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SPIN

INFN Istituto Nazionale di Fisica Nucleare

HTS Superconductor beam screen for the future collider FCC at CERN

CERN

Sergio Calatroni, CERN TE-VSC Division (project leader)

Istituto SPIN-CNR

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E.Bellingeri et al.

ICMAB
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T. Puig et al.

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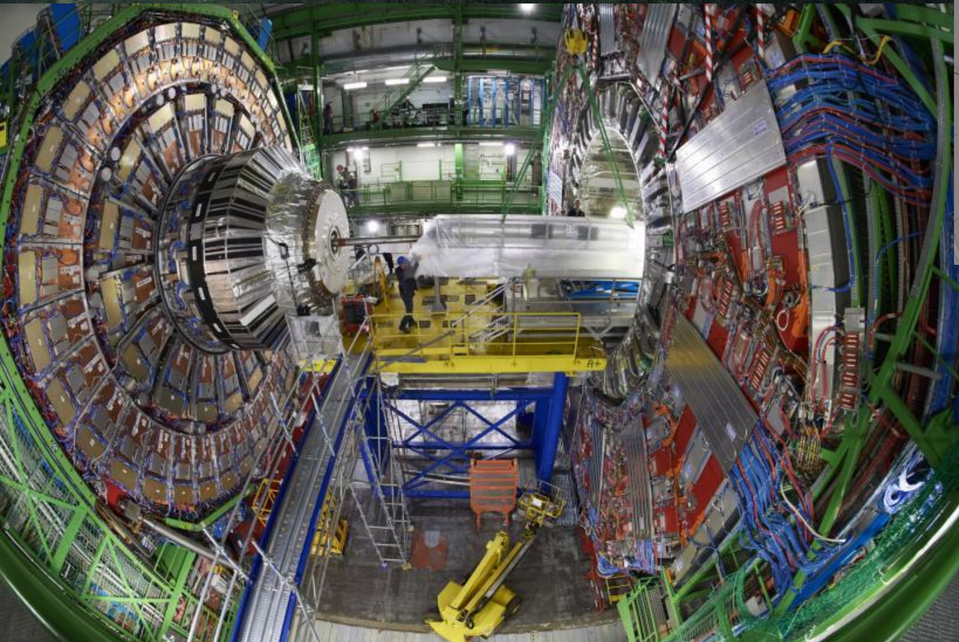
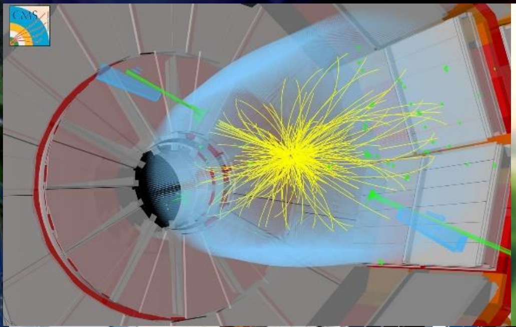
M. Eisterer et al.

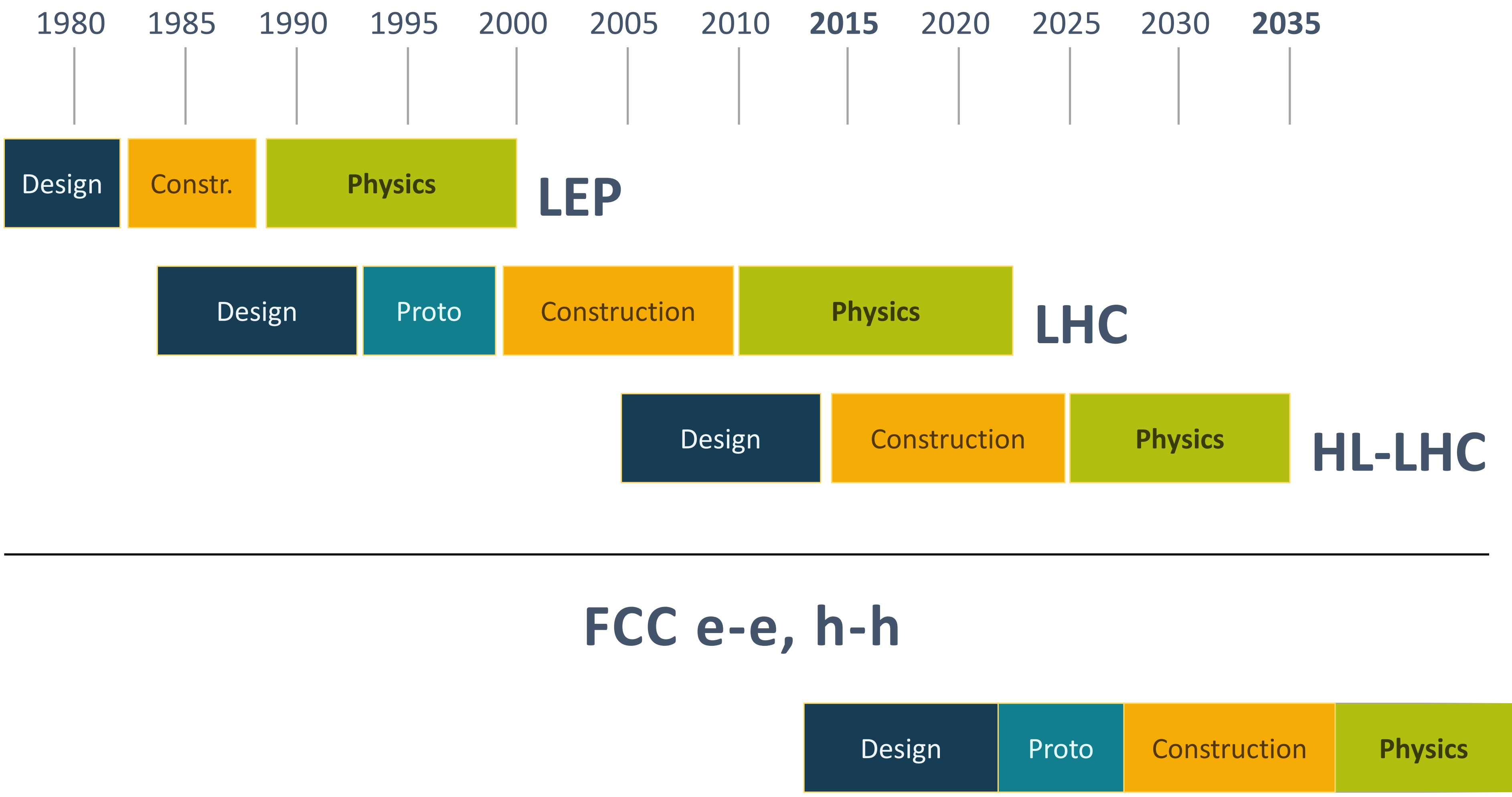
CERN (LHC)


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km





It is time to plan for a Future Circular Collider at CERN!
Drive: pushing the energy frontier of a factor 10



1980 1985 1990 1995 2000 2005 2010 **2015** 2020 2025 2030 **2035**

Design | Constr. | **Physics** — **LEP**

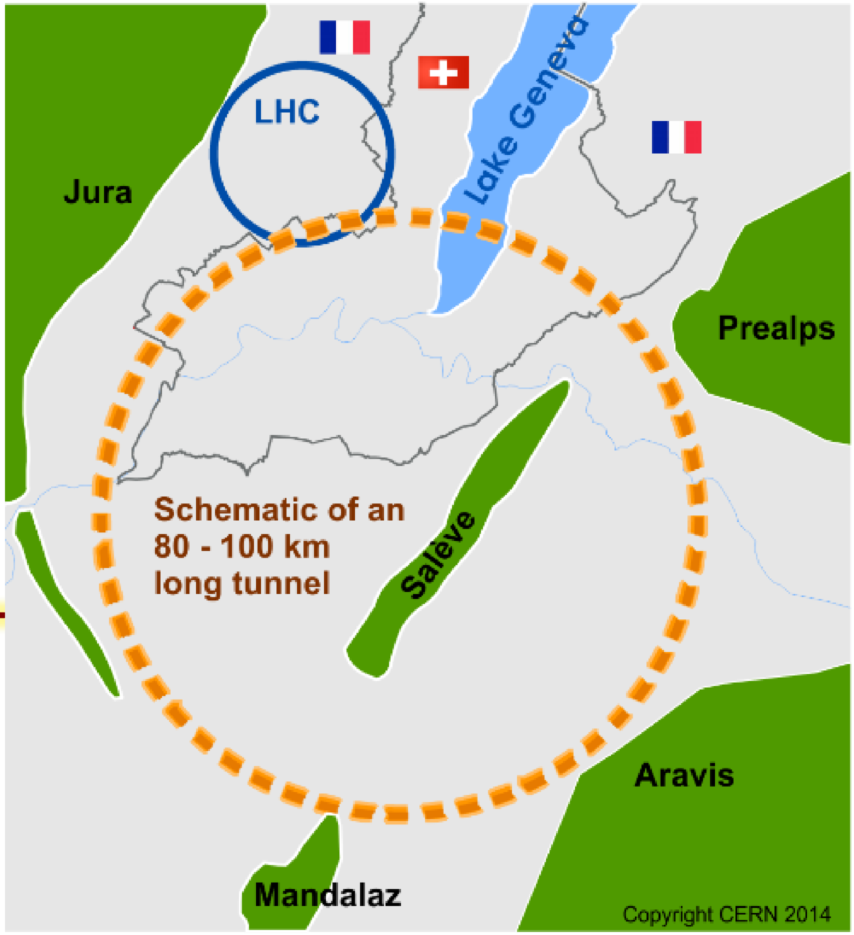
Design | Proto | Construction | **Physics** — **LHC**

Design | Construction | **Physics** — **HL-LHC**

FCC e-e, h-h

Design | Proto | Construction | **Physics**

Future Circular Collider at CERN



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Future h-h Circular Collider at CERN

- FCC h-h will reach 100 TeV c.m. collision energy (50TeV+50TeV)
- Energy depends on both collider radius and curving magnetic field :

