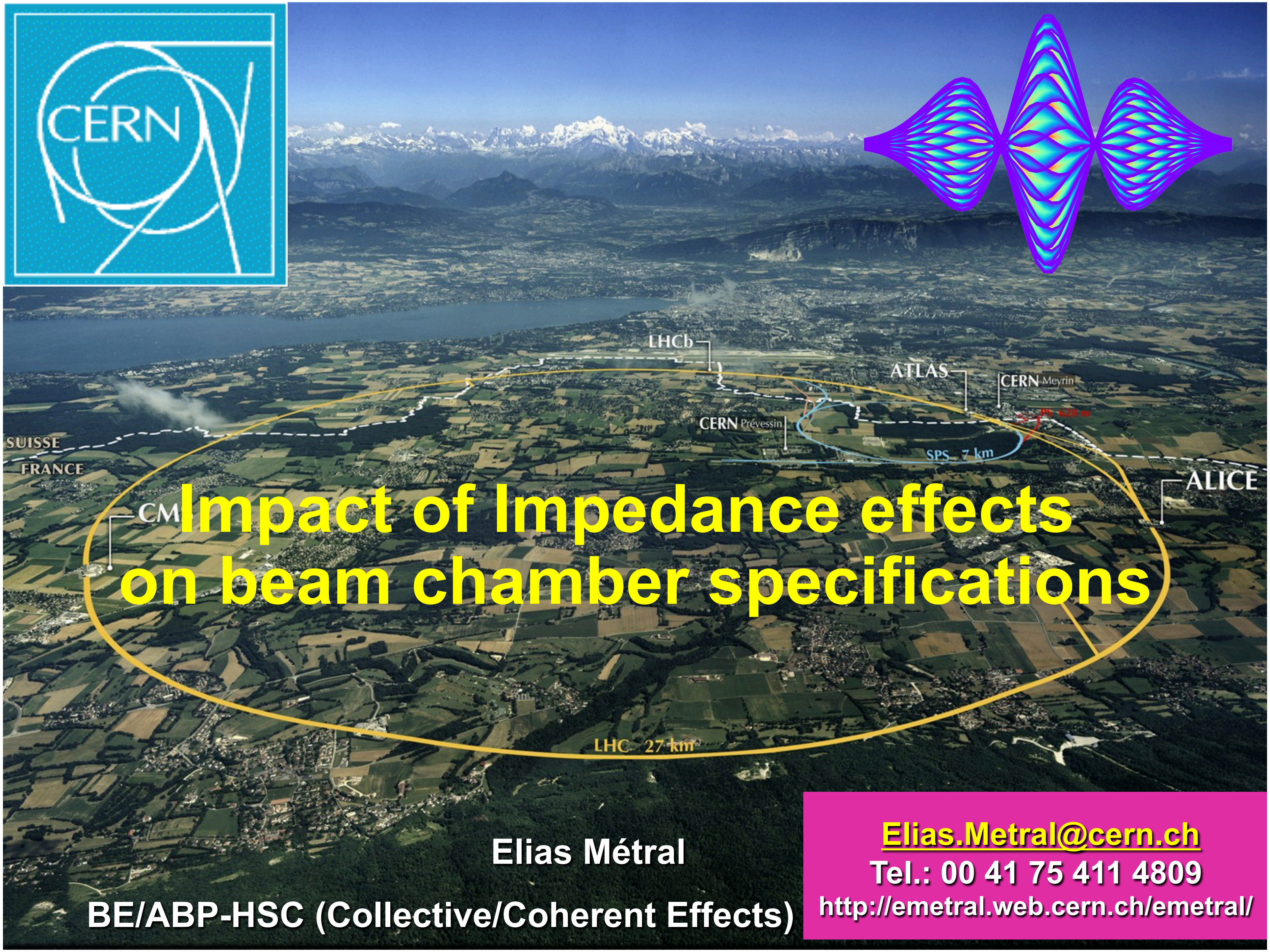
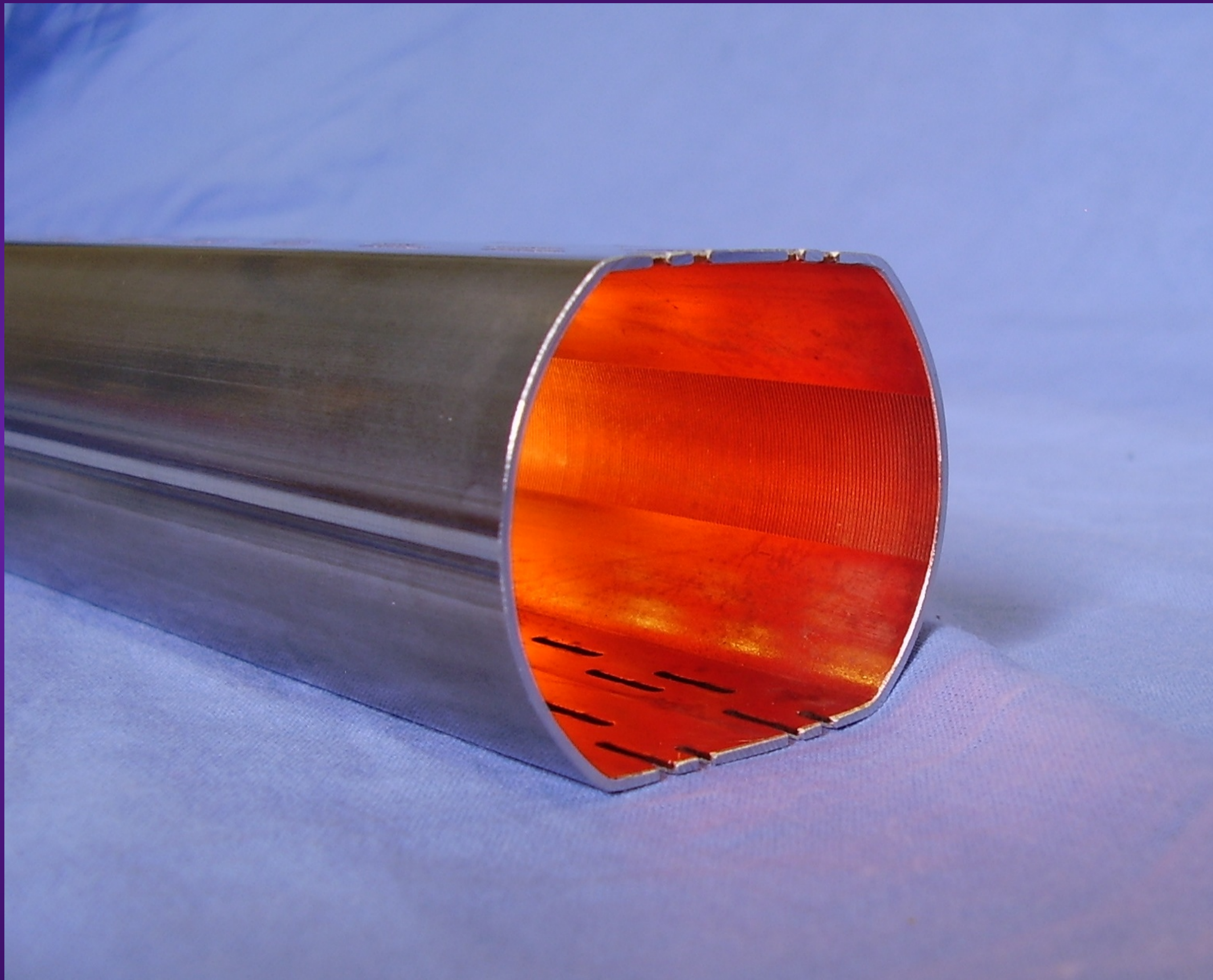


Impact of Impedance effects on beam chamber specifications

Elias Métral
BE/ABP-HSC (Collective/Coherent Effects)
Elias.Metral@cern.ch
Tel.: 00 41 75 411 4809
http://emetral.web.cern.ch/emetral/

