen, and why HTS
- Beam impedance and HTS
- HTS in RF and a strong B field
- Strategies:
  - REBCO tapes
  - Tl-based coatings
- Highlights of three years of collaboration
- Further developments



The FCC-hh: pushing the energy frontier

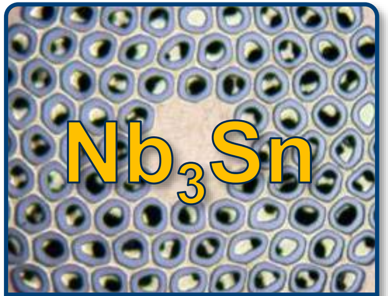
The *raison d’être* of a hadron collider is the energy reach

$$\boxed{E_{cm} \propto B_{dipole} \times R_{bending}}$$

Compared to the LHC:

- Factor ~3 in radius → 100 km circumference
- Factor ~2 in field → ~16 T dipoles, Nb_3Sn at 1.9 K
- Factor ~6 in energy → E_{cms} 100 TeV in the FCC-hh

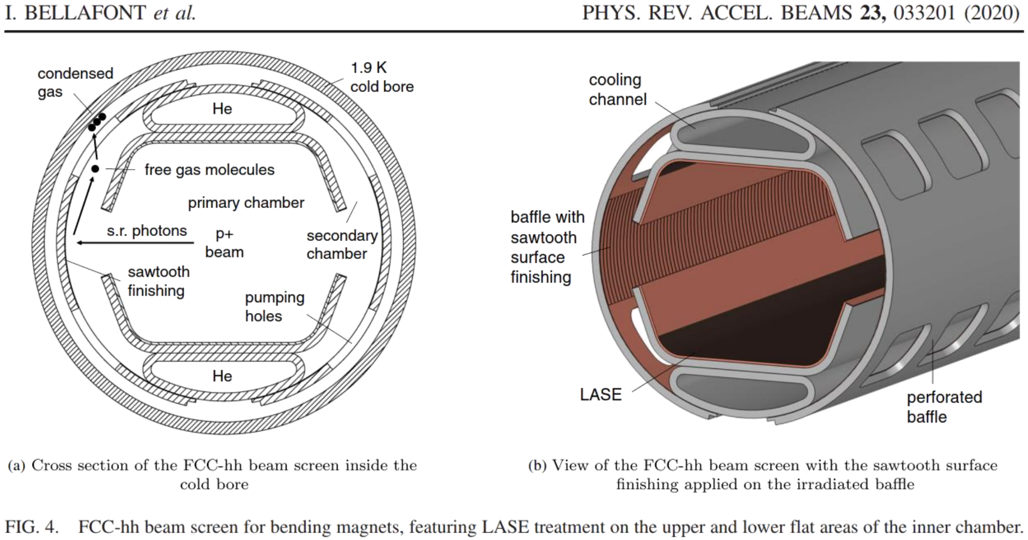
Synchrotron radiation → $\propto \frac{E^4}{R^2}$ → ~ 150 times more than in the LHC



Conductor R&D

Magnet Design

Need for a beam screen in a p-p collider

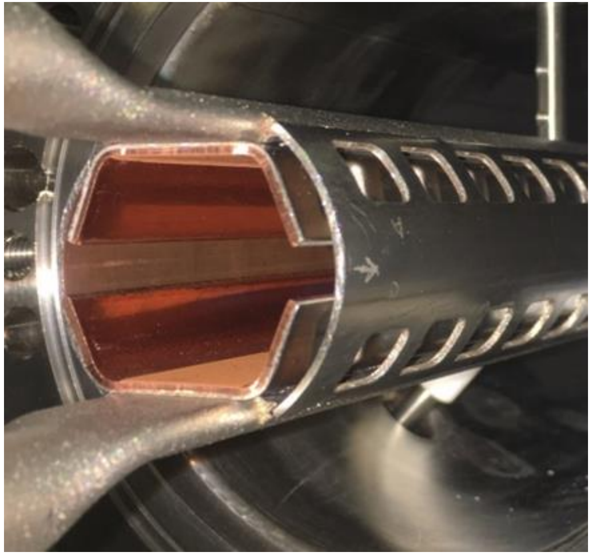


I. BELLAFONT *et al.* PHYS. REV. ACCEL. BEAMS **23,** 033201 (2020)

(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.

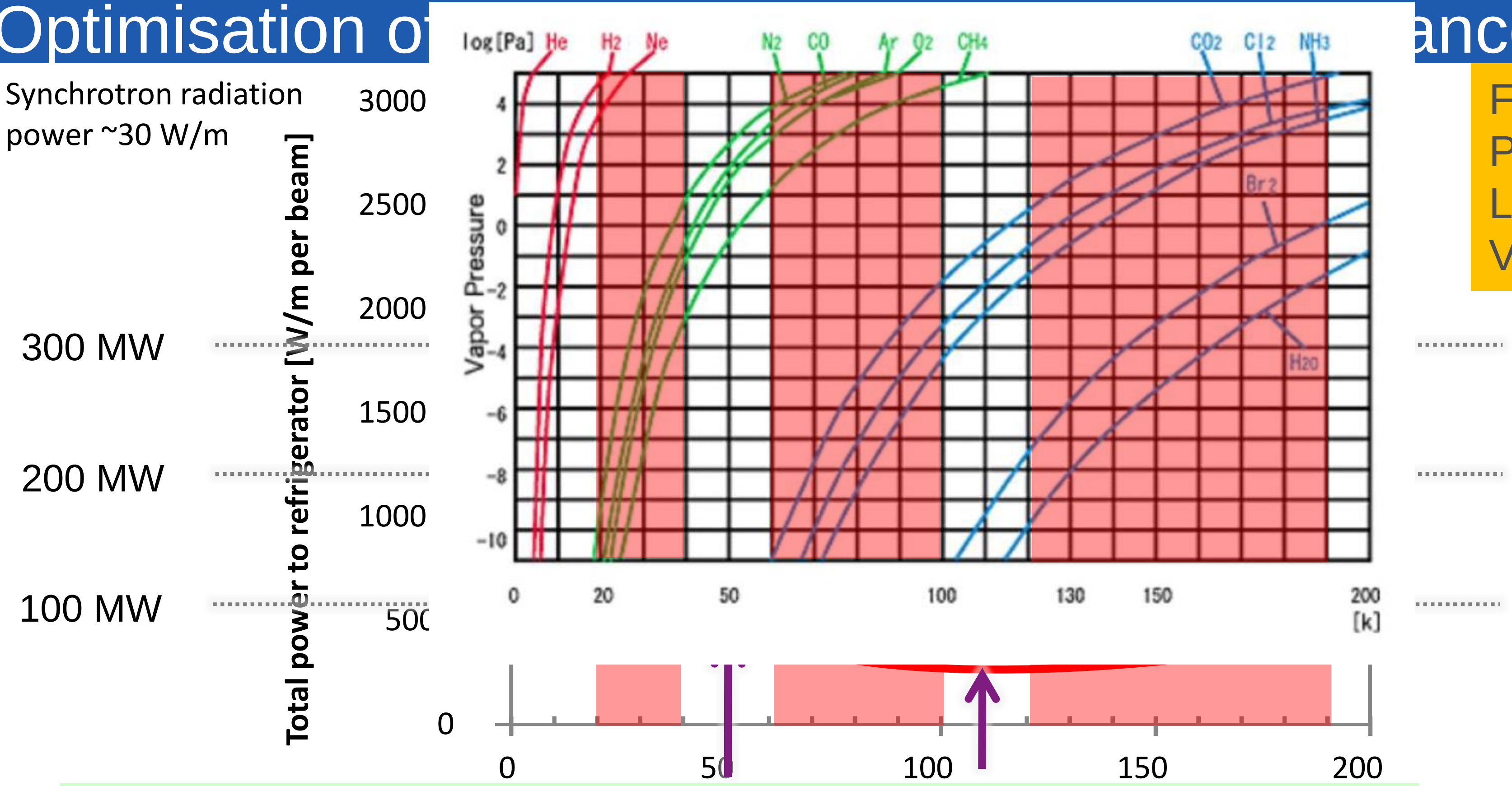


Synchrotron radiation load:

- → ~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

Optimisation o ance



From:
Ph. Lebrun
L. Tavian
V. Baglin

Multi-bunch instability growth time: 25 turns 9 turns ($\Delta Q=0.5$)

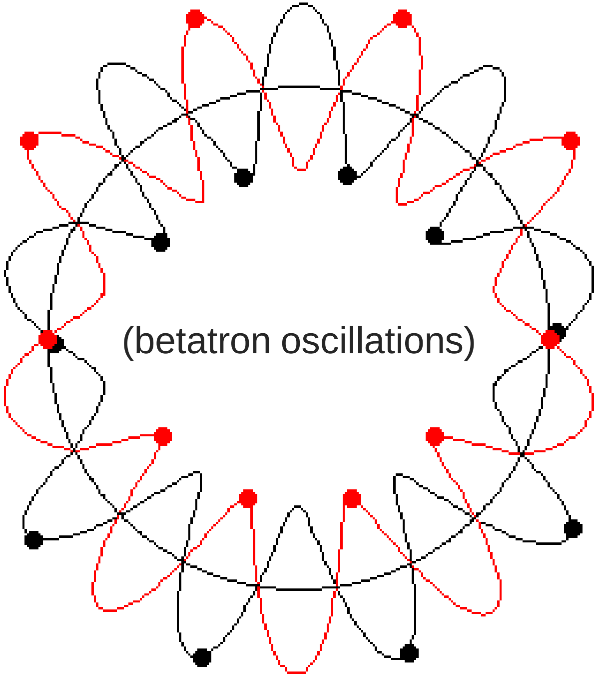
A particle accelerator

This is a particle accelerator. There is *one* reference orbit, set by dipoles

It's *impossible* to have particles exactly on the reference orbit

Quadrupoles keep the particles close to it, like a spring does: particles oscillate → ω

It's like breathing, a particle accelerator without such oscillations cannot exist… but oscillations can be perturbed → Δω



$$x(t) = x_0 e^{j(\omega_\beta + \mathrm{Re}|\Delta\omega| t + \varphi)} e^{-\mathrm{Im}|\Delta\omega| \tau}$$

$$\frac{1}{\tau} = -\mathrm{Im}|\Delta\omega|$$ ← Growth rate of instability

Surface impedance: the key

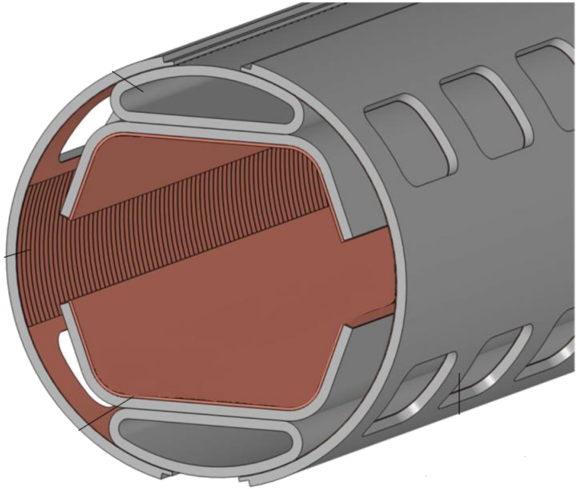
τ Risetime of beam instabilities

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

Z_T Transverse impedance (property of the beam)

$$\boxed{\mathrm{Re}(Z_T) = \frac{R\,c}{\pi b^3\ f} R_S = \frac{R\,c}{\pi b^3\ f}\sqrt{\rho\mu_0 \pi f}}$$

R_S Surface resistance
(property of the surface)



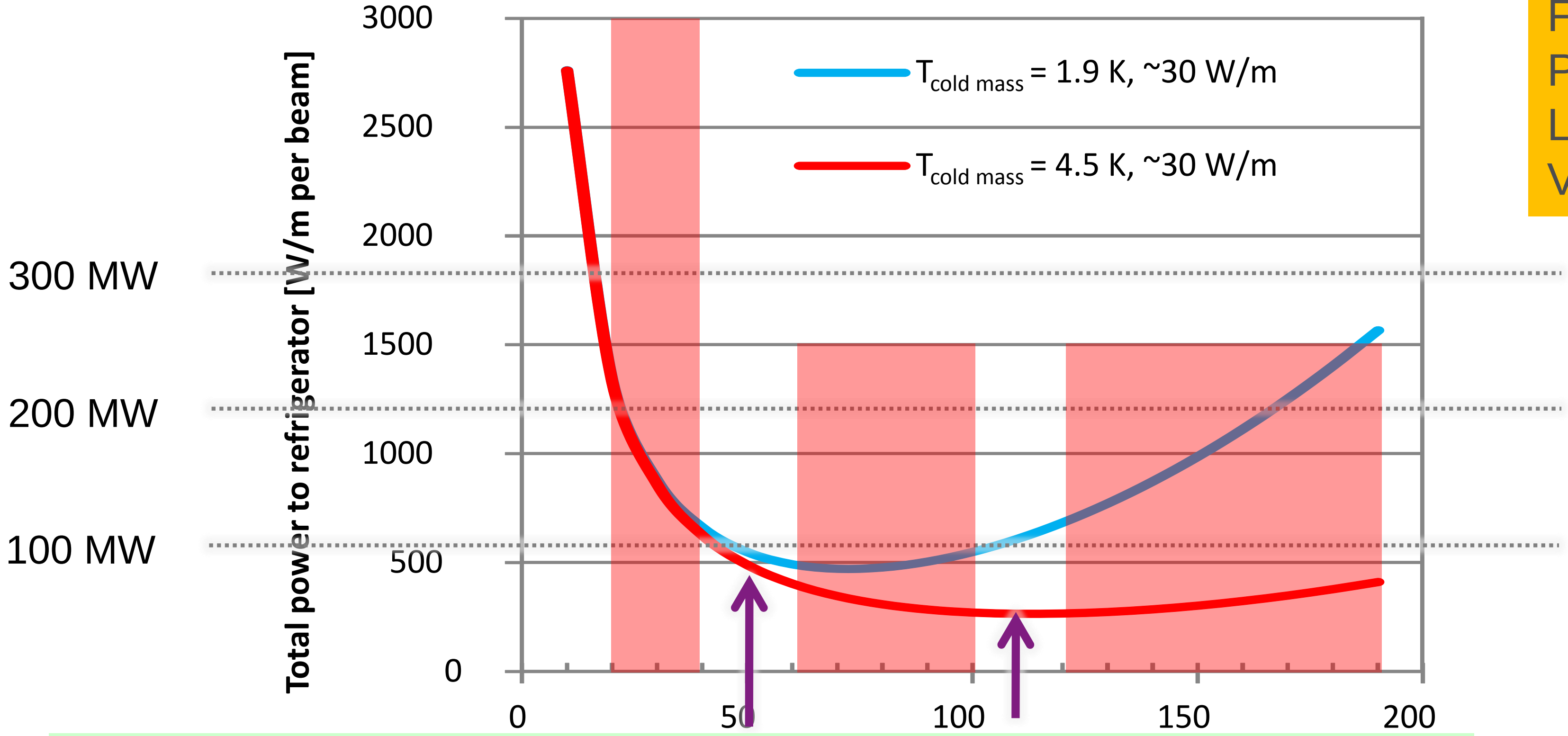
τ: instabilities rise-time
$\Delta\omega$: betatron tune-shift
I_b: bunch current
M: number of bunches
E: beam energy
L: bunch length
R: accelerator radius
c: speed of light
b: vacuum chamber radius
f: wakefields frequency
ρ: electrical resistivity

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

Note: R_S is also related to resistive wall impedance heating

Optimisation of cryo-power, vacuum and impedance

From:
Ph. Lebrun
L. Tavian
V. Baglin



Multi-bunch instability growth time: 25 turns 9 turns (ΔQ=0.5)

Surface impedance: the key

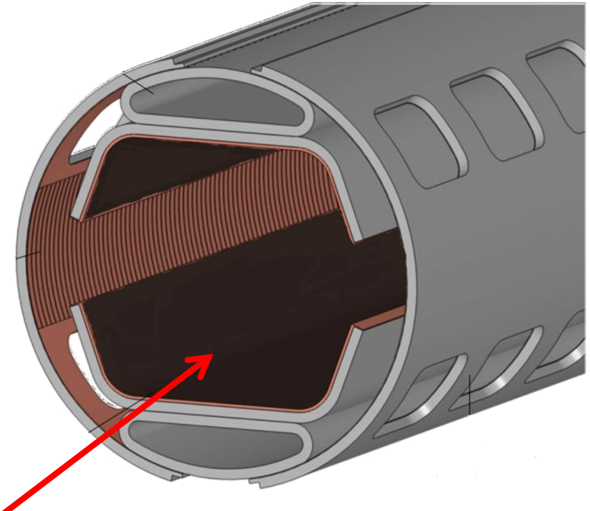
τ Risetime of beam instabilities

$$\frac{1}{\tau} \propto -\mathrm{Im}\left(F\right) \propto \frac{I_b M}{EL}\mathrm{Re}(Z_T)$$

Z_T Transverse impedance (property of the beam)

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

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

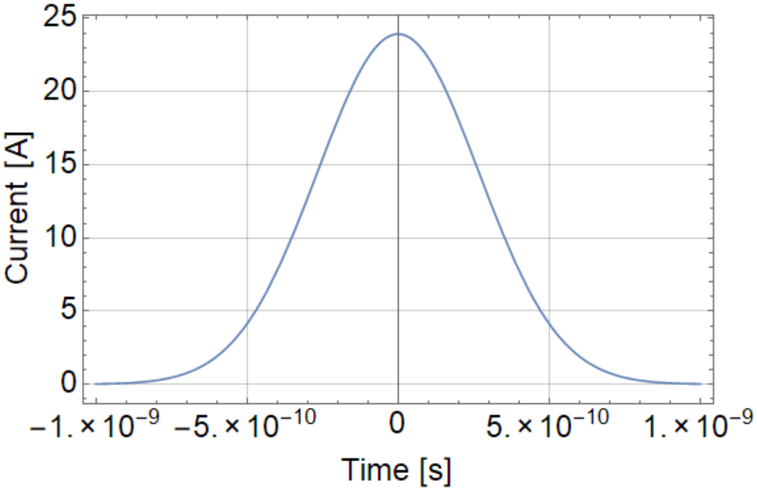
What could be better than copper?

High-Temperature Superconductors (HTS)

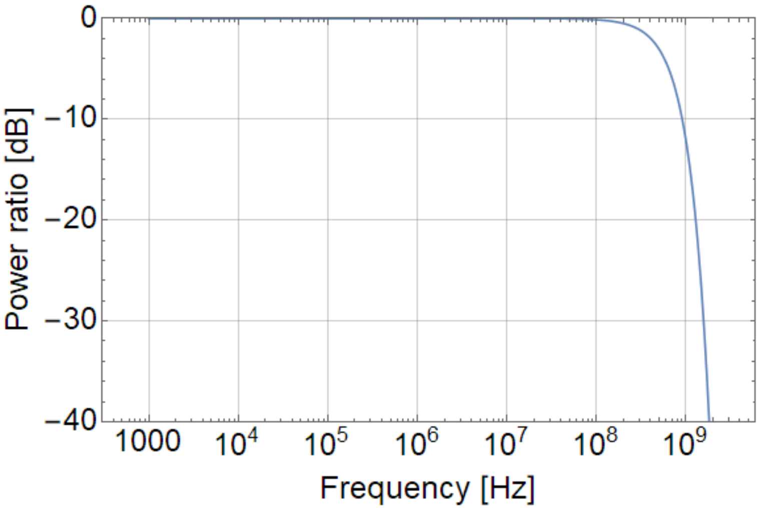
Current density and frequency spectrum

Bunches of 10^{11} protons, 8 cm rms length

Beam instantaneous image current



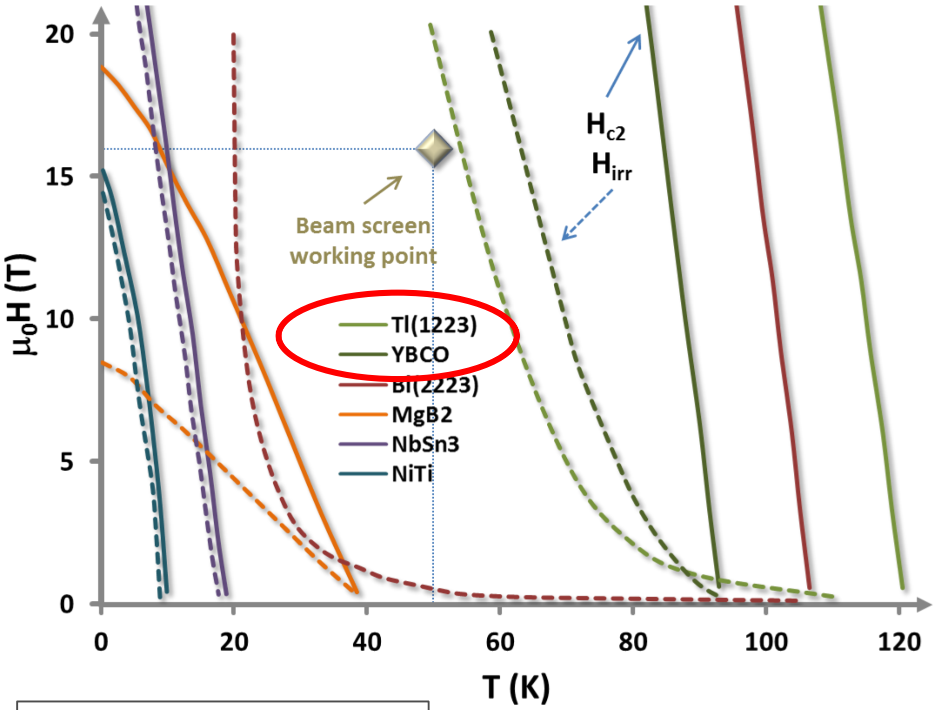
Frequency spectrum



Choice of HTS for the FCC-hh beam screen

Nature 414, 368-377 (15 November 2001)
High-Tc superconducting materials for electric power applications
David Larbalestier, Alex Gurevich, D. Matthew Feldmann & Anatoly Polyanskii

Superconductor Science and Technology, Volume 11, Number 8
Synthesis and properties of fluorine-doped Tl(1223): bulk materials and Ag-sheathed tapes
E Bellingeri, R E Gladyshevskii, F Marti, M Dhallé and R Flükiger



Courtesy: E. Bellingeri

Requirements:
HTS must operate at 50 K and 16 T

Critical field (FCC-hh dipoles):
Hc_2 , H_{irr} >> 16T

Critical current (1μm thickness):
$J_c > 25$ kA/cm^2 (2.5×10^8 A/m^2)

Surface resistance:
R_s better than for copper

Interlude

I have this idea, can it work?