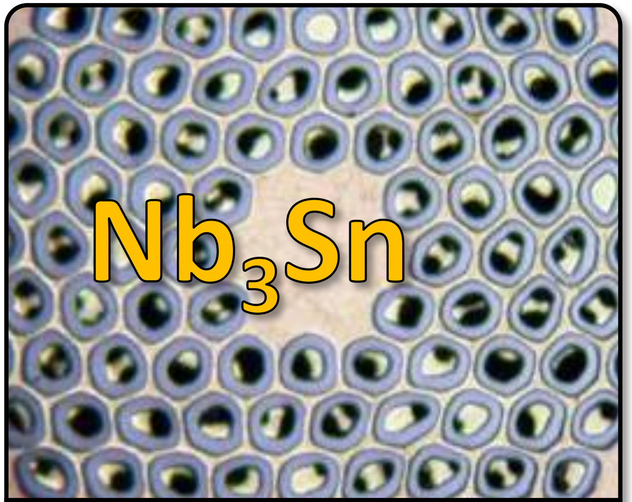
$\mathrm{E} \propto \boldsymbol{r}\mathrm{x}\boldsymbol{B}\ \ (\mathbf{100TeV}: \ \mathbf{r} = \mathbf{16Km}, \mathbf{B} = \mathbf{16T})$

- Goal: Access to new particles (direct production) far beyond LHC reach and much-increased rates for phenomena at lower energies

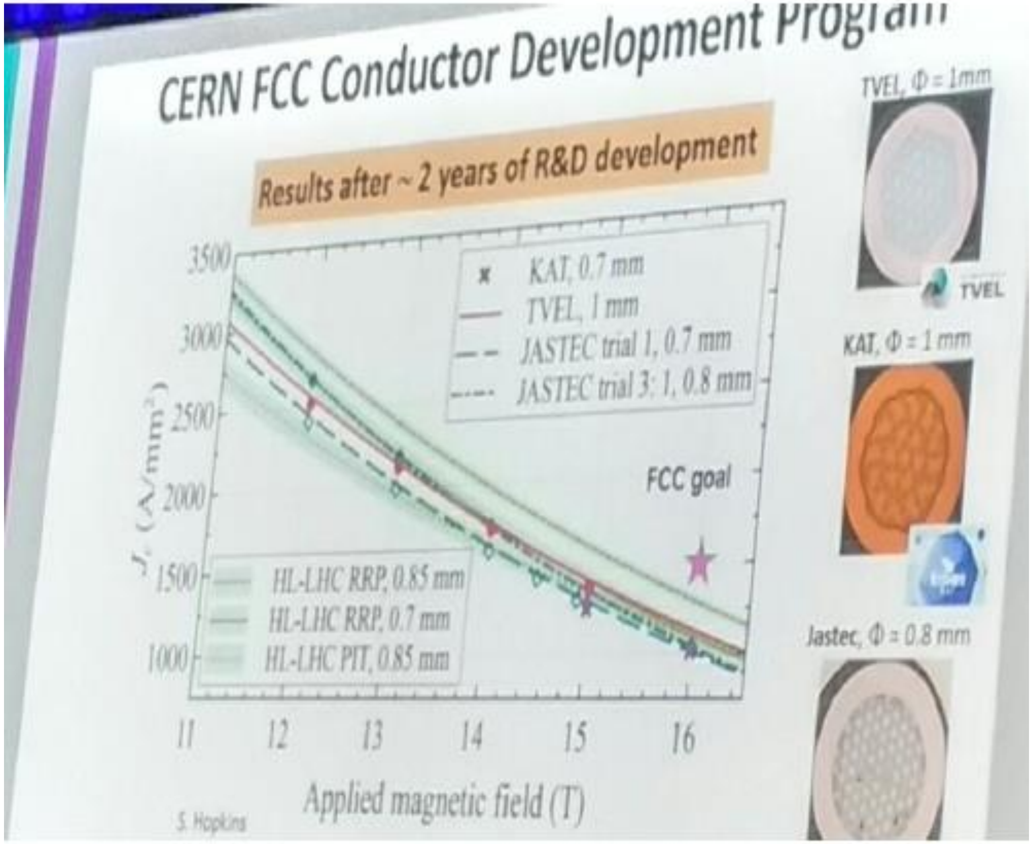
The beam will be made of 12500 bunches of 10^{11} protons,
8 cm long, traveling at a distance of about 8 m each other
Overall energy : 10^{10} J !

Freccia Rossa: m=500T, v =300km/h
$E_k = (½)mv^2 = 2 \cdot 10^9$ J

Examples of Key Technology R&D for FCC : 16T Magnets



Conductor R&D

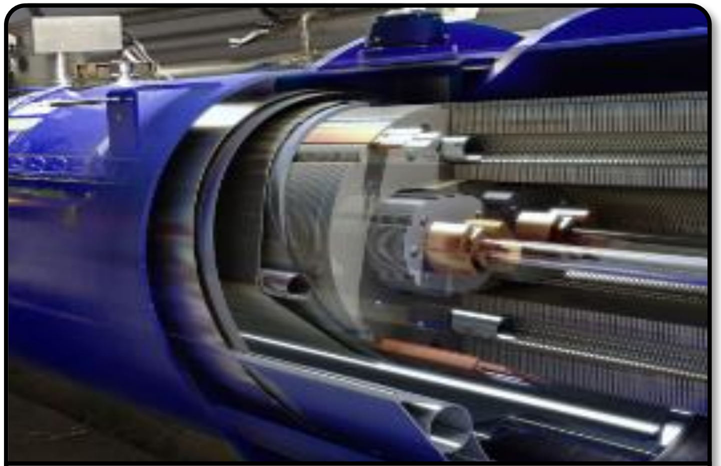


CERN FCC Conductor Development Program

Results after ~ 2 years of R&D development

- Increase critical current density
- Obtain high quantities at required quality

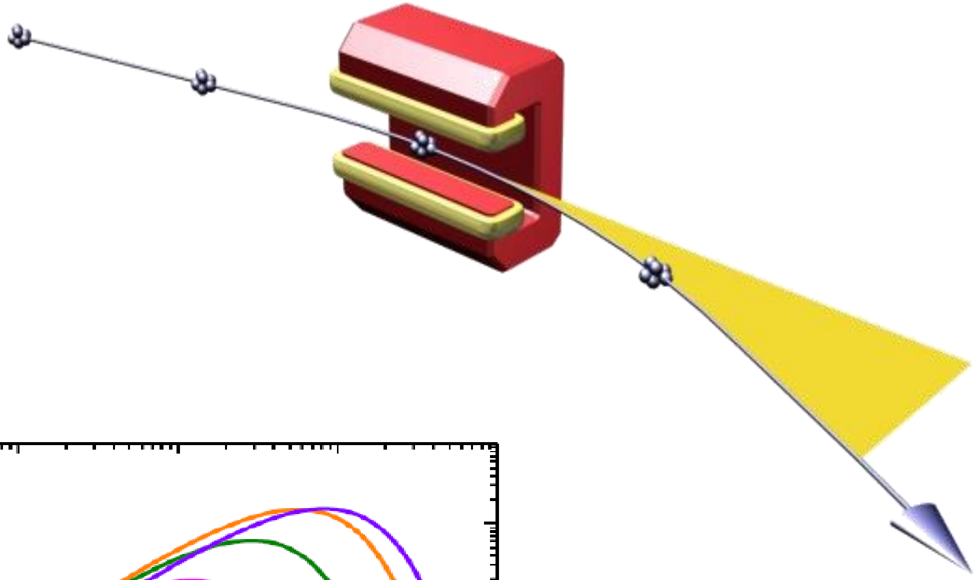
Examples of Key Technology R&D for FCC : 16T Magnets



Magnet Design

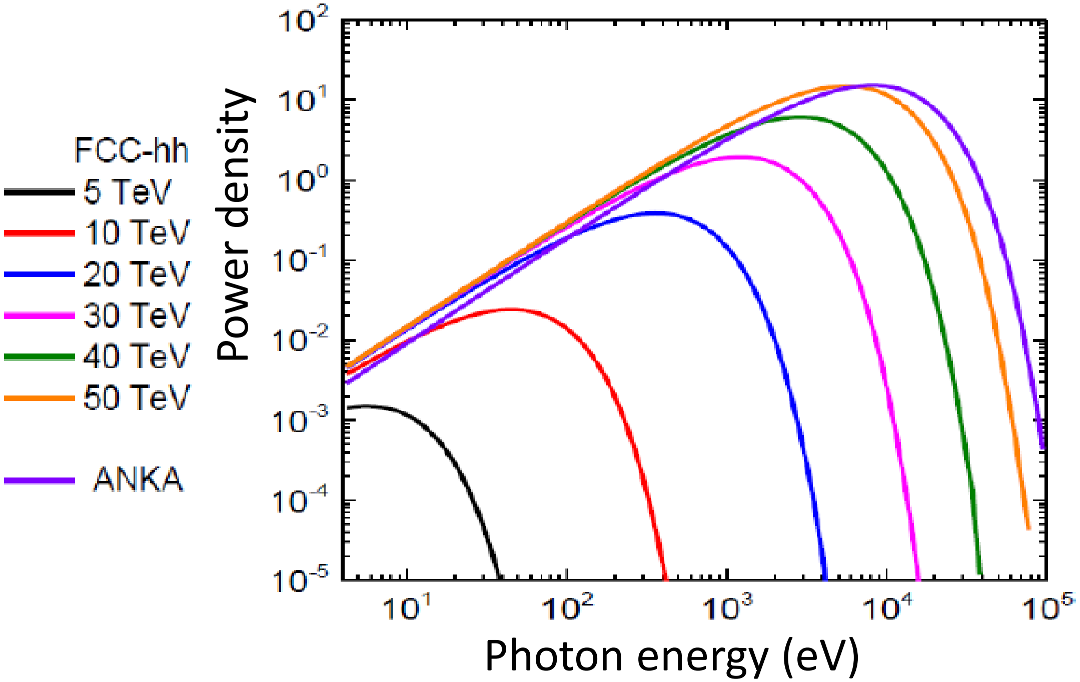
- 4700 dipole magnets, 14m long : 10.000 tons Nb
- Design optimum coil geometry to achieve the required field quality
- Mechanical design (foreseen peak stress 200MPa)
- Thermal management and quench protection
- Manufacturing and cost optimisation