INTRODUCTION: THE LHC BEAM CHAMBER



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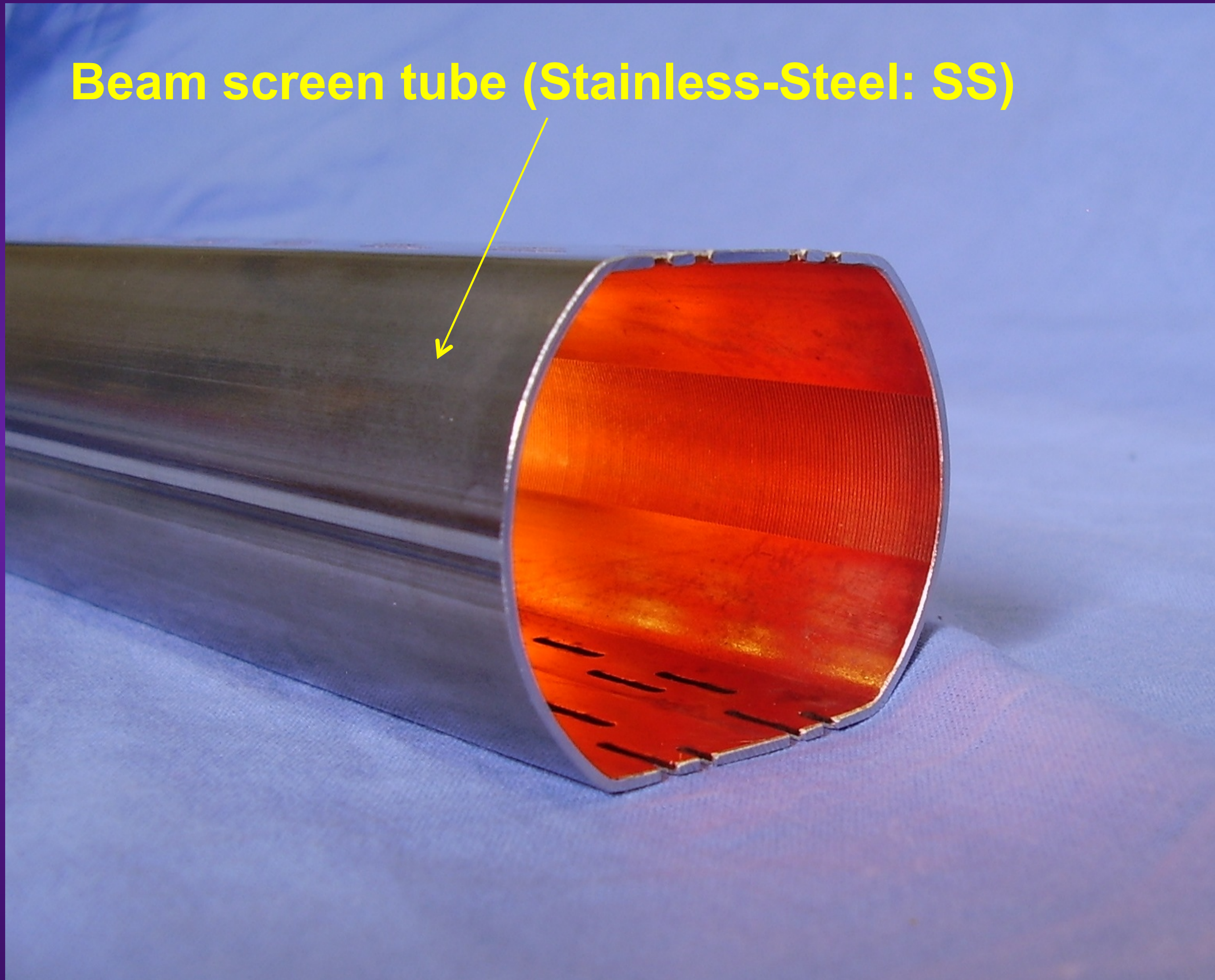

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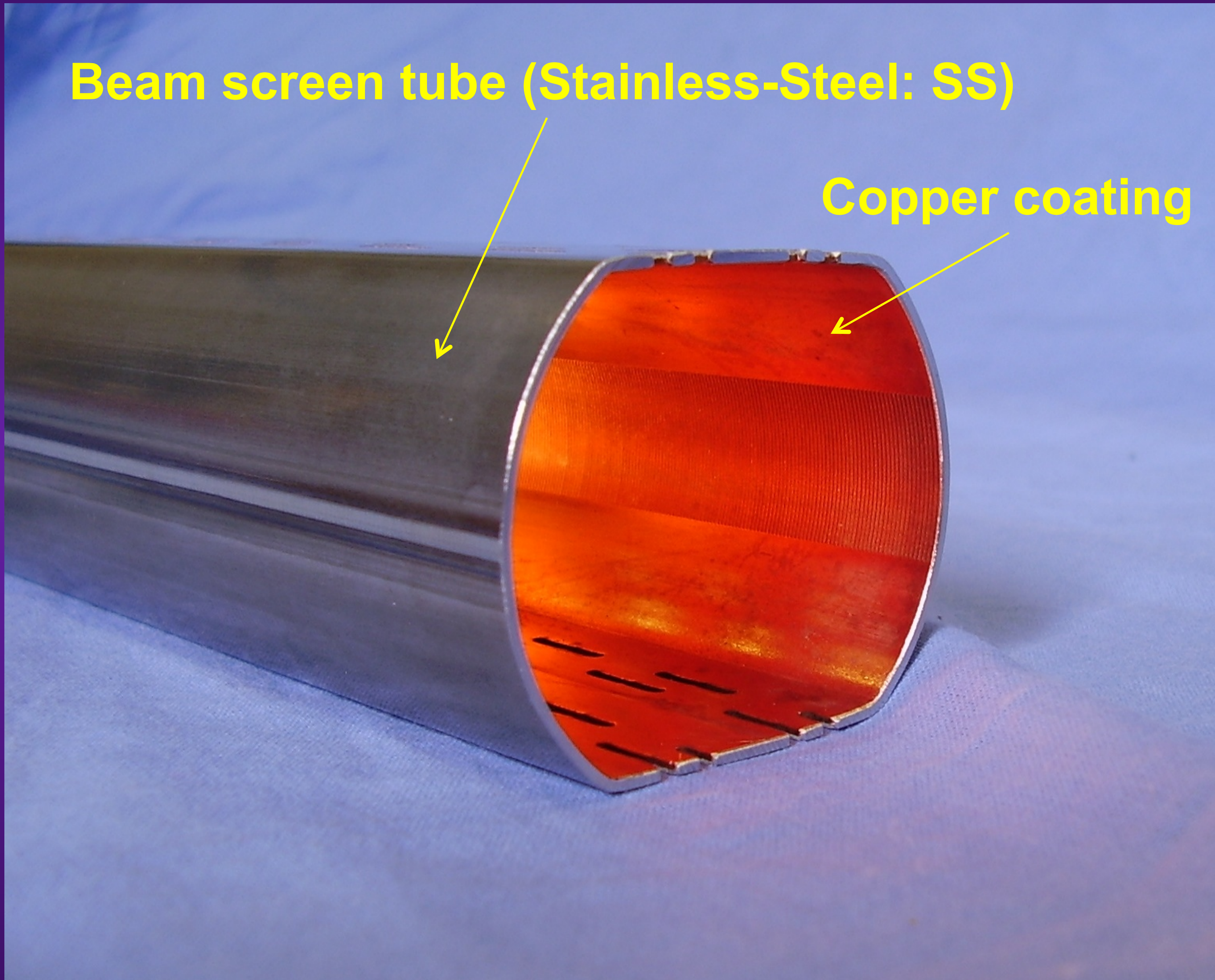