But wait, better to double check

(scribble, scribble…) yes it should be possible

A famous theoretician

It is not possible

There is some literature…

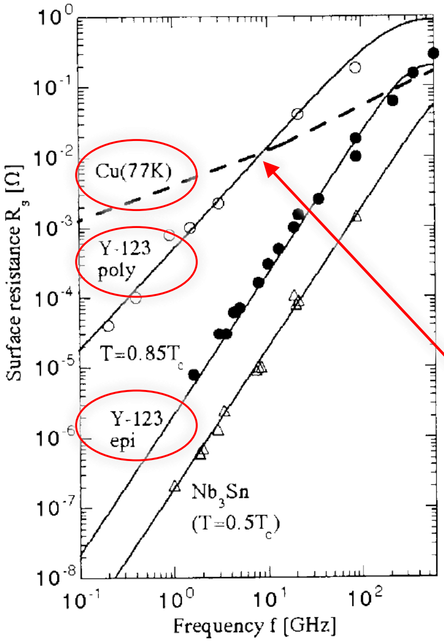
I’d be glad to help with accurate estimates

It is an RF problem

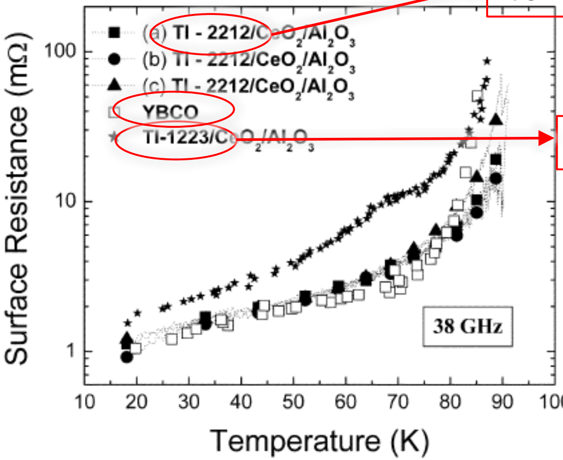
- In SRF cavities $Q = \frac{\Gamma}{R_s}$
- In general: $R_s = R_{BCS} + R_{res} + R_f$
    - R_{BCS} : intrinsic
    - R_{res} : defects
    - R_f : trapped magnetic flux

Expected performance

Surface resistance at zero H_{rf} and zero B_{ext}



M. Hein, “High-Temperature Superconductor Thin Films at Microwave Frequencies”, Springer



Tc ~100 K

Tc ~120 K

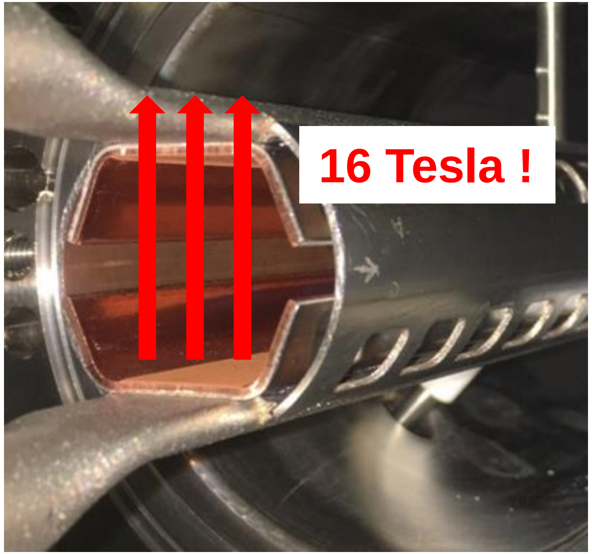
Sundaresan et al. , IEEE TRANS. APPL. SUPERCOND. 13 (2003) 2913

HTS can have surface resistance lower than Cu at T< 77 K and 0 T f < 10 GHz

RF in strong magnetic field

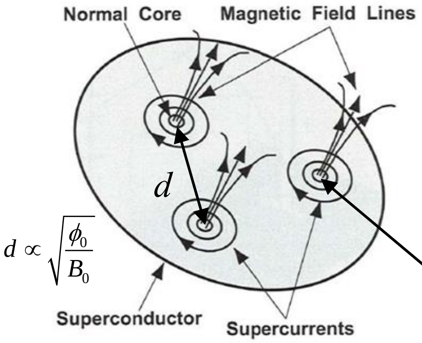
Surface resistance better than copper?

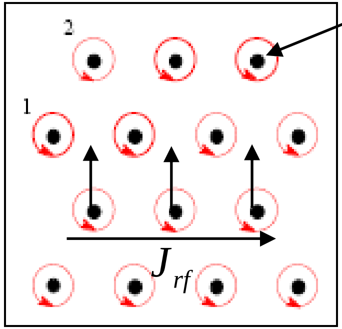
How does it work?



16 Tesla !

Some theory background: fluxon motion in RF





Pinning centers

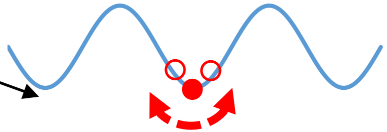
B field is normal to surface: worst case

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

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

Simplified model, neglecting thermally activated flux creep

Useful for estimates and scaling



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

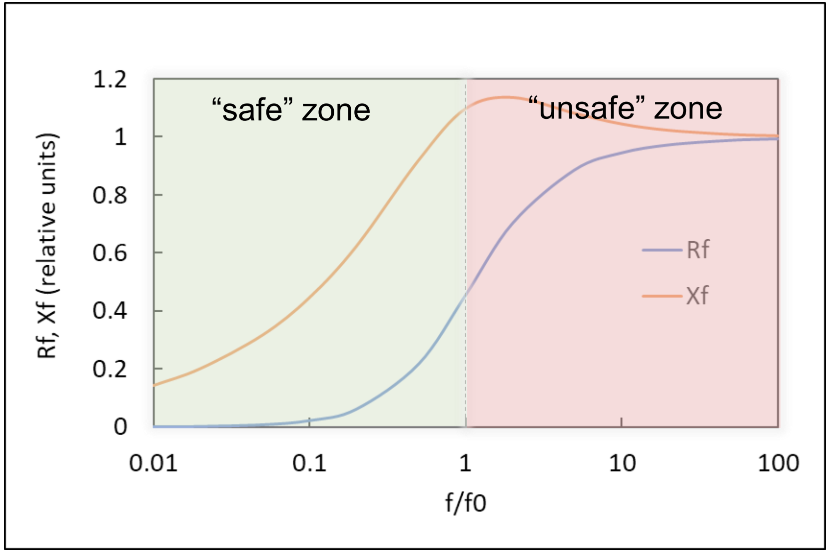
The “depinning frequency”

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

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)

Effect of magnetic field: fluxon losses in RF

Surface resistance, reactance due to vortex motion



Case $f < f_o$

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

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

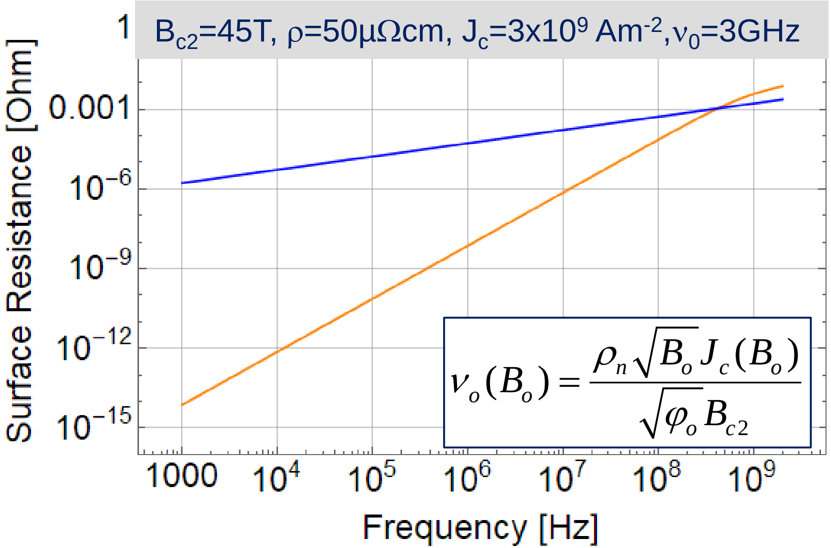
The surface resistance due to flux lattice oscillation scales as f^2

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

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

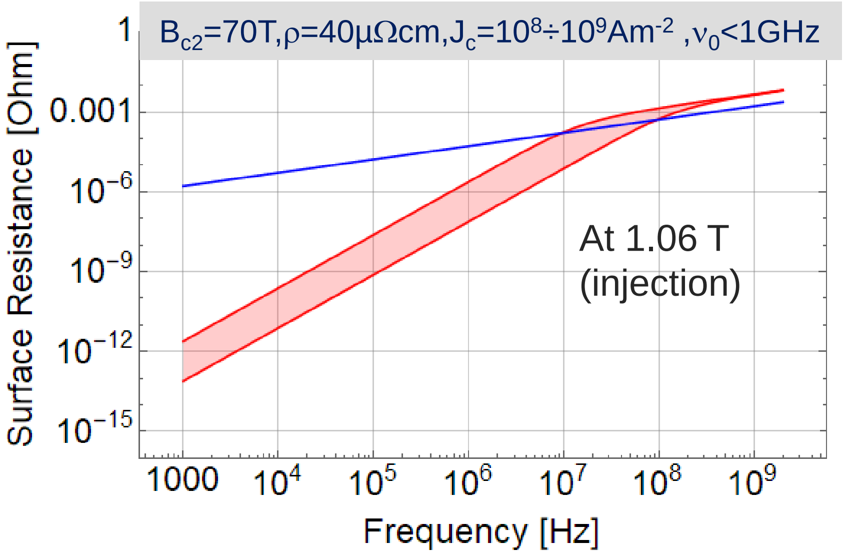
Predicted surface resistance of HTS in 16 T field

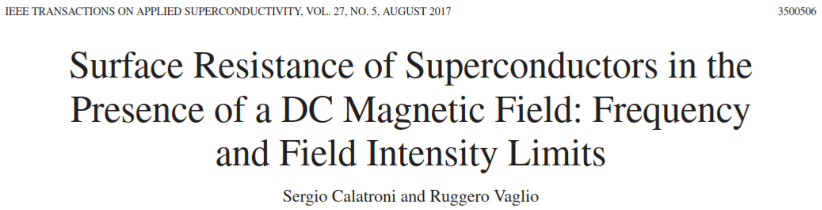
YBCO at 50 K compared to Cu



$$\nu_o(B_o) = \frac{\rho_n \sqrt{B_o} J_c(B_o)}{\sqrt{\varphi_o} B_{c2}}$$

Tl-1223 at 50 K compared to Cu

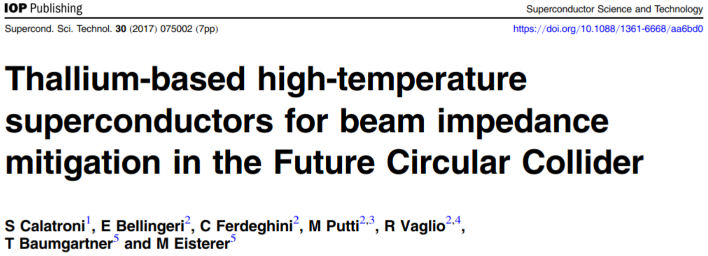




IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 27, NO. 5, AUGUST 2017 3500506

Surface Resistance of Superconductors in the Presence of a DC Magnetic Field: Frequency and Field Intensity Limits

Sergio Calatroni and Ruggero Vaglio



IOP Publishing Superconductor Science and Technology

Supercond. Sci. Technol. **30** (2017) 075002 (7pp) https://doi.org/10.1088/1361-6668/aa6bd0

Thallium-based high-temperature superconductors for beam impedance mitigation in the Future Circular Collider

S Calatroni[1], E Bellingeri[2], C Ferdeghini[2], M Putti[2,3], R Vaglio[2,4], T Baumgartner[5] and M Eisterer[5]

How to make it in practice ?

Manufacture the screen using REBCO tapes soldered to the screen

Coat the inside of the screen with Tl-1223 films

ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA
EXCELENCIA SEVERO OCHOA
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

ALBA

IFAE
Institut de Física d'Altes Energies
EXCELENCIA SEVERO OCHOA
BIST Barcelona Institute of Science and Technology

UPC
CommSensLab
EXCELENCIA MARÍA DE MAEZTU
2017 - 2020

EASITrain

CERN

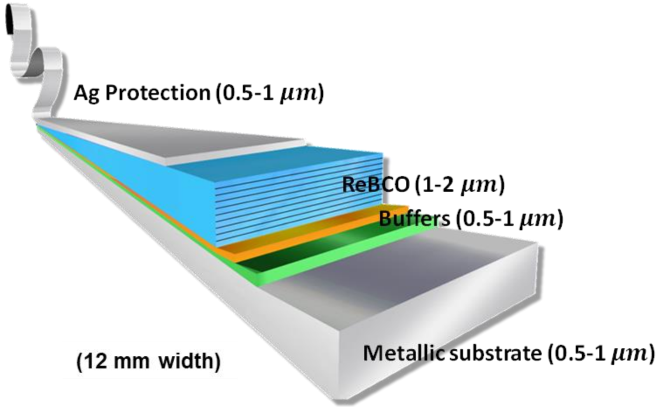
SPIN

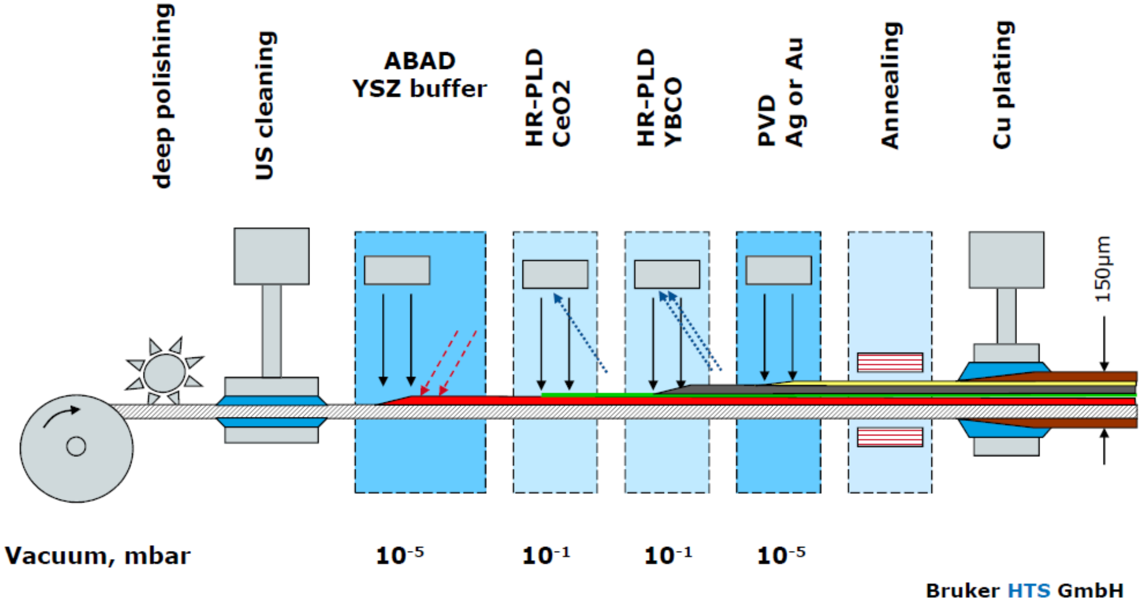
ATOMINSTITUT

TU WIEN
TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

USTEM

HTS Coated Conductor (Y, Nd, Sm, Gd, Dy)$Ba_2Cu_3O_{7-\delta}$





Bruker HTS GmbH

Scalable technology for growing km-length REBCO CC

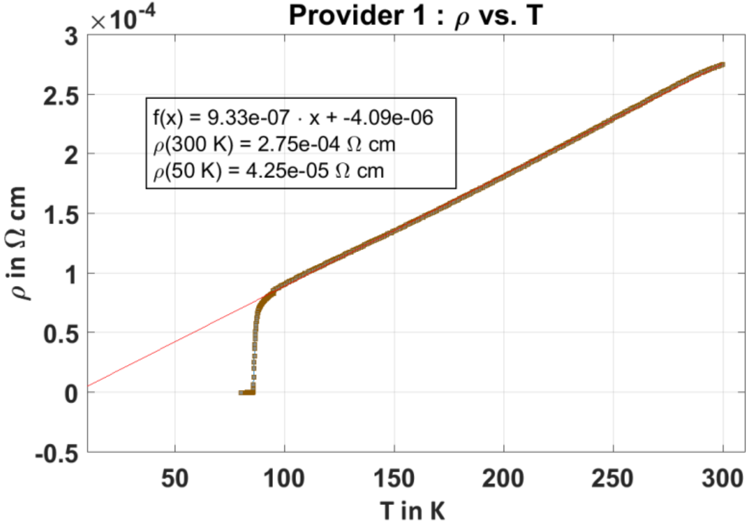
Presently produced by American Superconductor, BRUKER, Fujikura, SuNAM, SuperOx, SuperPower Inc. A Furukawa Company, STI, THEVA, Shanghai 上海超导, OXOLUTIA, deutsche nanoschicht, MetOx

Collaboration program - Barcelona

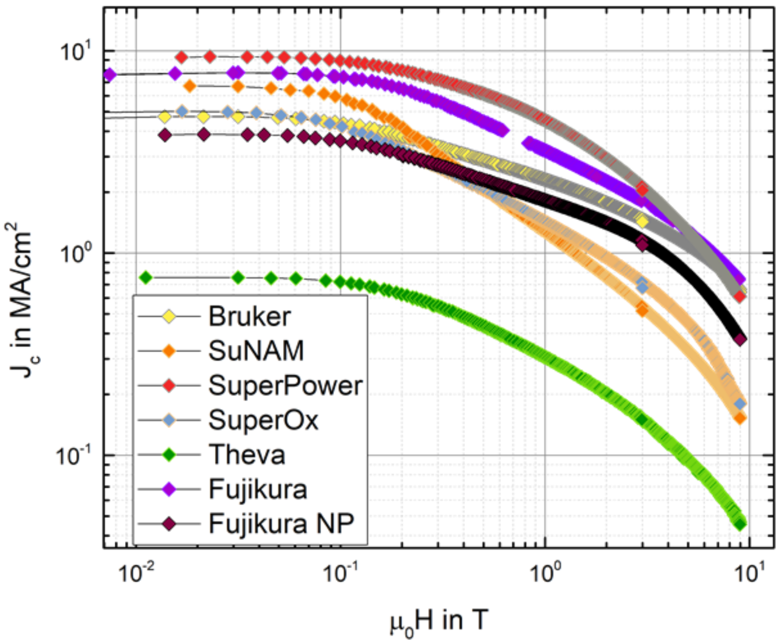
- Qualification and selection of tapes (Jc, Hc, Tc, magnetization and transport measurements) – (ICMAB)
- Validation of RF performance up to 9 T and higher (UPC)
- Development and assessment of tapes' mechanical properties and of soldering technique preserving the properties (IFAE)
- Resistance to synchrotron radiation, and transport + RF properties in-situ (ALBA)
- Vacuum compatibility, SEY, outgassing… (CERN)

