High-Temperature Superconductor Coating for the Future Circular Collider Beam Pipe

Patrick Krkotić, Uwe Niedermayer, Oliver Boine-Frankenheim

Future Circular Collider Study (FCC)
Beam Screen Design

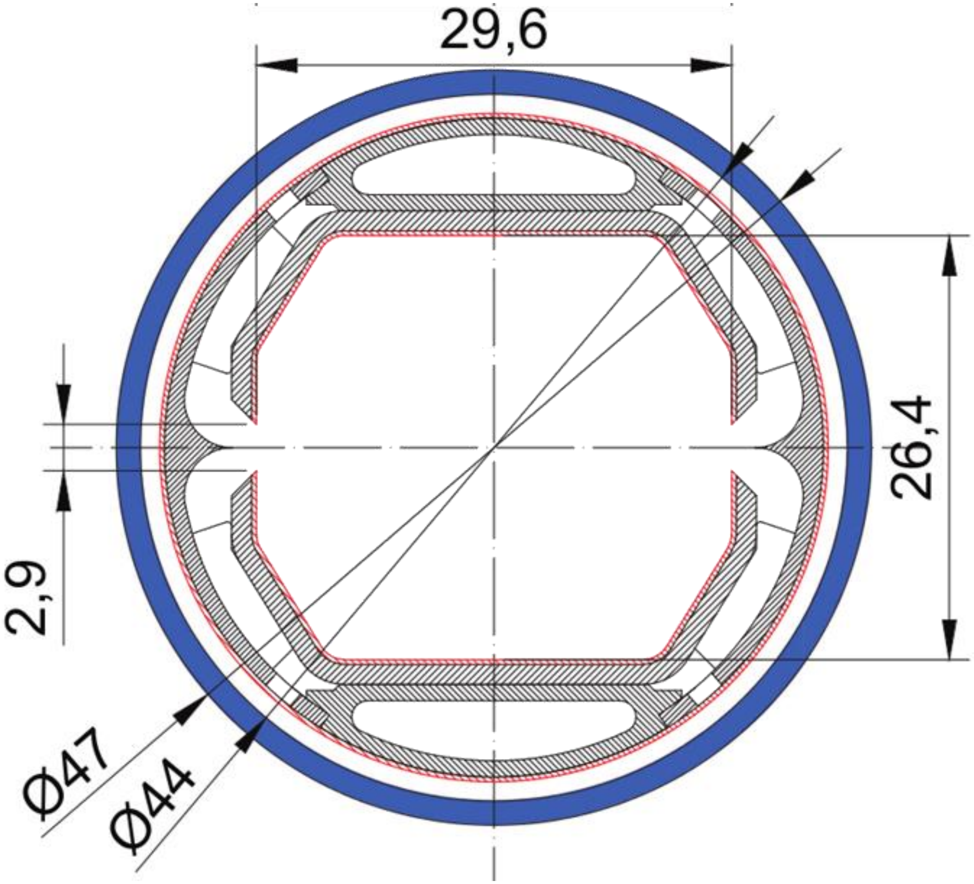
Cold bore diameter 44/47 mm

Nominal aperture:
- H: 29.6 mm
- V: 26.4 mm

Slit height: 2.9 mm → 5 mm

Temperature: 50 ± 10 K

Beam screen wall
- 1.25 mm steel
- 0.3 mm copper
- 1 µm High-Temperature Superconductor
- Thin-film coating e.g amorphous carbon
  → Secondary electron emission yield



C. Garion, FCC-hh beam screen studies and cooling scenario, FCC week 2016, Rome

Future Circular Collider Study (FCC)

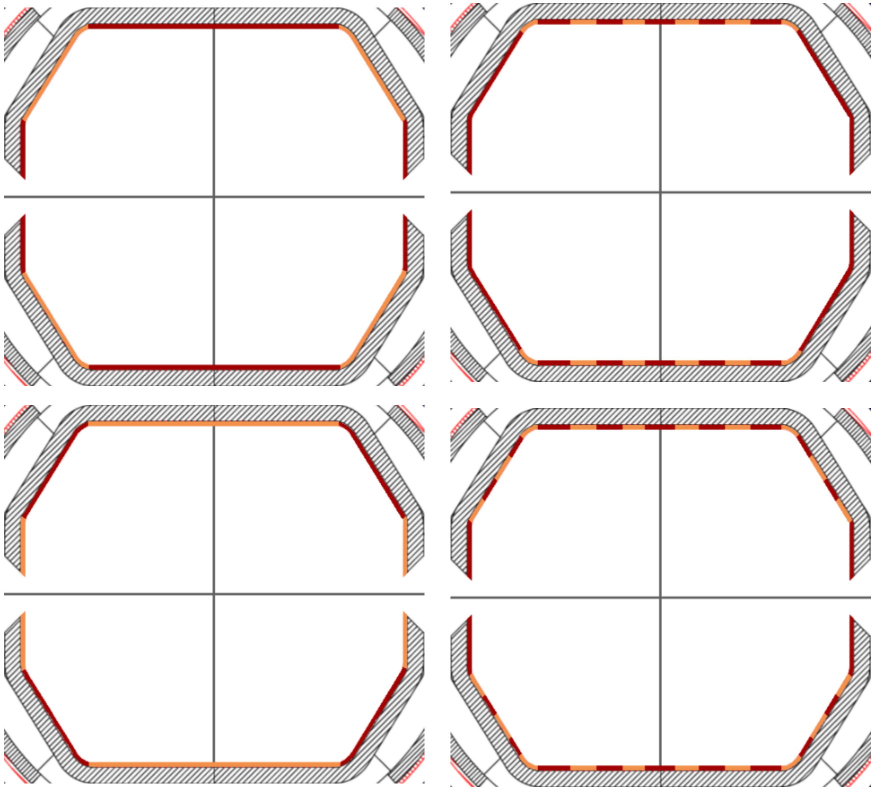
Beam Screen Design

Basic Idea

- HTS carries the image currents to reduce power dissipated
- Provides lower electric impedance
- Reducing coupling impedance
  - Longitudinal and transversal direction
  - Small impedance for sufficient beam stability

Hybrid solution

- Stripes
- Overall symmetrical distributed
- Alternating HTSC and Cu
- Using Coated Conductors
- Overall covered with Carbon

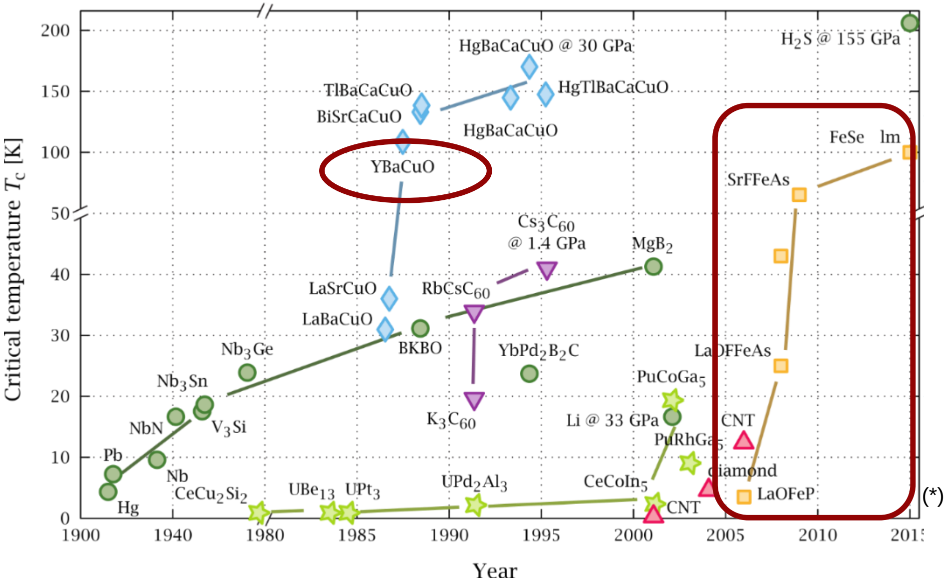


🟧 Cu 🟥 YBCO

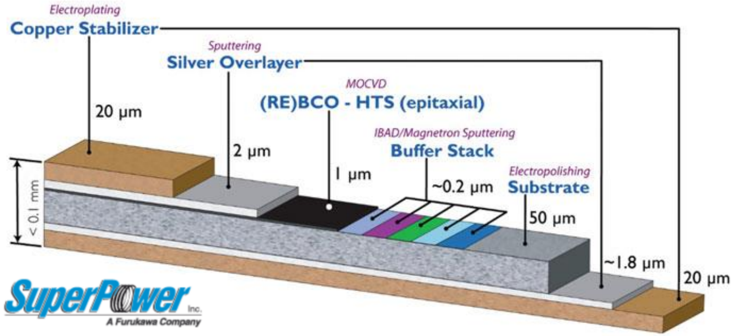
High-Temperature Superconductor

Properties of HTS

- High critical values
- Anisotropic
- Ceramics
- Brittle
- Stoichiometry
- Type II Superconductor



Coated Conductor



Configuration of SuperPower® 2G HTS Wire

	Parallel to c-axix	Parallel to ab-plane
$\lambda(nm)$	150	800
$J_C(Acm^{-2}\ 77K)$	10^6	10^7
H_{c2}(T)	110	240

W.Buckel, Supraleitung Grundlagen und Anwendung, Wiley-VCH Verlag GmbH & Co. KGaA

(*) P.J.Ray, ‘‘Structural investigation of - Following staging as a function of temperature‘‘, M.Sc. Thesis, Niels Bohr Institute, Copenhagen, Denmark, 2015.

Electrodynamics
Surface Impedance

Normal Conductors

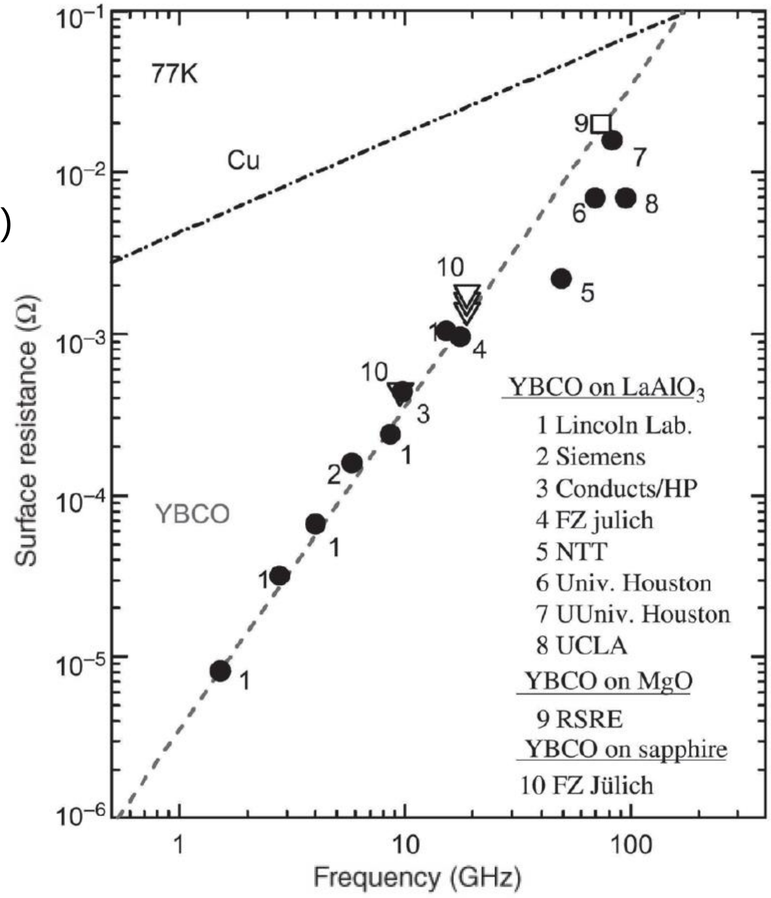
- Skin depth δ proportional to $\omega^{-1/2}$
- Surface Resistance proportional to $\omega^{1/2}$
- Surface resistance independent of temperature (low T)

$$Z_S = R_S + X_S = \frac{(1+i)}{\delta \cdot \kappa} \qquad \delta = \sqrt{\frac{2}{\omega\mu\kappa}}$$

Superconductors

- London Theory and Two-Fluid-Model
- London penetration depth λ_L independent of ω
- Surface resistance proportional to ω^2
- Surface resistance strongly dependent of temperature

$$R_S = \frac{1}{2}\kappa_n \mu_o^2 \omega^2 \lambda_{\boldsymbol{L}}^3 \qquad X_S = \omega\mu_o\lambda_L \qquad \lambda_L = \sqrt{\frac{m}{\mu_0 n_s e^2}}$$

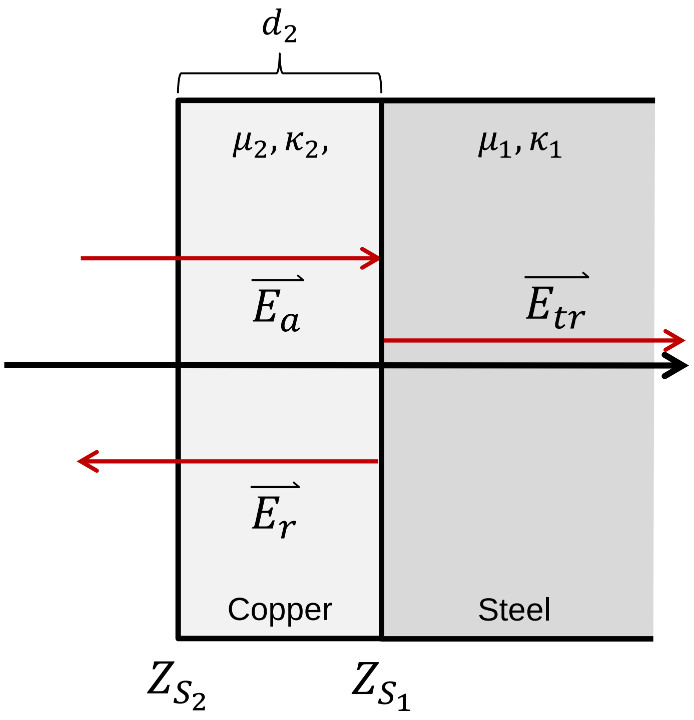


W.Buckel, Supraleitung Grundlagen und Anwendung,
Wiley-VCH Verlag GmbH & Co. KGaA