The synchrotron radiation problem



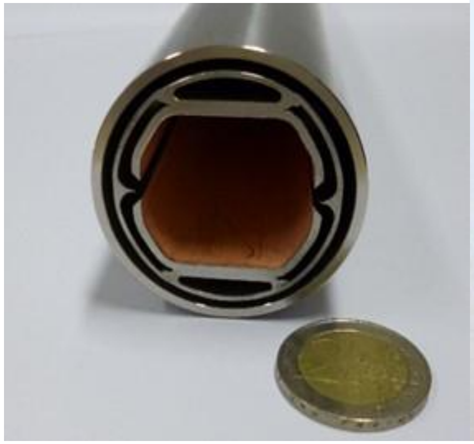
Synchrotron radiation load for protons @50 TeV:

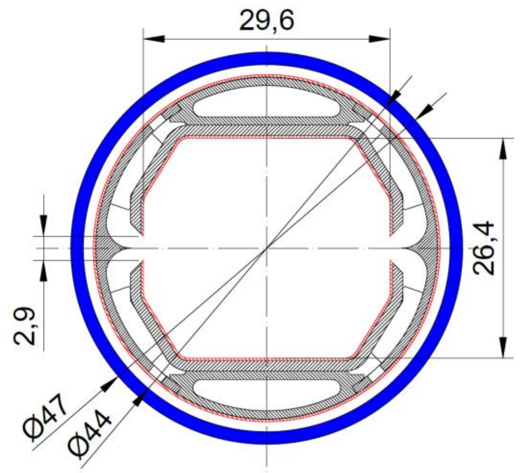
~ 25-45 W/m (@16 T)
(LHC <0.2W/m !!)

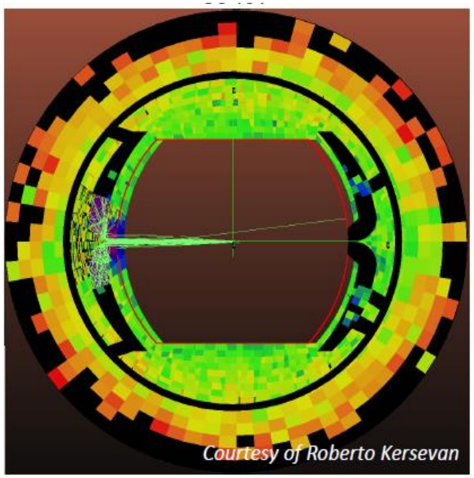


Beam screen design (tentative)

Taking into account overall cryogenic efficiency and power consumption of the accelerator, the synchrotron radiation has to be absorbed by a copper screen held at low temperature





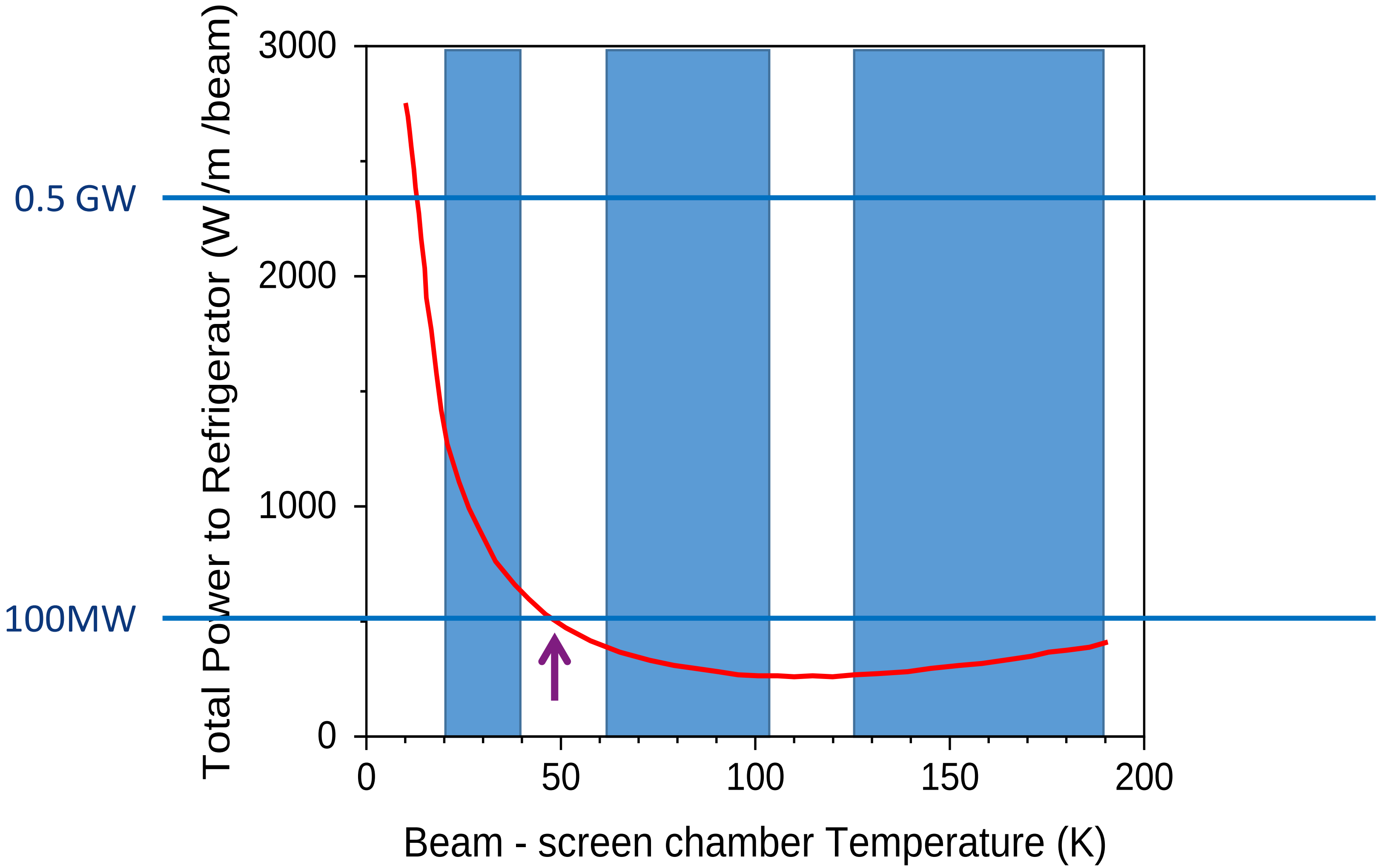


Courtesy of Roberto Kersevan

The synchrotron light does not hit directly the internal beam screen surface !!

Cryo-power for cooling of SR heat

Overall optimization of cryo-power and vacuum
Termperature ranges: 40K-60K, 100K-120K



Impedance: image charges

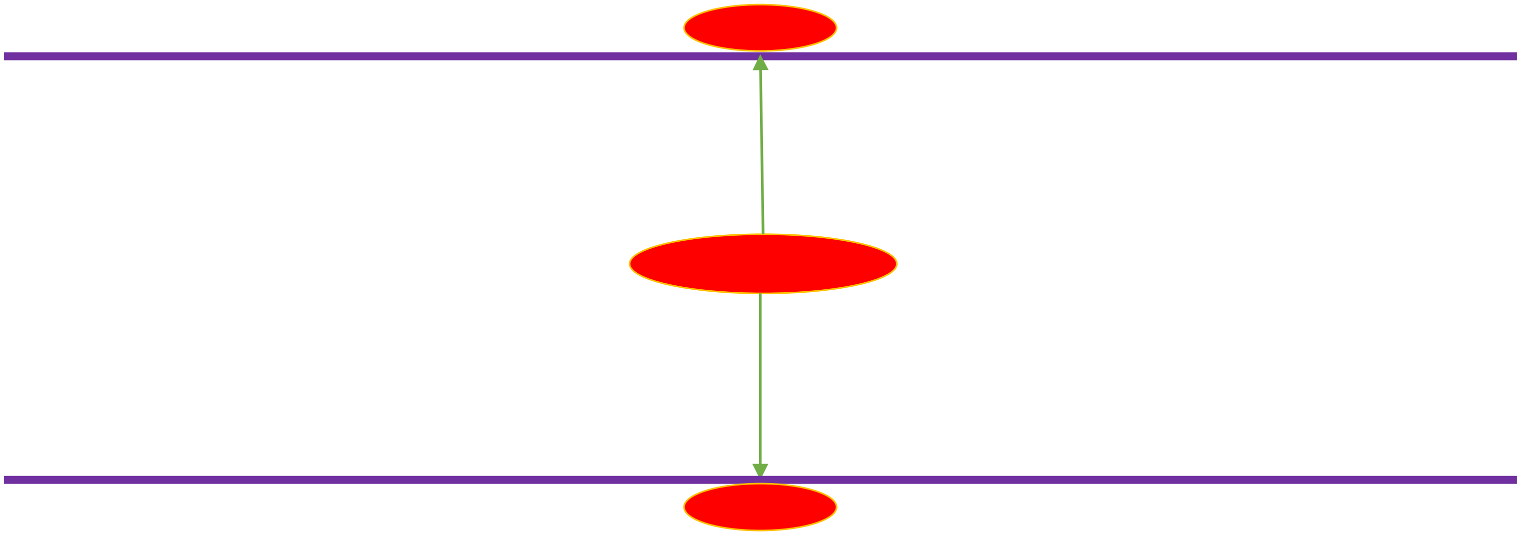


Image charges flow on the surface of the beampipe, generating "wakefields"