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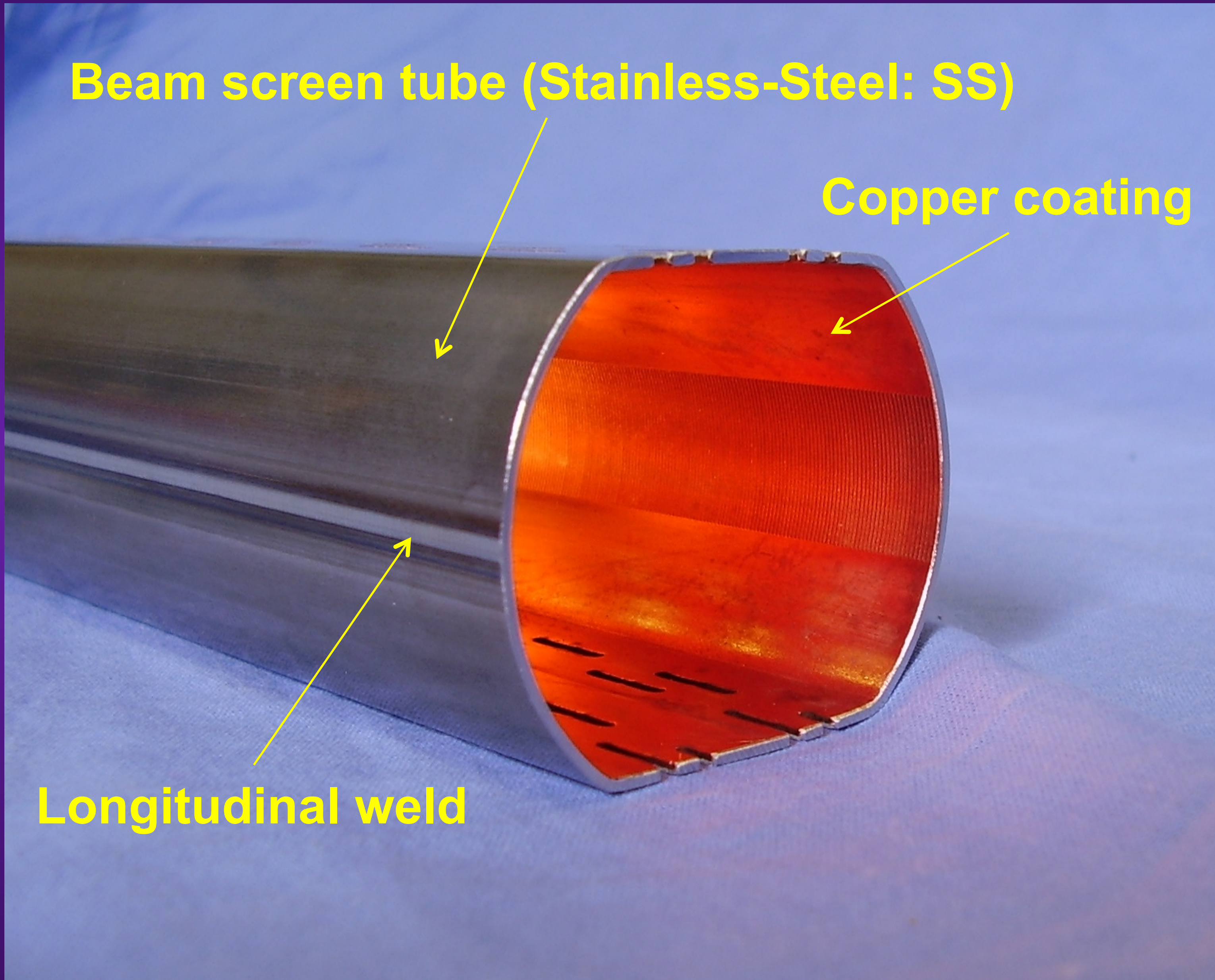

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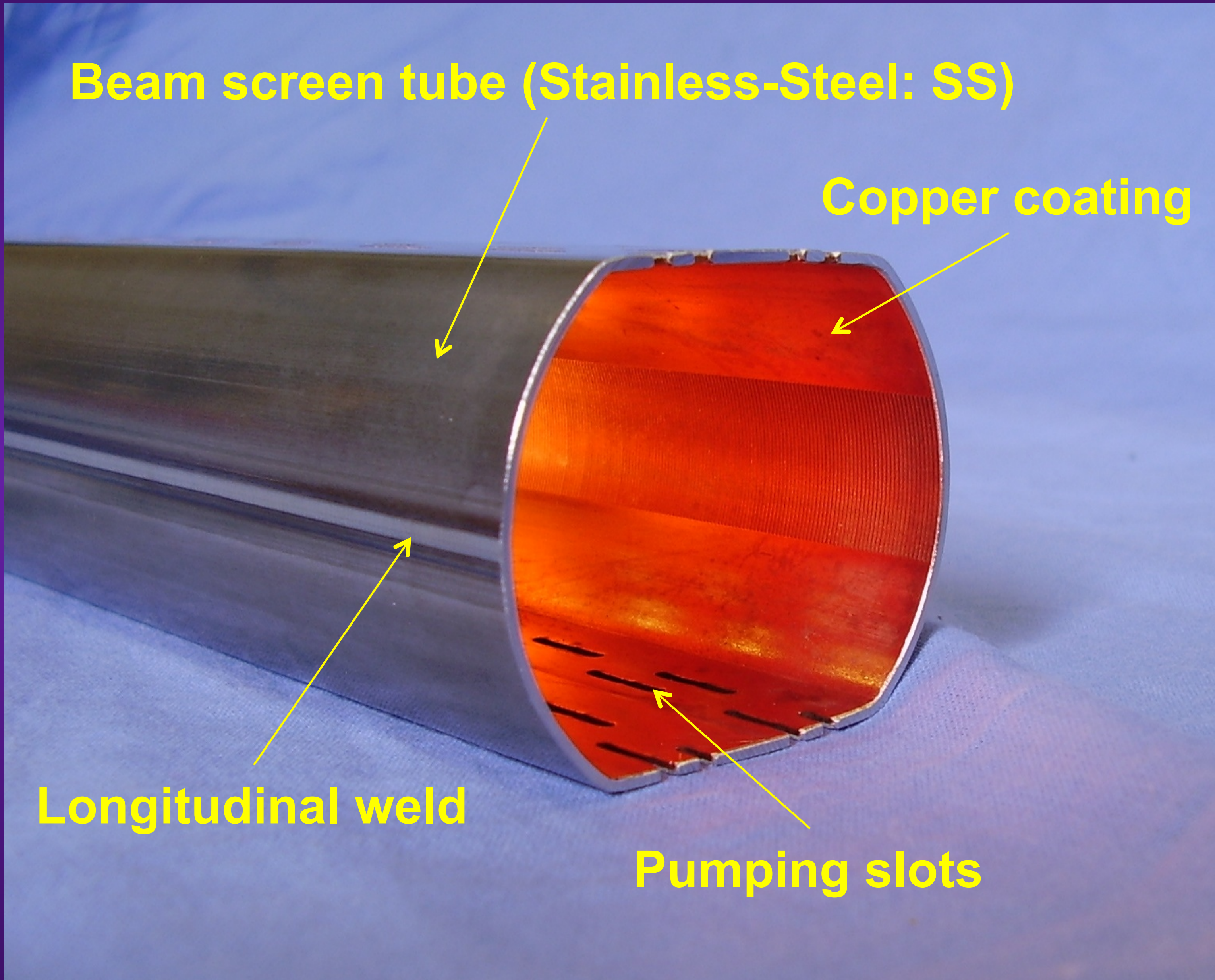

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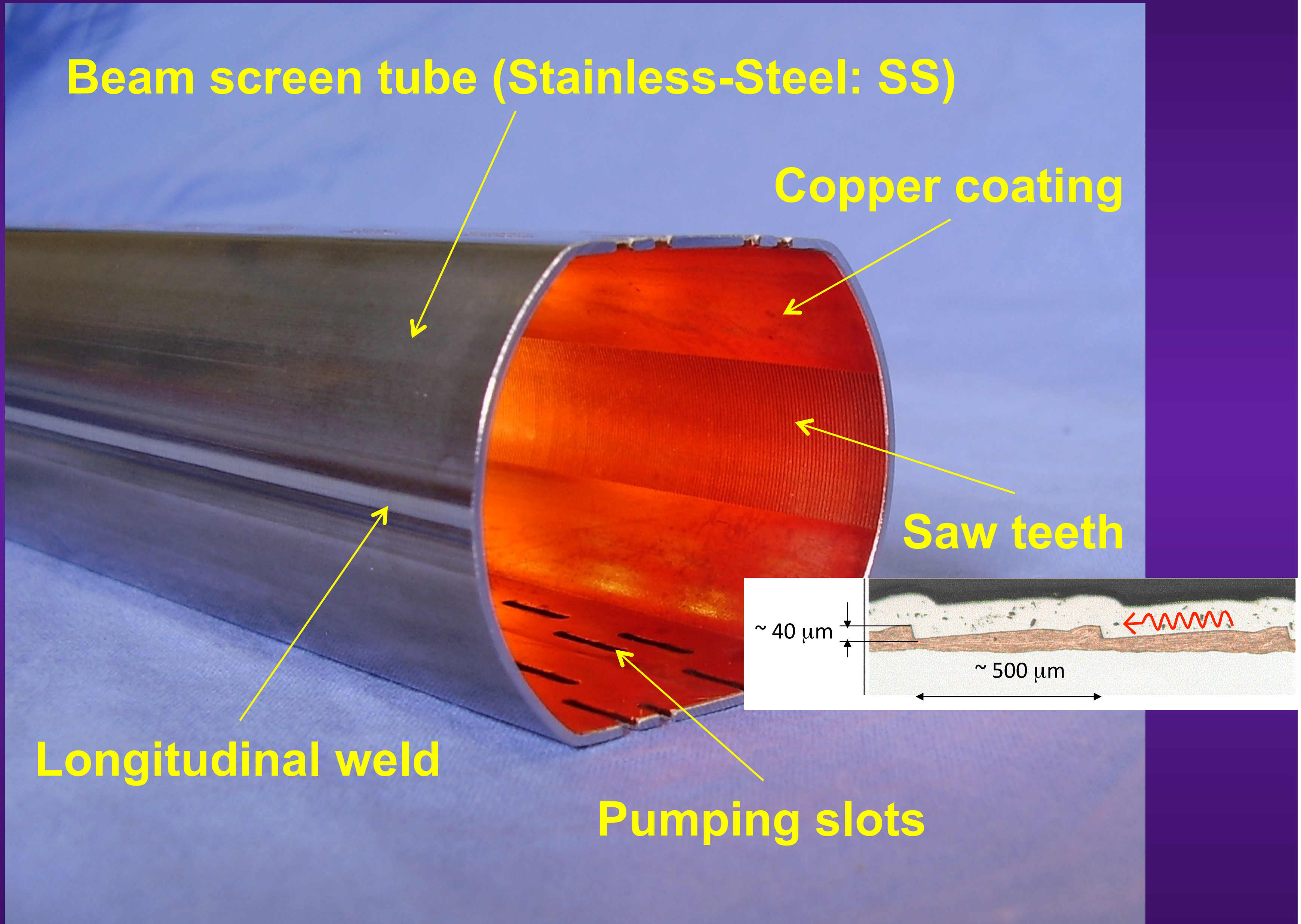