Transport measurements (ICMAB)

Normal resistivity $\rho_n(50K)$

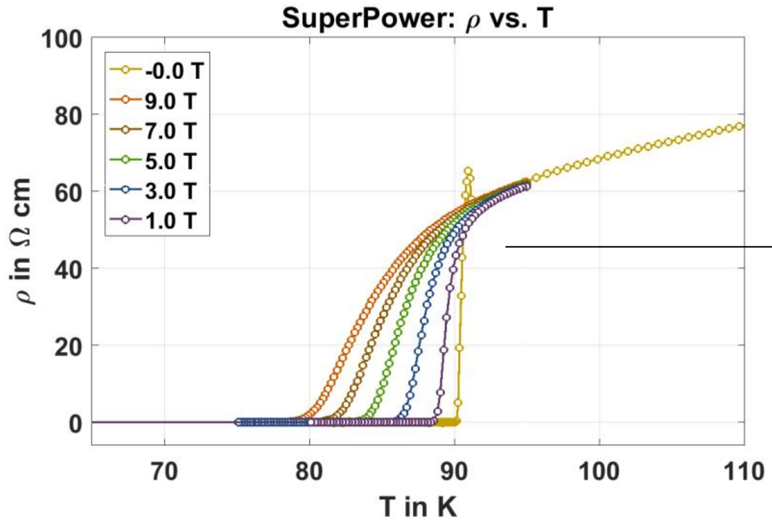


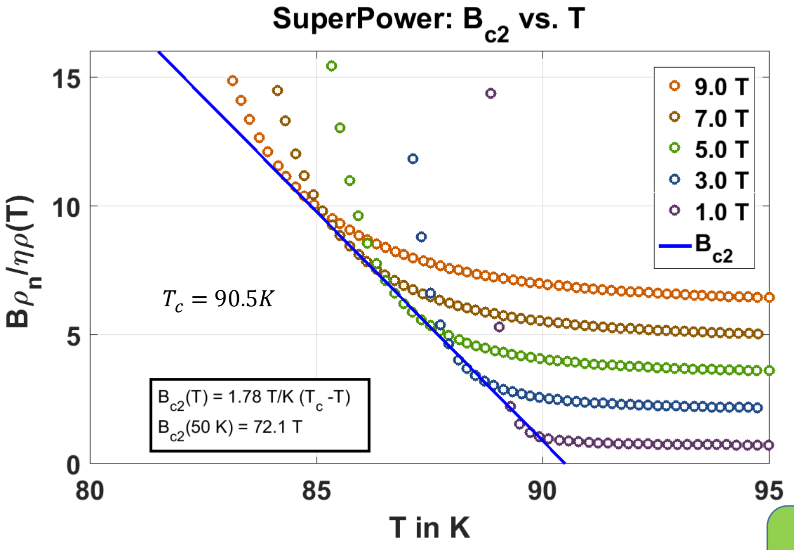
$J_c\ vs. H\ @\ 50K$



Qualification and selection of tapes, evaluation of depinning frequency and estimate RF performance

Estimates of Bc2 (ICMAB)



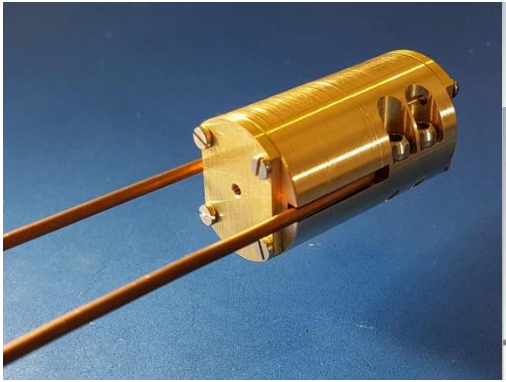


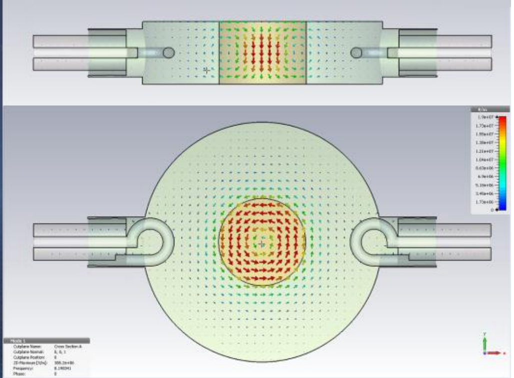
> 16T !

	Bruker	Sunam	SuperOx	SuperPower	Theva	Fujikura FYSC (no NP)
B_{c2}(50K) in T	60.1	76.3	77.1	72.1	108.9	71.4

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

Validation of RF performance (UPC - ICMAB)





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

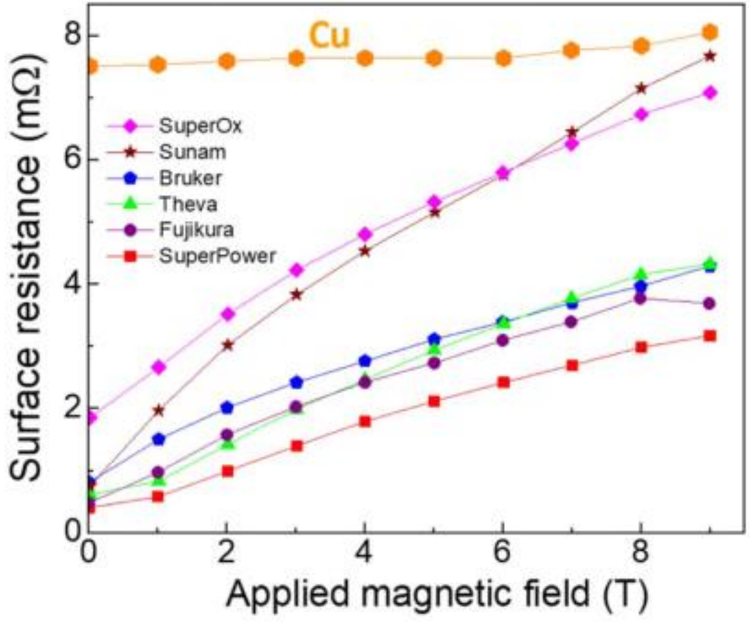


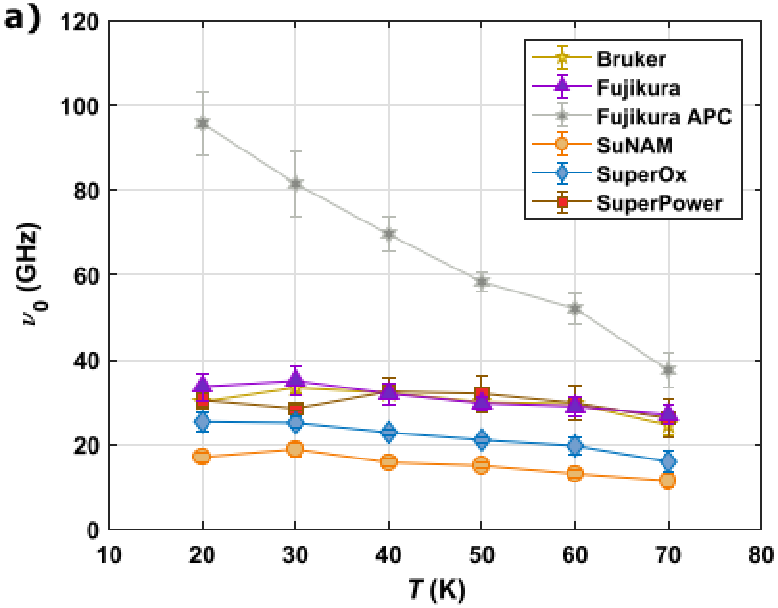
Figure 3. Magnetic field dependence of the surface resistance at 8 GHz and 50 K. Up to 9 T, CCs' R_s outperforms that of copper.

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

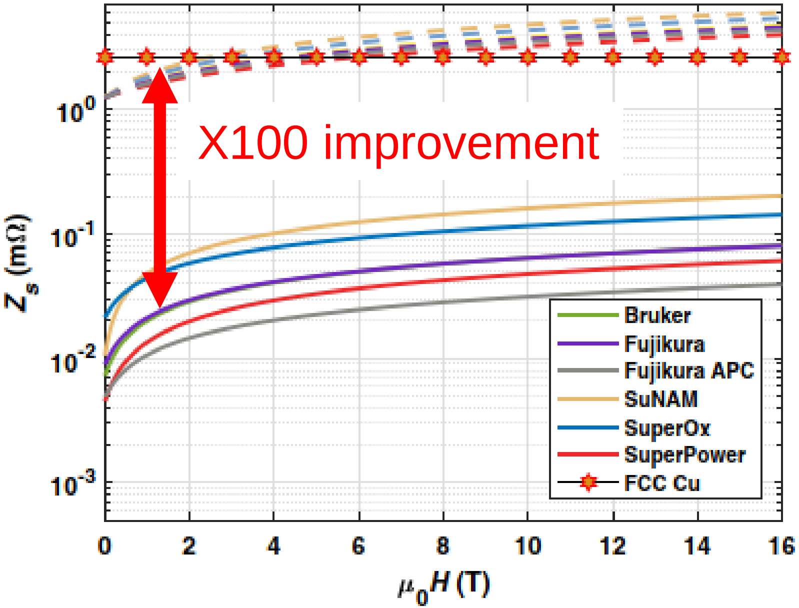
T. Puig et al., Supercond. Sci. Technol. 32 (2019) 094006 (8pp)

Depinning frequency, and frequency scaling

Depinning frequency

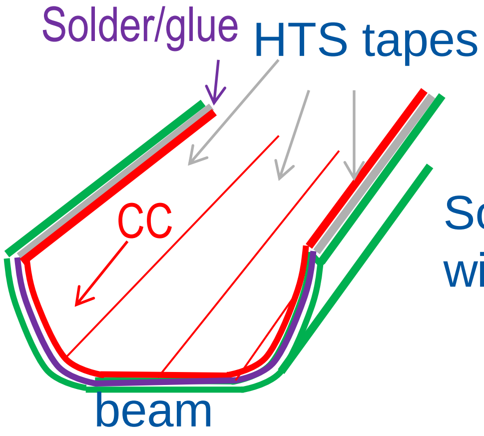


Rs scaling to 1 GHz



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

Development of soldering technology (IFAE)

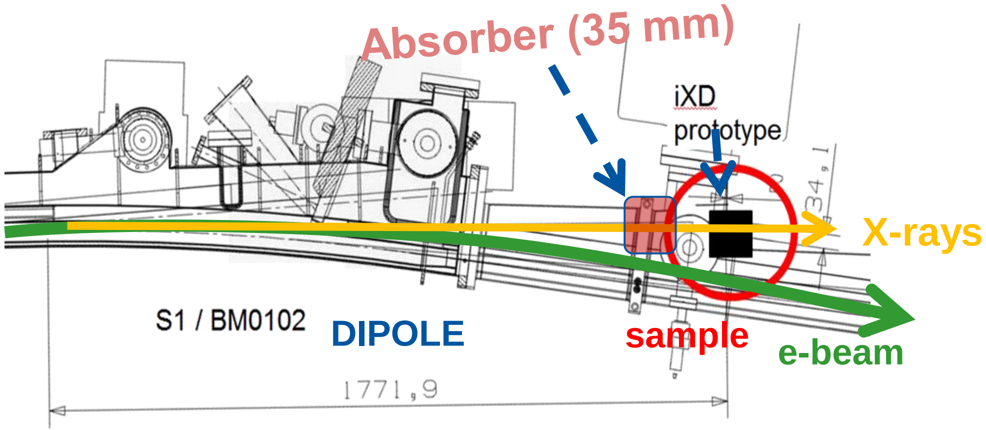


Solders based on Sn / Pb / Cu / Bi & In will be tested at temperatures < 220ºC

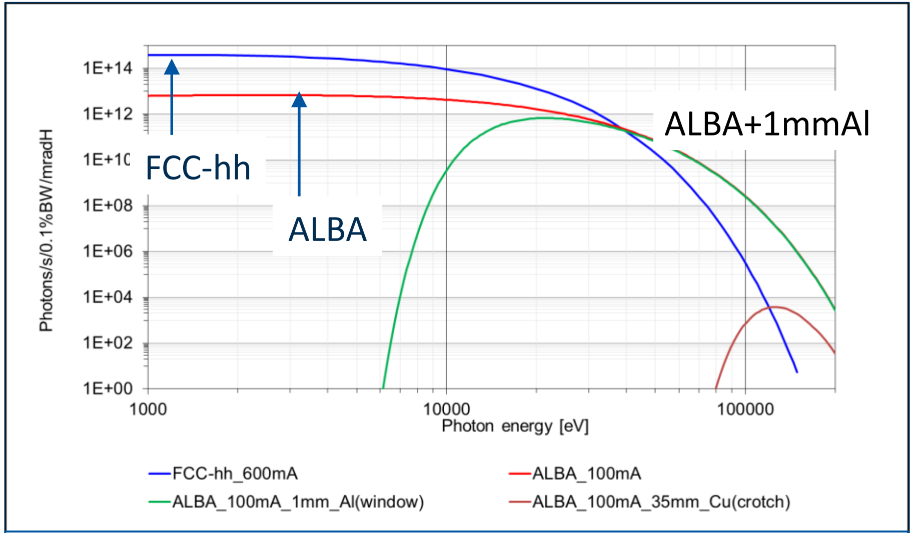
A cryogenic system to assess 2D /3D stress maps based on optical image correlation with in situ monitoring of the I_c is under commissioning

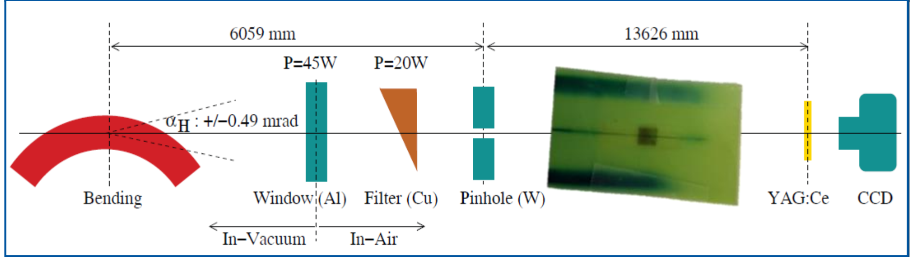
Synchrotron irradiation (ALBA)

- HTS tapes were irradiated with high energetic synchrotron radiation (E_c 130 keV) for four weeks in ALBA synchrotron



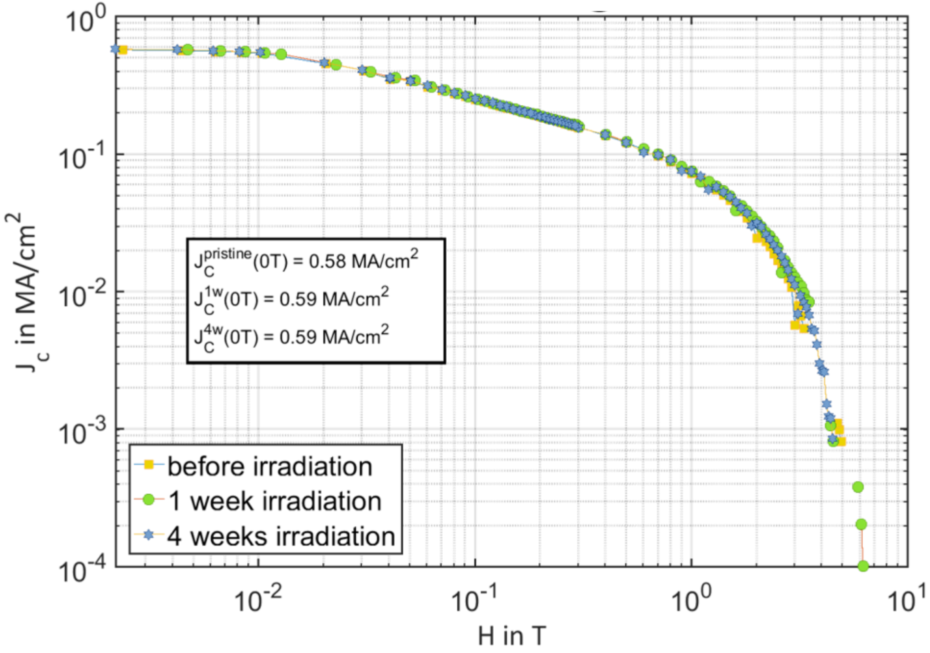
Courtesy of U.Iriso and M. Pont



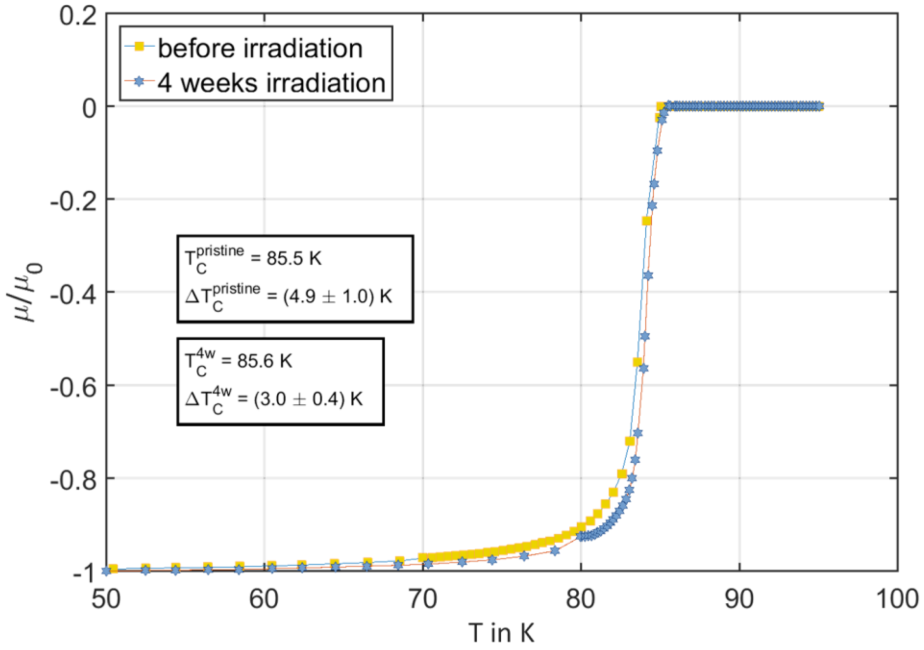


Synchrotron irradiation: first results (ALBA)

SC properties of samples before and after irradiation are compared by means of inductive measurements

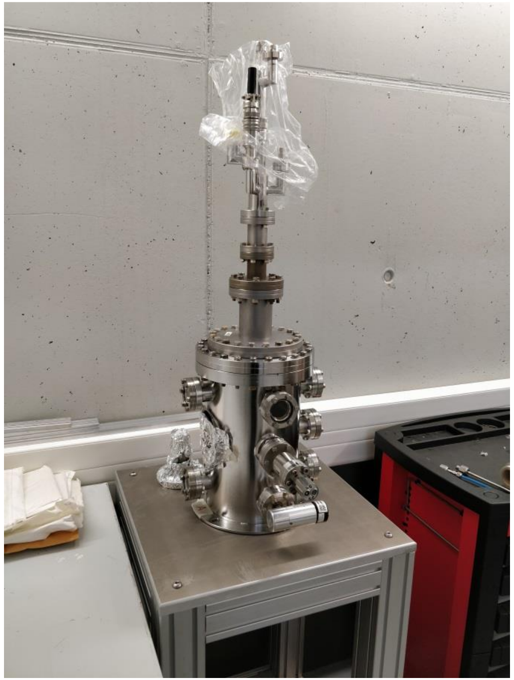


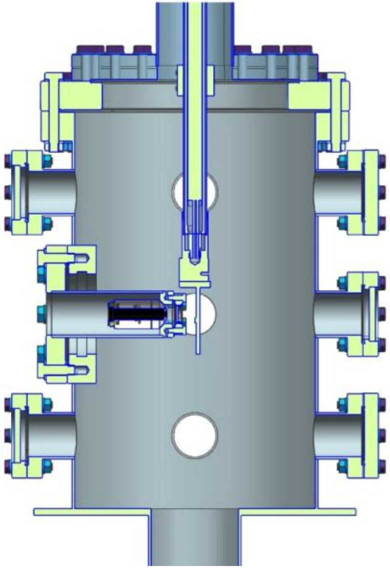
1. $J_C(0T)$ does not change within the uncertainties
2. Field behavior is the same