Electrodynamics

Surface Impedance - Iterative Model

Surface Impedance $Z_s \equiv \frac{E_t}{H_t} \xrightarrow{\text{metal}} Z_{S_1} = \frac{(1+i)}{\kappa_1 \cdot \delta_1}$



Boundary conditions

$\vec{n} \times (\vec{E}_1 - \vec{E}_v) = 0$ $\vec{n} \times (\vec{E}_2 - \vec{E}_v) = 0$

$\vec{n} \times (\vec{H}_1 - \vec{H}_v) = 0$ $\vec{n} \times (\vec{H}_2 - \vec{H}_v) = 0$

$$\vec{n} \times (\vec{E}_1 - \vec{E}_2) = 0$$

$$\vec{n} \times (\vec{H}_1 - \vec{H}_2) = 0$$

Surface impedance for 2nd layer

$$Z_{S_2}(Z_{S_1}) = \frac{1+A_2}{1-A_2} \cdot \alpha_2$$

$$A_2 = \frac{[\,Z_{S1} - \alpha_2] \cdot \exp\{-D_2\}}{[\,Z_{S1} + \alpha_2] \cdot \exp\{+D_2\}} \cdot \alpha_2$$

$$\alpha_2 = \frac{(1+i)}{2} \cdot \omega \delta_2 \mu_2 \qquad D_2 = (1+i) \cdot \frac{d_2}{\delta_2} \qquad \delta_2 = \sqrt{\frac{2}{\mu_2 \kappa_2 \omega}}$$

Electrodynamics

Surface Impedance - Iterative Model

Surface Impedance $Z_s \equiv \frac{E_t}{H_t} \xrightarrow{\text{metal}} Z_{S_1} = \frac{(1+i)}{\kappa_1 \cdot \delta_1}$

Boundary conditions

$$\vec{n} \times \left(\vec{E}_3 - \vec{E}_v\right) = 0 \qquad \vec{n} \times \left(\vec{E}_2 - \vec{E}_3\right) = 0$$

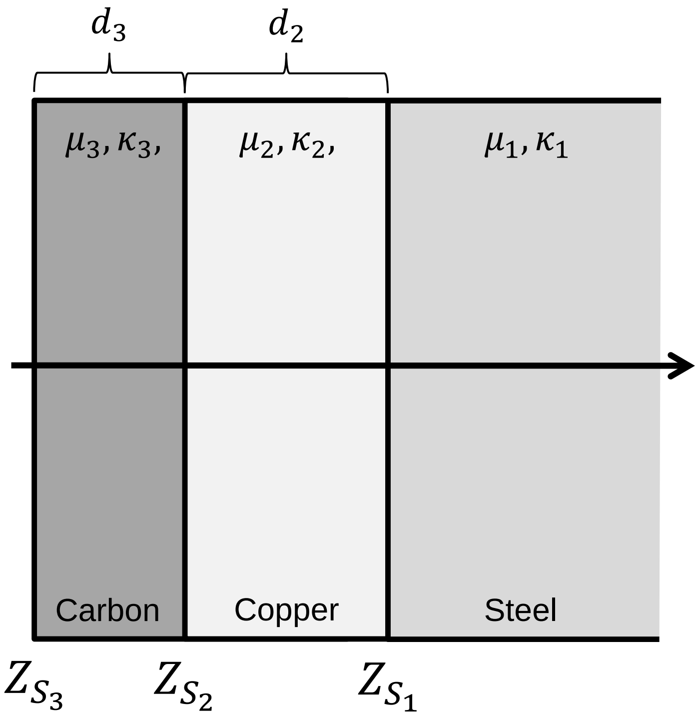
$$\vec{n} \times \left(\vec{H}_3 - \vec{H}_v\right) = 0 \qquad \vec{n} \times \left(\vec{H}_2 - \vec{H}_3\right) = 0$$

Surface impedance for 3nd layer

$$Z_{S_3}(Z_{S_2}) = \frac{1+A_3}{1-A_3} \cdot \alpha_3$$

$$A_3 = \frac{[\,Z_{S2} - \alpha_3]\cdot\exp\{-D_3\}}{[\,Z_{S2} + \alpha_3]\cdot\exp\{+D_3\}} \cdot \alpha_3$$

$$\alpha_3 = \frac{(1+i)}{2} \cdot \omega \delta_3 \mu_3 \qquad D_3 = (1+i) \cdot \frac{d_2}{\delta_2} \qquad \delta_3 = \sqrt{\frac{2}{\mu_3 \kappa_3 \omega}}$$



Electrodynamics

Surface Impedance - Iterative Model

Surface Impedance $Z_s \equiv \frac{E_t}{H_t} \xrightarrow{\text{metal}} Z_{S_1} = \frac{(1+i)}{\kappa_1 \cdot \delta_1}$

Boundary conditions

$$\vec{n} \times \left(\vec{E}_k - \vec{E}_{k+1}\right) = 0$$

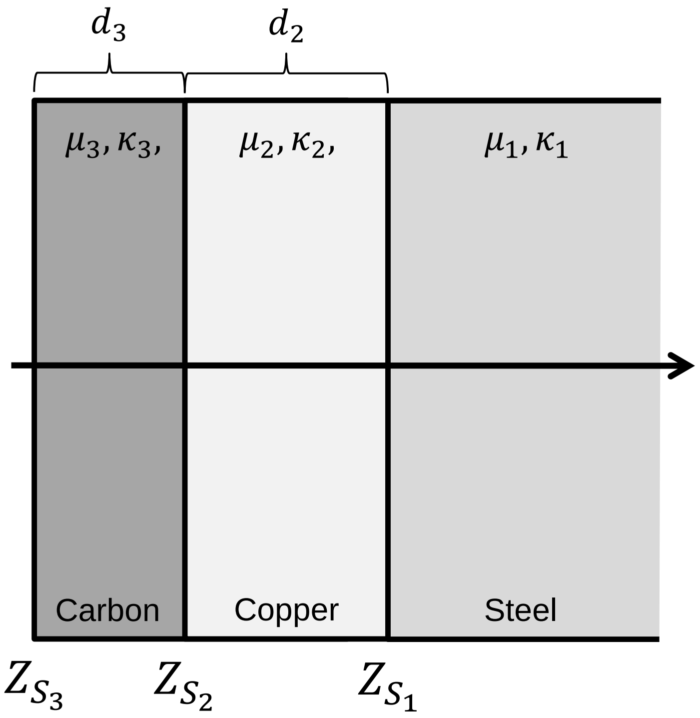
$$\vec{n} \times \left(\vec{H}_k - \vec{H}_{k+1}\right) = 0$$

Surface impedance for k-th layer

$$Z_{S_k}(Z_{S_{k-1}}) = \frac{1+A_k}{1-A_k} \cdot \alpha_k$$

$$A_k = \frac{[\,Z_{Sk-1} - \alpha_k] \cdot \exp\{-D_k\}}{[\,Z_{Sk-1} + \alpha_k] \cdot \exp\{+D_k\}} \cdot \alpha_k$$

$$\alpha_k = \frac{(1+i)}{2} \cdot \omega \delta_k \mu_k \qquad D_k = (1+i) \cdot \frac{d_k}{\delta_k} \qquad \delta_k = \sqrt{\frac{2}{\mu_k \kappa_k \omega}}$$

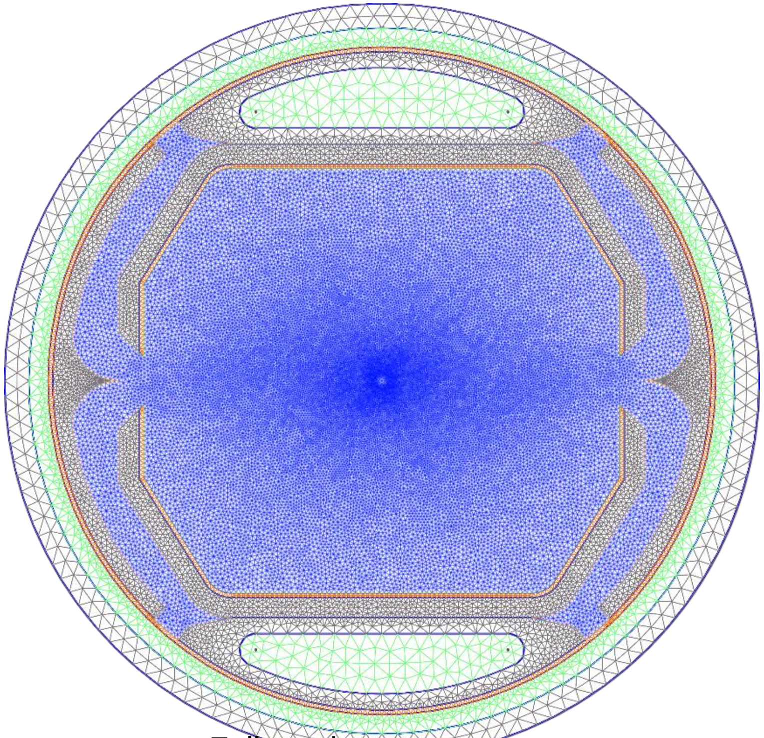


Impedance Calculation

Beam Screen : 2D impedance simulation (BI2D)

BI2D: 2D frequency domain solver

- Computational tool for longitudinal and transverse coupling impedance
- Finite-Element-Method (FEM)
- Input: mesh of the geometry



Two methods:

- Surface Impedance Boundary Condition (SIBC)
- Meshing whole Structure → range of skin frequency
  - Copper : skin frequency for 300 µm coating

$$f = \frac{1}{\kappa_n \pi \mu_0 \delta^2} \approx 469\ \text{Hz}$$

→ Full mesh not necessary

  - YBCO : penetration depth (frequency independent)

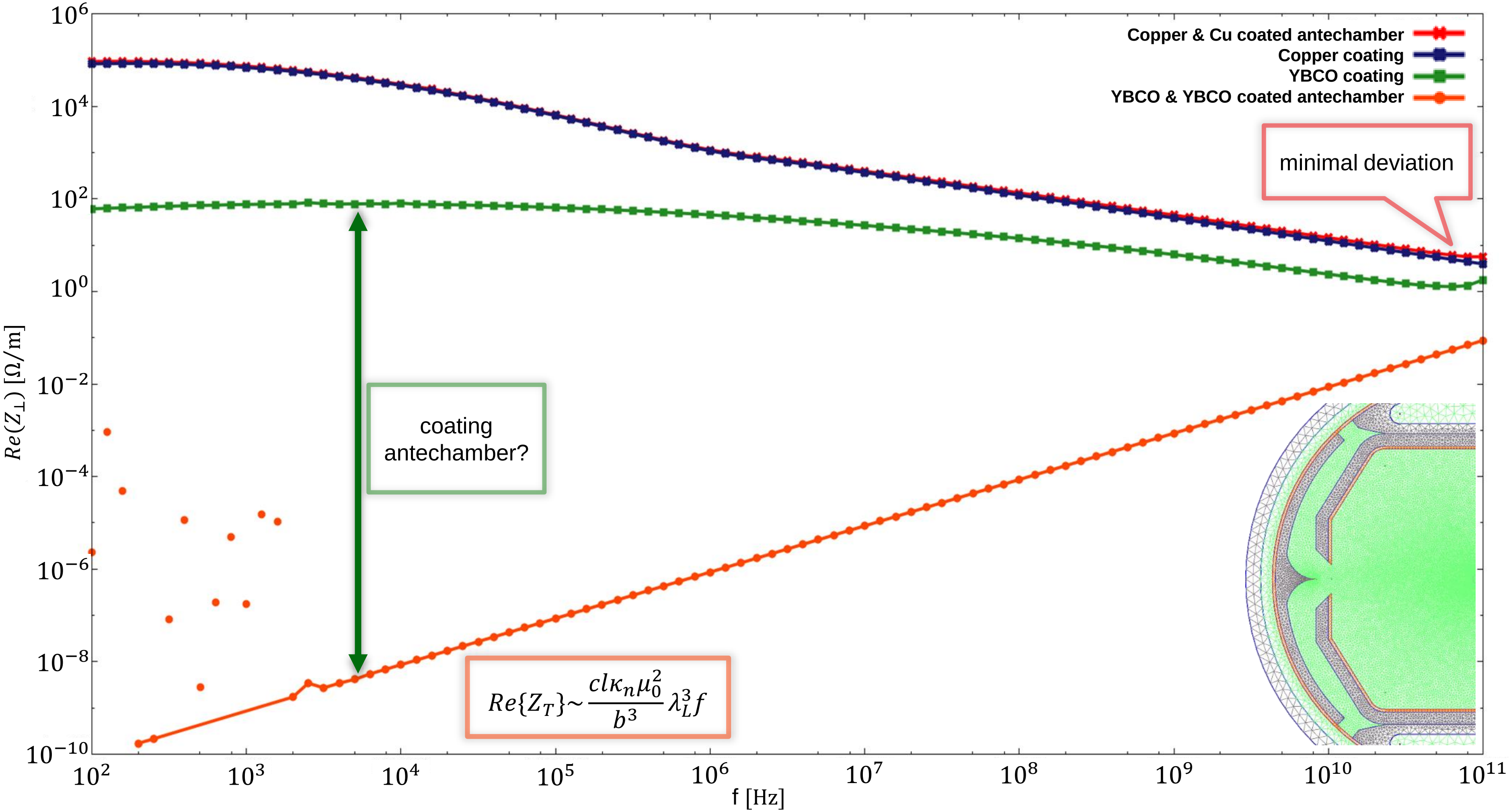
$$\lambda_L(50K) = 157\ \text{nm}$$

Coating: copper	Coating: YBCO
$\kappa = 6$ GS/m	$\kappa_n = 1.37$ MS/m
$\delta = 300$ µm	1 µm thickness