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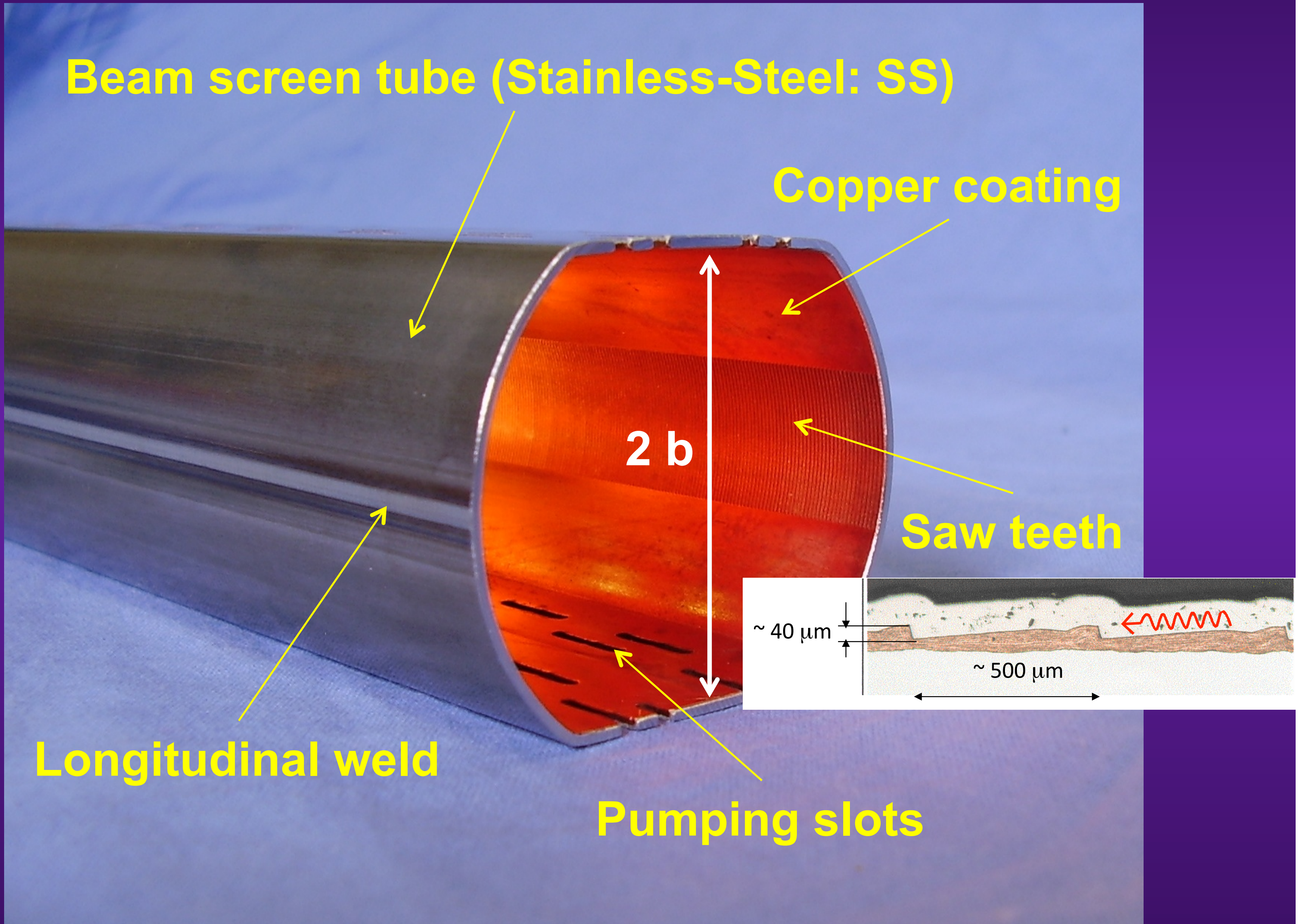

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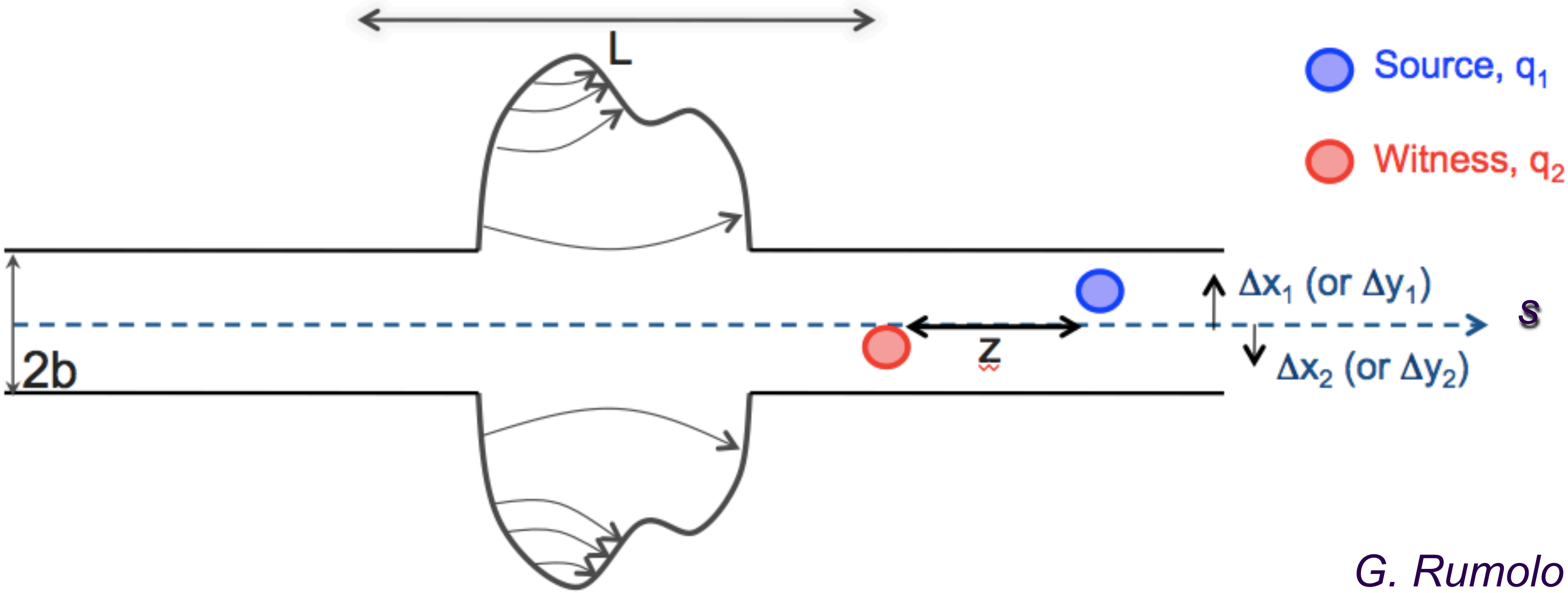
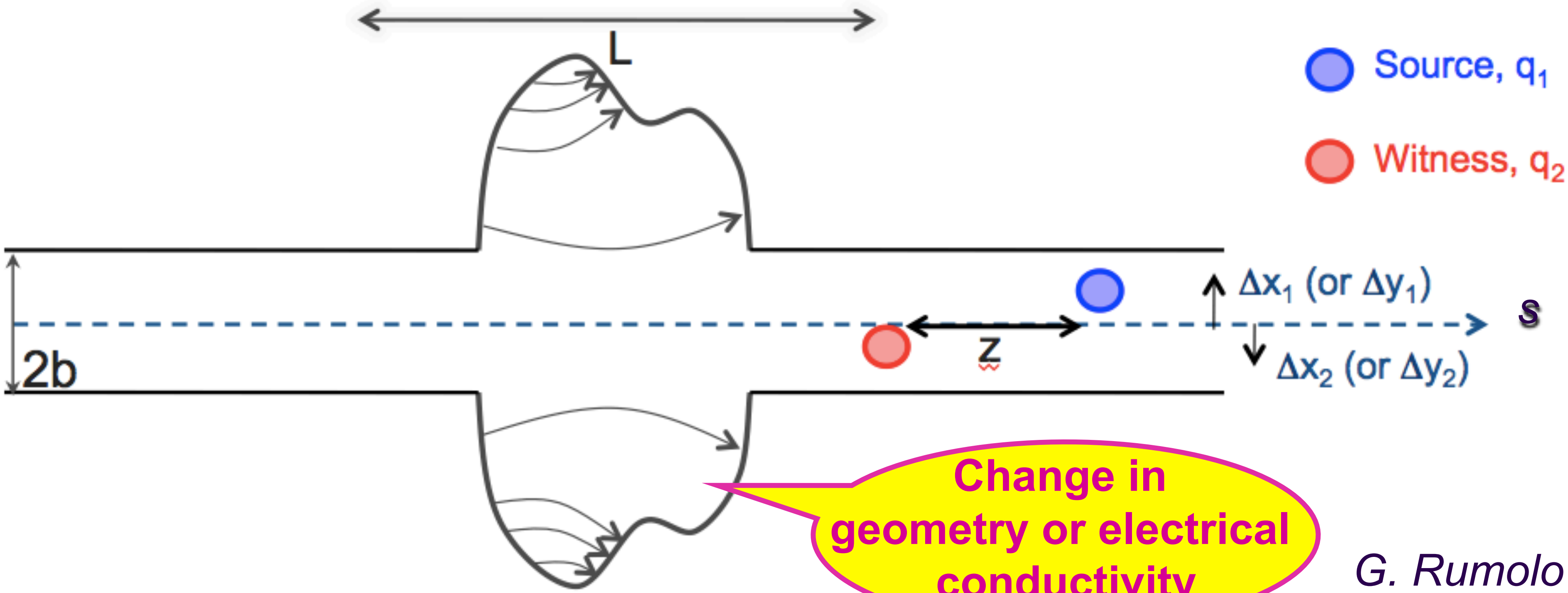