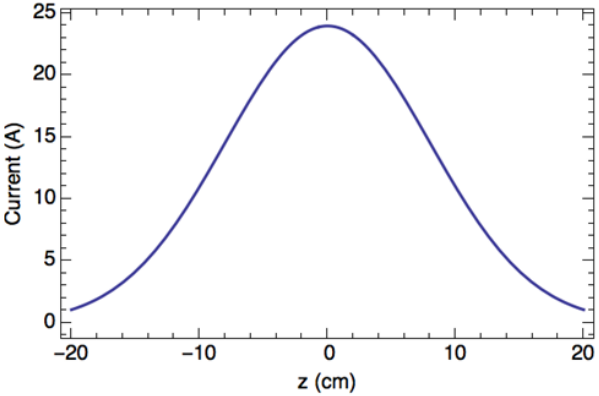
Wakefields have an effect on beam stability, in particular both the risetime of resistive wall transverse instabilities and the Intensity threshold of transverse mode coupling instabilities depend on the surface impedance of the material :

$$\tau \propto \frac{1}{\mathrm{Re}\left[Z_T\right]} \;;\; I_b \propto \frac{1}{\mathrm{Im}\left[Z_T\right]} \quad \textbf{with} \quad Z_T = \frac{2\pi R\, c}{\pi b^3\, \omega} Z_s$$

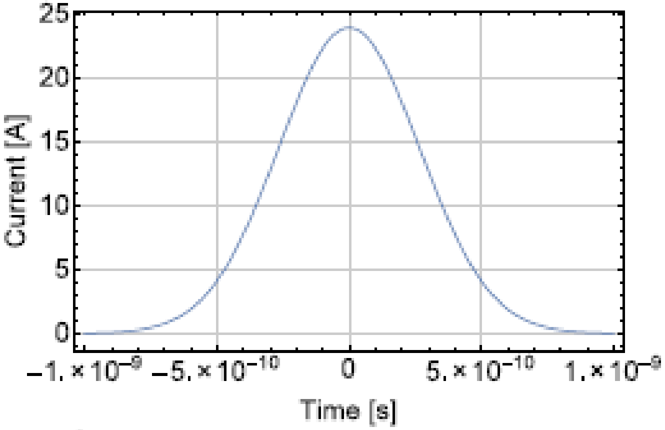
Copper at 50 K may not guarantee a large enough stability margin of the beam!

Frequency spectrum

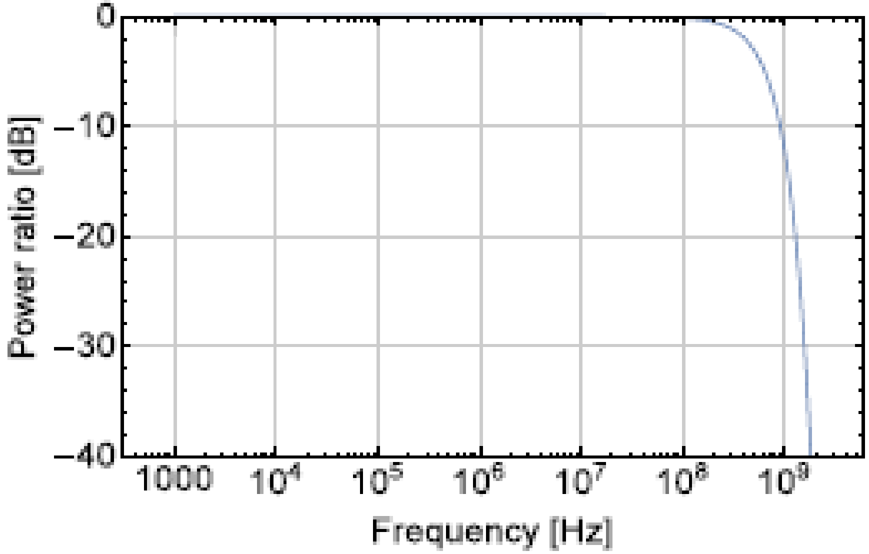
Beam instantaneous image current



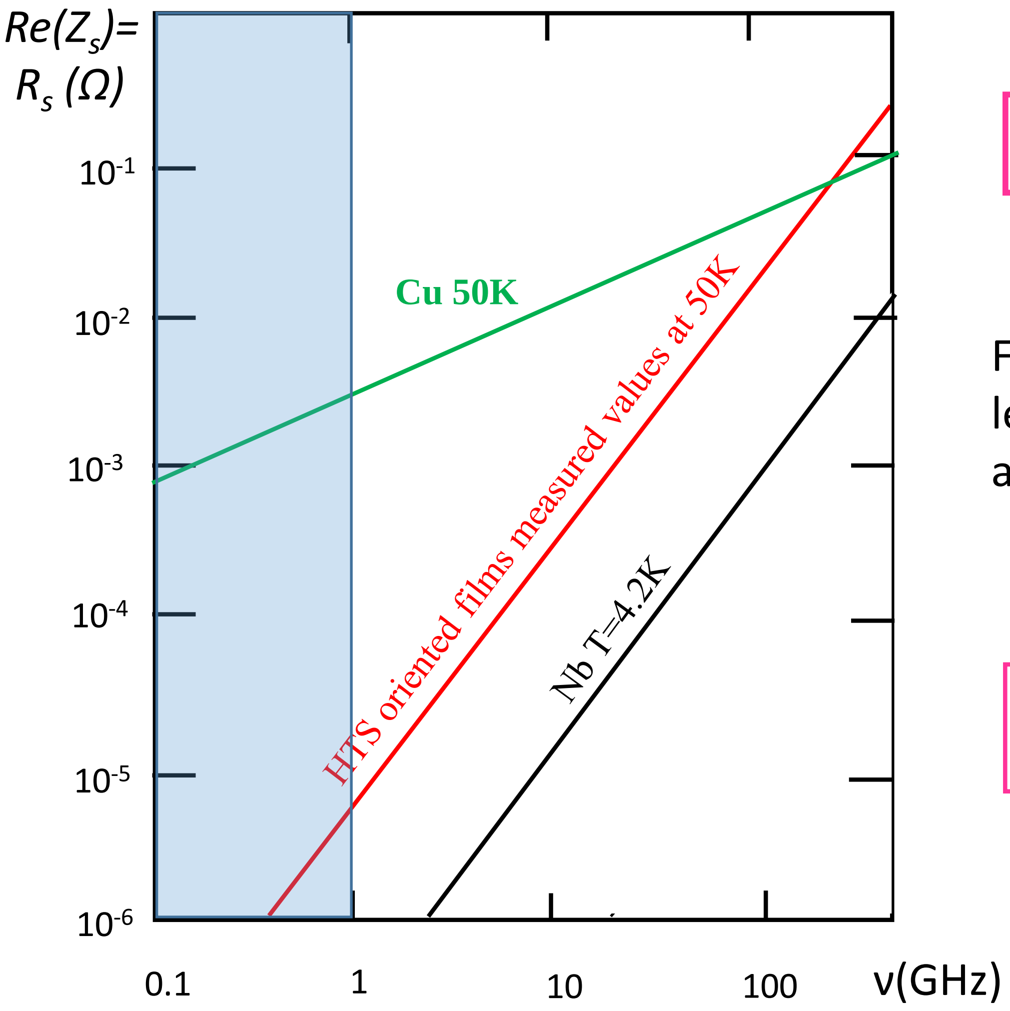
Time evolution at a fixed point



Frequency spectrum



High Temperature Superconductor at low fields present a Surface Impedance much lower than Copper at 50K!!!



$$P_{rf} \propto R_s I_{rf}^2$$

FCC calculations for a Cu beam screen lead to $I_{rf} \cong 2.5 \cdot 10^8\, A/m^2$ (peak value) and to $P_{rf} \cong 1 W/m^2$ (average value)

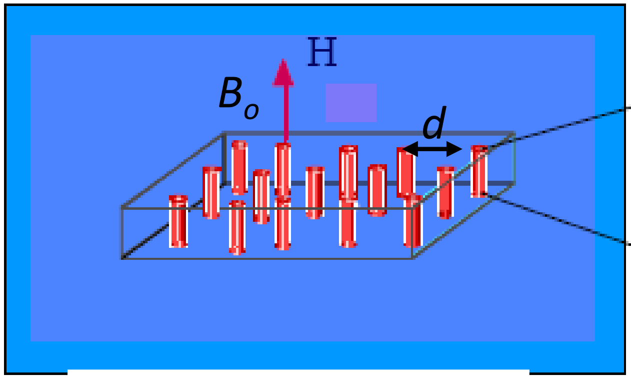
Superconductors : $\mathrm{Re}(Z_s) \propto \omega^2$
(normal metals : $\mathrm{Re}(Z_n) \propto \sqrt{\omega}$

But…the HTS film should operate in a 16T magnetic field and present $J_c >> 2.5\cdot10^8$ A/m^2 over a 100Km long narrow tube!

HTS Surface Impedance will still be well below copper in the assumed frequency, field, temperature and current regimes ???

