Can HTS coating help to lower the resistive wall beam impedance in FCC-hh?

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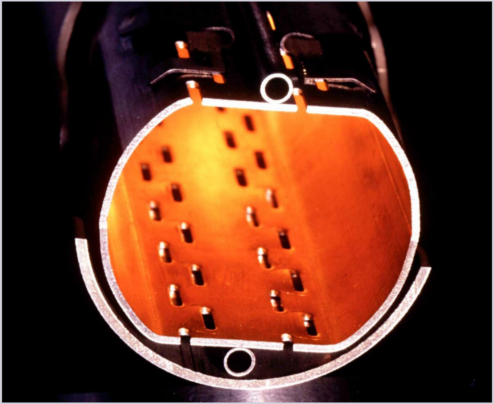
[1] S. Calatroni, Surface impedance of HTS films and applications to FCC beam screens, March 2015.

Motivation: beam screen in FCC



The beam screen in FCC will be immersed into the magnetic field of 16T at temperature about 50-80K. The concern is that the resistive wall impedance would drive beam instabilities. Proposed solution: cover the copper with a thin film of high-temperature supeconductor (HTS).

Parameters of interest

With $\sigma_z = 8$ cm, $N_p = 1.0 \times 10^{11}$, the peak current is about 25 A. The frequency corresponding to the bunch length

$$\omega \sim \frac{c}{\sigma_z} \approx 2\pi \times 500\ \mathrm{MHz}$$

This is the frequency of interest for the TMCI instability.

A much smaller frequency is associated with the sidebands of the betatron oscillations

$$\omega \sim 2\pi \times (1 - 10)\ \mathrm{kHz}$$

This is the frequency of interest for the multi-bunch instability.

What is the resistive wall impedance of copper-coated wall?

Resistive wall impedance of cold Cu

RW impedance of a copper coated beam screen has been previously analyzed[2].

- Copper conductivity increases at low temperature (RRR factor ~ 100)
- Possible anomalous skin effect
- Magnetoresistance increases the resistivity:

$$\rho(B) = (1 + 3.8 \times 10^{-3} B[\mathrm{T}] \cdot \mathrm{RRR})\rho|_{B=0}$$

For the isotropic material in a strong magnetic field the conductivity is a tensor ($\vec{B}$ along z):

$$\sigma_{ij} = \begin{pmatrix} \sigma_1 & \sigma_2 & 0 \\ -\sigma_2 & \sigma_1 & 0 \\ 0 & 0 & \sigma_3 \end{pmatrix}$$

What is RW beam impedance with tensorial wall conductivity?

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[2] E. Metral, “Beam screen issues” (AccNet Mini workshop HE-LHC10, 2010); N. Mounet and G. Rumolo, “VHE-LHC: first study of the effect of beam screens resistive wall impedance”.

HTS film on top of copper

Properties of some HTS[3]

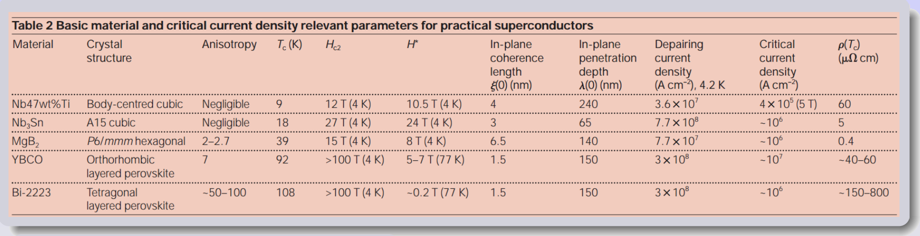
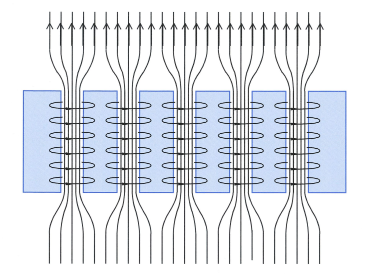


Table 2 Basic material and critical current density relevant parameters for practical superconductors

Material	Crystal structure	Anisotropy	T_c (K)	H_{c2}	H^*	In-plane coherence length $\xi(0)$ (nm)	In-plane penetration depth $\lambda(0)$ (nm)	Depairing current density (A cm^{-2}), 4.2 K	Critical current density (A cm^{-2})	$\rho(T_c)$ ($\mu\Omega$ cm)
Nb47wt%Ti	Body-centred cubic	Negligible	9	12 T (4 K)	10.5 T (4 K)	4	240	3.6×10^7	4×10^5 (5 T)	60
Nb_3Sn	A15 cubic	Negligible	18	27 T (4 K)	24 T (4 K)	3	65	7.7×10^8	$\sim 10^6$	5
MgB_2	*P6/mmm* hexagonal	2–2.7	39	15 T (4 K)	8 T (4 K)	6.5	140	7.7×10^7	$\sim 10^6$	0.4
YBCO	Orthorhombic layered perovskite	7	92	>100 T (4 K)	5–7 T (77 K)	1.5	150	3×10^8	$\sim 10^7$	~40–60
Bi-2223	Tetragonal layered perovskite	~50–100	108	>100 T (4 K)	~0.2 T (77 K)	1.5	150	3×10^8	$\sim 10^6$	~150–800



HTS are superconductors of the second type. Magnetic field penetrates into the HTS in vortices (“fluxons”).