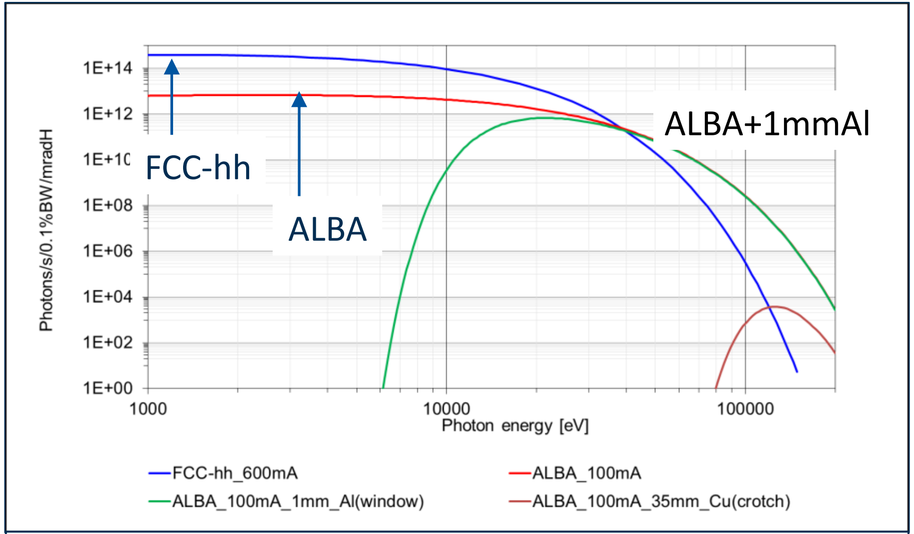
1. T_C stays the same within uncertainties
2. ΔT_C decreases after irradiation slightly

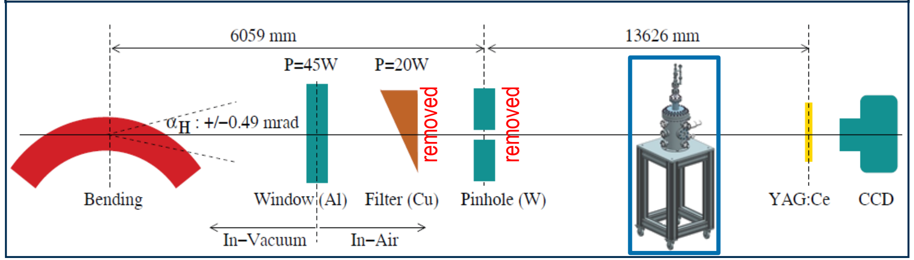
Cryogenic irradiation tests (ALBA)





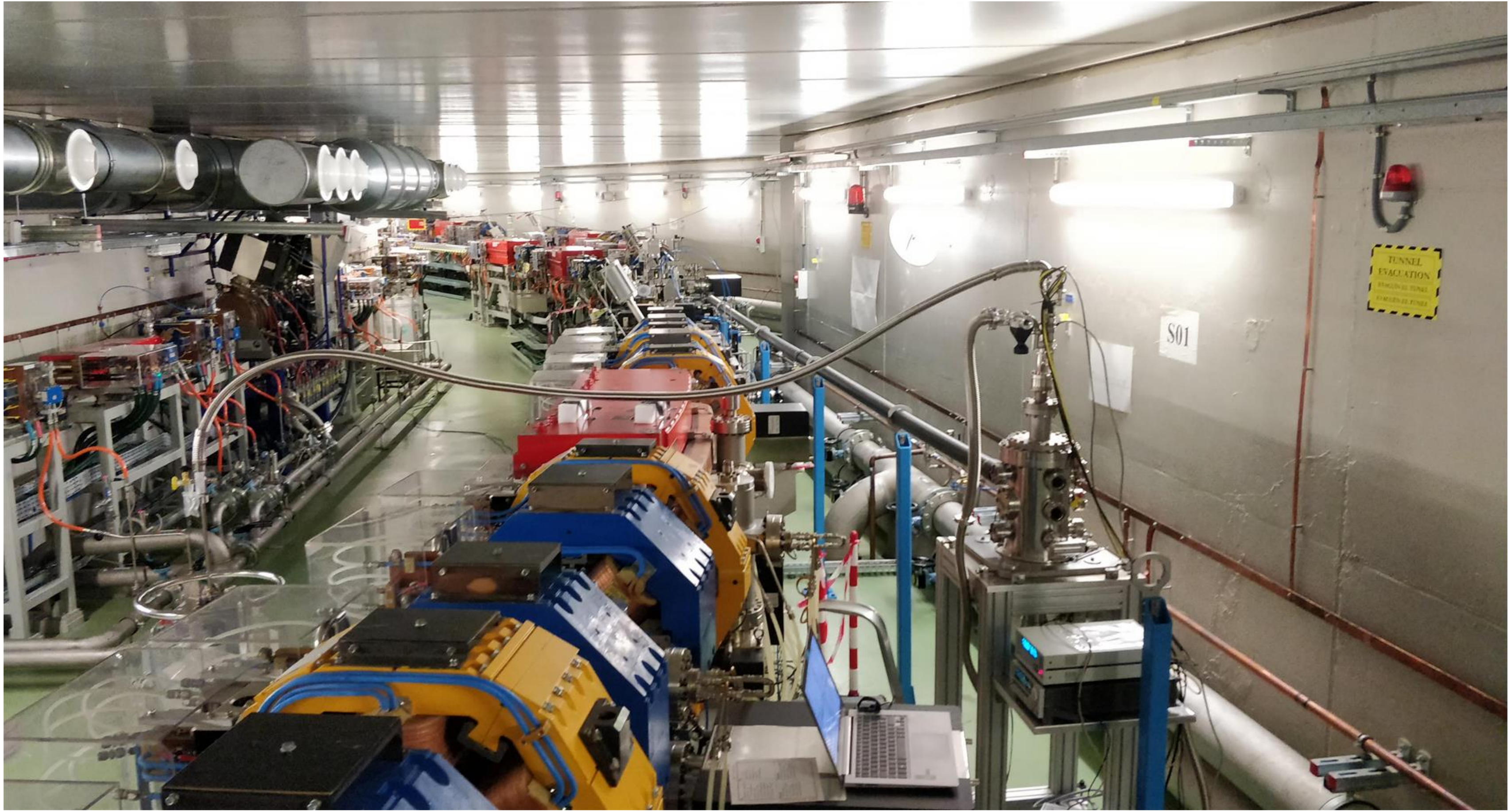
Temperature range 2-500K





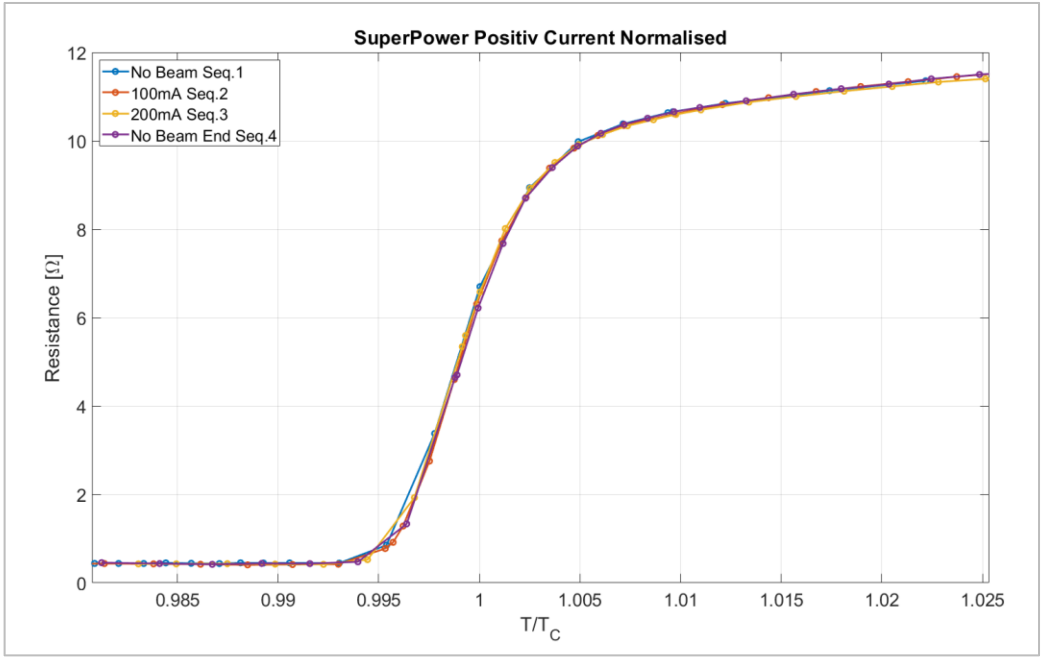
- DC resistivity online
- RF test with synchrotron radiation as final goal

Test system @ ALBA



Irradiation: online measurement (ALBA) 1 mm Al window

- The second temperature sensor (Cernox) revealed that the intrinsic temperature sensor did not measure the sample temperature
  - Radiation shield removed
  - Sample not attached on supposed place
- The curves overlap within 0.05 K
- This confirms the statement that synchrotron radiation at this energy spectrum has no impact on CCs
- New measurements with different material planned
- Simulations are ongoing to estimate the dose



Tl-1223 tapes: CNR-SPIN, TU-Wien

	YBCO	Tl-1223
PROs	- Very good properties - Indiustrially available in tapes	- Very high Tc - High Jc - Very high Bc2 - Tolerant for out stoichiometry - Substrate-tolerant (Ag coating) - Weak link effects my be cured by overdoping
CONs	- Very expensive and complex preparation - Lower Tc	- Tl is toxic - Weak link effects may not be overcome easily

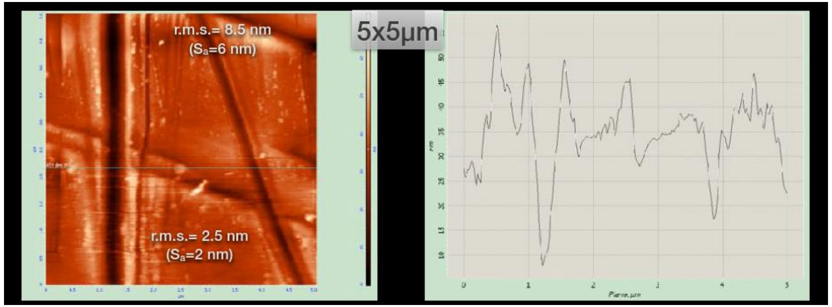
May open up the 100-120 K operating window
Power consumption from 100 MW down to 50 MW

Collaboration program CNR-SPIN, TU-Wien

- Construction of a safe laboratory
- Definition and selection of precursors for Tl-1223 coating (CNR-SPIN)
- Optimization of coating procedure through:
- Assessment of transport properties (TU-Wien Atominstitut)
- And correlation with microstructural properties (TU-Wien USTEM)
- (and repeat)
- Produce high-quality coatings by electroplating (few cm^2) on textured substrate (Ag)

Sample preparation (CNR-SPIN)

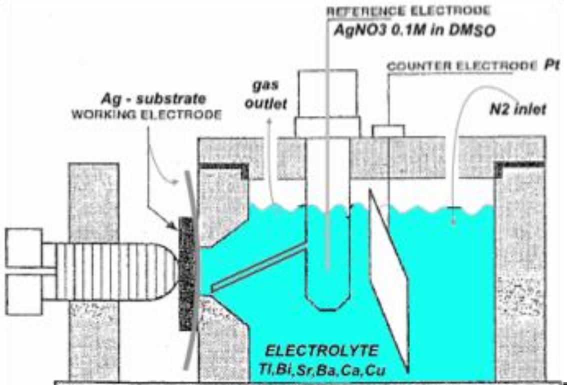
- Step 1: preparation of the substrate
    - Laminated Ag ribbon
    - Polishing
    - Heat treatments

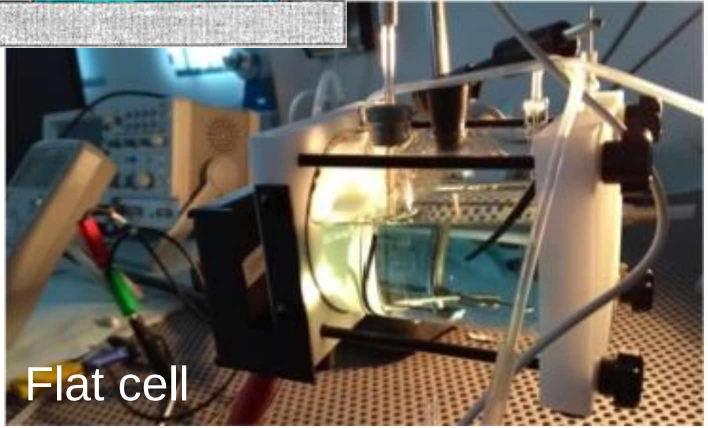


- Step 2: preparation of the precursors
    - $TlNO_3$ + $Bi(NO_3)3 \cdot 5H_2O$ + $Sr(NO_3)_2$ + $Ba(NO_3)_2$, + $CaNO_3 \cdot H_2O$ + $Cu(NO_3)_2 \cdot xH_2O$
    - In dimethyl sulfoxide (DMSO)

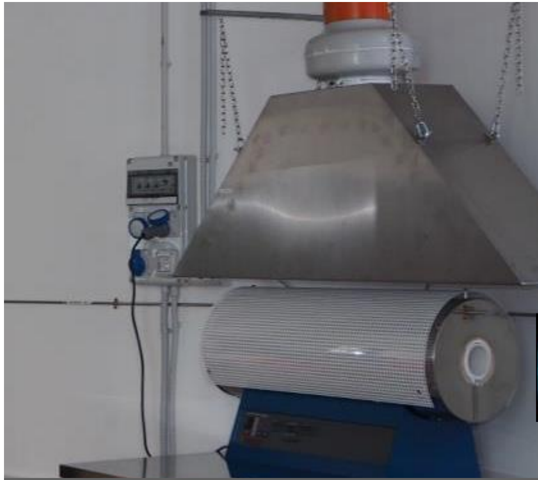
Sample preparation (CNR-SPIN)

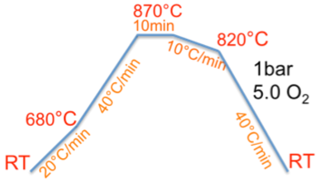
- Step 3 :Electroplating

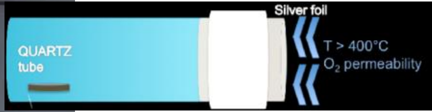



Flat cell

- Step 4: Heat treatment



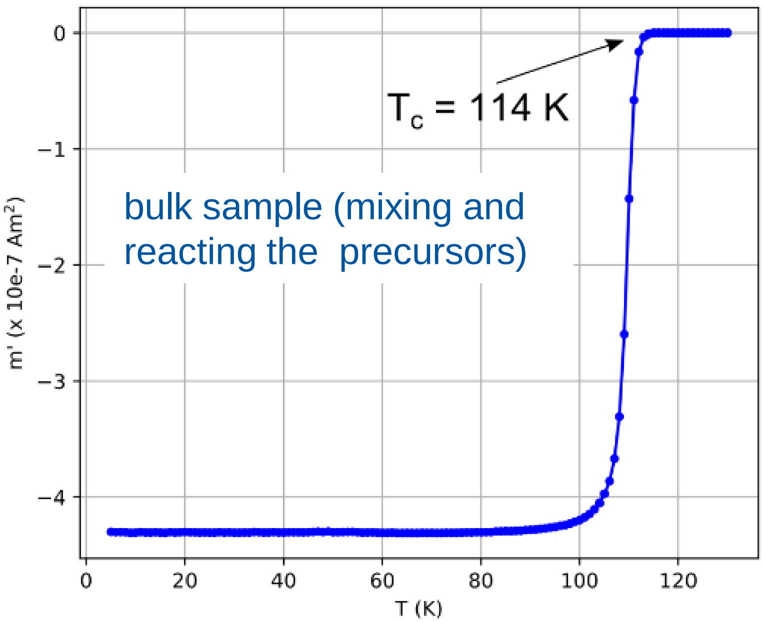




(Thallium (oxide) is volatile above 700-715°C)

SQUID measurements (Atominstitut)

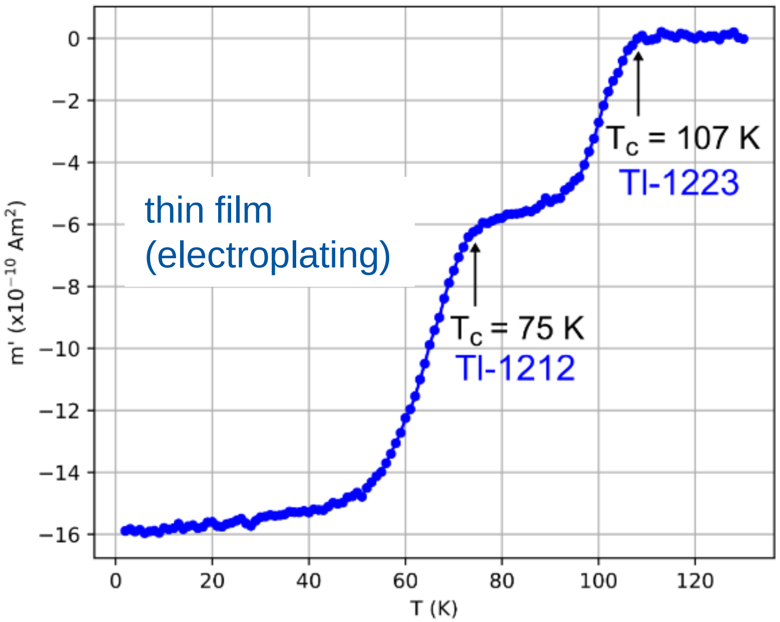
Critical temperature Tc



T_c = 114 K

bulk sample (mixing and reacting the precursors)

Single phase



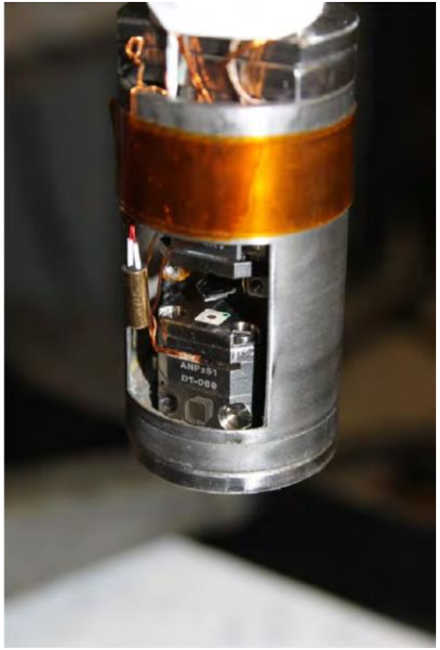
thin film (electroplating)