Space charge and resistive wall impedance computation in the frequency domain using the finite element method
Uwe Niedermayer, Oliver Boine-Frankenheim, and Herbert De Gersem
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 18, 032001 (2015)

Impedance Calculation

Transversal Impedance - Effect of the Radiation Slit



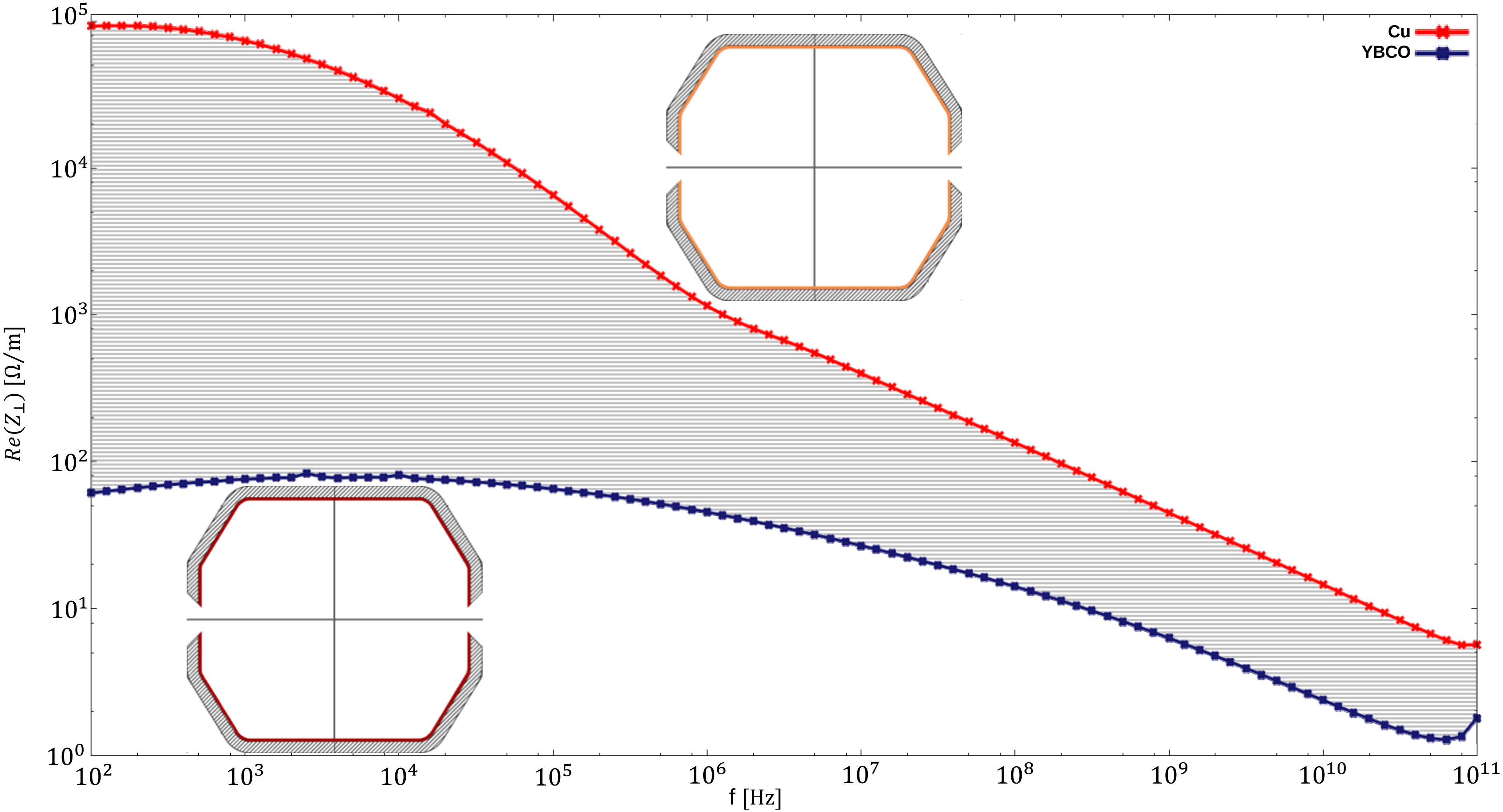
minimal deviation

coating antechamber?

$$Re\{Z_T\} \sim \frac{c l \kappa_n \mu_0^2}{b^3} \lambda_L^3 f$$

Impedance Calculation (BI2D)

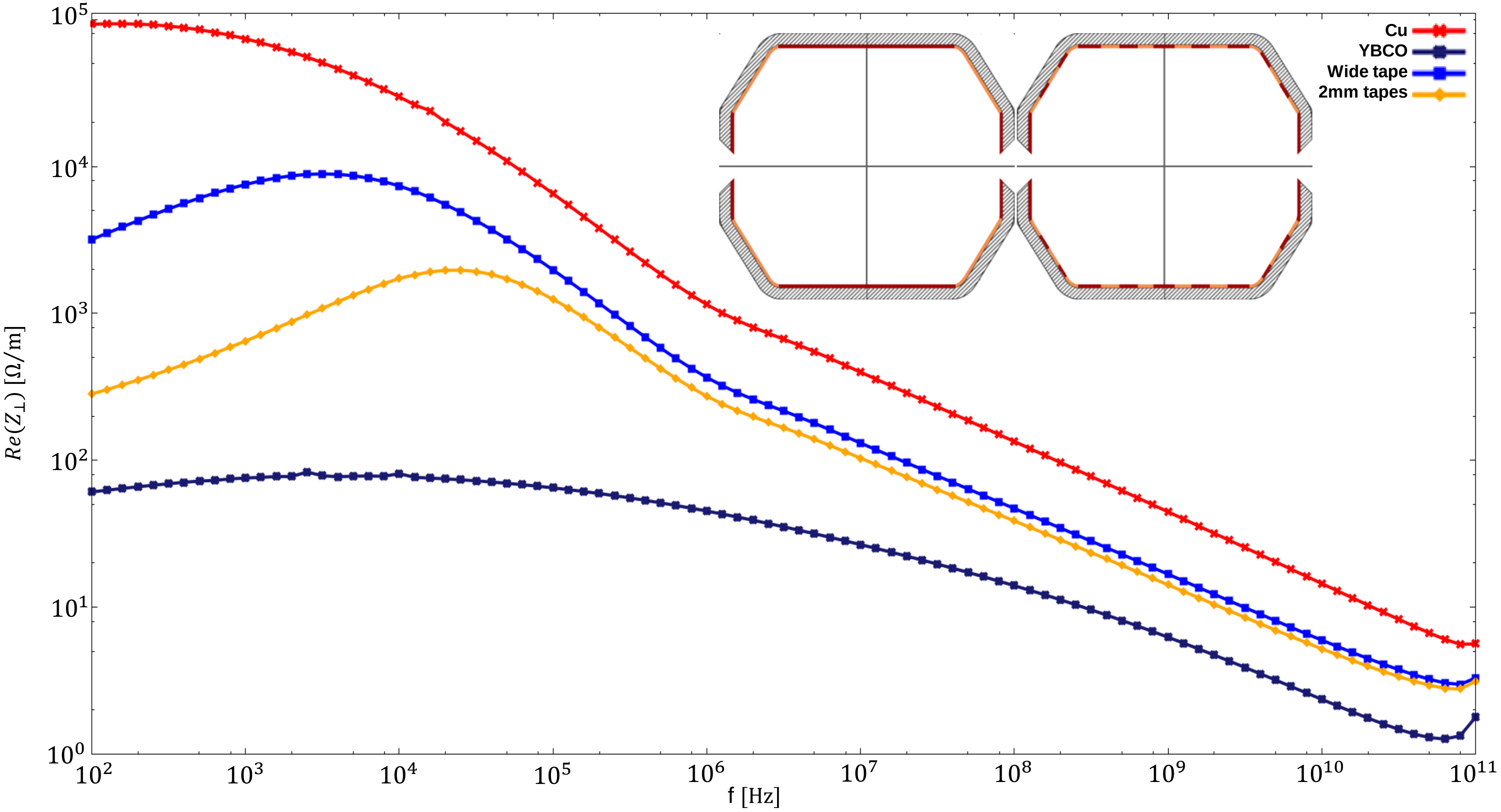
Transversal Impedance – horizontal dipol source



Cu YBCO

Impedance Calculation (BI2D)

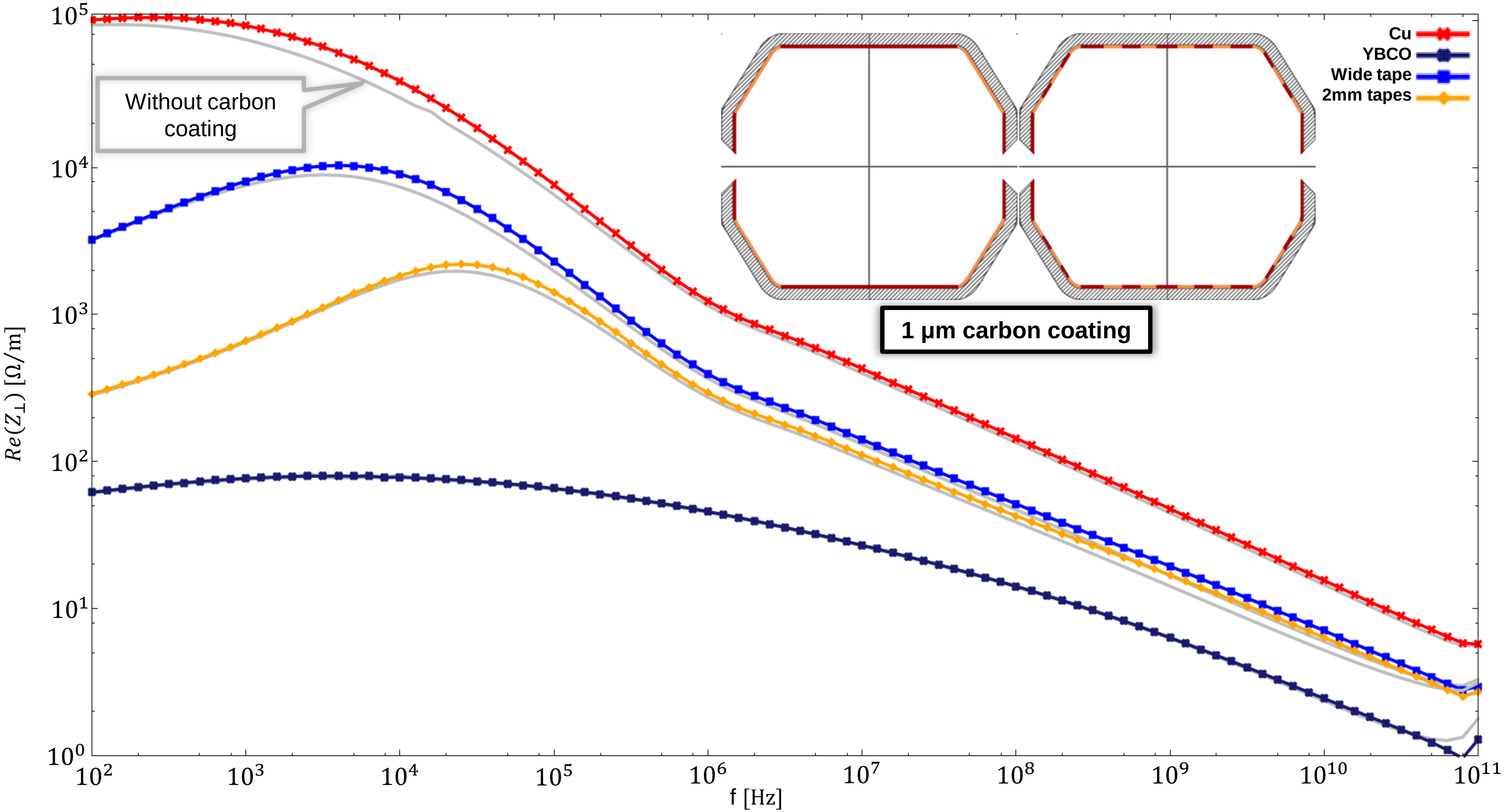
Transversal Impedance – horizontal dipol source



▬ Cu ▬ YBCO

Impedance Calculation (BI2D)