Superconductors in high fields: Abrikosov Vortices

Type II superconducting sample in a magnetic field

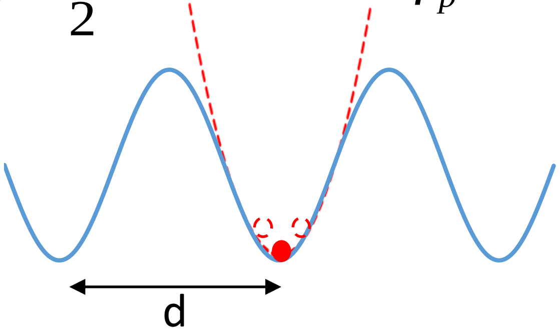


$$B_o = \frac{\phi_o}{d^2} = n\phi_o$$

$$B_{c2} = \frac{\phi_o}{\pi\xi^2}$$

Gittleman and Rosenblum: - Phys Rev. Lett. 16, 734 (1966) discuss the effect of a rf applied field (J_{rf}). At $B_o \gg B_{c1}$ repulsion forces between fluxon lines are higher in respect to the pinning forces. The fluxon array moves rigidly and feels a periodic force of the form :

$$U(x) = \frac{1}{2}kx^2 \qquad f_p = -kx$$



$$(J_{rf} \ll J_c)$$

Equation of motion for the fluxon lattice

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

m : fluxon mass per unit lenght

$\eta = \dfrac{\phi_o B_{c2}}{\rho_n}$: fluxon viscosity per unit lenght

$$(m \cong 0) \qquad J_{rf} = J_{rfo}e^{i\omega t}, \; \dot{x} = v = v_o e^{i\omega t}$$

$$\boxed{v_o = \frac{J_{rfo}\phi_o}{\eta}\left(\frac{\omega^2}{\omega^2 + \omega_o^2} + i\frac{\omega\omega_o}{\omega^2 + \omega_o^2}\right)}$$

$\left(\omega_o = \dfrac{k}{\eta}\right)$ «depinning frequency»

S. Calatroni, R.Vaglio : IEEE Trans. Superconductivity 2017

$$\vec{J}_{rf} = (\sigma_1 - i\sigma_2)(\vec{E}_{rf} - \vec{v}\times\vec{B}_o)$$ + Maxwell equations

General expression for the surface impedance of a superconductor in presence of a rigid vortex array, with the rf current perpendicular to the magnetic field

$$R_{sf} = R_n\sqrt{\sqrt{A^2+B^2}-B}$$

$$A = \frac{\sigma_1/\sigma_n}{(\sigma_2/\sigma_n)^2} + \frac{B_o}{B_{c2}}\alpha(\omega)$$

$$B = \frac{1}{\sigma_2/\sigma_n} + \frac{B_o}{B_{c2}}\beta(\omega)$$

$$\alpha(\omega) = \frac{\omega^2}{\omega^2+\omega_o^2}$$

$$\beta(\omega) = \frac{\omega\omega_o}{\omega^2+\omega_o^2}$$

Surface resistance

$$X_{sf} = R_n\sqrt{\sqrt{A^2+B^2}+B}$$

$$\frac{X_{sf}}{R_{sf}} = \frac{\sqrt{A^2+B^2}+B}{A}$$

Surface reactance

Surface Impedance in the Large Field, Low Frequency limit

FROM THE LITERATURE, FOR HIGH QUALITY HTS:

$$\boxed{f_o = \frac{\omega_o}{2\pi} \cong 10 - 20GHz}$$

Large B_o, $\omega \le \omega_o \Rightarrow \quad A \cong \frac{B_o}{B_{c2}}\frac{\omega^2}{\omega_o^2} \quad ; \quad B \cong \frac{B_o}{B_{c2}}\frac{\omega}{\omega_o}$

$$\boxed{R_{sf}(\omega, B_o) \cong \frac{R_n}{\sqrt{2}}\sqrt{\frac{B_o}{B_{c2}}}\left(\frac{\omega}{\omega_o}\right)^{3/2}}$$

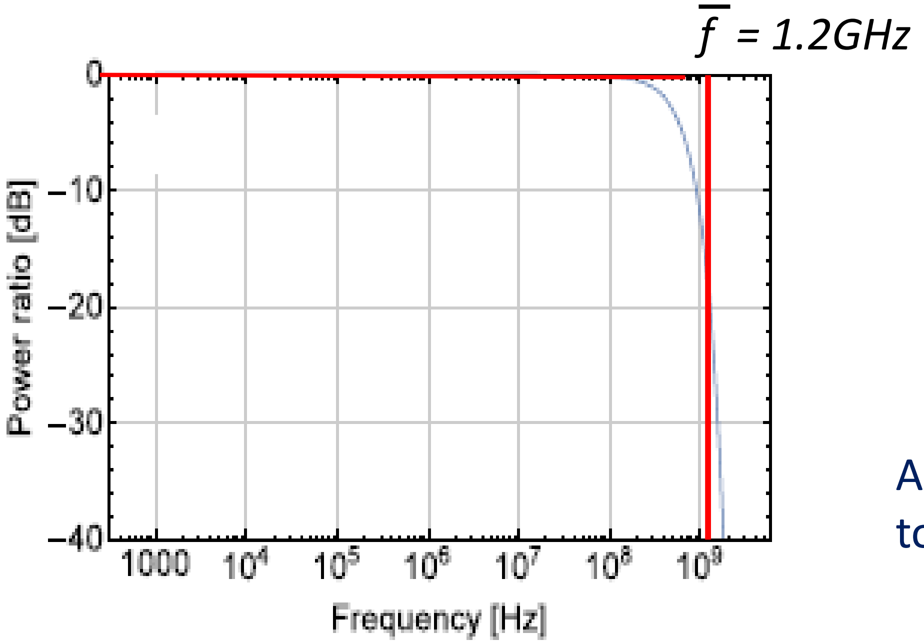
$$\boxed{\frac{X_{sf}}{R_{sf}} \cong 2\frac{\omega_o}{\omega}}$$

$$\boxed{X_{sf}(\omega, B_o) \cong X_n\sqrt{2}\sqrt{\frac{B_o}{B_{c2}}}\left(\frac{\omega}{\omega_o}\right)^{1/2}}$$

$$\boxed{\lambda_{sf} = \frac{X_{sf}}{\mu_o\omega} \cong \delta_n\sqrt{\frac{B_o}{B_{c2}}}\sqrt{\frac{\omega}{\omega_o}}}$$

Average value of R_{sf} over the FCC frequency spectrum

$$\bar{R}_{sf}(T) = \int_0^{\infty} S(f) R_{sf}(\omega, T) d\omega$$



Approximating the real spectrum to a step function, we get :

$$\boxed{\bar{R}_{sf}(T) = R_{sf}(\omega^*, T) \;\; ; \;\; \frac{\omega^*}{2\pi} = 0.65 GHz}$$

Calculations performed using high quality HTS (YBCO) parameters show a large R_{sf} reduction in respect to Copper

T_c =92K

T=50K

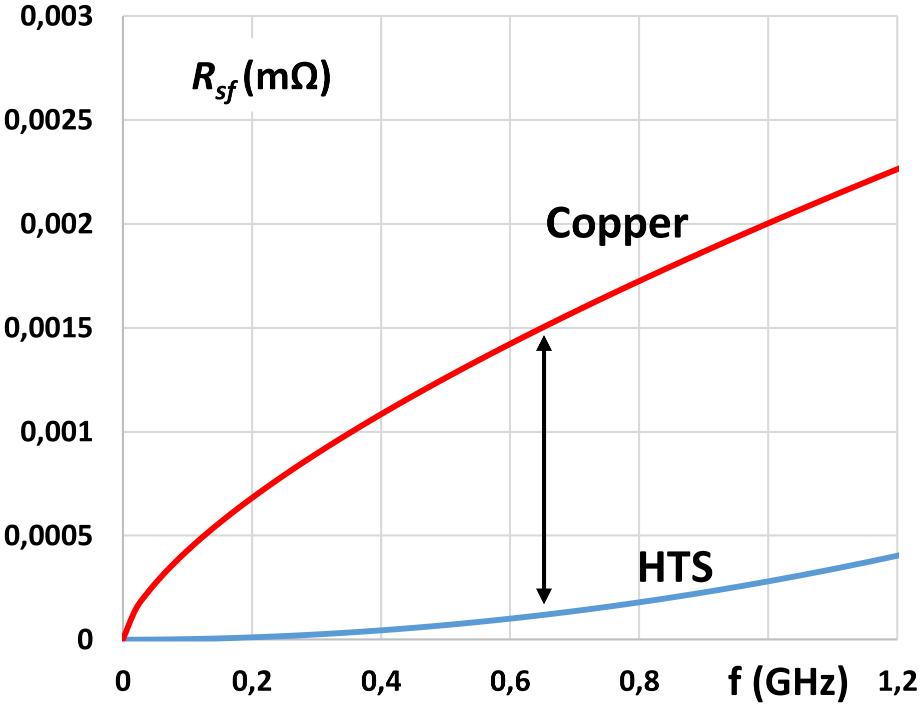
B_o=16T

J_c (50,16)=7.5 10^9/m^2

B_{c2} (50)=40T

ρ_n =60μΩ cm

$f_o = \omega_o/2\pi$=20Ghz



Possible HTS materials:

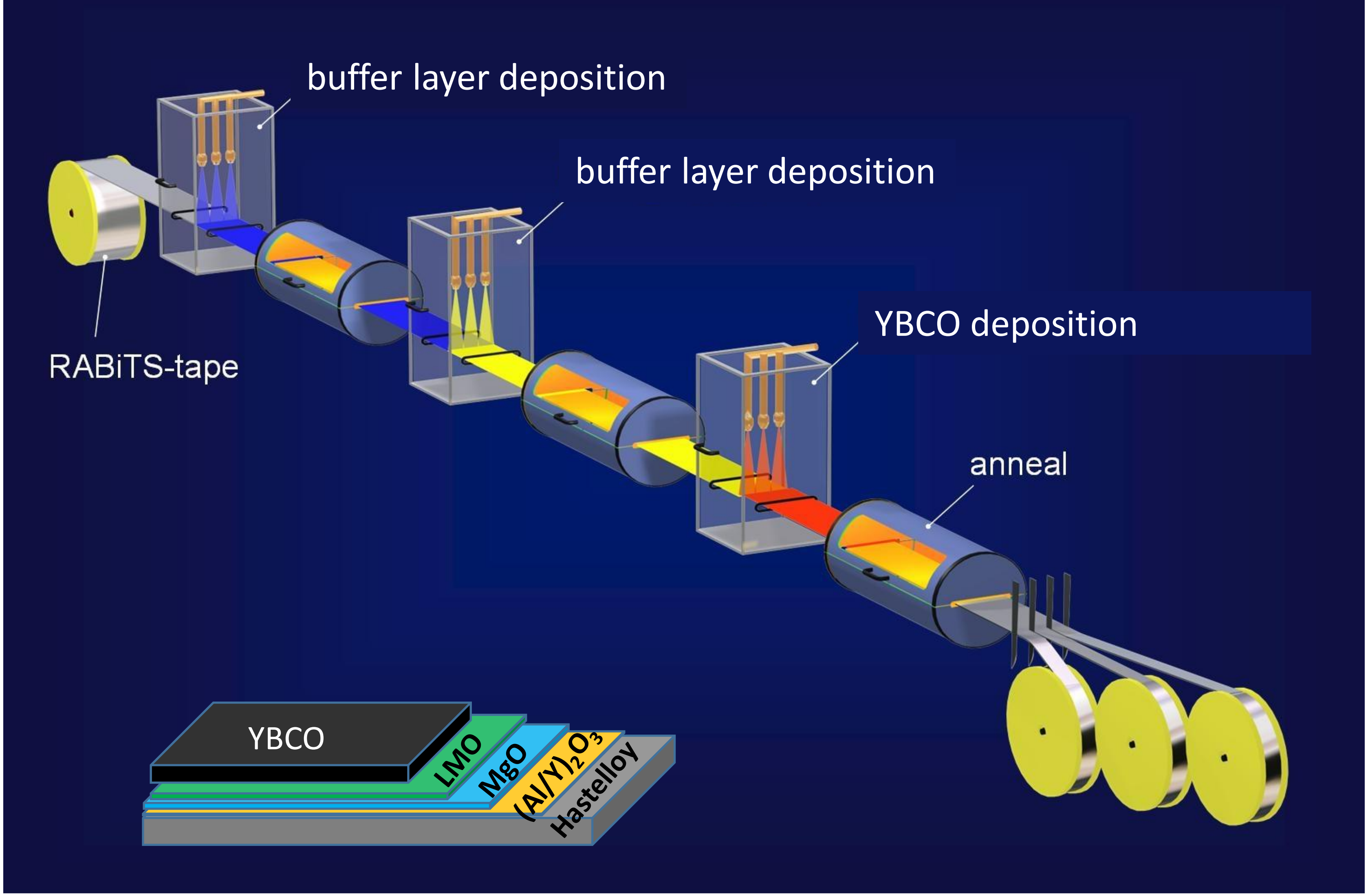
HTS	T_c	B_{c2}(50K)	Anisotropy	Substrate requirements
YBCO	92 K	40T	~ 7	High quality, biaxial texture
~~Bi-2212~~	~~85 K~~	~~70T (very low B_{irr})~~	~~>20~~	~~No special texture requirements~~
Tl-1223	125 K	80T	~ 8	No special texture requirements

The YBCO solution is developed by the ICMAB group

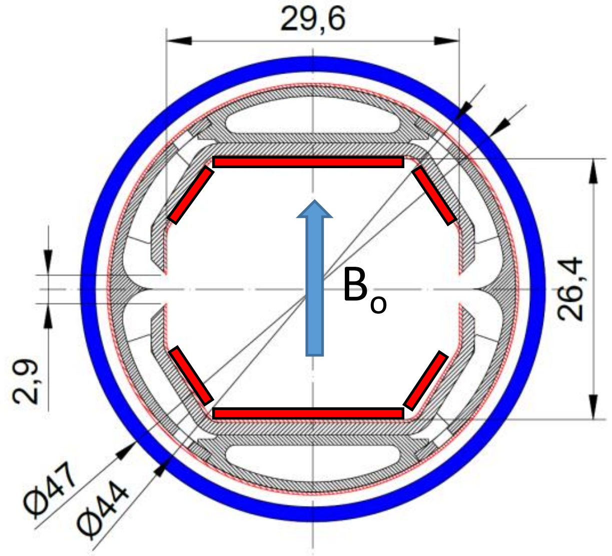
The Tl-1223 solution is developed by the CNR-SPIN group

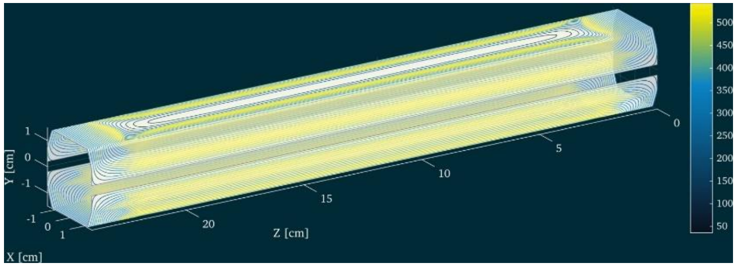
Solution 1: YBCO tapes glued on the beam screen

YBCO deposition on Ni–W alloy rolling-assisted biaxially textured tapes (**RABiTS)**)



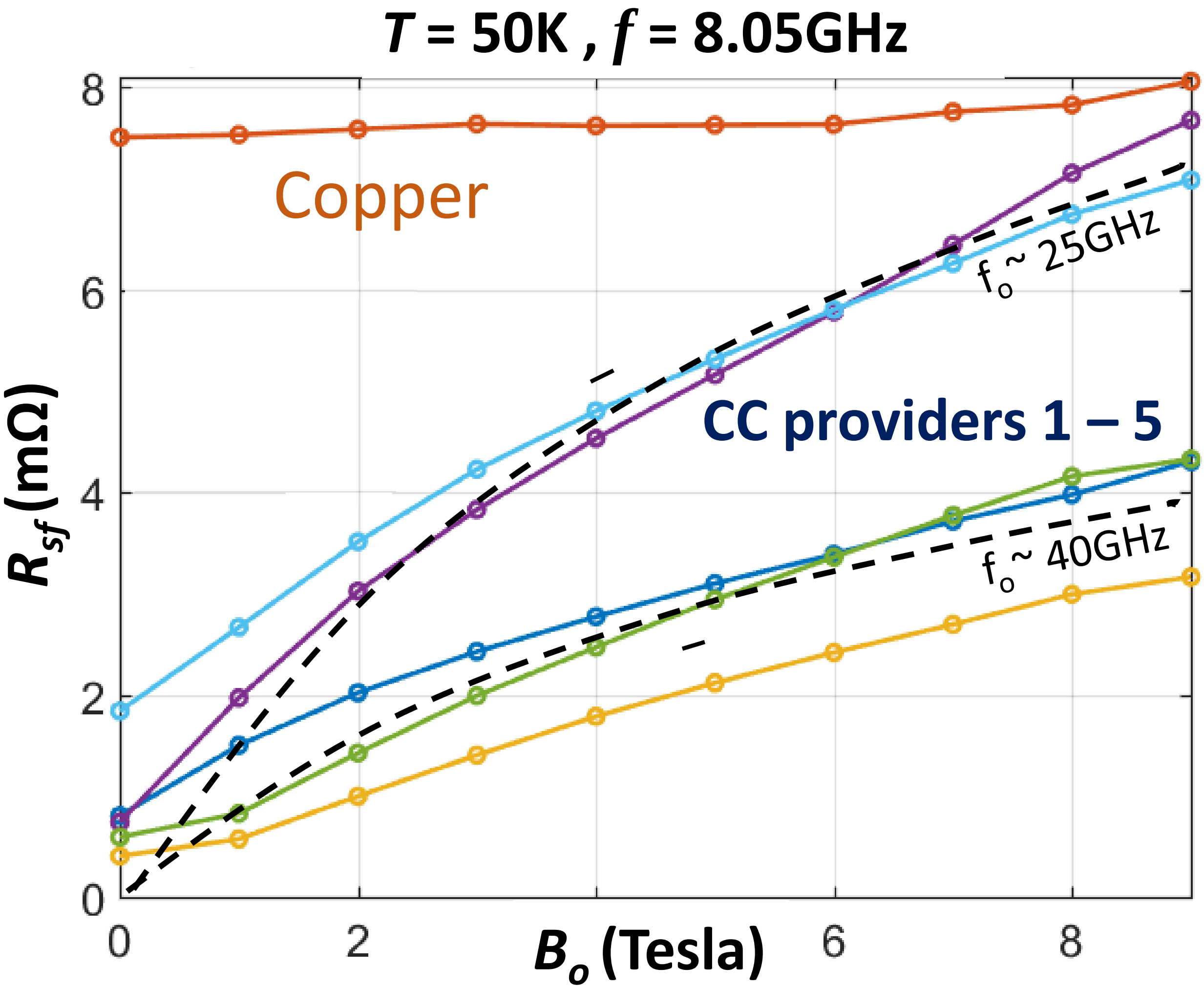
Presently produced by American Superconductor, BRUKER, Fujikura, SuNAM, SuperOx, SuperPower Inc. A Furukawa Company, STI, THEVA, Shanghai, 上海超导, OXOLUTIA, deutsche nanoschicht, MetOx

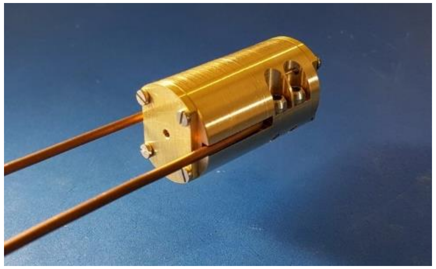




Segmentation should also reduce potential problems due to persistent currents generated during field ramping

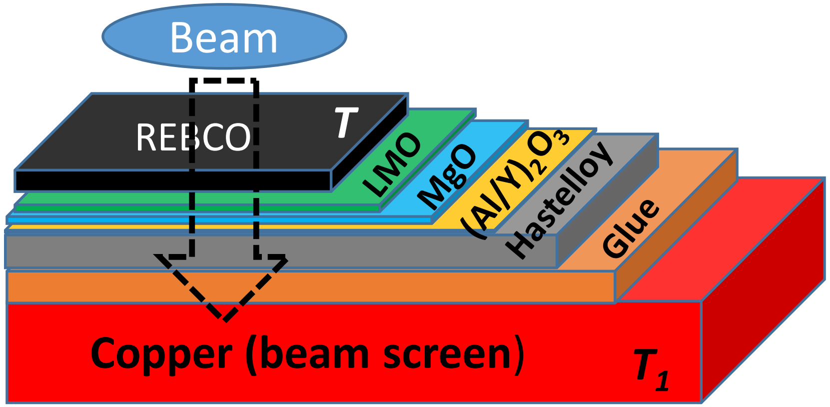
Preliminary measurements performed on small samples from 5 different providers, show very good agreement with the theory and extremely encouraging results!