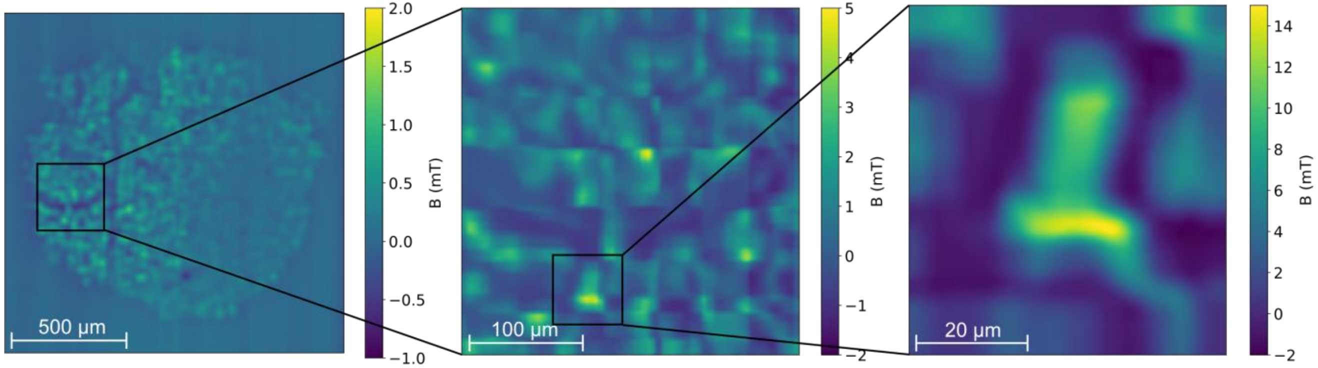
T_c = 107 K
Tl-1223

T_c = 75 K
Tl-1212

Different phases present

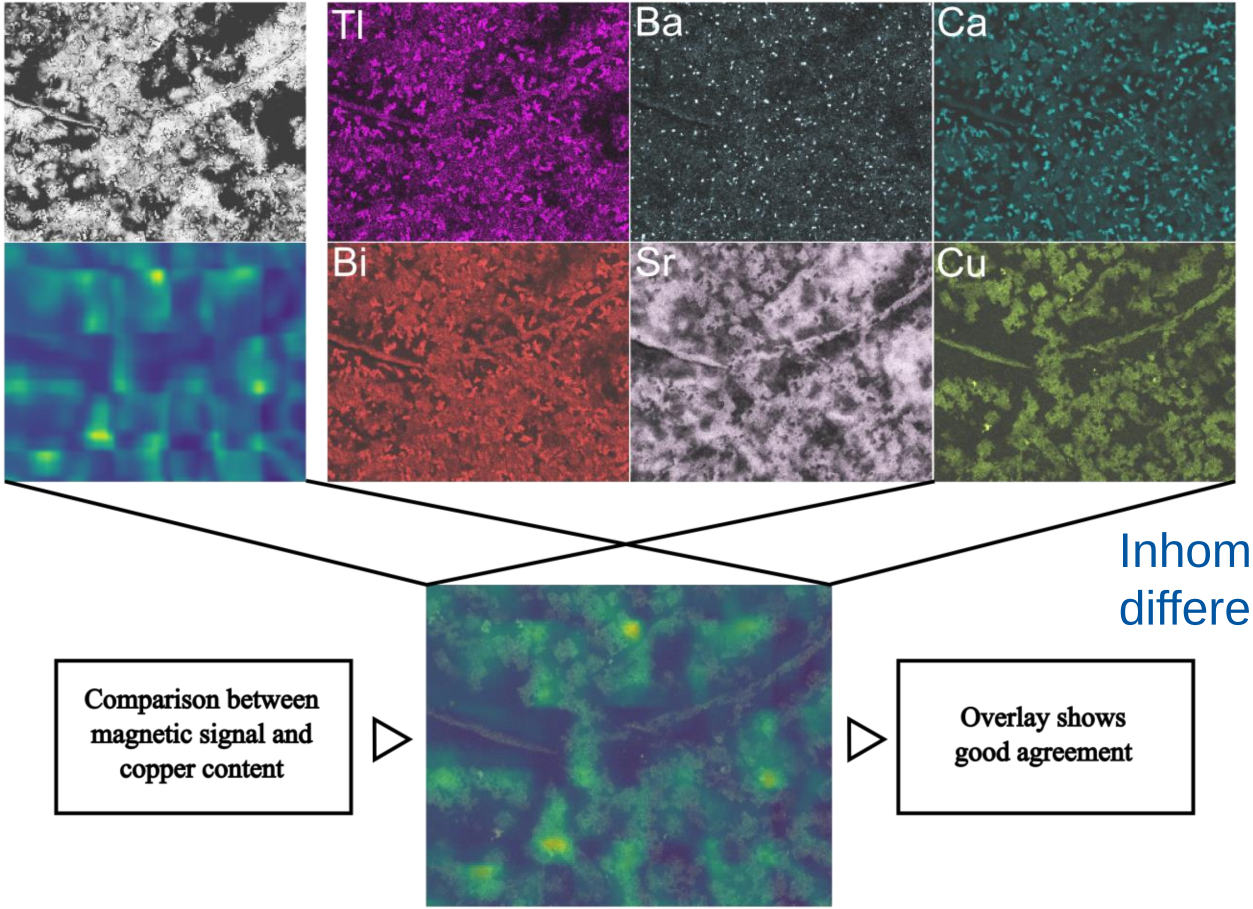
Scanning Hall Probe Microscopy (Atominstitut)





zoom into different areas for high resolution scans

SEM – EDX elemental mapping (USTEM)



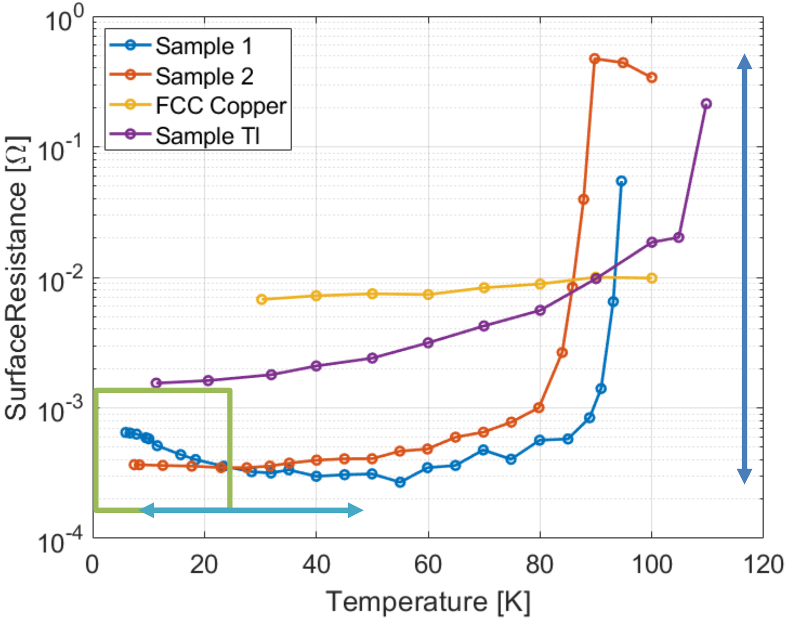
Comparison between magnetic signal and copper content

Overlay shows good agreement

Inhomogeneities: different phases

First RF results of Tl-1223 sample (CNR – UPC)

- Cryostat cooling
  - Temperature interval 40 – 100 K
- Comparison of Copper
  - LHC and FCC Copper are basically equal
- Different behaviour in low temp. region
  - Influence of Gadolinium (Sample 1)
- Measurement of Thallium based sample
  - Superconducting state at $T_c > 100\ \mathrm{K}$

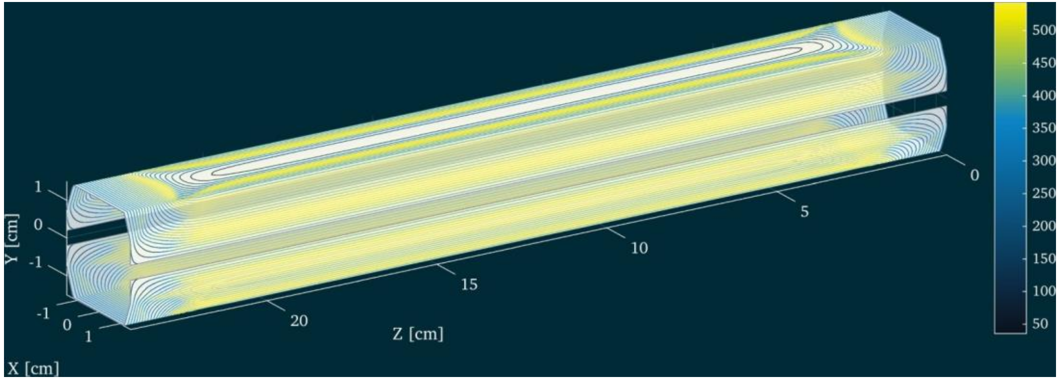


Other requirements: accelerator compatibility

- Magnetic field quality
- UHV compatibility
- Low SEY (e-cloud suppression)
- Self heating
- Lifecycle environmental radiation protection
- Radiation hardness of HTS (p^+, n, pions, …)

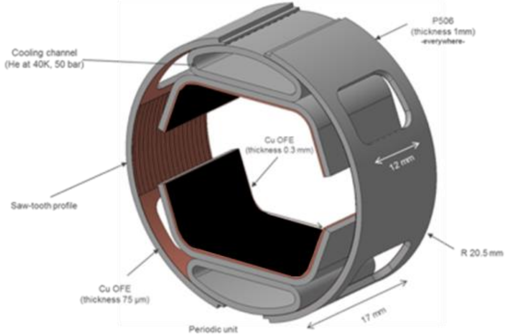
Striated configuration to minimize trapped fields

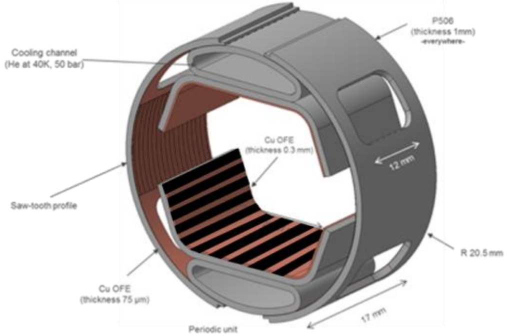
Screening currents during magnetic field ramping will produce unacceptable field quality effects

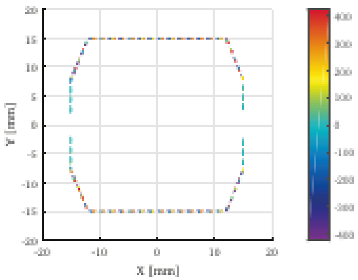


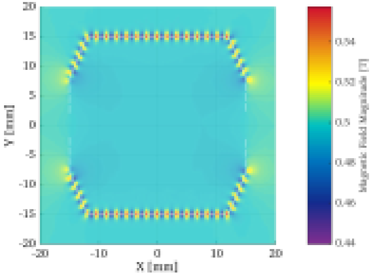
A striated geometry will drastically reduce trapped magnetic fields in the superconductor, recovering acceptable levels of field quality during ramping

J. van Nugteren, S. Bermudez,
S. Calatroni, G. Kirby, G. de Rijk









Tailored thickness profile

Eliminating field distortions caused by the HTS beam screen coating

Kristóf Brunner, Dániel Barna
Wigner Research Centre for Physics
Budapest

E-mail:
brunner.kristof@wigner.mta.hu
barna.daniel@wigner.mta.hu

3) Proposed solution:

Instead of trying to eliminate the Eddy-currents (difficult), we can try to master them. Goal: find a **specific thickness profile of the coating** such that the field generated by the Eddy currents have the **same symmetry** as the external field. This does **not distort** the field, only **adds an offset** to it, which can be compensated by adjusting the power supply.

Note: if $J_c(B)$=const and the beam screen is cylindrical, $d(\vartheta) \sim \cos(\vartheta)$ would give a dipole contribution.

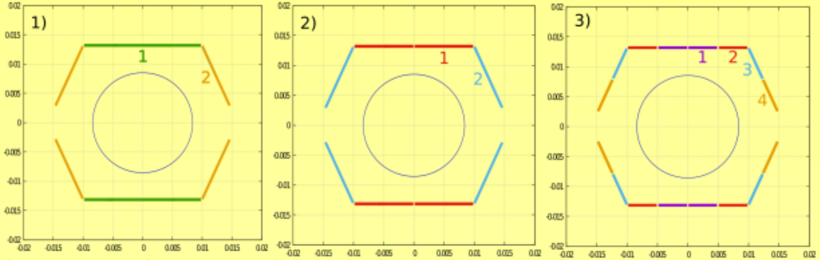


***Figure 1**: Three possible configurations. Colors indicate segment groups with the same thickness of the HTS layer. The circle in the middle represents the 2/3 aperture where the generated field was sampled*

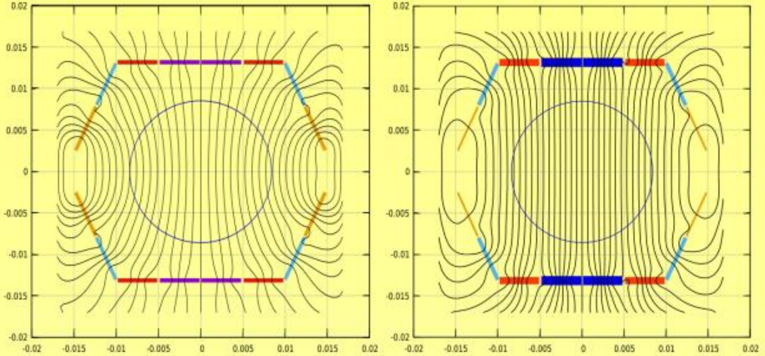


***Figure 2**: The induced B field in case of 1 μm tapes (left), and with a tailored thickness profile (right)*

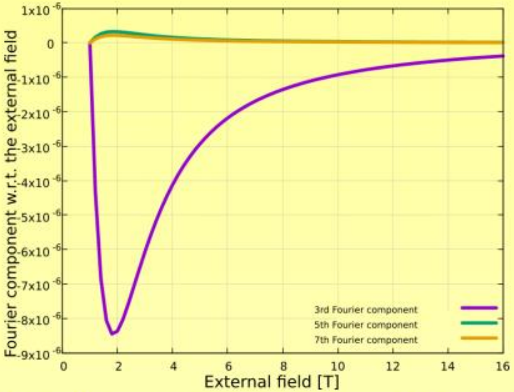
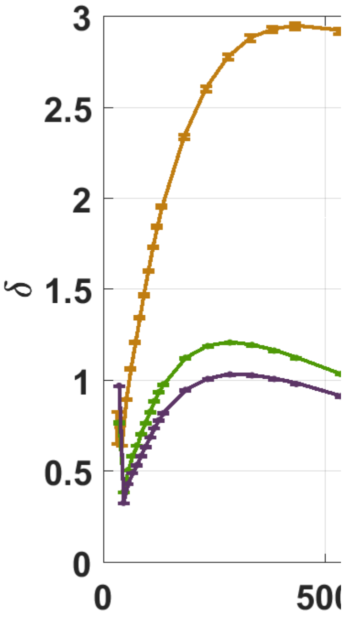
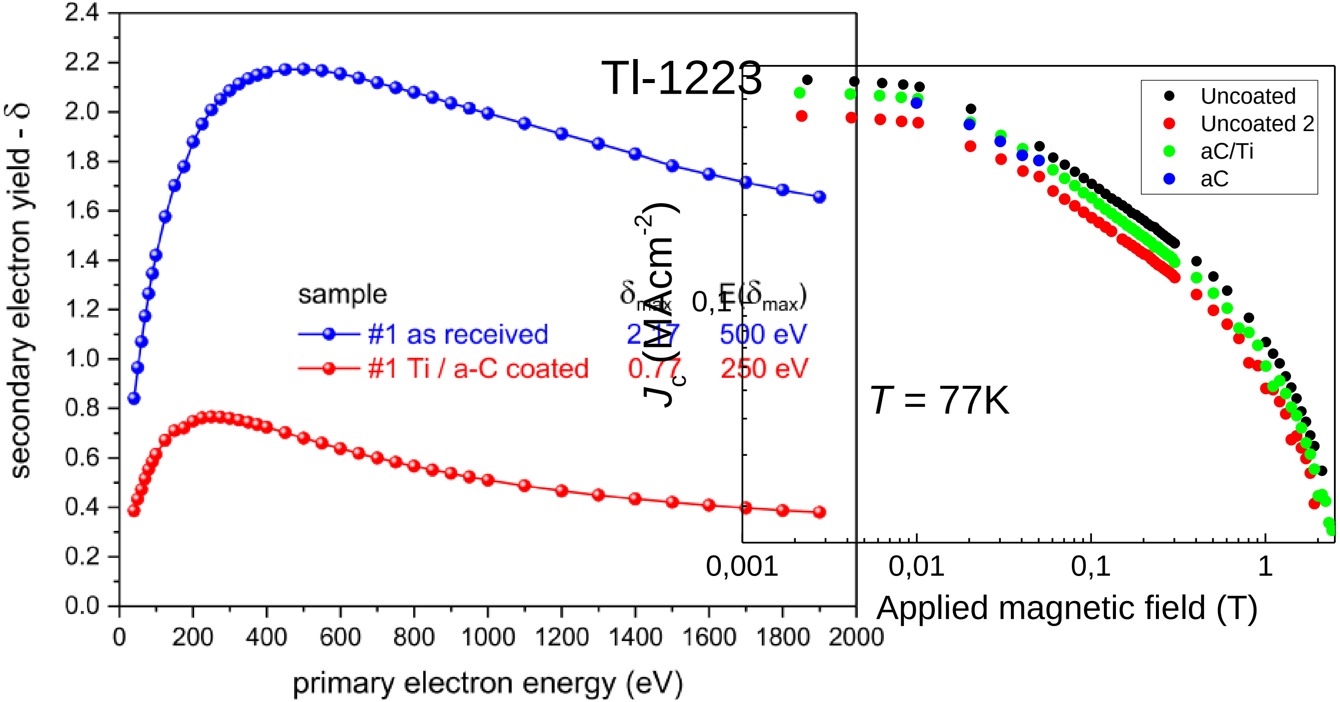


***Figure 3**: Multipole components as a function of B for configuration 3 (thickness profile optimized at B=1 T)*

Accelerator compatibility: SEY

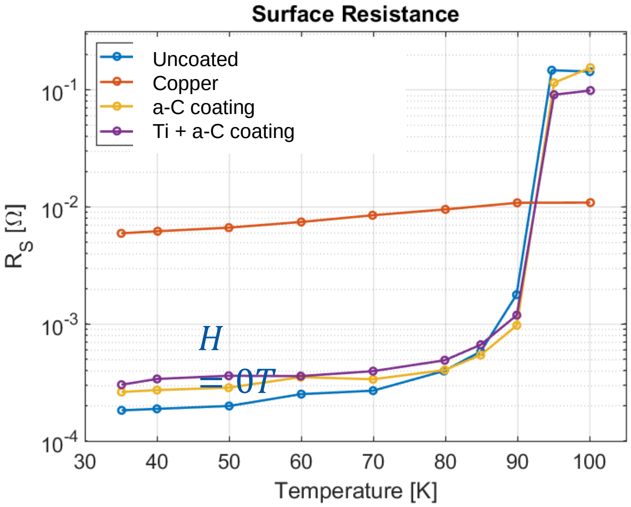


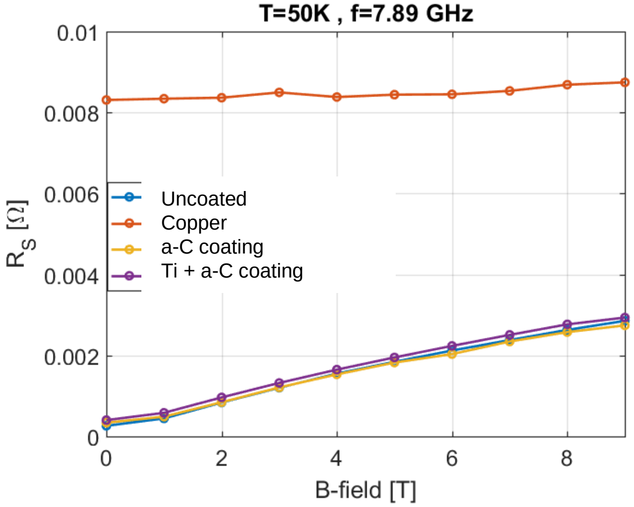


No degradation of superconducting properties
due to amorphous carbon sputter coating

a-C coating: RF compatibility

- In untreated form not suitable for use in the FCC-hh
- Coating of a-C decreases SEY under the desired limit
- Ti as adhesion and protection layer
- NO significant change in surface resistance





About 85 % of the sample is coated

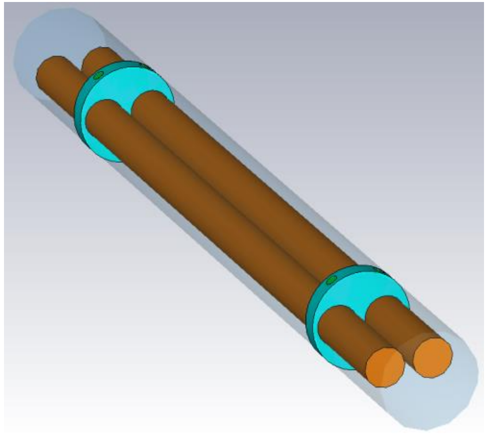
New Proposal for 2021-2023

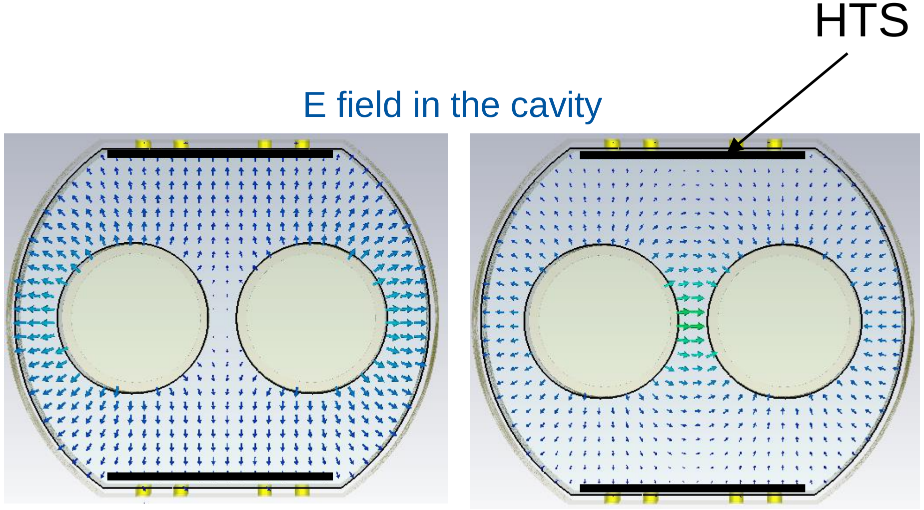
- New collaboration addenda are signed
- Coated Conductors (Barcelona)
  - Demonstrate proof-of-principle device, i.e. short segment of beam screen with coated conductors
  - Confirm mechanical properties in correlation with SC properties
  - Assess RF performance on samples up to 16 T and down to 1 GHz
  - Assess RF at 1 GHz in presence of SR irradiation
- Tl-based HTS
  - Scale-up the fabrication process to large sizes
  - Improve on quality (preferential growth of Tl-1223 phase) by high-pressure treatment and using large-size oriented Ag substrate
  - Improve RF characterization with study of non-linearities