Transversal Impedance – horizontal dipol source



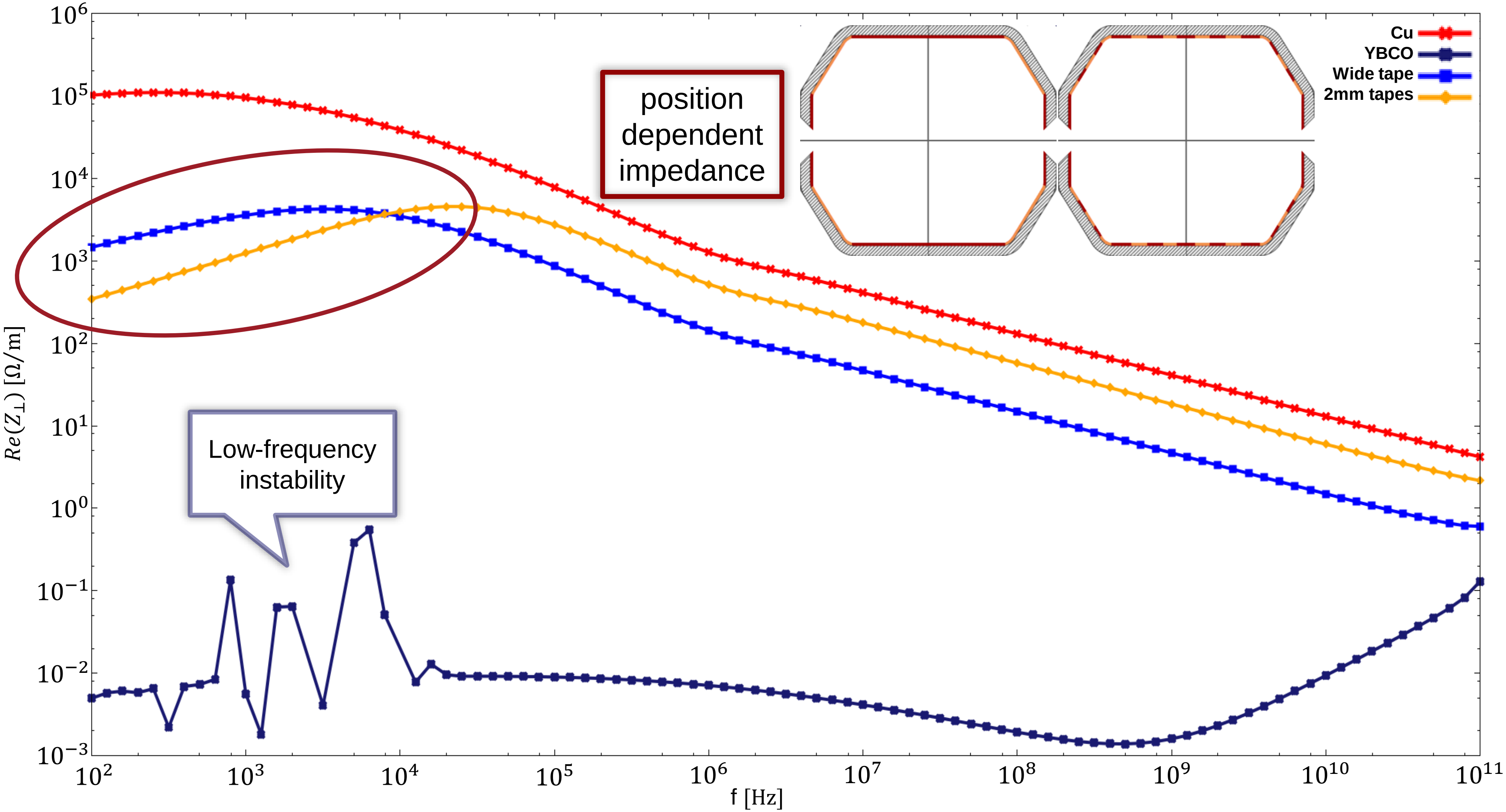
Without carbon coating

1 µm carbon coating

🟧 Cu 🟥 YBCO

Impedance Calculation (BI2D)

Transversal Impedance – vertical dipol source



position dependent impedance

Low-frequency instability

Conclusion & Outlook

Impedance

Intended reduction of the impedance with HTS can be reached

- Effect of the radiation slit
  - Coating of the ante-chamber could reduce impedance further
  - What is the effect on the intended function?
- Hybrid solution
  - Percentage of superconducting surface yields a gradual reduction of the impedance
  - Using narrow stripes shows lower impedance at low frequencies
  - Suggested solution : Hybrid system with very narrow alternating stripes
  - Further simulations with different distributions should be done

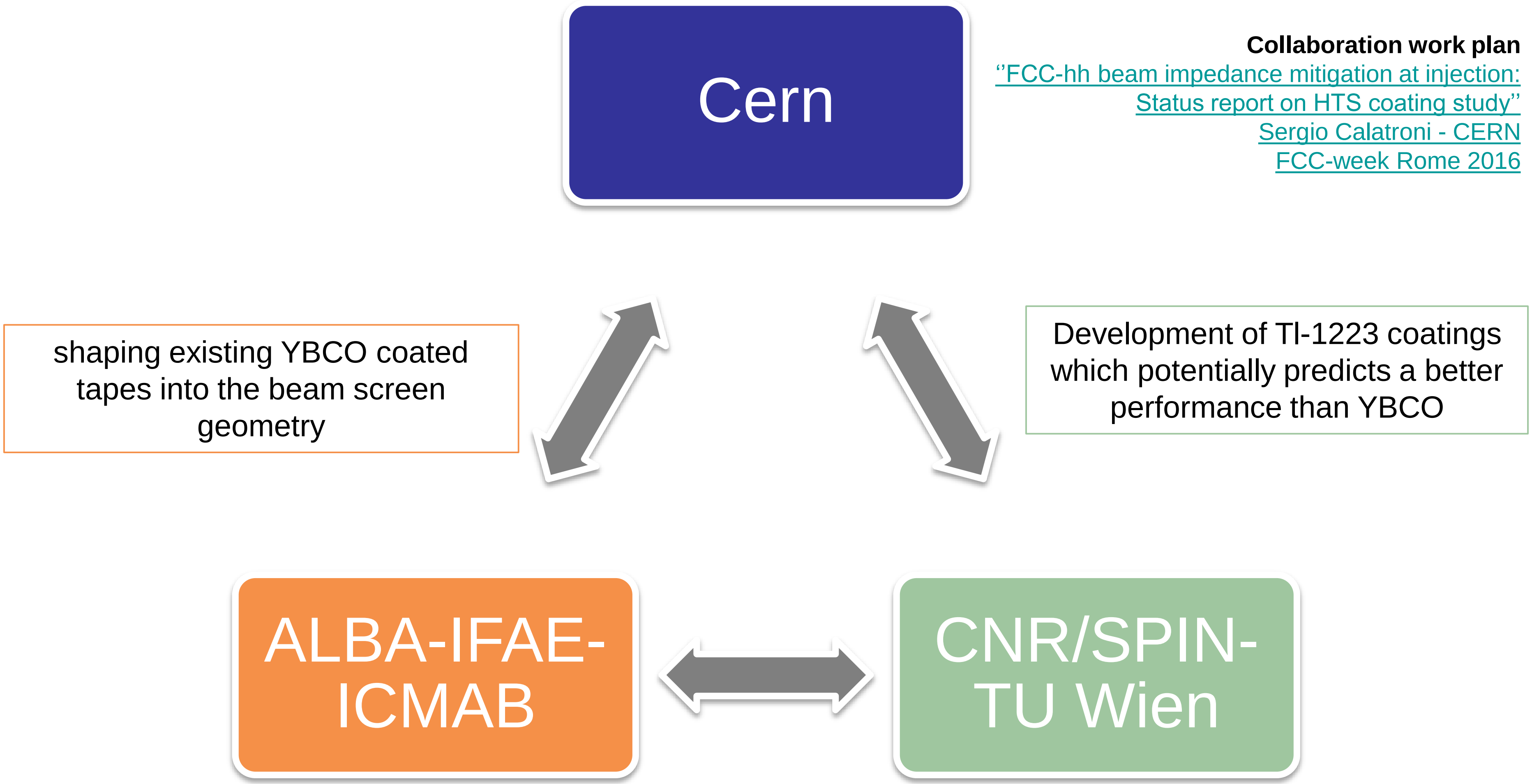
Secondary electron emission yield

- Amorphous Carbon coating to reduce the electron cloud effect
- Just a small raise in the resistance visible
- The question arises how the coating thickness relates to the SEY value
- Dust-particle-beam-interactions?

- Coating properties need extensive experimental validation

Conclusion & Outlook
Experiments & Collaborations

There are two collaborations on HTS which have been established under the FCC by **Sergio Calatroni - (Cern)**



Cern

Collaboration work plan
''FCC-hh beam impedance mitigation at injection:
Status report on HTS coating study''
Sergio Calatroni - CERN
FCC-week Rome 2016

shaping existing YBCO coated tapes into the beam screen geometry

Development of Tl-1223 coatings which potentially predicts a better performance than YBCO

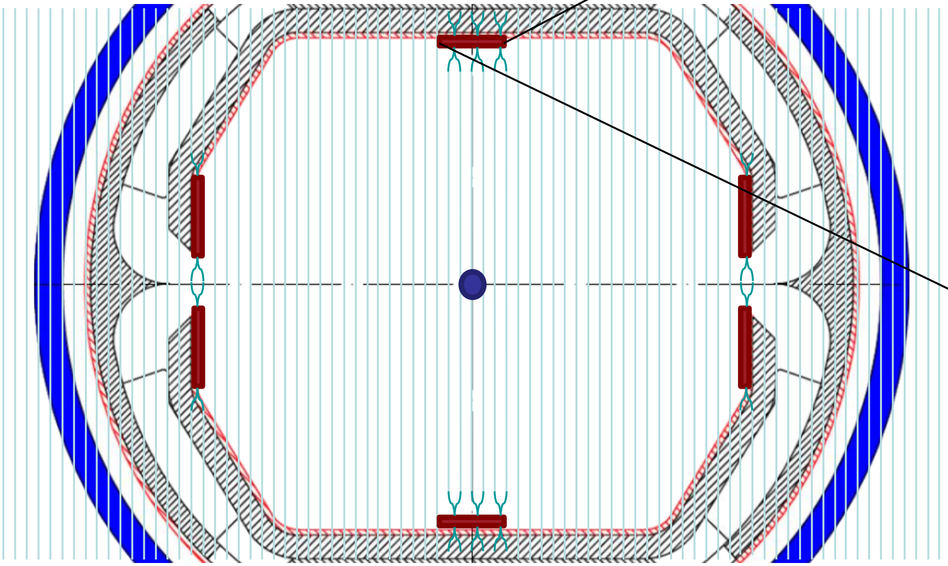
ALBA-IFAE-ICMAB

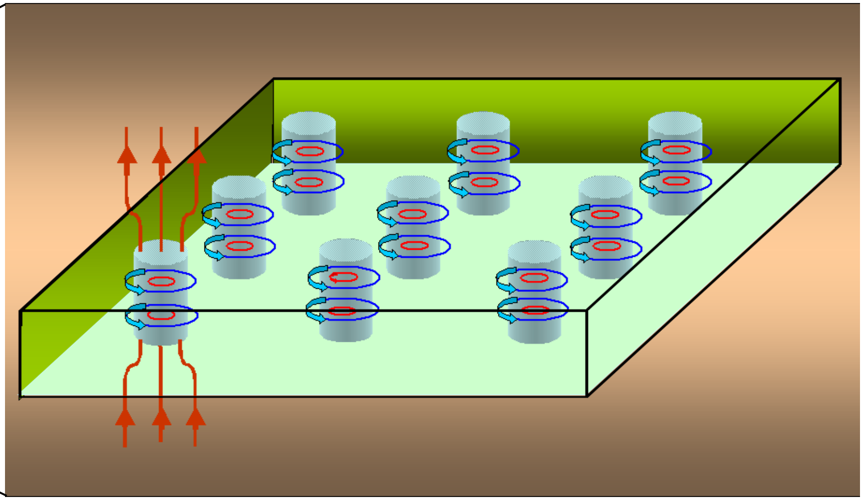
CNR/SPIN-TU Wien

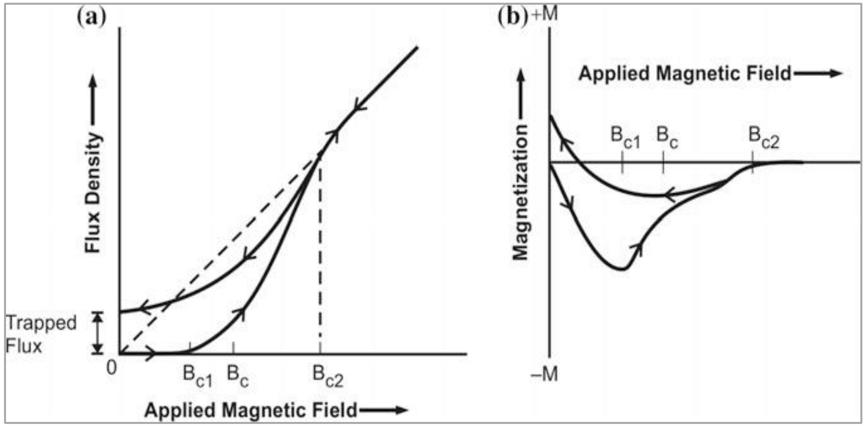
Conclusion & Outlook
Magnetic field

Question:

What value has the distortion of the magnetic field?