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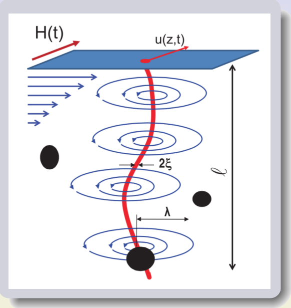
[3] D. Larbalestier et al. Nature, **414**, 368 (2001).

Physics of the surface impedance of HTS in magnetic field

To compute the beam impedance one needs to know the surface impedance of the SC film. The fluxons oscillate in applied external ac electric field. Their motion leads to dissipation → resistivity of the conductor. The resulting resistivity depends on properties of HTS, the external magnetic field and the ac frequency.



Oscillating vortex segment pinned by a defect spaced by ℓ from the surface.

Picture from: A. Gurevich and G. Ciovati, Phys. Rev. B **87**, 054502 (2013).

Superconductor resistivity

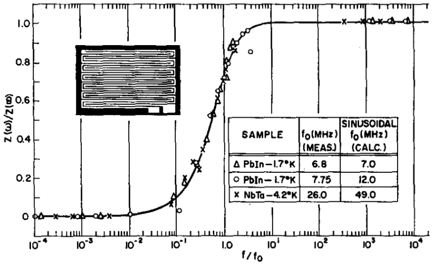
$$R_{SC} = R_{BCS} + R_{res} + R_{fl}$$

For calculation of the beam impedance we need to know the surface impedance

$$Z_s = Z_0 \frac{E_t}{H_t}$$

Surface impedance as a function of frequency

A simple surface impedance model for R_{fl} is developed in[4].



SAMPLE	f_0 (MHz) (MEAS.)	SINUSOIDAL f_0 (MHz) (CALC.)
Δ PbIn – 1.7°K	6.8	7.0
○ PbIn – 1.7°K	7.75	12.0
× NbTa – 4.2°K	26.0	49.0

INTRINSIC IMPEDANCE vs. FREQUENCY

$$Z = R_n \frac{H}{H_{c2}} \frac{\omega(\omega + i\omega_0)}{\omega^2 + \omega_0^2}$$

R_n is the normal-state resistance, ω_0 is the "depinning" frequency.

S. Calatroni estimates that at 700 MHz, at $H = 16$ T, the surface resistance of YBCO 1 μm film will be 0.22 mΩ, which is about 1/6 of the copper resistance. My estimate is that the film does not change the surface impedance of cold Cu.

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[4] J. Gittleman and B. Rosenblum, Journal of Appl. Phys., **39**, 2617 (1968)

Surface impedance at low frequencies

At low frequencies the surface conductivity will be increased by orders of magnitude.

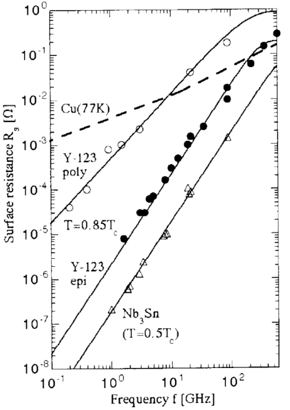

Figure 2: Surface resistance at 77 K of YBCO films, polycrystalline (empty circles) and epitaxial (full circles) compared with Cu (dotted line) and Nb_3Sn films (triangles) [10]

Plot from: M. Hein, High-Temperature Superconductor Thin Films at Microwave Frequancies, Springer, 1999. Zero magnetic field case.

Material choice

Thallium-based compounds, Tl-SCCO, seem to be the best candidate for the coating. They have good flux pinning properties akin to those of YBCO, and high T_c values (~ 130 K for Tl-1223, depending on stoichiometry and doping).

Electroplating has also been demonstrated for producing good quality Tl-1223 films, the main advantage of this technology being its easy scalability to large dimensions. The toxicity of Tl would require carefully managed production facilities.

Conclusions and recommendation

- At high frequencies, $\omega \sim c/\sigma_z$, extrapolation of known RF behavior of LTS and HTS when immersed in Tesla-scale external magnetic fields, indicates that the added R_{fl} surface resistance is large, but still would allow a factor 6 reduction compared to copper for the best-quality HTS films, at the full 16 T field (S. Calatroni). No reduction is predicted by G. Stupakov.
- At low frequencies, $\omega = 2\pi(1-10)$ kHz, considerable improvement in surface conductivity is expected in comparison with Cu.
- A strong thin films and material development and characterization is needed in order to achieve the goals of HTS coatings for a large scale facility such as the FCC-hh. A reasonable first step in this direction would be to develop a surface impedance measurement facility for small-scale HTS films, able to operate in the temperature range 4.2-77 K, up to 16 T external applied magnetic field and at < 1 GHz frequency. This would serve the purpose of validating existing HTS thin film coating technologies and select the most promising materials, and promote the developments needed for the FCC-hh.