G. Rumolo

INTRODUCTION: THE IMPEDANCE



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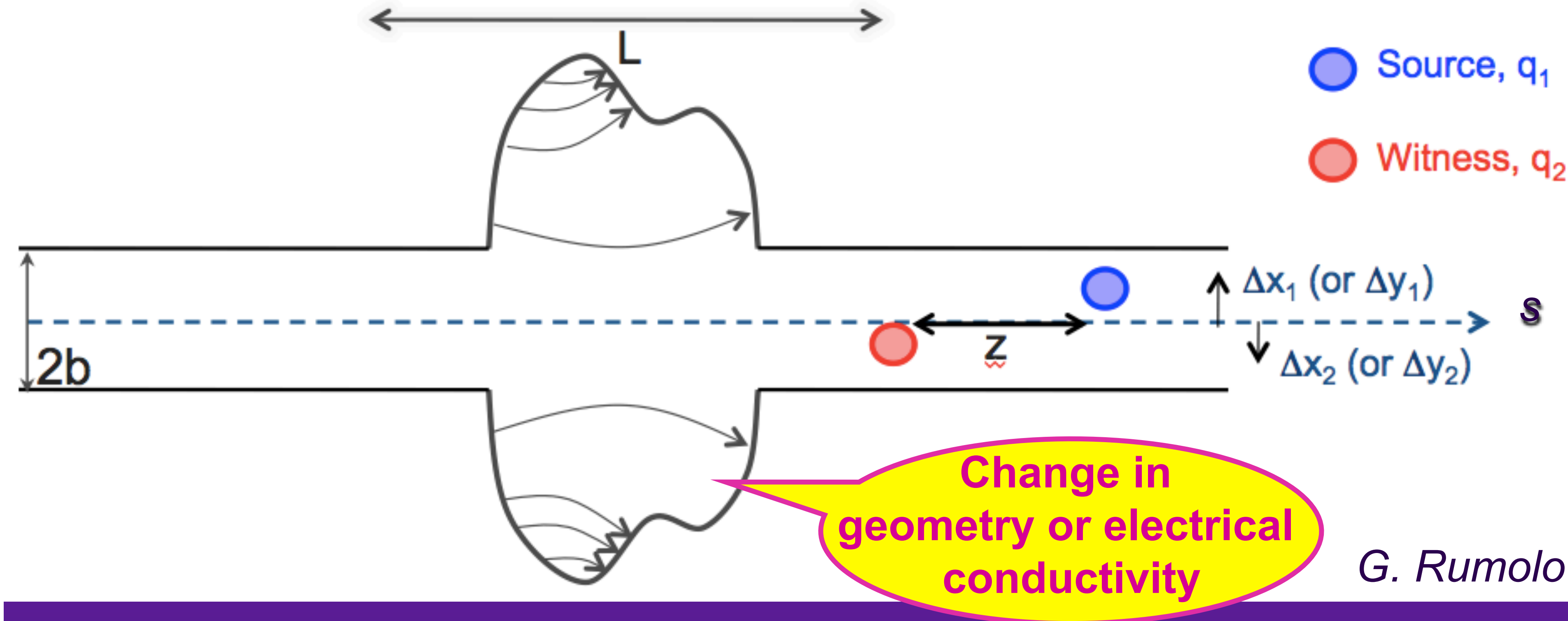

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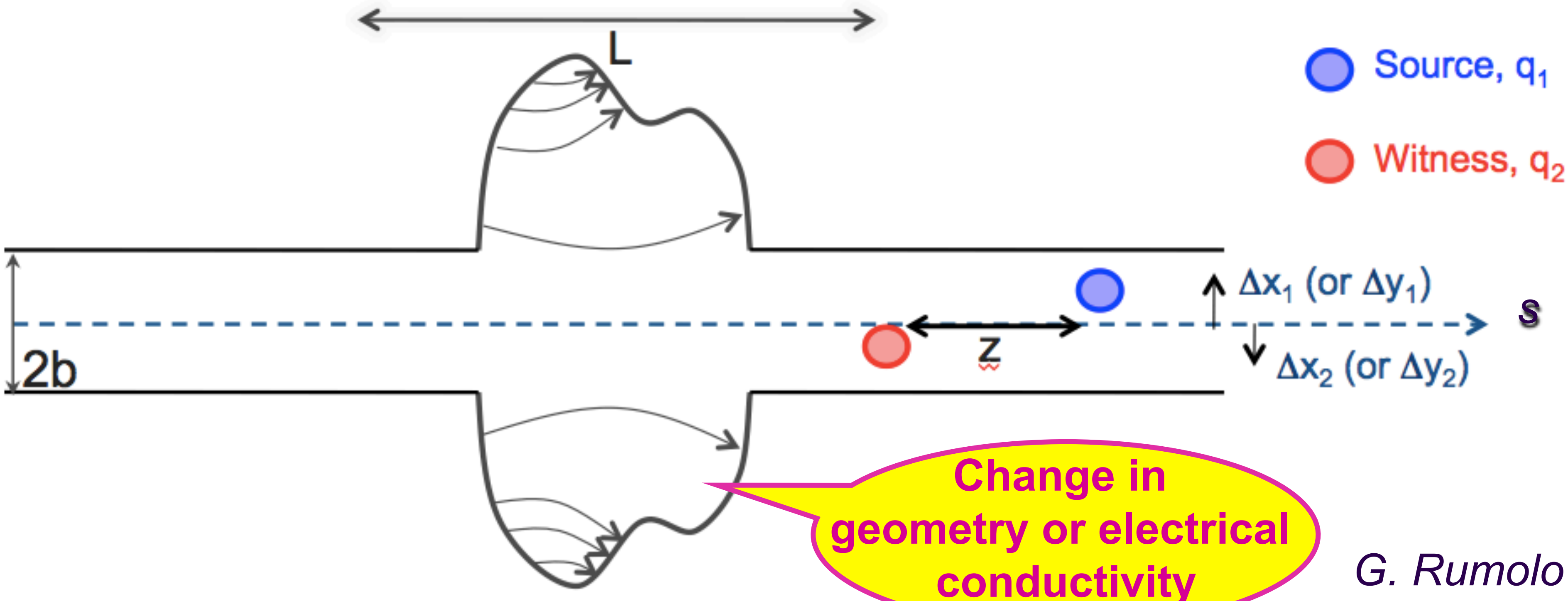