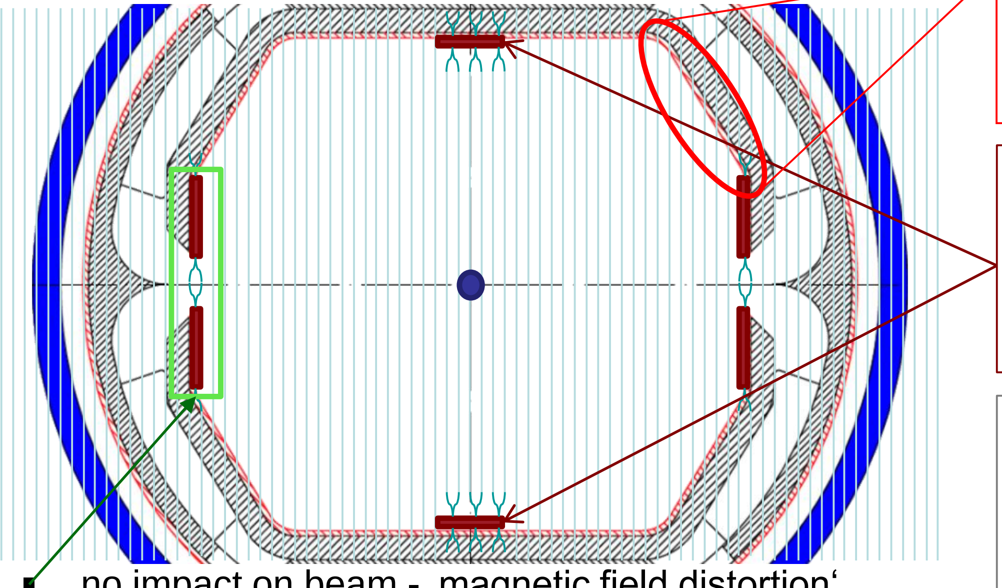




Conclusion & Outlook
Magnetic field

Question:

What value has the distortion of the magnetic field?



- no impact on beam - ‚magnetic field distortion‘
- High synchrotron radiation load of protons @ 50 TeV
  - Heat deposition of 31 W/m on beam screen edge (*)
  - HTS strongly dependent on temperature
  - Effect on the superconducting material

- Assumption:
  - not applicable for wide tapes
  - Properties depend on field orientation
  - Flux Line Lattice behaviour $T \approx \frac{T_c}{2}$

- stronger magnetic field
  - more vortices lead to less distortion
- Mechanical analysis needed
  - During magnetic quench

- Hysteresis
  - Pinning and impurities
  - Multipole field error
  - Destroying superconductivity by warming → unattainable
  - Has to be quantified

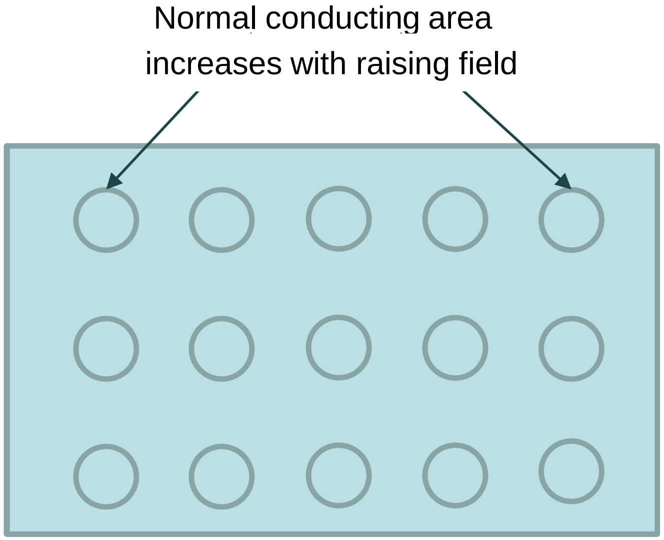
(*) Research program on the cryogenic beam-vacuum of the FCC-hh
R. Kersevan (CERN-TE-VSC)
38th International Conference on High Energy Physics

Superconductor surface resistance in the presence of a dc magnetic field: frequency and field intensity limits

Sergio Calatroni – (submitted to PR-AB)

The presence of a magnetic field modifies the surface impedance of the superconductor

- Flux Line Lattice
    - Normal conducting cores
    - Ratio of normal conducting and superconducting surface area
    - Dependent on magnetic field strength



Normal conducting area increases with raising field

“Low frequency large field“ – approximation

$$R_{sf} = \frac{R_n}{\sqrt{2}}\sqrt{\frac{B}{B_{c2}}}\left(\frac{\omega}{\omega_{dep}}\right)^{3/2}$$

- Resistivity scales with reduced magnetic field $\frac{B}{B_{c2}}$
    - At 50 K the critical field B_{c2} is in the range of 30-50 T
- $R_n \propto \sqrt{\omega}$ $\rightarrow R_{sf}$ still dependent on frequency as ω^2

Conclusion & Outlook

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Secondary electron emission yield

- Amorphous Carbon coating to reduce the electron cloud effect
- Just a small raise in the resistance visible
- The question arises how the coating thickness relates to the SEY value
- Dust-particle-beam-interactions?

▪ Coating properties need extensive experimental validation
▪ Need to measure RF performance as a function of T, B, J at the relevant frequencies for the FCC
▪ Thermal, mechanical and cryogenic aspects have to be studied

HTS coating?
Lots of work
Impedance, coating technology, ecloud, …

Thank you for your attention!

Electrodynamics

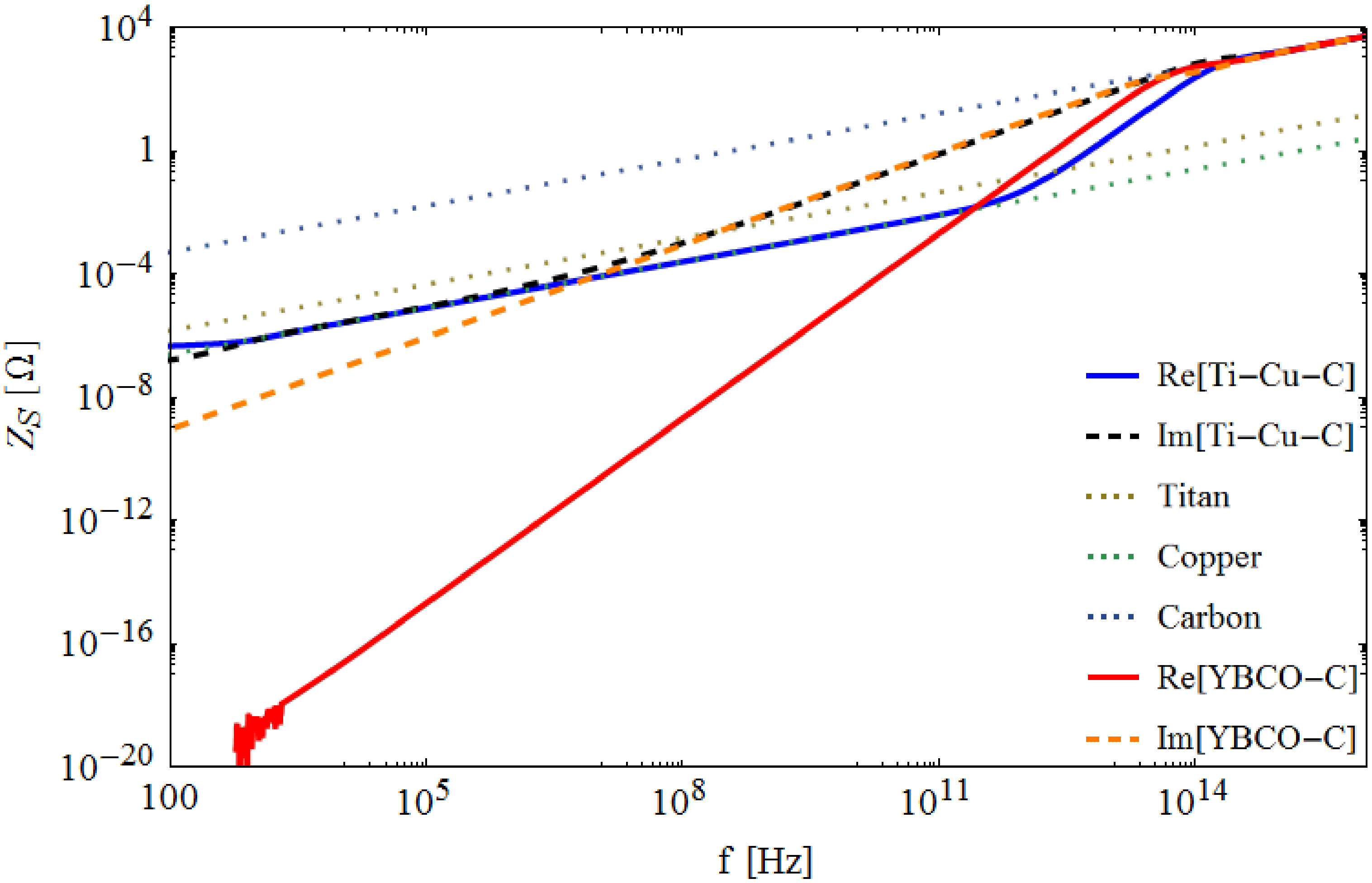
Surface Impedance - Iterative Model

Steel beam screen:
κ = 180 MS/m

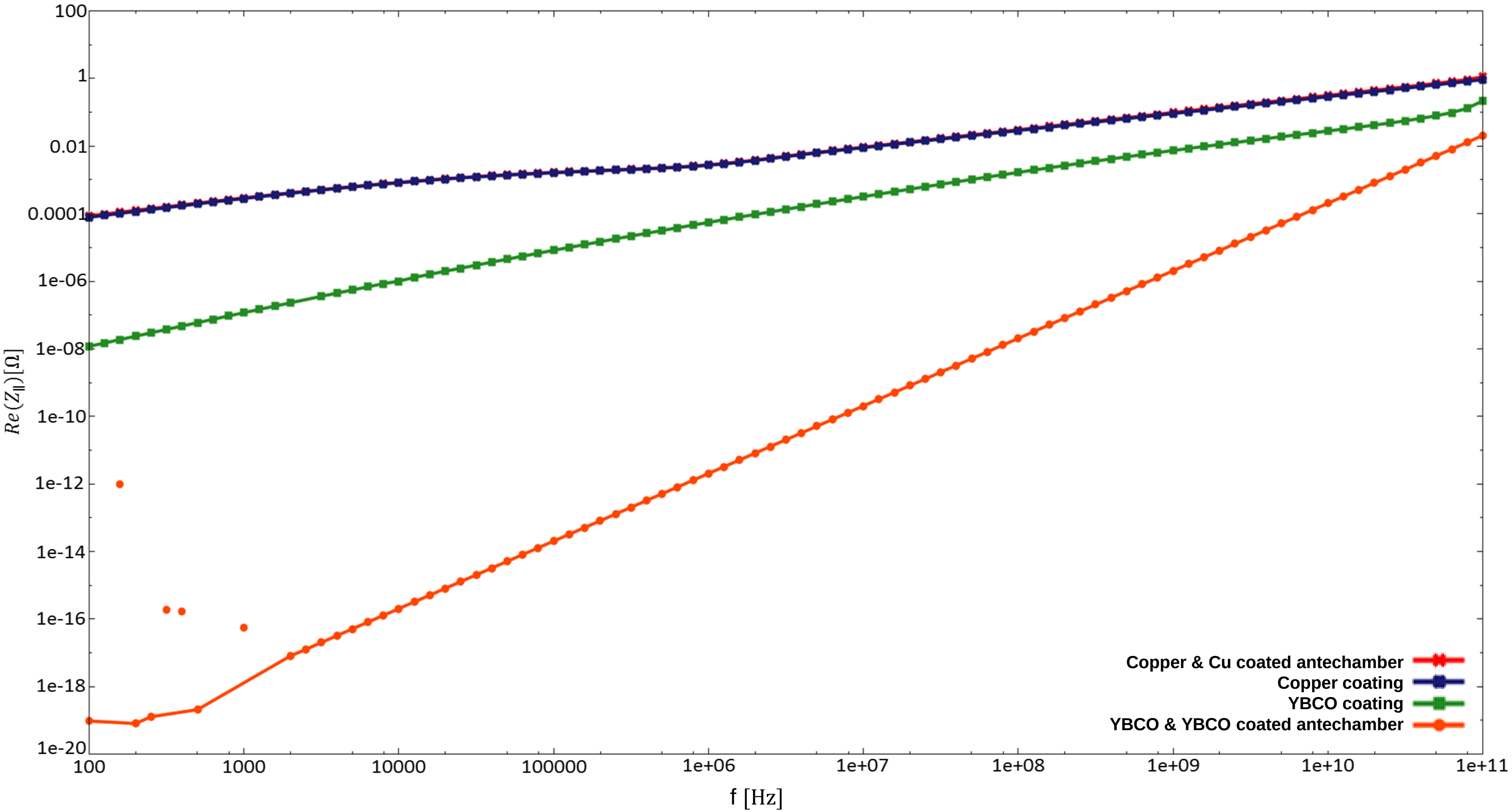
Copper coating:
κ = 6 GS/m
Thickness: 300 µm

YBCO coating:
κ_n = 1.37 MS/m
Thickness: 1 µm

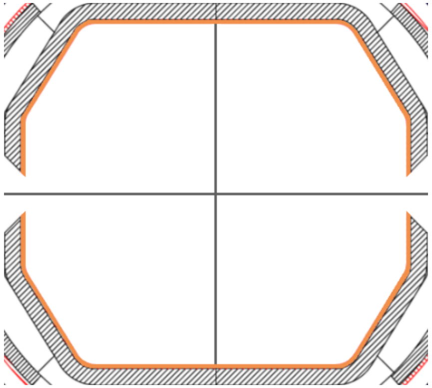
Carbon coating:
(amorphous)
κ = 1.4 kS/m
Thickness: 1 µm



Impedance Calculation
Longitudinal Impedance - Effect of the Radiation Slit



Various Configurations



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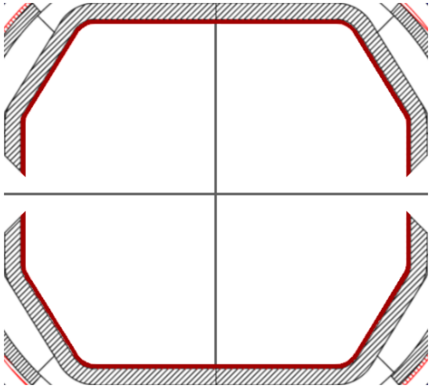