- We will manufacture a short-sample demonstrator (50 cm length) once the technology is ready.
  - At CERN we are preparing a RF impedance test system dedicated to beam screens, at cryo-temperature and high magnetic field

How to measure impedance of a beam screen

- The beam screen will be coated with HTS
- All the rest will be normal conducting





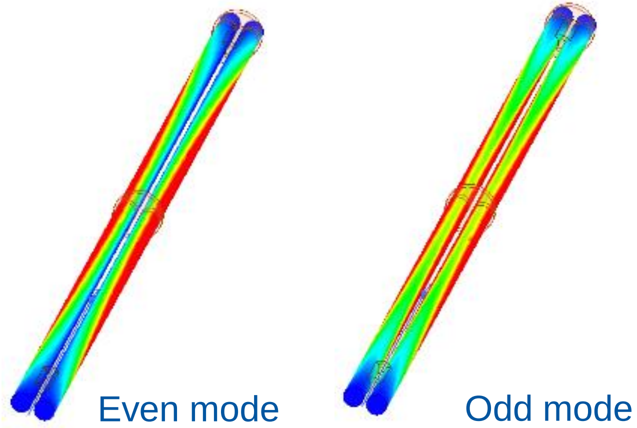
Even mode

Odd mode

Kristóf Brunner

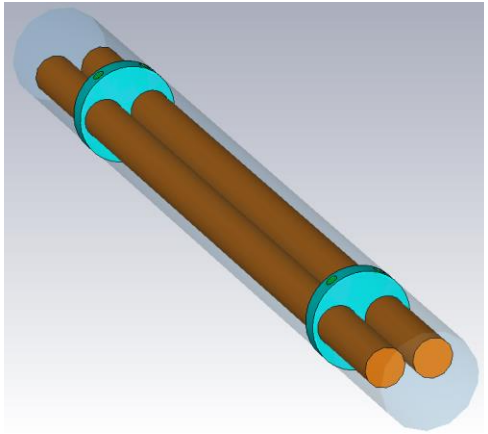
Method of the “two-rod” measurement

- Resonator with 2 fundamental modes (420 MHz and 425 MHz): material properties do not change
- Q-factor measurement of both modes makes it possible to “subtract the contribution” of the inner rods from the losses (two unknowns – two equations)
- Demonstrated on copper at cryogenic temperatures
- Novel idea to use this method to measure an HTS within a normal-conducting resonator: to be assessed



Even mode

Odd mode



Kristóf Brunner

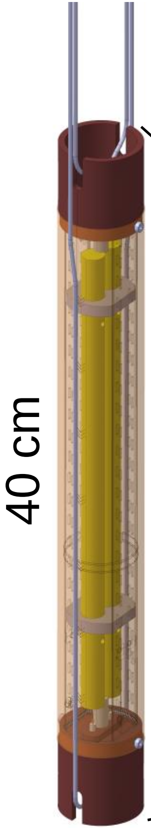
Test system for FRESCA: 4.2 to 300 K

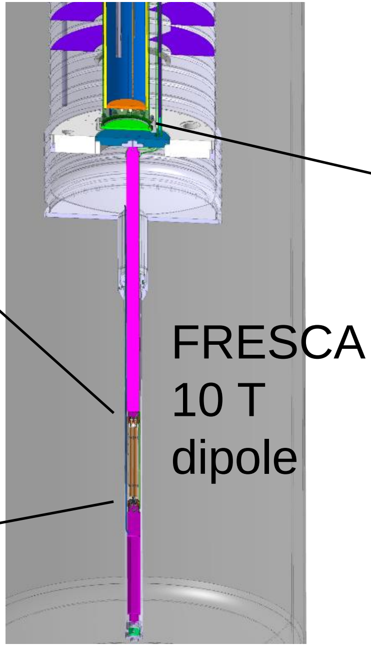
Design concluded, fabrication under way

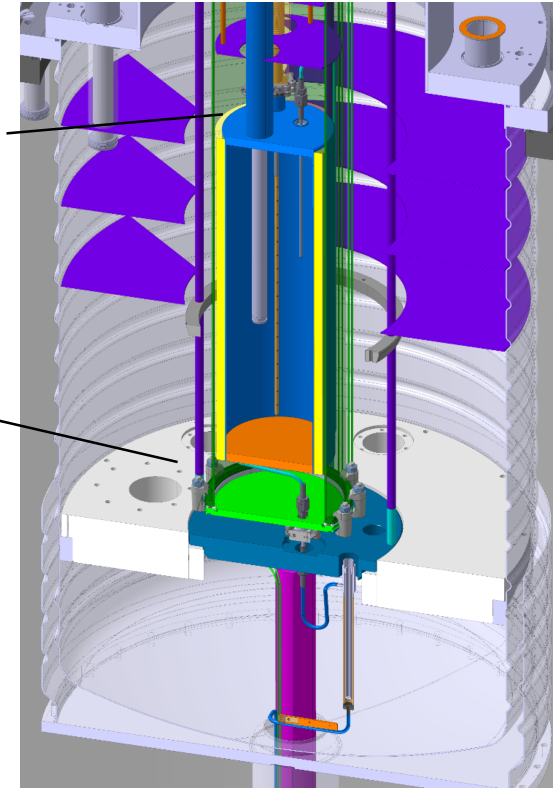
Construction due start in Summer 2021

Commissioning from Fall 2021

(PhD of Kristof Brunner)

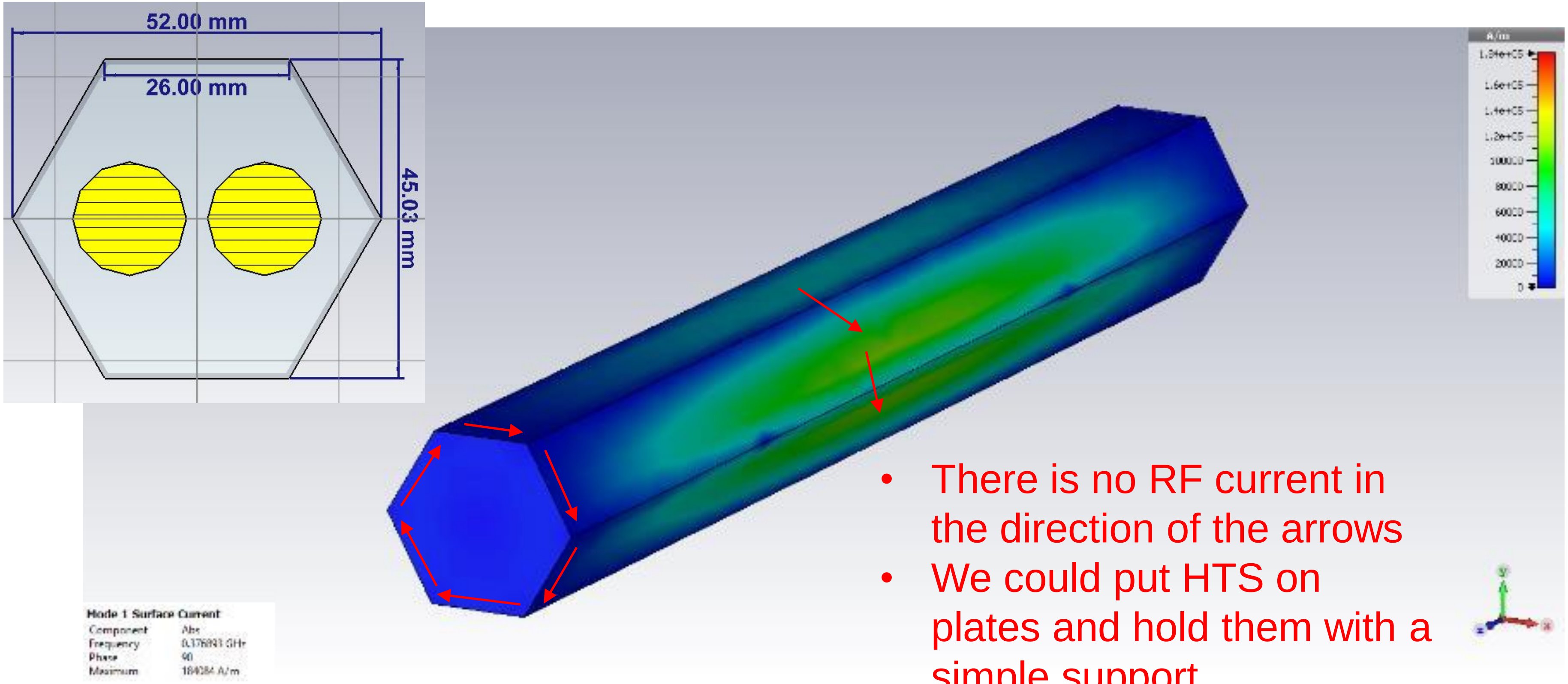






Emiliano Urrutia, Luca Dassa

How to test HTS?

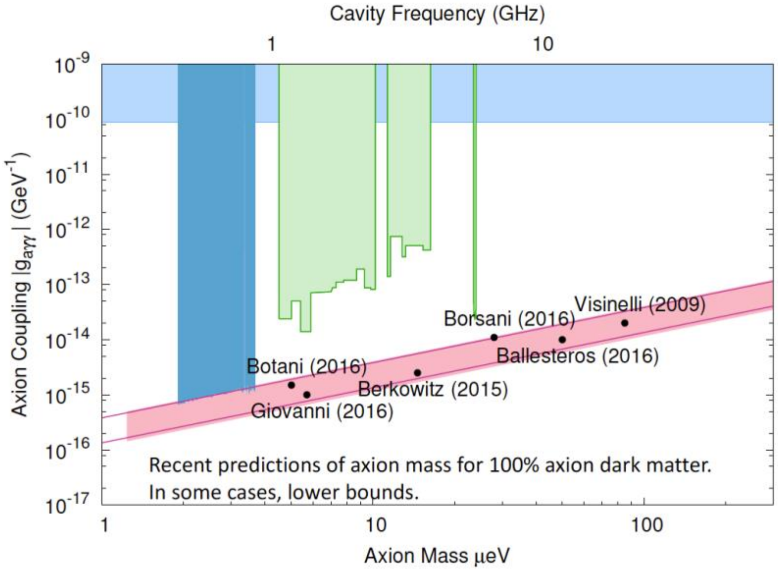


- There is no RF current in the direction of the arrows
- We could put HTS on plates and hold them with a simple support

Kristóf Brunner

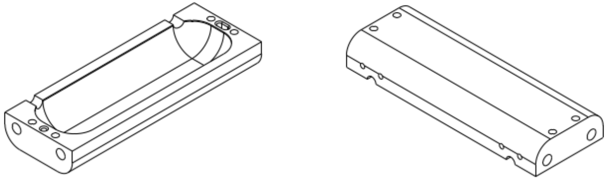
Spin-off: axion detection

- Axions as dark matter candidates:
-
  - Dark matter axions (low mass) converting to photons in B-Field
  - By means of microwave cavities in solenoid magnet
  - Sensitivity goes as $B^2\ V\ Q_{cav}$ where B is the applied field, V the total volume, Q is the quality factor of the cavity



RADES: Relic Axion Detector Exploratory Setup

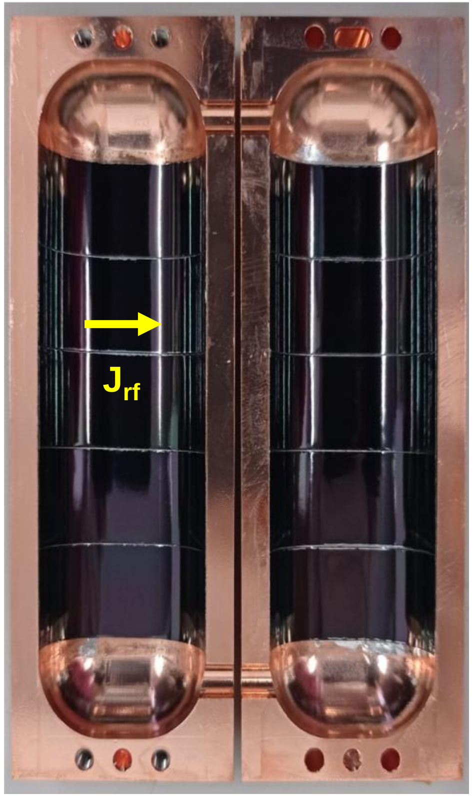
9 GHz cavity for Axion detection



Copper

Nb_3Sn by sputtering (CERN)

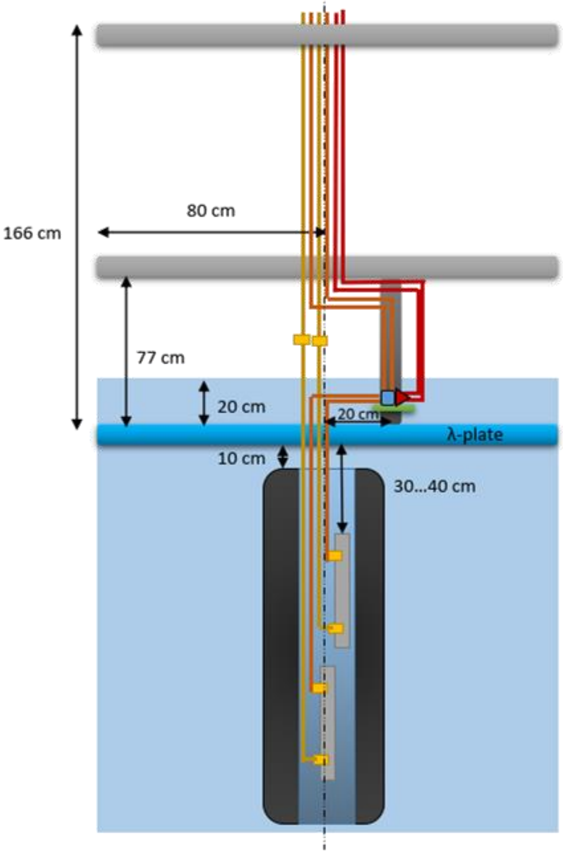
REBCO coated conductors (soldered)
Prepared by ICMAB

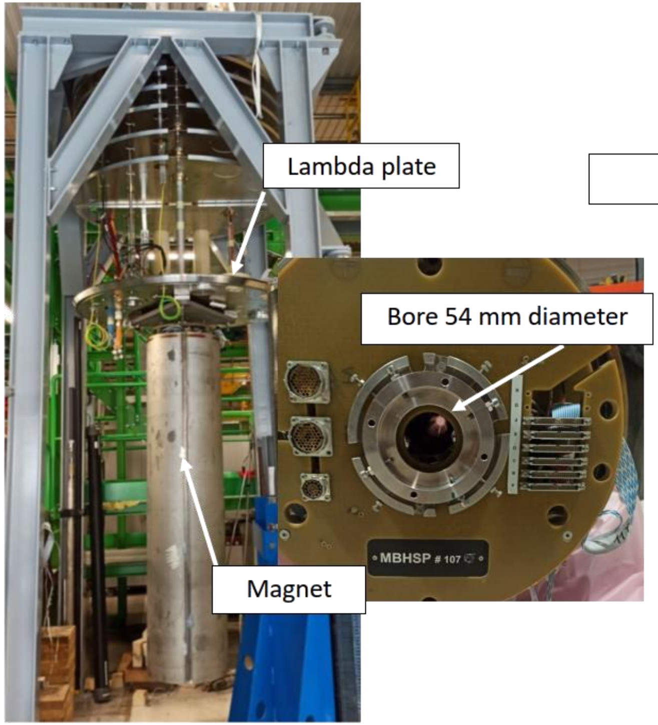


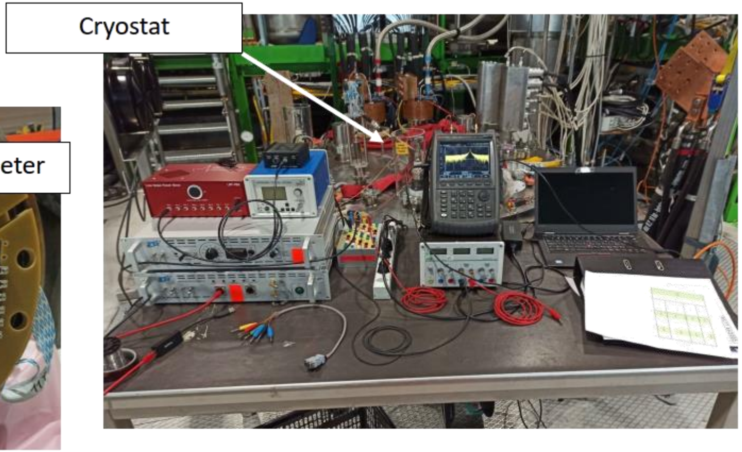
Preliminary tests performed @ Cryolab (4.2 K, zero B field)
First test in 11T magnet at SM 18 performed first week of June