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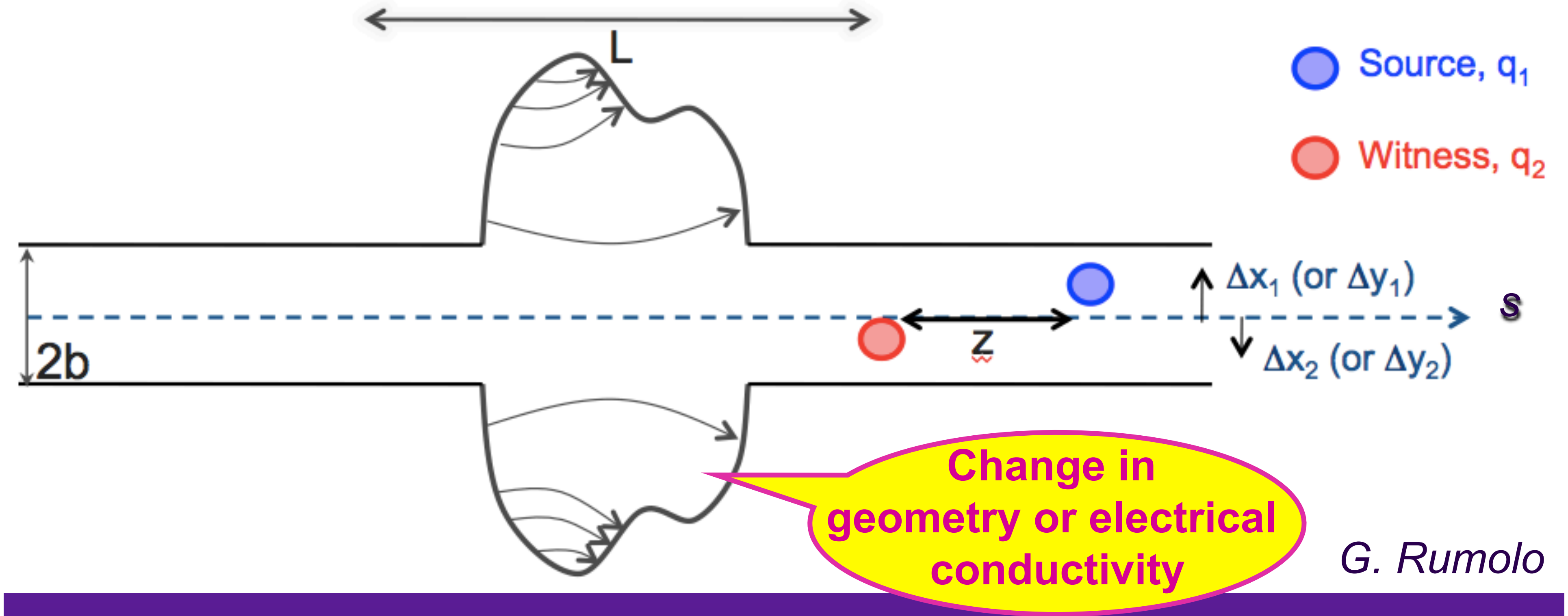

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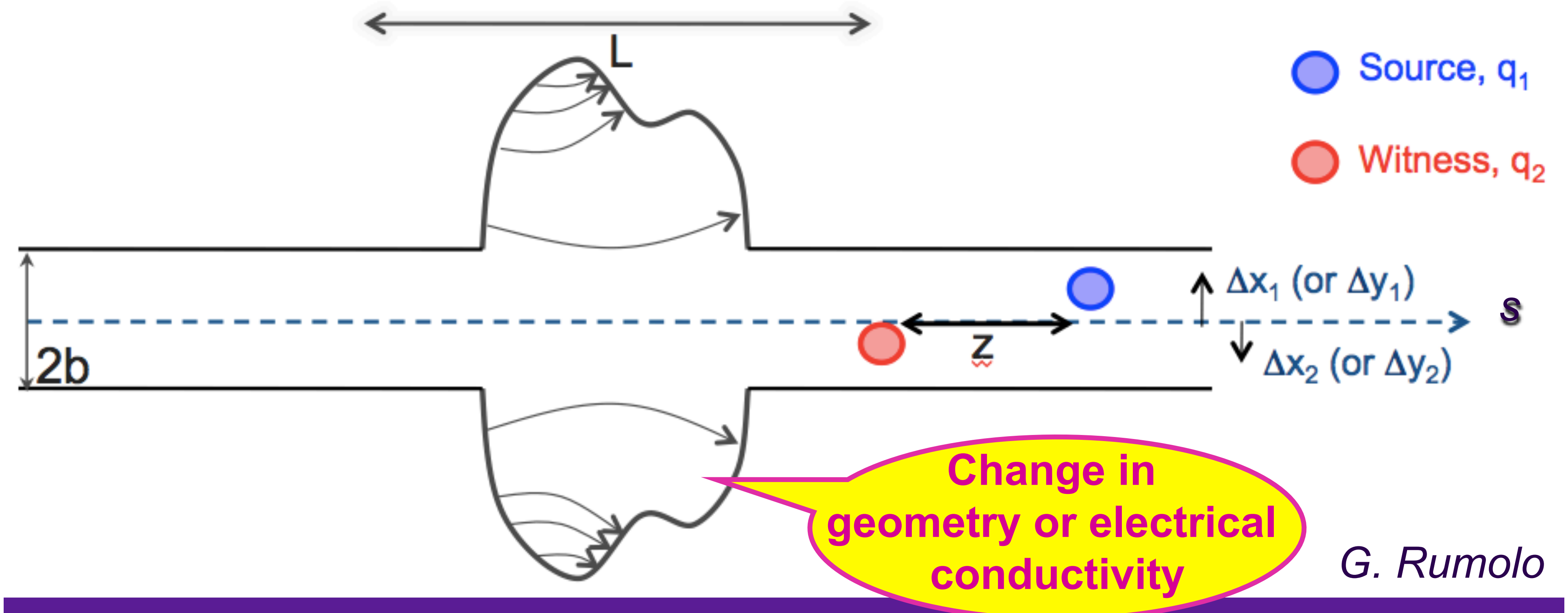

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- **Impedance** = Fourier transform of the wake field (wake function)

INTRODUCTION: THE IMPEDANCE

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- **Longitudinal case** $\int_0^L F_l \, ds = -e^2 \, W_l(z)$

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Driving (or dipolar) wake

Detuning (or quadrupolar) wake

Angular wake => Fast damping in VEPP-2 and BEP

INTRODUCTION: THE IMPEDANCE

- **The impedance is a complex function of frequency and at least 5 contributions are needed to correctly characterized an equipment**
  - Longitudinal impedance
  - Horizontal dipolar/driving impedance
  - Vertical dipolar/driving impedance
  - Horizontal quadrupolar/detuning impedance
  - Vertical quadrupolar/detuning impedance

In case of non axi-symmetric vacuum chambers (assuming that the particles are travelling at the speed of light => Assumption made in this talk)

CONTENTS

a-C = amorphous carbon
LESS = Laser treatment of the surface
HTS = High Temperature Superconductor