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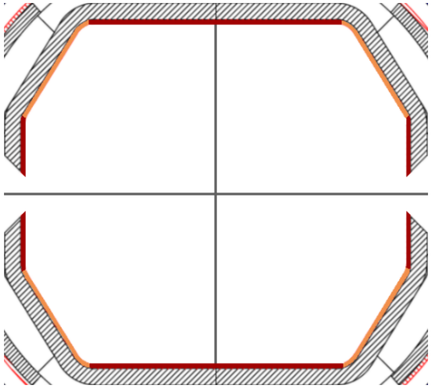

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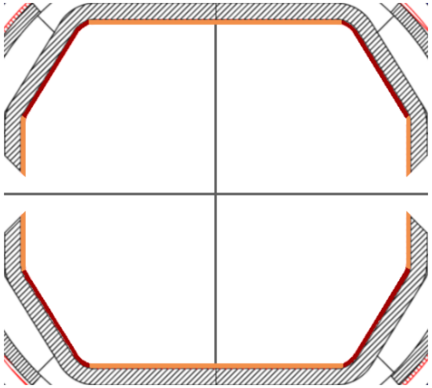

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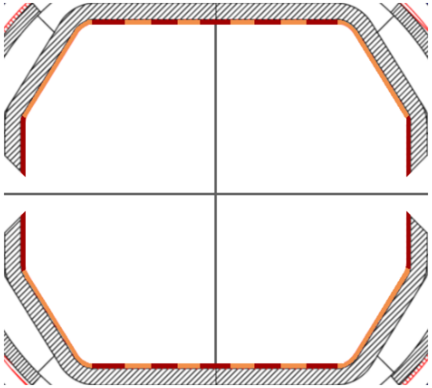

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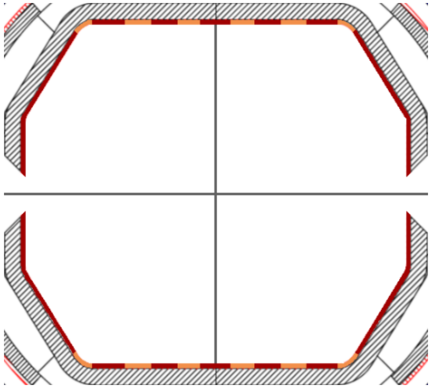

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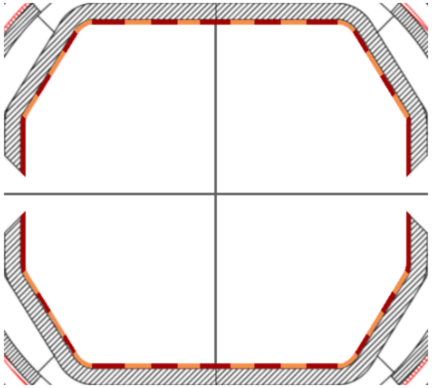
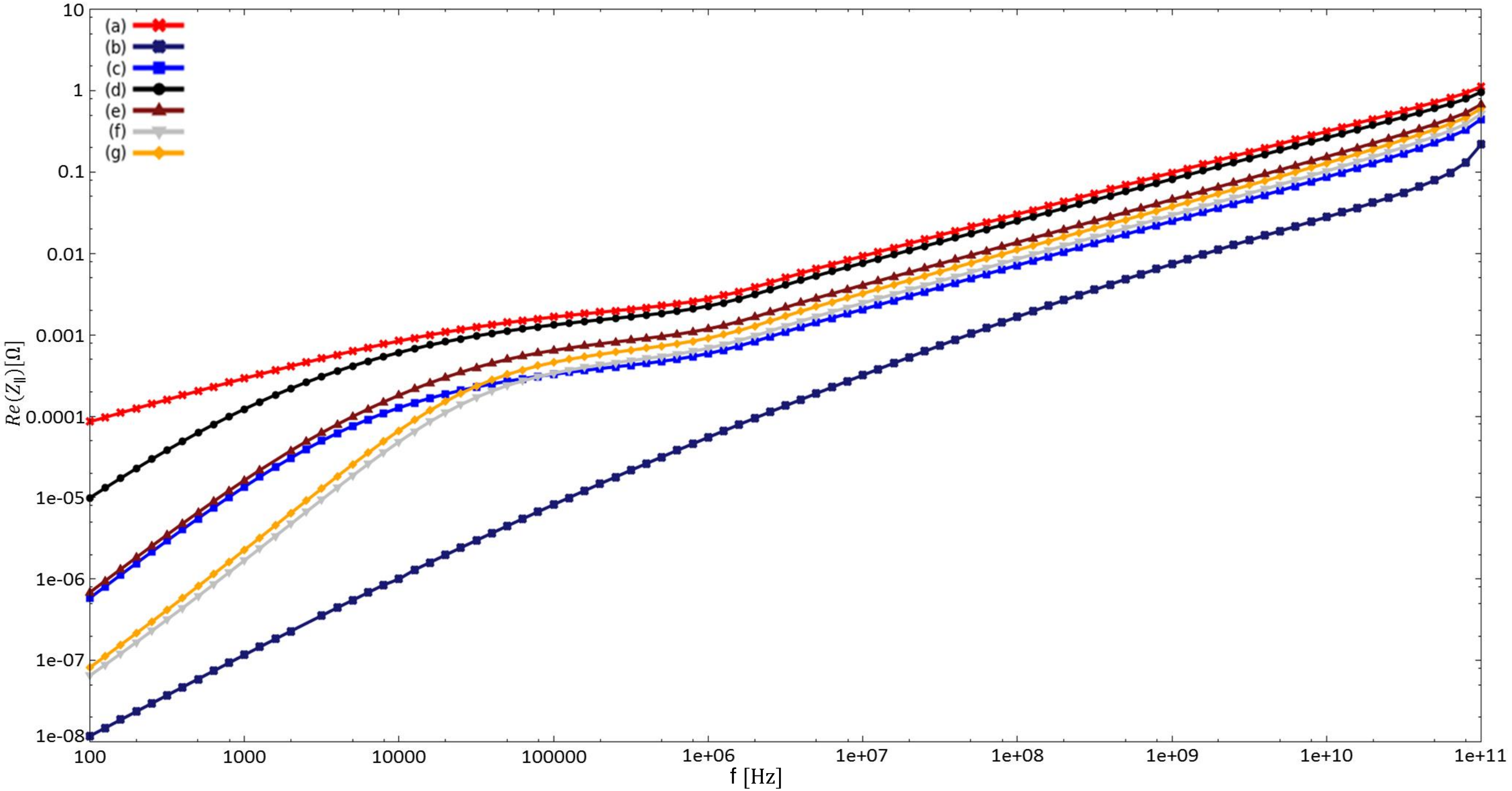


g

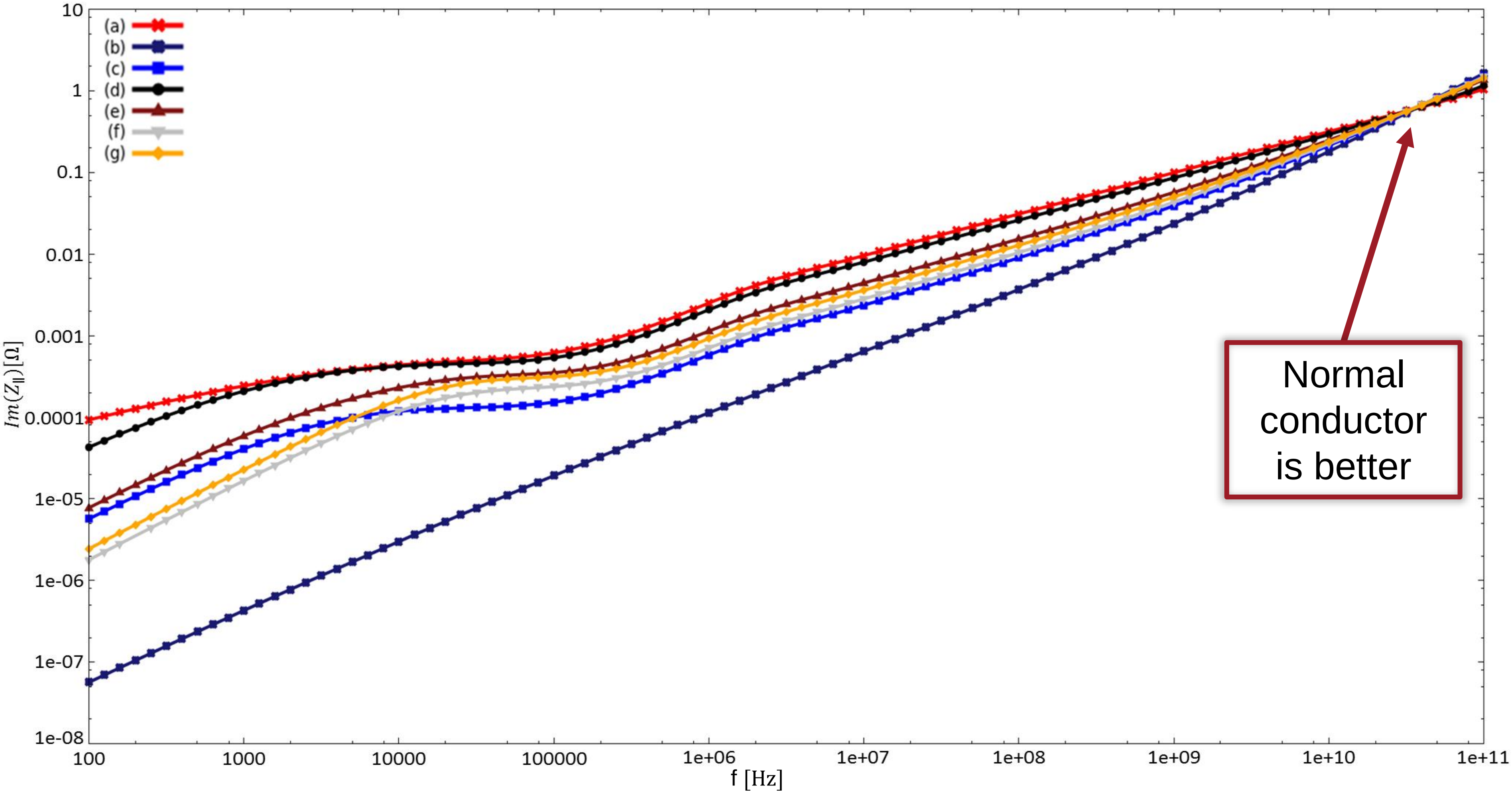
Impedance Calculation (BI2D)
Longitudinal Impedance



🟧 Cu 🟥 YBCO

Impedance Calculation (BI2D)

Longitudinal Impedance

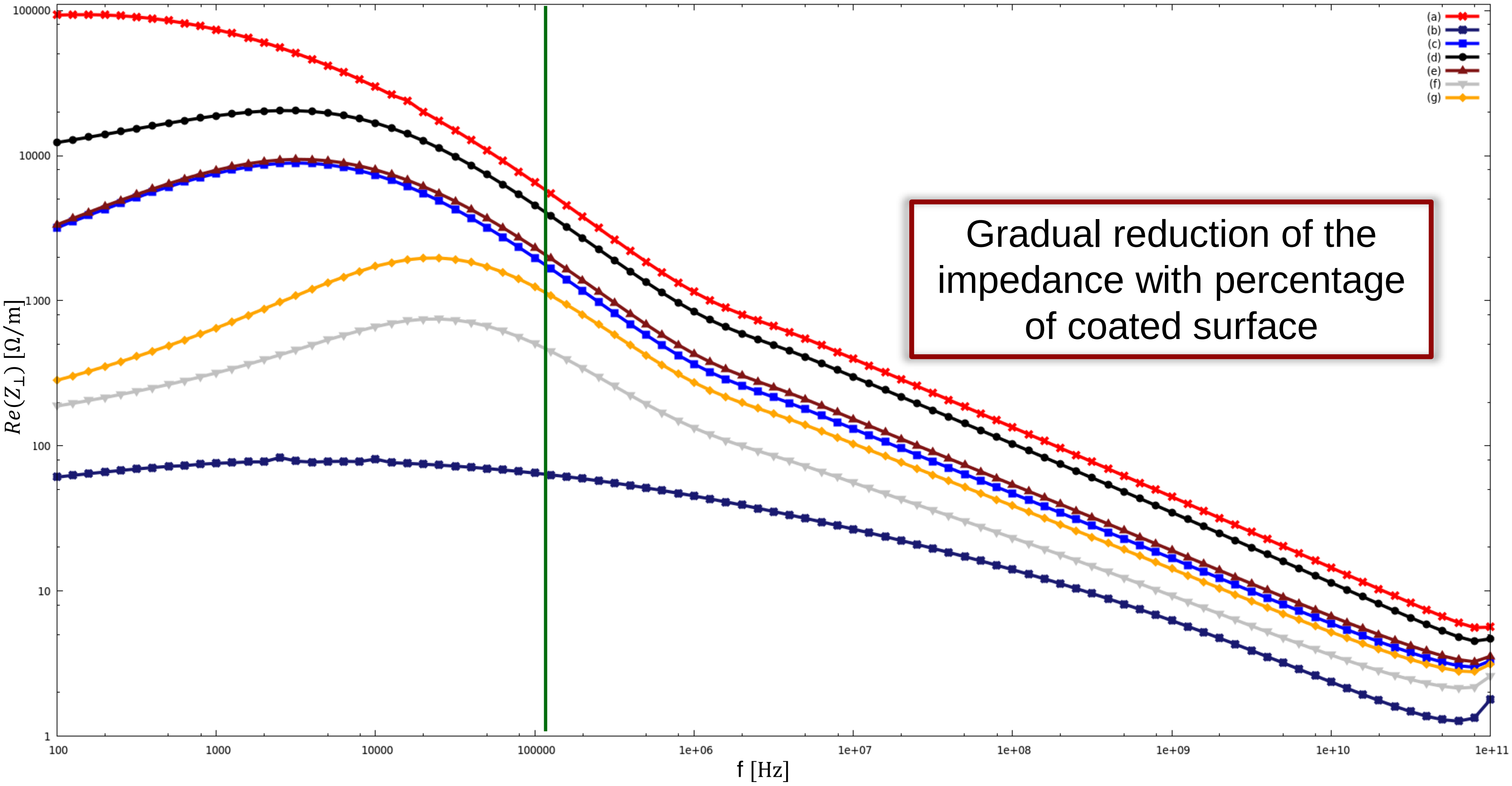


Normal conductor is better

Cu YBCO

Impedance Calculation (BI2D)