From: Jessica Golm

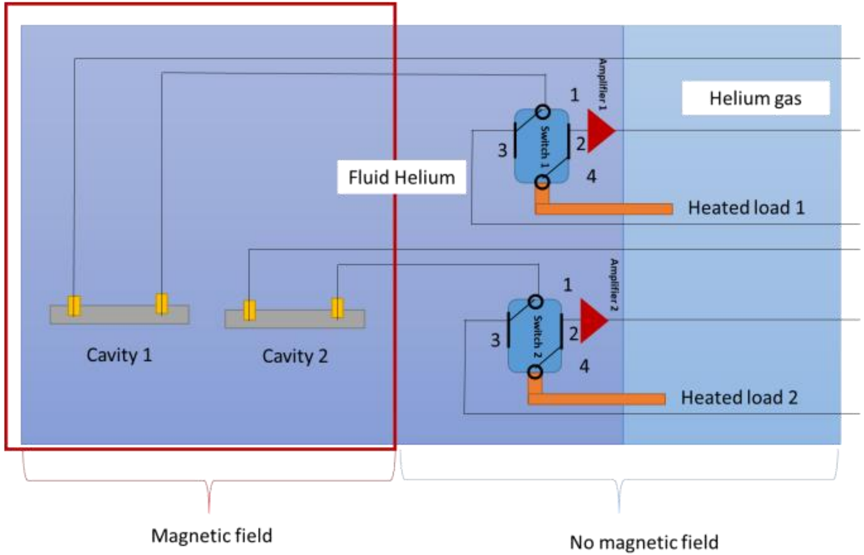
SM18 test setup

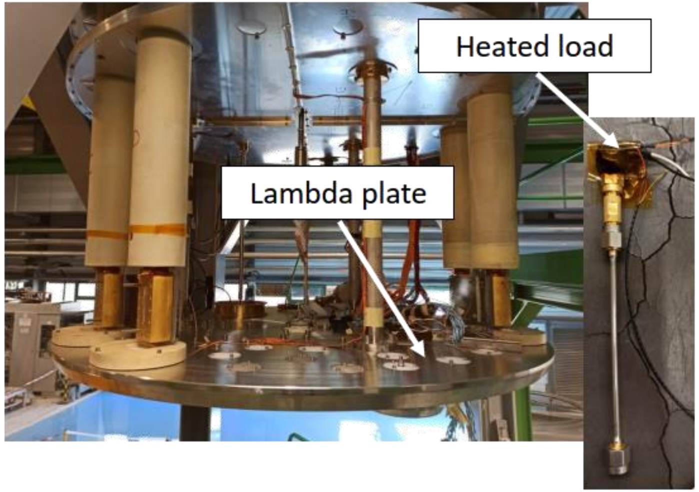


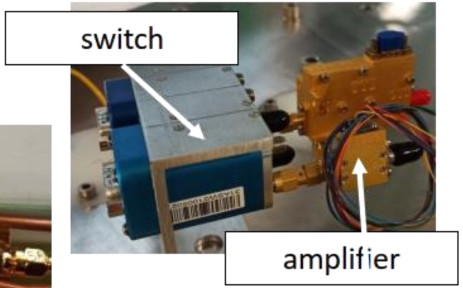


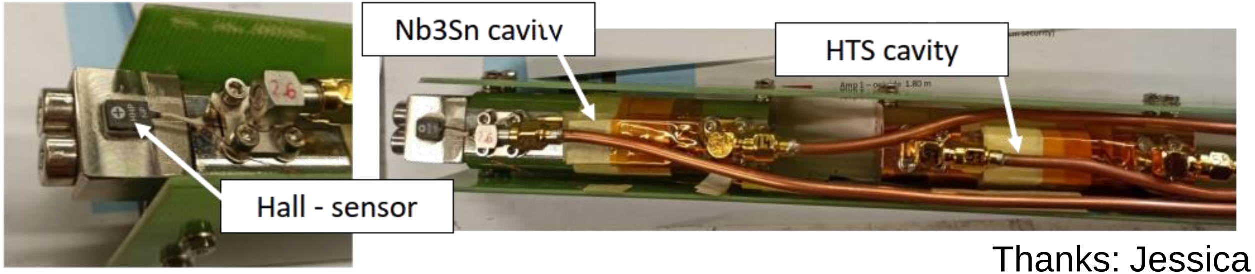


Thanks: Jessica Golm & SM18 team + ARIES





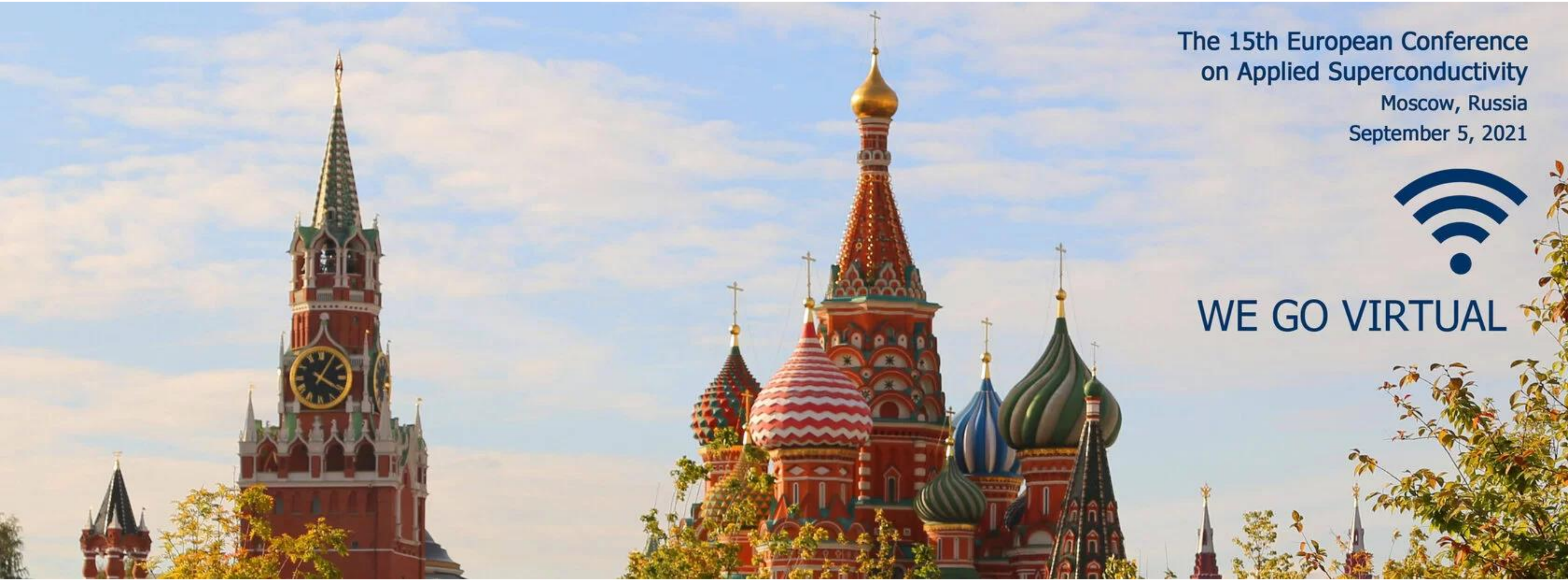




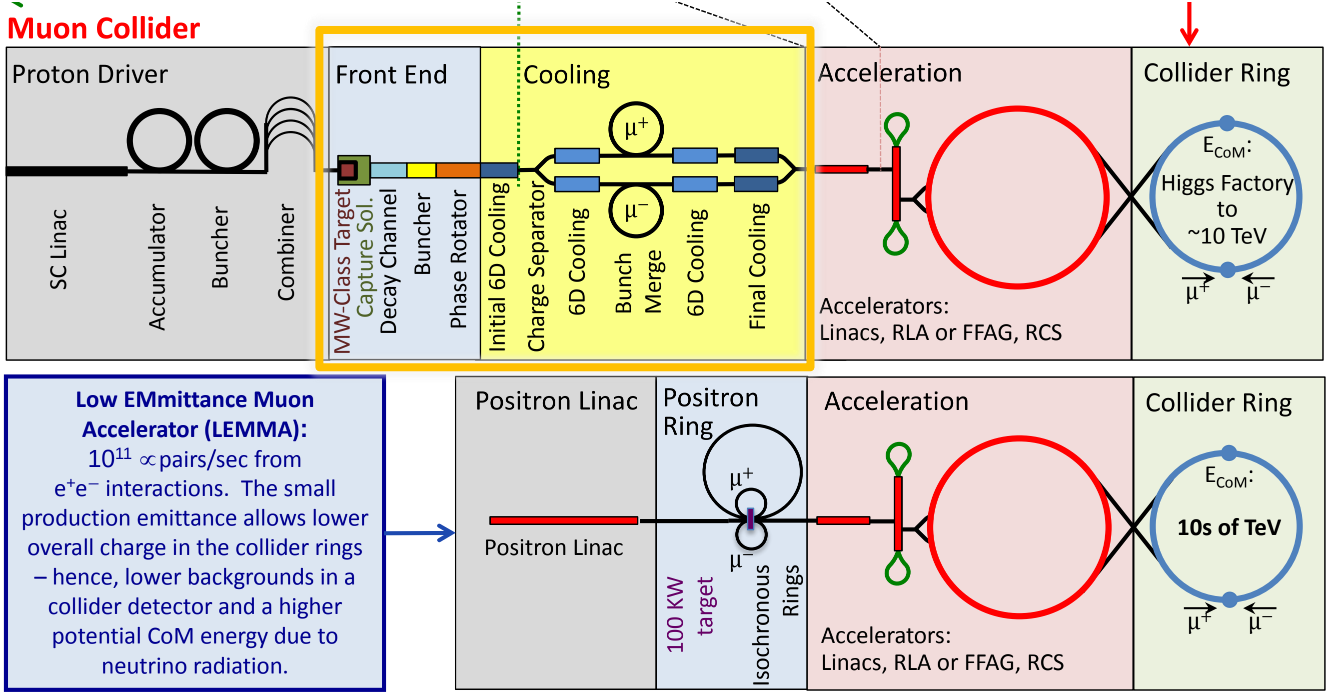
Thanks: Jessica Golm & SM18 team + ARIES

Results

SORRY! You will have to wait!



Spin off: capture cavities for muon colliders?

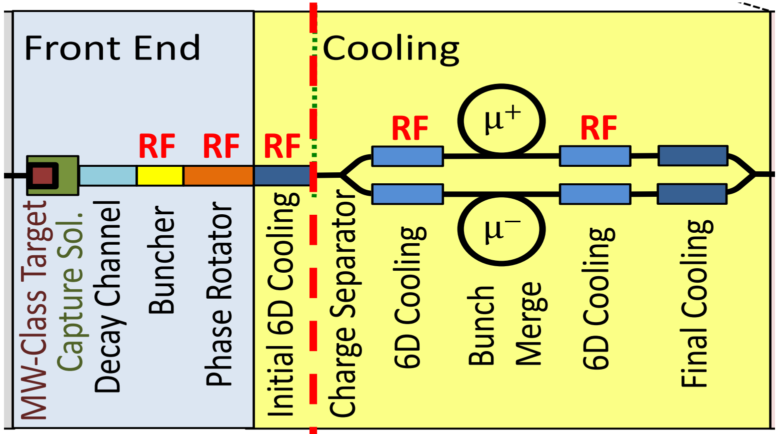


Low EMmittance Muon Accelerator (LEMMA):
10^{11} ∝pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

From Alexej Grudiev CERN

Muon collider (with muons from p^+ target): challenges

So far it was always assumed that due to very high levels of magnetic field only normal conducting RF can be used.
It is not true anymore for HTS superconductors.
Can we use them?
Should we use them?



Complex RF system:
- 318 cavities,
- 1700 MV,
- 1000 MW peak,
- 31 frequencies: 325-490 MHz
- Gradient: 0 – 25 MV/m

Parameters from : D. Neuffer et al, 2017, JINST 12

More cavities,
few GV,
few GW peak,

~10^{11} A/m^2 for 1 µm thickness
Further motivation for studying
HTS behavior at high H_{RF}

From Alexej Grudiev CERN

Final word

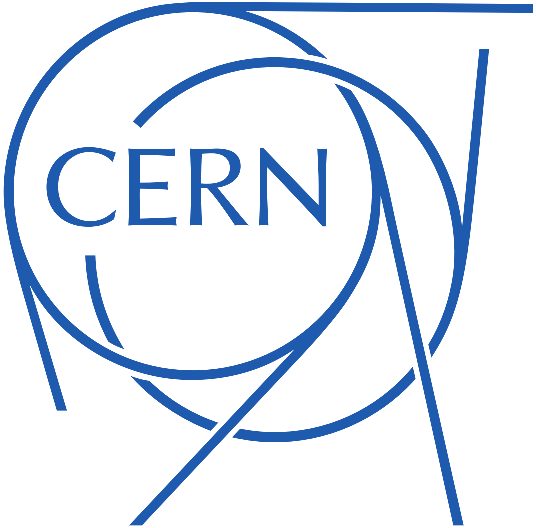
- Impedance reduction for the FCC-hh: an application which can be done only with HTS

- First approach: ReBCO Coated-Conductors
  - State-of-the-art tapes, ensure they guarantee the requested performance for FCC (and tailor them if needed), develop soldering technology for beam screen fabrication, maintaining the properties: extensive RF, DC testing

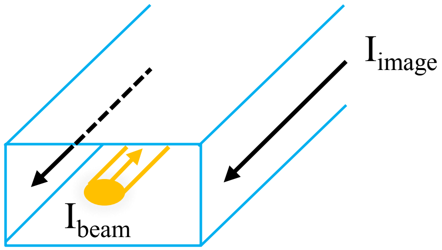
- Second approach: Tl-1223 thin films
  - Opens-up 100-120 K window, 100 MW ↓ 50 MW consumption ! Complex
    5-components electroplating and annealing. Once established, should be scalable to large dimensions

Acknowledgements

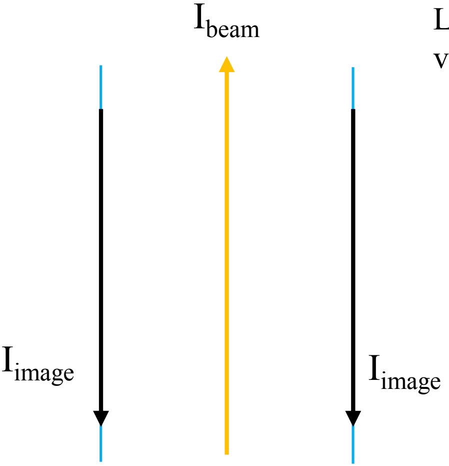
- CNR-SPIN: Carlo Ferdeghini, Emilio Bellingeri, Alessandro Leveratto, Marina Putti, Aisha Saba, Ruggero Vaglio
- TU-Wien: Michael Eisterer, Thomas Baumgartner, Sigrid Holleis, Johannes Bernardi, Michael Stoeger-Pollach, Alice Moros
- ALBA: Francis Peréz, Montse Pons, Patrick Krkotic
- ICMAB-CSIC: Teresa Puig, Artur Romanov, Joffre Gutierrez, Xavier Granados, Guilherme Telles, Xavier Obradors
- IFAE: Ilya Korolkov, Pedro Gonzalez Melis, Juli Mundet Caballero
- UPC: Joan O'Callaghan
- CERN: Mauro Taborelli, Pedro Costa Pinto, Pierre Demolon, Danilo Zanin, Elisa Garcia-Tabares Valdivieso, Jeroen van Nugteren, Susana Bermudez, Markus Widorski, Kristóf Brunner


CERN

Transverse impedance



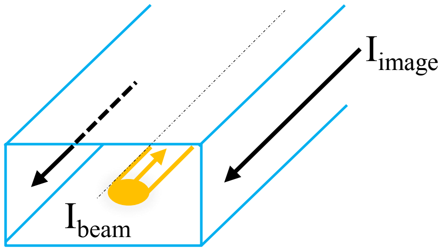
View from the front of the
vacuum chamber



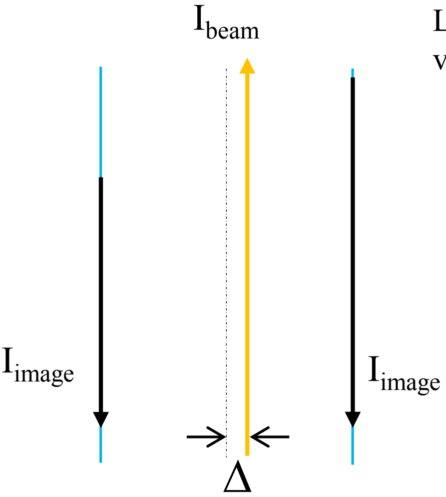
Looking down on the
vacuum chamber

Inspired by: F. Sacherer in *Proceedings of the First Course of the International School of Particle Accelerators*, CERN 77-13, p. 198

Transverse impedance



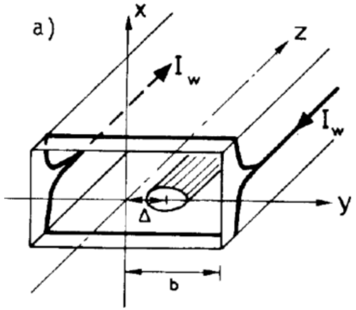
View from the front of the vacuum chamber

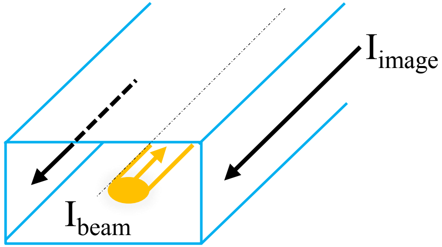


Looking down on the vacuum chamber

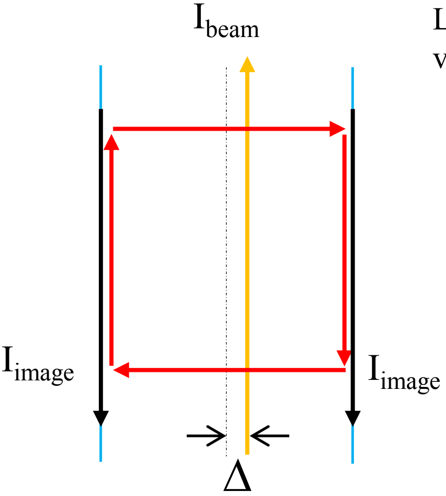
Inspired by: F. Sacherer in *Proceedings of the First Course of the International School of Particle Accelerators*, CERN 77-13, p. 198

Transverse impedance





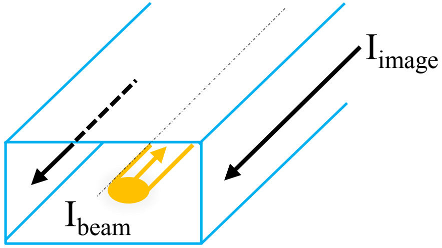
View from the front of the vacuum chamber



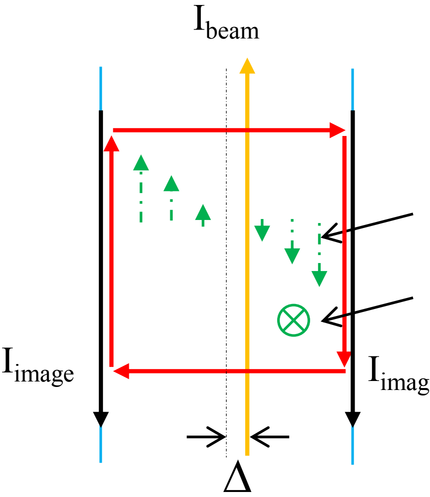
Looking down on the vacuum chamber

Inspired by: F. Sacherer in *Proceedings of the First Course of the International School of Particle Accelerators*, CERN 77-13, p. 198

Transverse impedance



View from the front of the vacuum chamber



Looking down on the vacuum chamber

Longitudinal electric field

Dipole magnetic field

$$Z_\perp = j \frac{\int_0^{2\pi R} \boxed{\left[E + c \times B\right]_\perp} ds}{I_{beam}\Delta} \quad [\Omega / m]$$

Lorentz force F that perturbates the beam

Definition of transverse impedance

Inspired by: F. Sacherer in *Proceedings of the First Course of the International School of Particle Accelerators*, CERN 77-13, p. 198

Beam instabilities in particle accelerators

Quadrupoles give the restoring (focussing) force -> harmonic oscillations

$\boxed{\ddot{x} + \omega_{\beta,0}^2 x = 0}$ Unperturbed motion of single particle with $\boxed{\omega_{\beta,0} = Q_x \omega_0}$ and $\boxed{\omega_0 = \frac{c}{R}}$ $Q_x = R/\beta_x$

$$\boxed{x(t) = x_0 e^{j(\omega_{\beta,0} t + \varphi)}}$$

The extra force we discussed adds a perturbation to the beam oscillations:

$\boxed{\ddot{x} + \omega_{\beta,0}^2 x = -Fx}$ Resulting in $\boxed{\Delta\omega \approx F / 2\omega_{\beta,0}}$ and $\Delta\omega$ is a complex number

$$\boxed{x(t) = x_0 e^{j(\omega_\beta + \mathrm{Re}|\Delta\omega| t + \varphi)} e^{-\mathrm{Im}|\Delta\omega| \tau}}$$

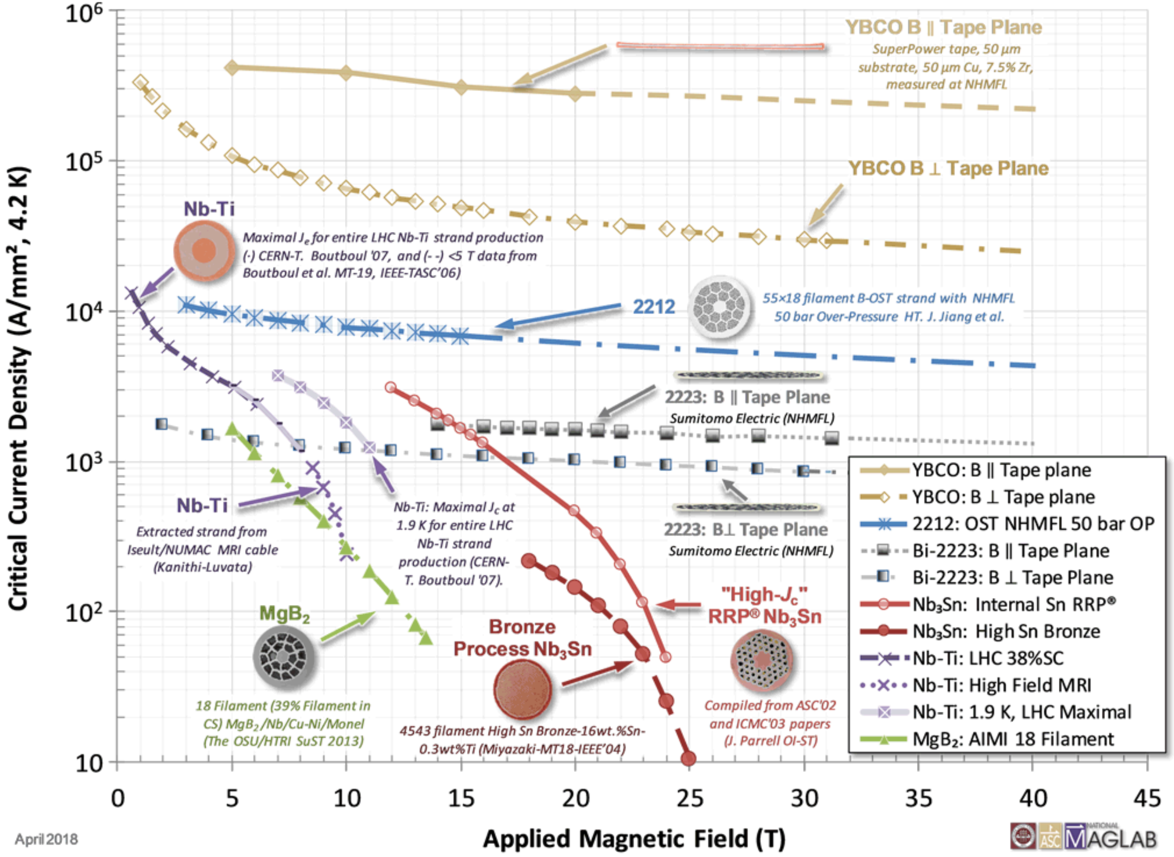
$\boxed{\frac{1}{\tau} = -\mathrm{Im}|\Delta\omega|}$ ← **Growth rate of instability**

Zoo of superconductors

J_c may vary of order of magnitudes.
H_{c2} has much smaller variation.