FREQUENCY RANGE OF INTEREST

- **Cut-off frequency (above which modes are propagating)**

$$f_{cut-off}^{lowest}\,[\mathrm{GHz}] \approx \frac{10}{b\,[\mathrm{cm}]}$$

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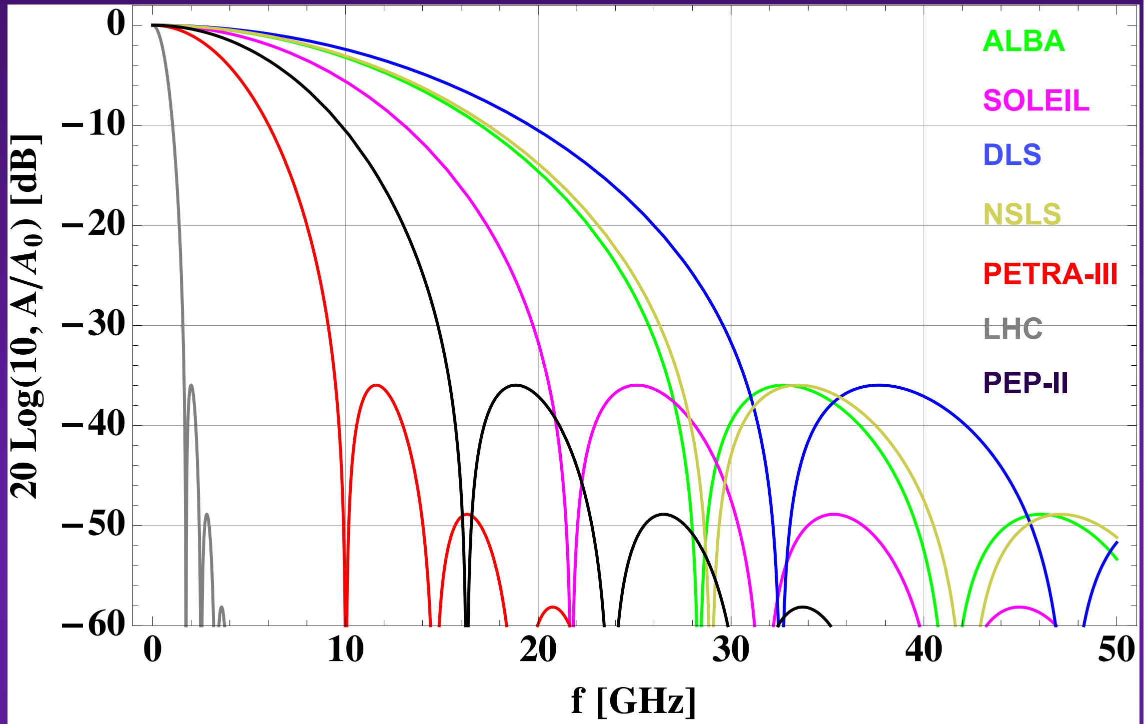
- **Lower limit => First Unstable (transverse) Betatron Line:**

$$f_{FUBL} = \left(n - Q \right) f_{rev}$$

  - **N.A. for LHC: (1 - 0.31) × 11245 ≈ 8 kHz**

FREQUENCY RANGE OF INTEREST

- **Bunch length and bunch spectrum**
  - **N.A. for LHC: τ_b (4 σ) ≈ *1 ns***



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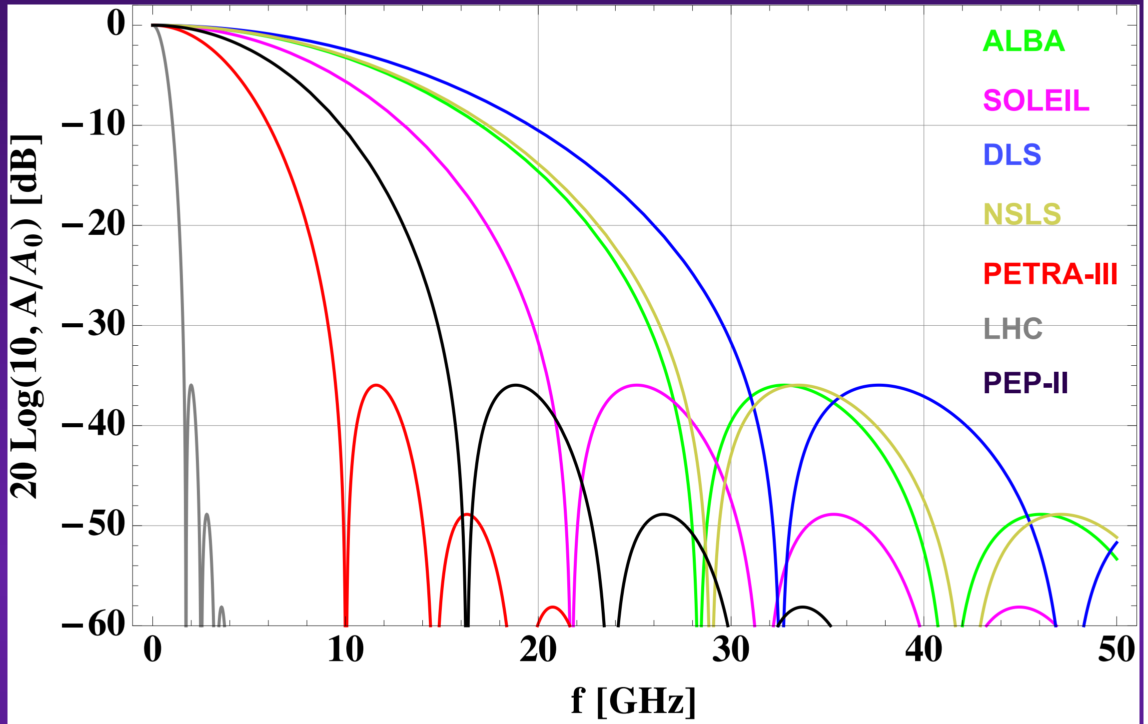

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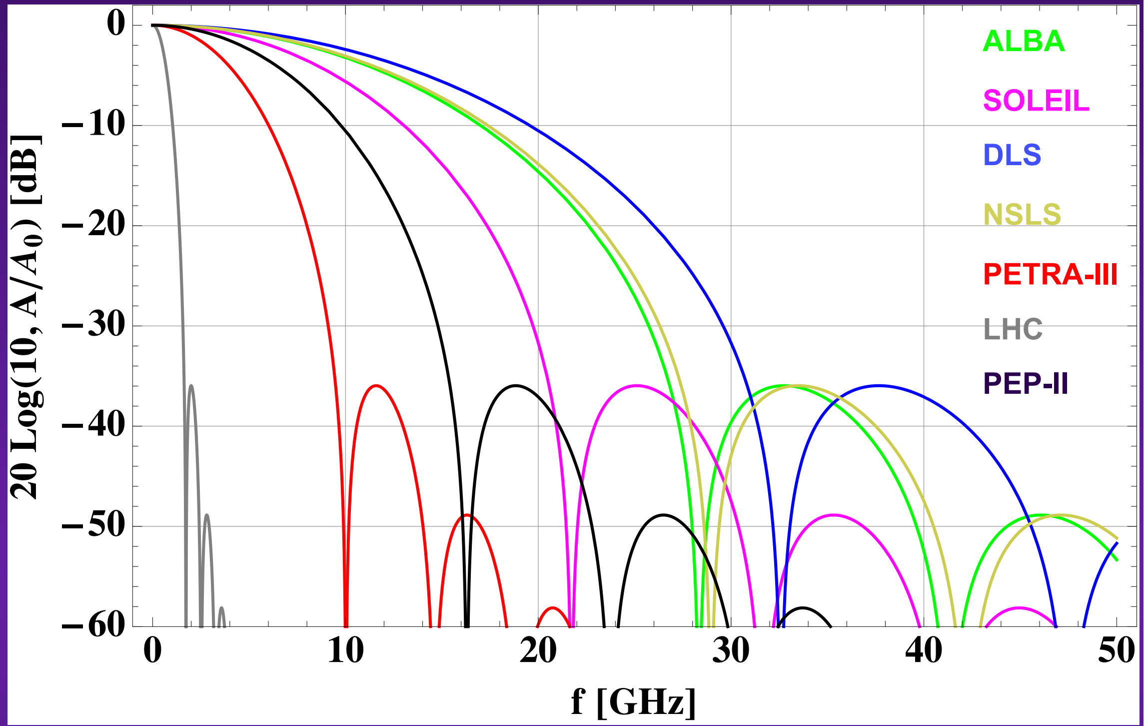

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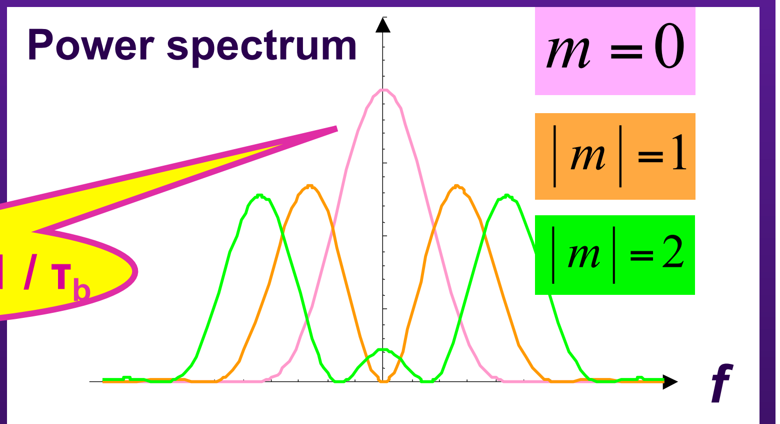

Extends up to ~ ± 1 / τ_b

=> For LHC: from 8 kHz to few GHz

COPPER COATING: WHY AND WHICH THICKNESS?