Transversal Impedance – horizontal dipol source

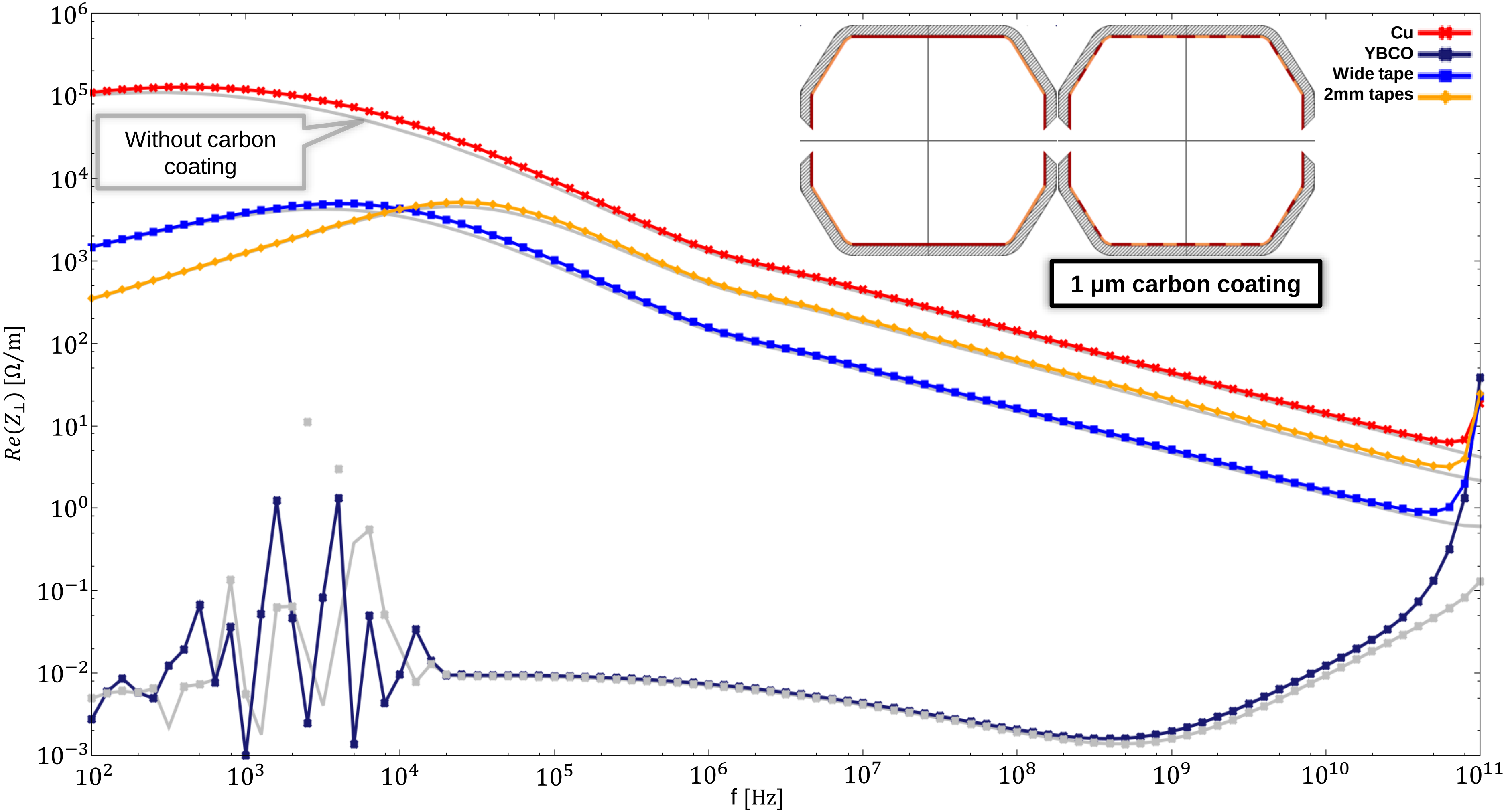


Gradual reduction of the impedance with percentage of coated surface

🟧 Cu 🟥 YBCO

Impedance Calculation (BI2D)

Transversal Impedance – vertical dipol source



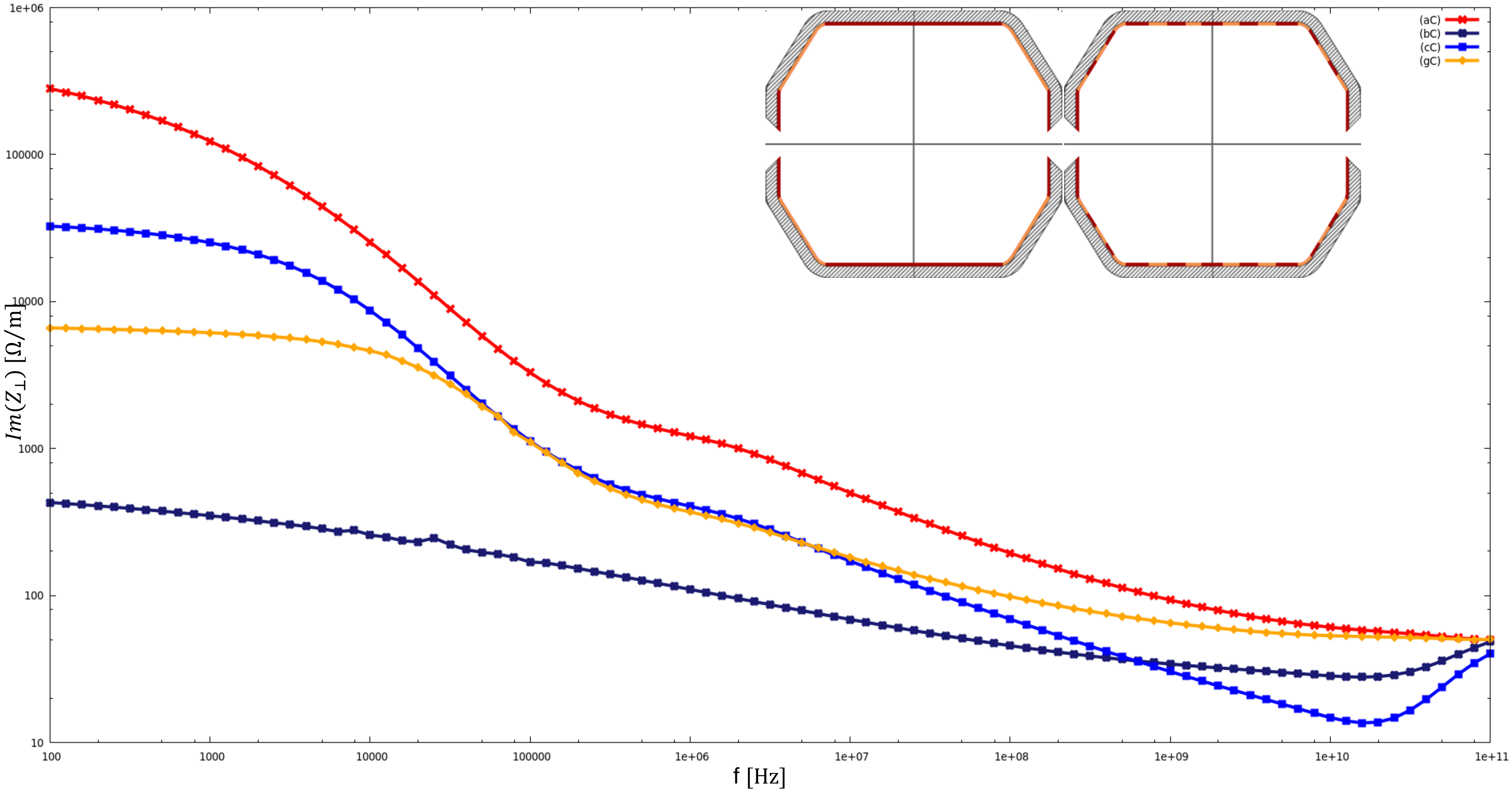
Without carbon coating

1 µm carbon coating

Cu YBCO

Impedance Calculation (BI2D)

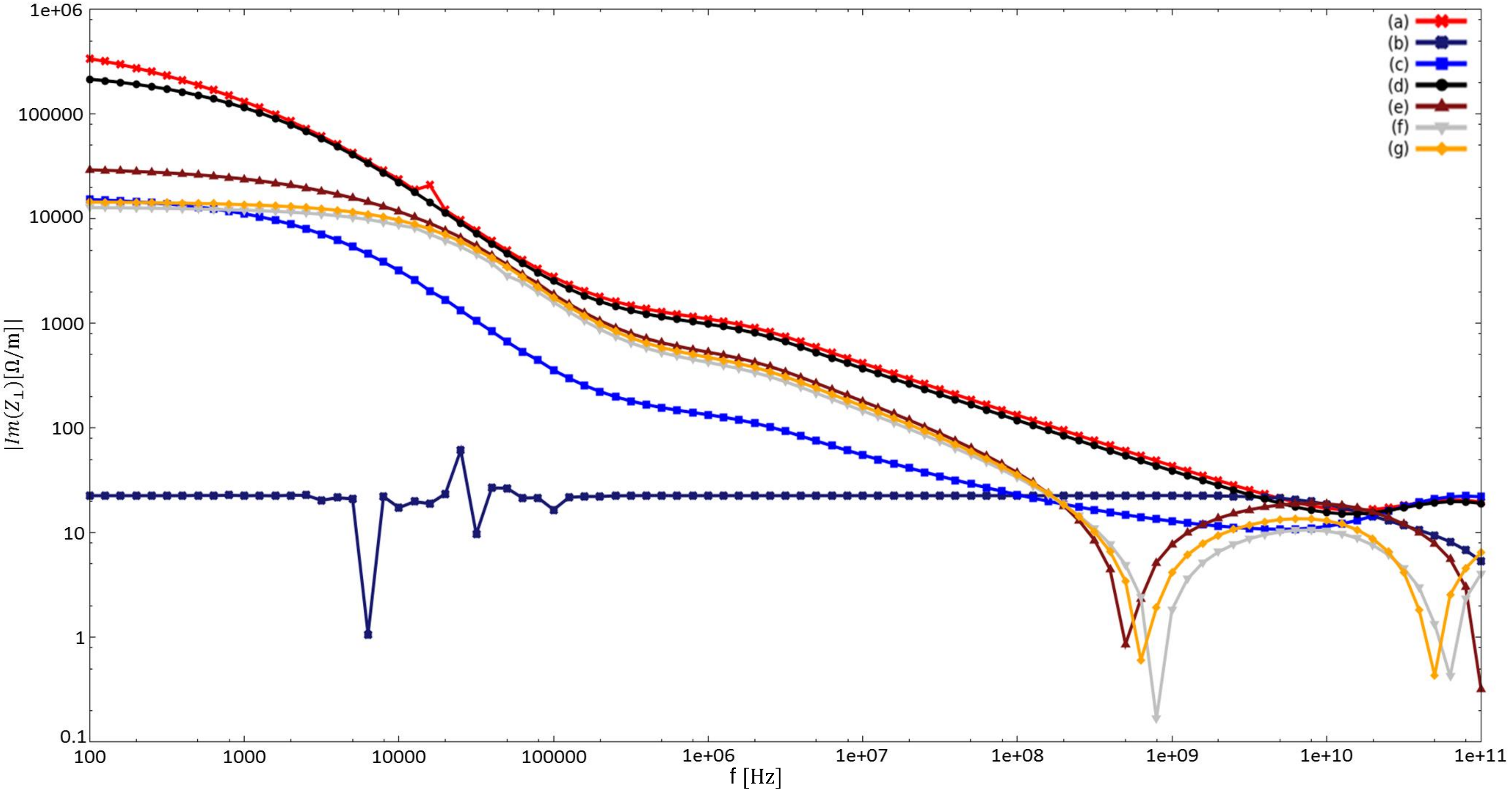
Transversal Impedance – horizontal dipol source



▬ Cu ▬ YBCO

Impedance Calculation (BI2D)