YBCO most promising candidate

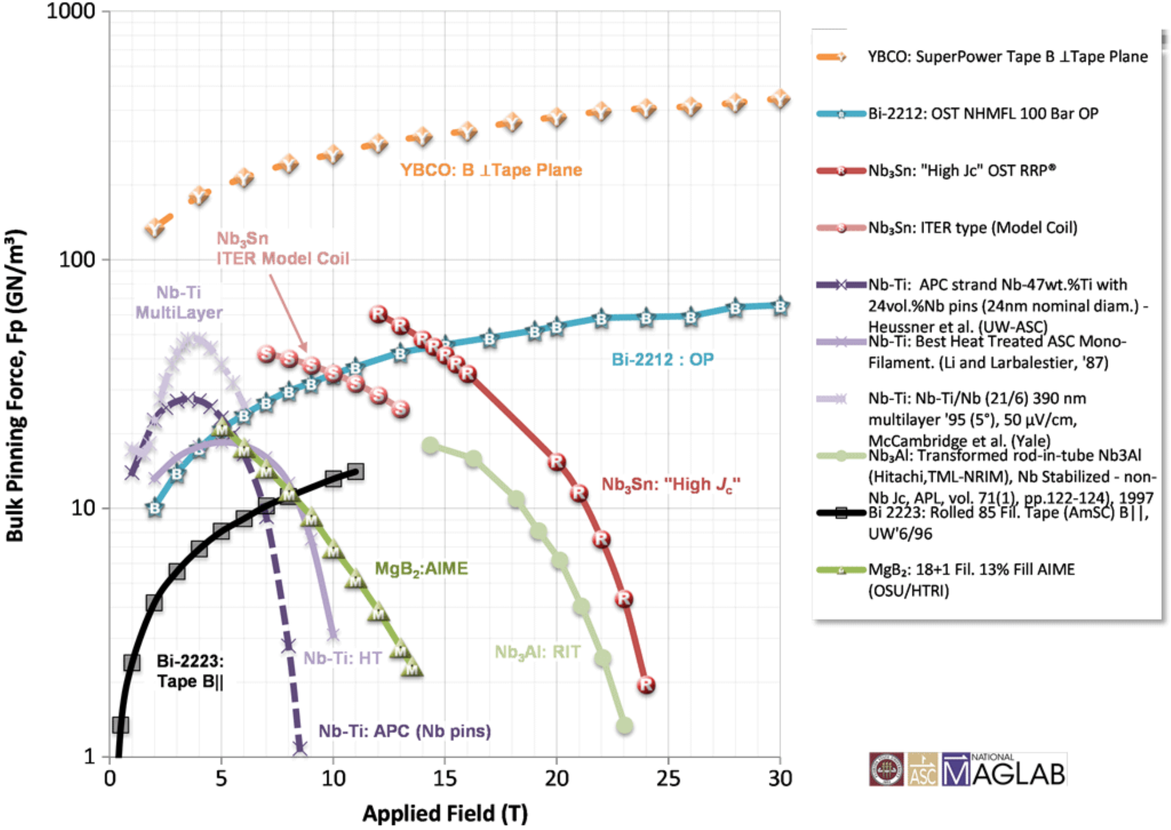
Remember: our benchmark is copper



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

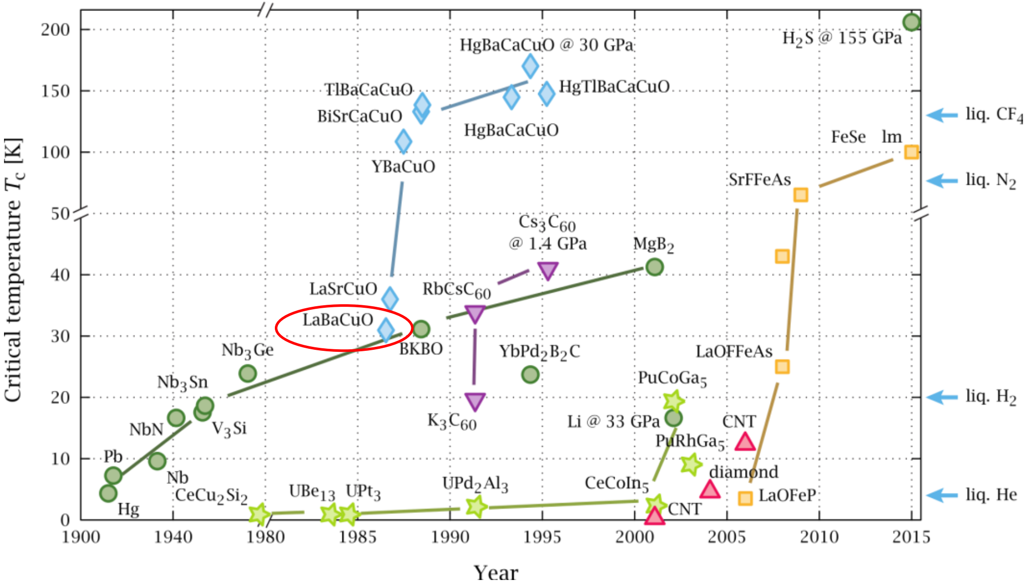
Zoo of superconductors

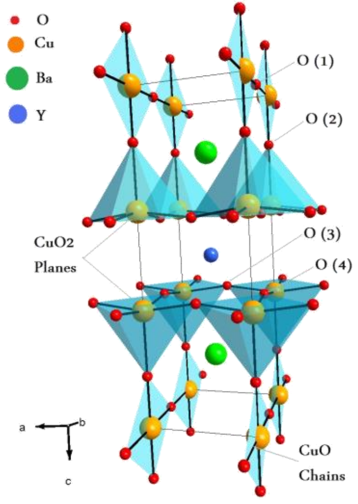
Pinning force

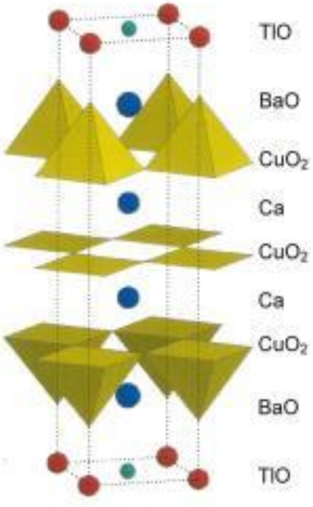


https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

High-Temperature Superconductors







Y-123
YBCO
REBCO

Tl-1223

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

Comparison: Y-123, Bi-2223, Tl-1223

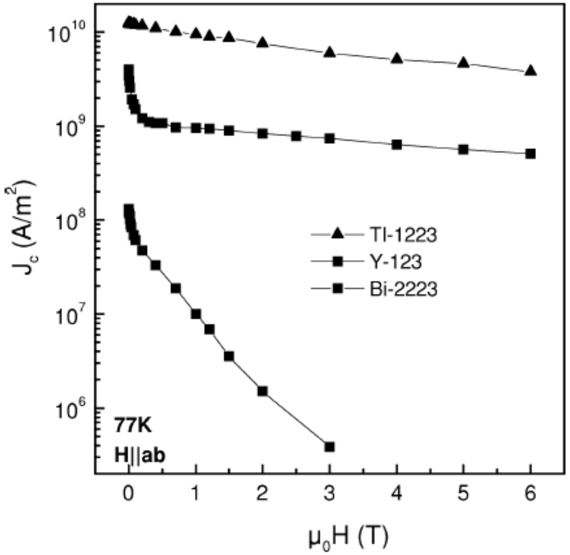


Fig. 1. J_c versus field at 77 K and $H\|ab$ for an Y-123 coated conductor, a Bi-2223 tape and a Tl-1223 thick film.

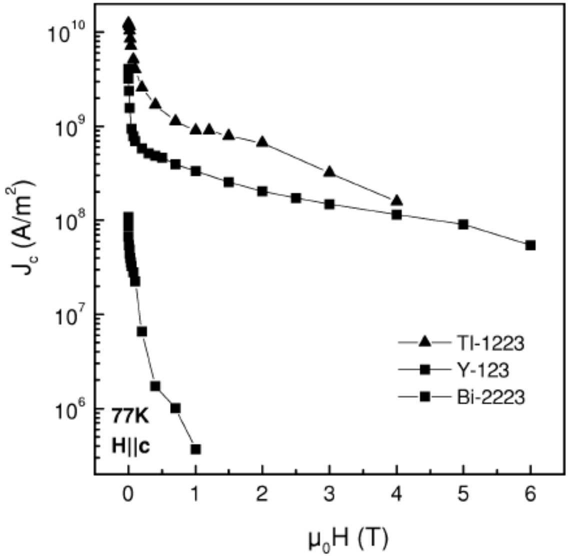
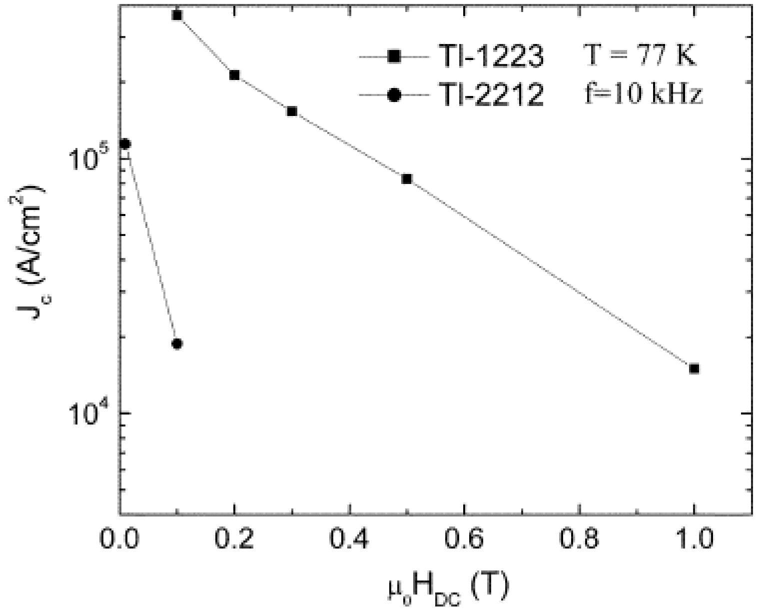


Fig. 2. J_c versus field at 77 K and $H\|c$ for an Y-123 coated conductor, a Bi-2223 tape and a Tl-1223 thick film.

Susanne Tönies, Harald W. Weber, Gerhard Gritzner, Oliver Heiml, and Mario H. Eder,
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 13, NO. 2, JUNE 2003

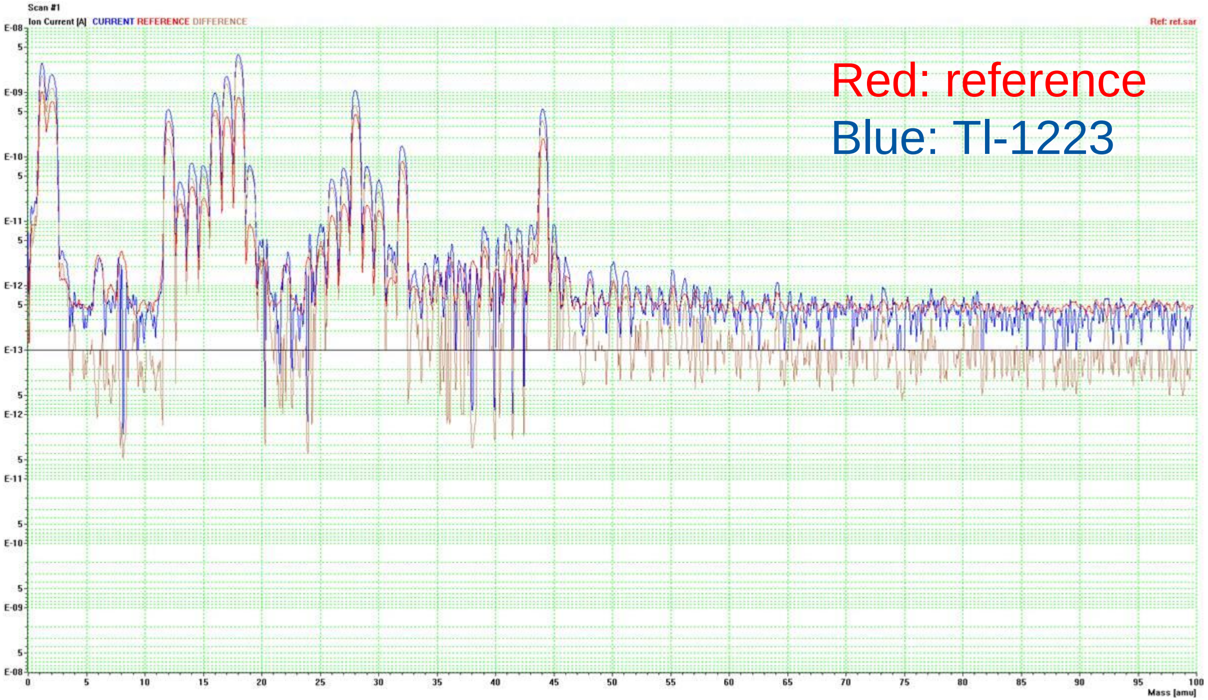
Comparison: Tl-1223 and Tl-2212



Sundaresan et al. , IEEE TRANS. APPL. SUPERCOND. 13 (2003) 2913

Vacum compatibility (Tl-1223)

RGA spectrum



Red: reference

Blue: Tl-1223

Pumpdown:

“The specific H_2O outgassing rate after 10 h of pumping was 2×10^{-7} mbar l^{-1} s^{-1} cm^{-2}, ~500 times the reference for unbaked, clean copper surfaces.

The vacuum pump-down exhibited a linear behaviour in logarithmic time/total pressure scale, with a slope very close to −1, indicating open porosities responsible for the large outgassing rate”

$Tl_xBa_2Ca_yCu_{y+1}O_z$

Site	Tl_x	Ba_2	Ca_y	Cu_{y+1}	O_z
Stoichiometry	X=1 o 2	2	Y=0,1,2	Y+1=1,2,3	Z=5…10
Substitution	Pb,Bi,Cu,Hg	Sr	Tl	NONE	F

Radiation hardness (CERN – Atominstitut)

Expected fluence

~ 25 years of FCChh operation

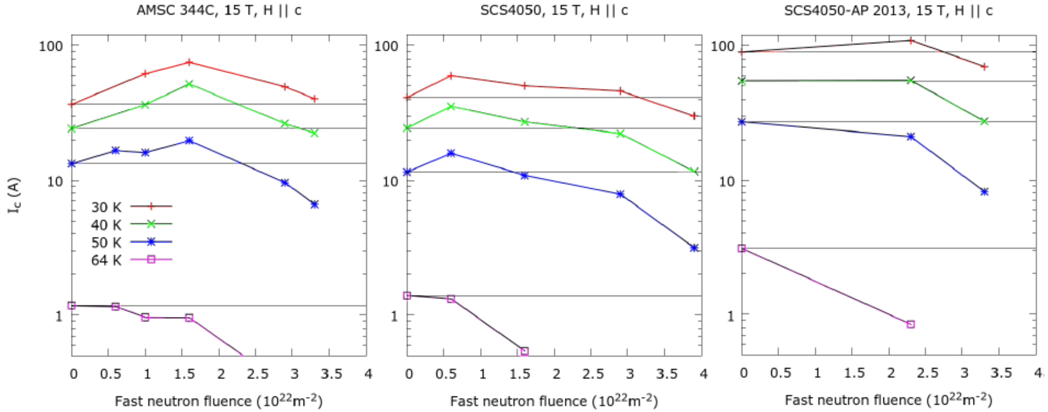
neutrons	**$5.31 \cdot 10^{20}$ m^{-2}**
neutrons > 0.1 MeV	**$3.69 \cdot 10^{20}$ m^{-2}**
neutrons > 1 MeV	$1.27 \cdot 10^{20}$ m^{-2}
Protons	**$1.13 \cdot 10^{19}$ m^{-2}**
pions+	$1.47 \cdot 10^{19}$ m^{-2}
pions-	$1.61 \cdot 10^{19}$ m^{-2}

Data provided by Markus Widorski

I cannot comment on the influence of pions!

Neutrons

Various commercial RE123 coated conductors



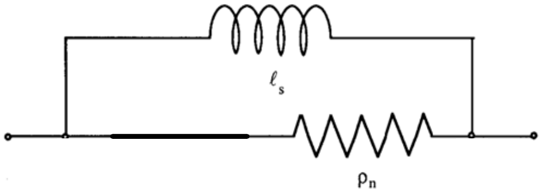
Degradation at 50 K starts at around 1-2·10^{22} m^{-2}
Expected fluence: ~4·10^{20} m^{-2}
An insignificant increase in J_c can be expected.
Avoid Gd-123?

neutrons	5.31·10^{20} m^{-2}
neutrons > 0.1 MeV	**3.69·10^{20} m^{-2}**
neutrons > 1 MeV	1.27·10^{20} m^{-2}
Protons	**1.13·10^{19} m^{-2}**
pions+	1.47·10^{19} m^{-2}
pions-	1.61·10^{19} m^{-2}

Conductivity: two-fluids

For perfect metals: $\sigma_n = \frac{ne^2\tau}{m} = \frac{ne^2\ell}{mv_F}$ $\sigma(\omega) = \frac{\sigma_n}{(1+i\omega\tau)}$ $\Rightarrow \lim_{\tau\to\infty} \sigma(\omega) = -i\frac{ne^2}{m_e\omega}$

For superconductors: $\boxed{\vec{J} = \vec{J}_n + \vec{J}_s = (\sigma_1 - i\sigma_2)\vec{E}}$



$$\sigma_2(t) = -i\frac{n_0e^2}{m\omega}(1-t^4)$$
$$\sigma_1(t) = \frac{n_0e^2\tau}{m}(t^4)$$

$$\sigma_2(0) = \frac{\sigma_n}{\omega\tau} = \frac{1}{\mu_0\omega\lambda_L^2}$$

Frequency independent

$1-t^4 = 1-\left(T/T_c\right)^4 \approx$ Density of “super-electrons”

Surface impedance: effect of magnetic flux

$$\sigma_1 << \sigma_2 \Rightarrow \qquad \vec{J} = (\sigma_1 - i\sigma_2)\vec{E} \cong -i\sigma_2\vec{E}$$

considering the additional electric field related to the fluxons motion :

$$\vec{J} = -i\sigma_2\vec{E} = -i\frac{1}{\mu_o\omega\lambda_L^2}\left(\vec{E} - \vec{v}\times\vec{B}_o\right)$$

$$\rho_f = \frac{\vec{E}}{\vec{J}} = \frac{\vec{v}\times\vec{B}_o}{\vec{J}} + i\mu_o\omega\lambda_L^2 = \frac{v_o B_0}{J_{rfo}} + i\mu_o\omega\lambda_L^2 = \rho_n\frac{B_o}{B_{c2}}\left(\frac{\omega^2}{\omega^2+\omega_o^2} + i\frac{\omega\omega_o}{\omega^2+\omega_o^2}\right) + i\rho_n(\omega\tau)$$

$$\boxed{\rho_f \approx \rho_n\frac{B_o}{B_{c2}}\left(\frac{\omega^2}{\omega^2+\omega_o^2} + i\frac{\omega\omega_o}{\omega^2+\omega_o^2}\right)}$$

$$\boxed{Z_f = \sqrt{\frac{\mu_o\omega}{2}\rho_f}\,(1+i);\;\; R_f = \sqrt{\frac{\mu_o\omega}{2}\rho_f}}$$