$$R_{sf}(f,T) = \frac{R_n}{\sqrt{2}}\sqrt{\frac{B_o}{B_{c2}}}\left(\frac{f}{f_0}\right)^{3/2}$$

A possible problem for YBCO tapes : thermal runaway



One dimensional thermal model : $R_T = \frac{d_1}{k_1} + \frac{d_2}{k_2} + \frac{d_3}{k_3} + \frac{d_4}{k_4} + \frac{d_5}{k_5}$ + Kapitza interface terms

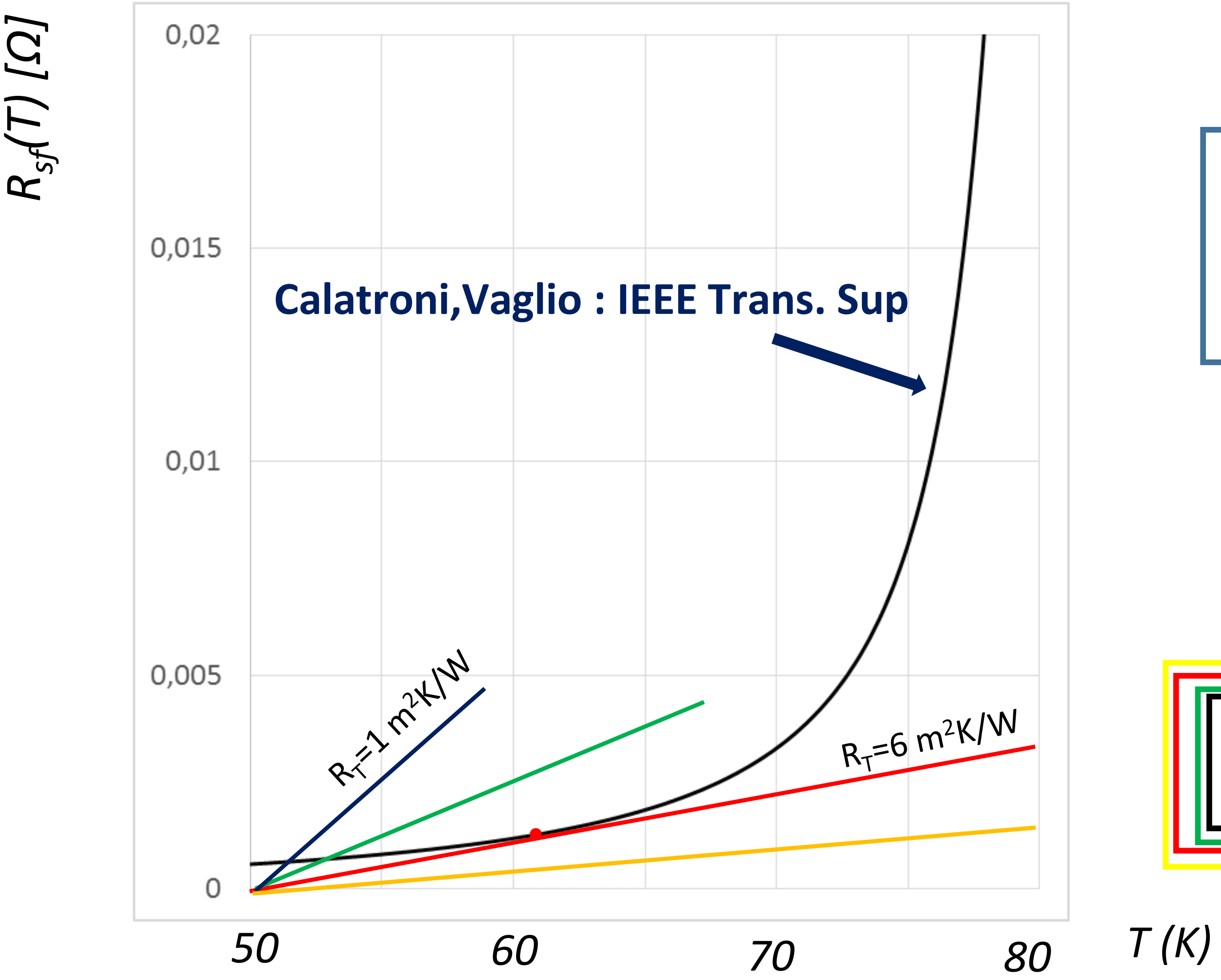
$$\begin{cases} T = T_1 + \Delta T \\ \Delta T = R_T P_{rf}(T) \\ P_{rf}(T) = a\bar{R}_{sf}(T) \end{cases}$$

a=10^{-3} W/Ωm^2
(FCC calculations)

$$\boxed{T = T_1 + aR_T\bar{R}_{sf}(T)}$$

An increase in *T* due to the *rf* power increases the superconductor surface resistance *R_{sf}(T)* that produces a further increase in *T.* The process leads to a surface equilibrium temperature *T > T_1,* or can lead to a thermal runaway !

Thermal runaway calculation
Eur. Phys. J. Special Topics 228, 749–754 (2019)



Calatroni,Vaglio : IEEE Trans. Sup

Assuming :

-T_1=50K
-P_{rfCu}= 1W/m²
-$R_{nCu}(f^*)$ = 1mΩ

$$\boxed{\overline{R}_{sf}(T) = \frac{T - T_1}{R_T}\,\frac{R_{nCu}}{P_{rfCu}}}$$

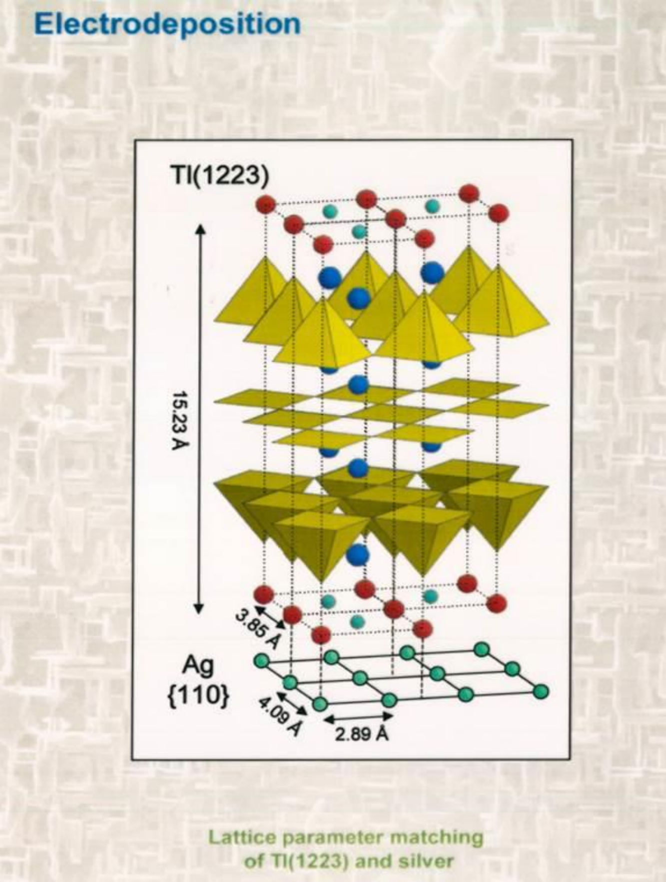
Solution 2: Tl 1223 directly grown on the Copper beam screen (with a Silver buffer layer)

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 9, NO. 2, JUNE 1999 1783

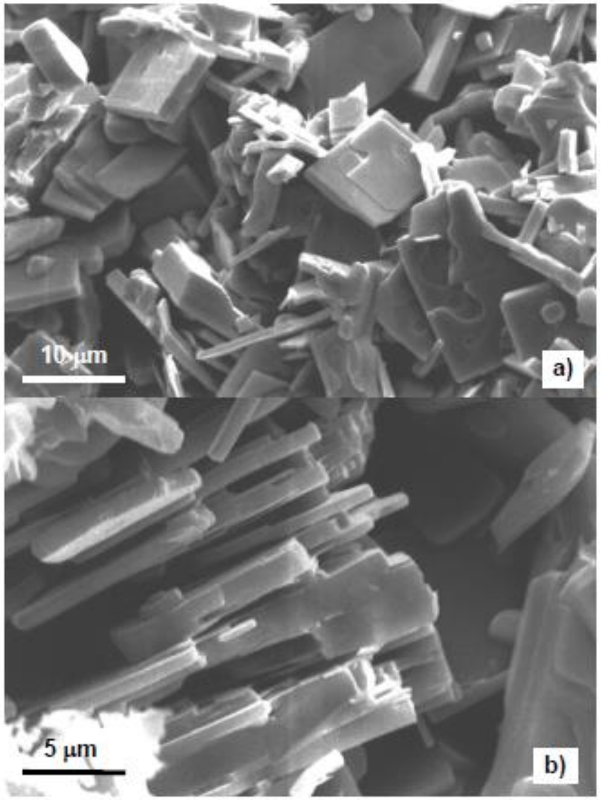
Preparation of Highly Textured Tl(1223)/Ag Superconducting Tapes

Emilio Bellingeri, Roman E. Gladyshevskii, Frank Marti and René Flükiger
Département de Physique de la Matière Condensée, Université de Genève, 24 Quai Ernest Ansermet, CH-1211 Genève 4, Switzerland