Transversal Impedance – vertical dipol source



Cu YBCO

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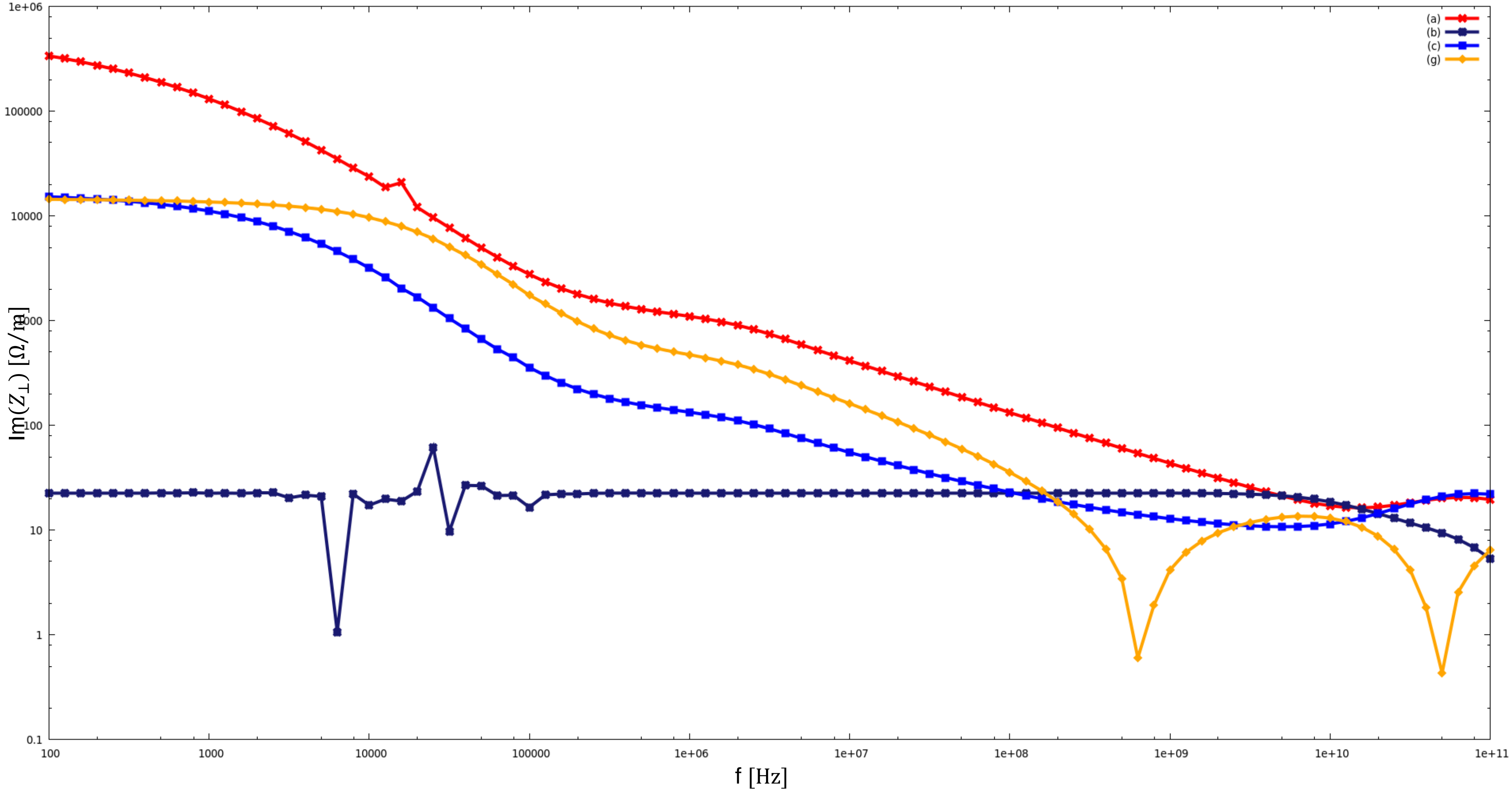
Transversal Impedance – vertical dipol source



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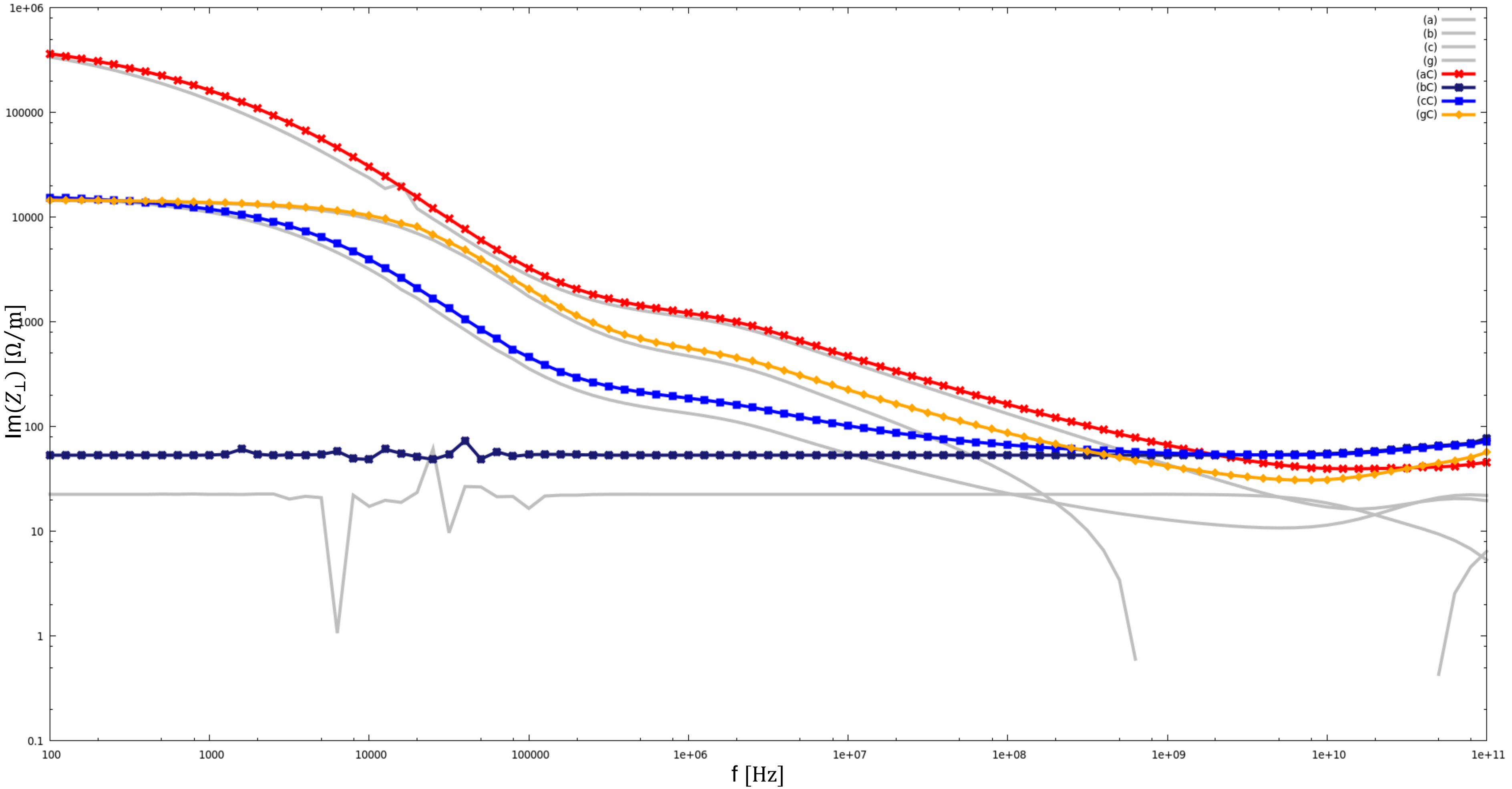


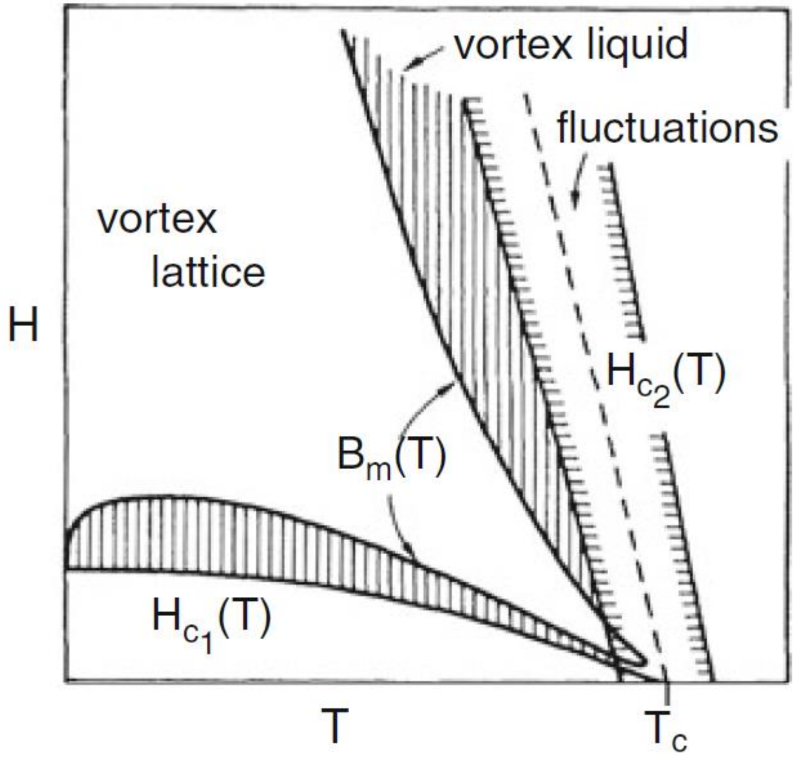
🟧 Cu 🟥 YBCO

HTS Coating
Magnetic Field – Vortex

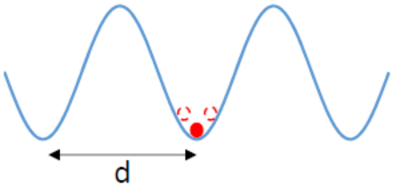
H-T phase diagram for cuprate superconductors shows several phases of vortex matters:

- ordered vortex-lattice at low fields

  $H_{c1} < H \ll H_{c2}$
- highly disordered vortex-solid at high fields and low temperatures (vortex-glass)
- vortex-liquid at high temperatures



N.Plakida, High-Temperature Cuprate Superconductors, Spinger Heidelberg



Prof. Ruggero Vaglio - Naples University

→ distorsion of magnetic field

*HTS Coating

normal dc-conductivity

Surface Resistance $R_S = \frac{1}{2}\kappa_n \mu_o^2 \omega^2 \lambda^3 \rightarrow \kappa_n = \frac{2R_S}{\mu_o^2 \omega^2 \lambda^3}$

London penetration depth for YBCO $\lambda \approx 150nm$

Buckel, Werner: Supraleitung, Grundlagen und Anwendungen, 7.Auflage, Wiley-VHC Verlag GmbH & Co.KGaA, 2013

Two fluid model predicts temperature dependence

$$\lambda(T) = \lambda(0)\left[1 - \left(\frac{T}{T_c}\right)^4\right]^{-1/2}$$

$\lambda(50K) = 157\ nm$

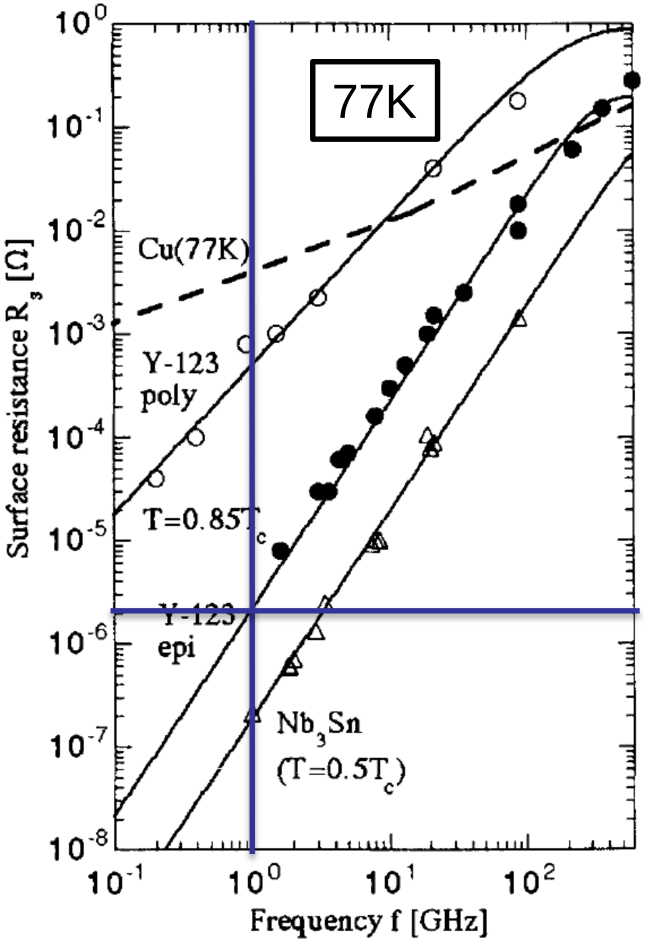
$\lambda(77K) = 206\ nm$

For $T = 77K$, $f = 1GHz$ and $R_S = 2.1 \cdot 10^{-6}\Omega$

$$\kappa_n\ (K) = \frac{2R_S}{\mu_o^2 \omega^2 \lambda(77K)^3} = 7.7\ \cdot 10^6\ S/m$$

Scaling the conductivity with TFM $\kappa_n\ (T) = \kappa_0 \left(\frac{T}{T_c}\right)^4$ | $\kappa_0 = \frac{ne^2\tau}{m_e}$

Ratio of $\frac{\kappa_n(50K)}{\kappa_n(77K)} \rightarrow \kappa_n(50K) = 1.37 \cdot 10^6\ S/m$



Hein, Matthias: High-Temperature-Superconductor Thin Films at Microwave Frequencies, Springer-Verlag Berlin Heidelberg (1999)