Electrodeposition

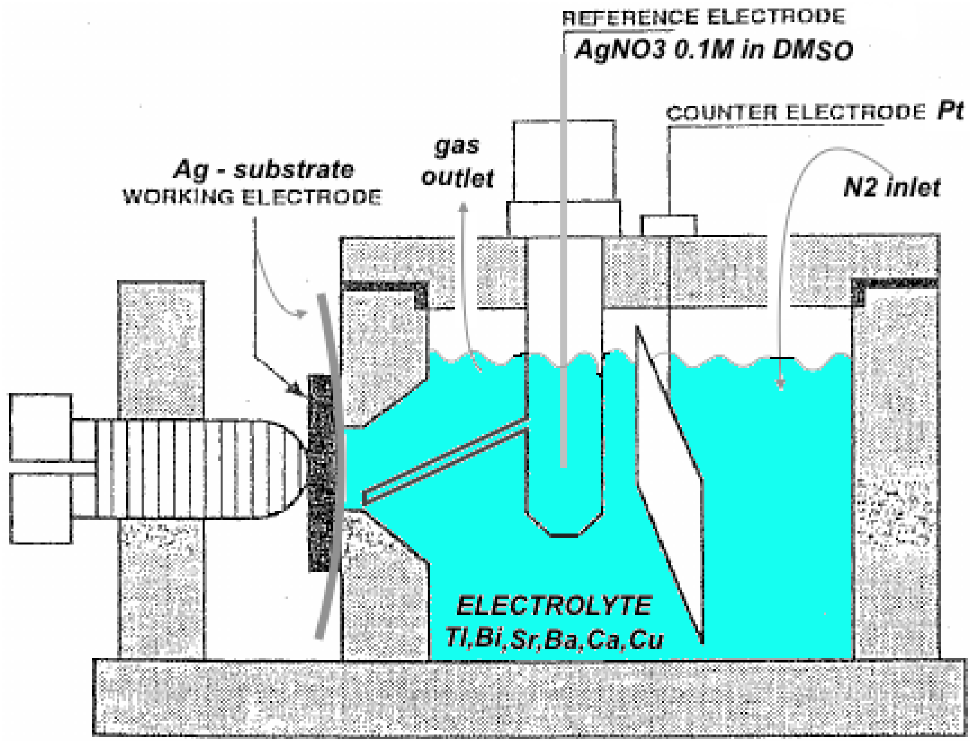


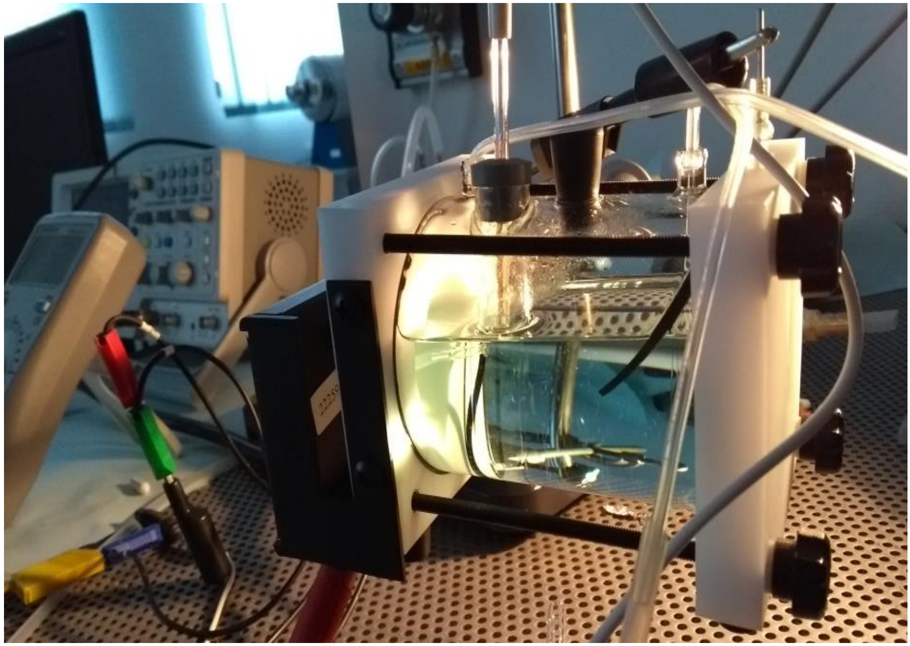
Lattice parameter matching of Tl(1223) and silver



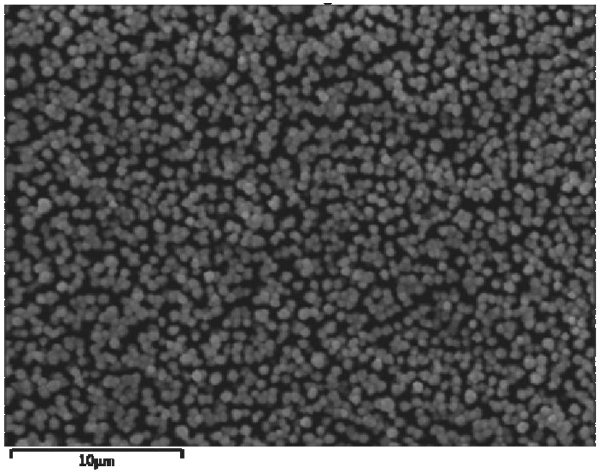
SEM images of a Tl,Pb,Bi(1223) powder melted at 1020°C (a), 1080°C (b) (0.5 h) after a second reaction at 930°C (3 h).

New Labs for safe Tl manipulation have been set up at SPIN-Ge

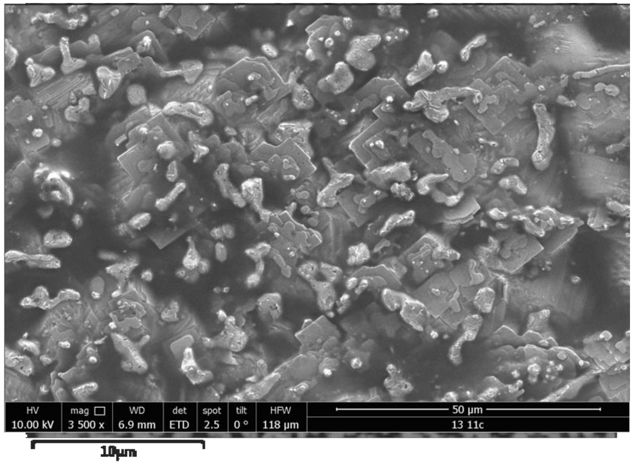




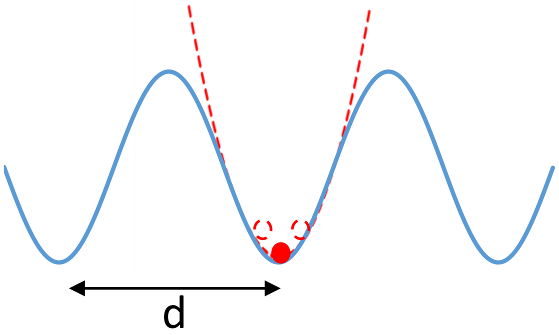
«as deposited» precursor



after thermal treatment



A further problem: effect of nonlinear pinning forces

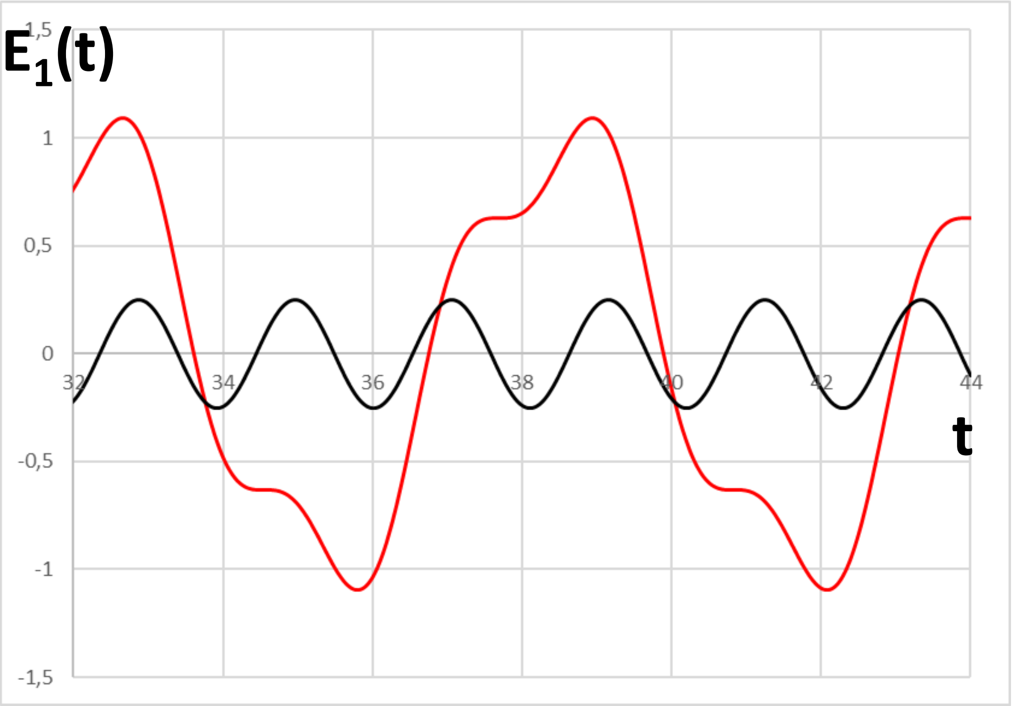


$$U(x) = \frac{1}{2}kx^2 + \qquad U(x) = -\frac{U_o}{1+(x/\xi)^2}$$

$$f_p = -kx \qquad f_p = -kx + \gamma x^2 + O(x^3)$$

Nonlinear Gittleman and Rosenblum equation : $\eta\dot{x} + kx = J_{rf}\phi_o - \gamma x^2$

The equation can be solved by perturbation methods.
The red curve represents the calculated first order peturbation term of the wakefield, for $J_{rf}=0.25J_c$ and $f=f_o$, showing a significative thir harmonic component (black curve)



Conclusions : Future directions and other facts….

- Measurements of the nonlinear component of the HTS rf surface impedance and comparison with calculations.

- Measurements of secondary electron emission from the HTS surface and effect of protective coatings on the surface impedance.

- Testing of the surface impedance at 1Ghz and 16T of a short (50cm) tube simulating the real beam screen.

- Our idea has been adopted for the design of the Chinese Super collider.

- Other accelerator physics & technology teams are following closely our research (Daresbury, Darmstadt……)

- Spin-offs may come out from this activity (axion detection, capture cavities for muon colliders)