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$$P_{loss/m}^{G,RW,1\text{layer}} = \frac{1}{2\pi R}\,\Gamma\left(\frac{3}{4}\right)\frac{M}{b}\left(\frac{N_b\,e}{2\pi}\right)^2\sqrt{\frac{c\,\rho\,Z_0}{2}}\;\sigma_t^{-3/2} \approx 101\ \text{mW/m}$$

Euler gamma function

$$\Gamma\left(\frac{3}{4}\right) = 1.23$$

$M = 2808$

$N_b = 1.15 \times 10^{11}$ p/b

$\sigma_t = 0.25$ ns

LHC circumference $= L = 2\pi R = 26658.883$ m

$\rho_{Cu}^{20K,7\text{TeV}} = 7.7 \times 10^{-10}\ \Omega\text{m}$

b = beam screen half height $= 36.8 / 2 = 18.4$ mm

COPPER COATING: WHY AND WHICH THICKNESS?

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  - For SS for instance, the power loss would be ~ 30 times more
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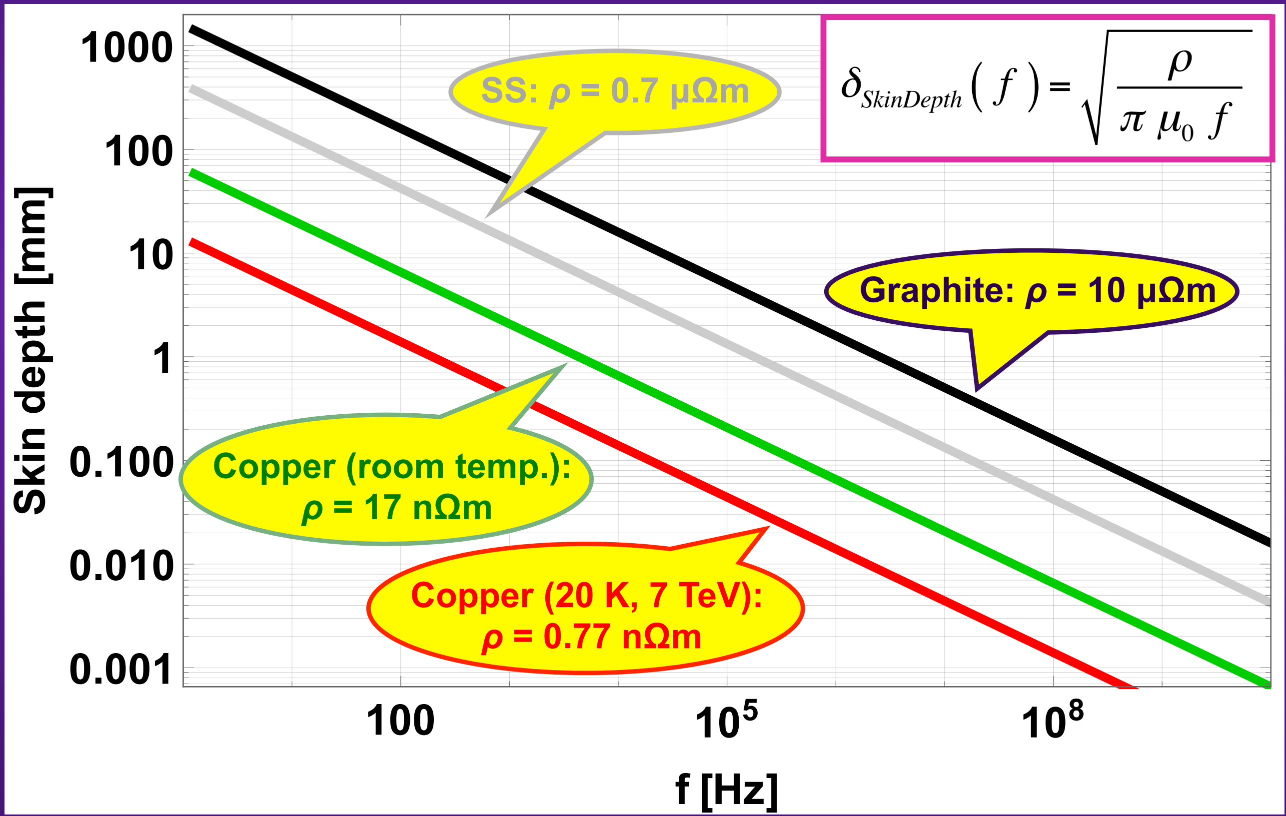

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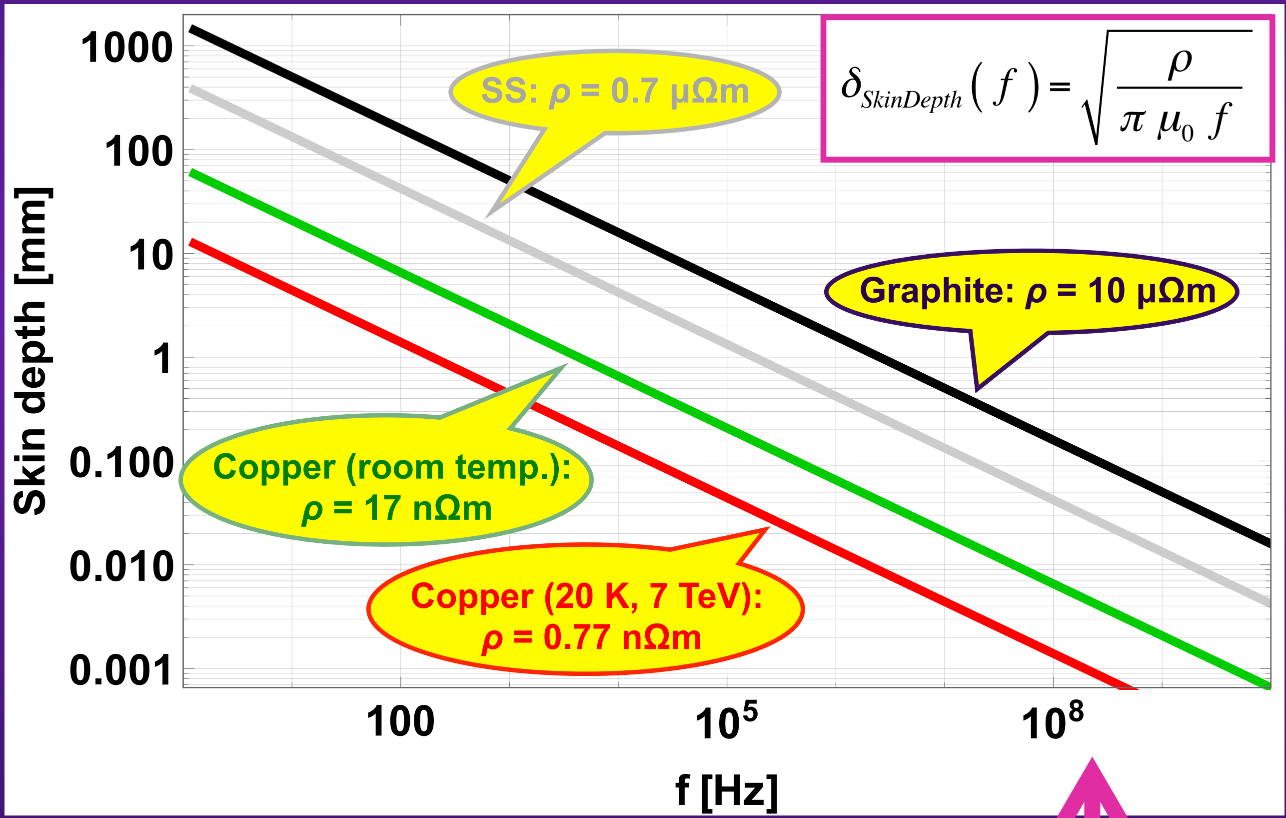

Power loss and TMCI

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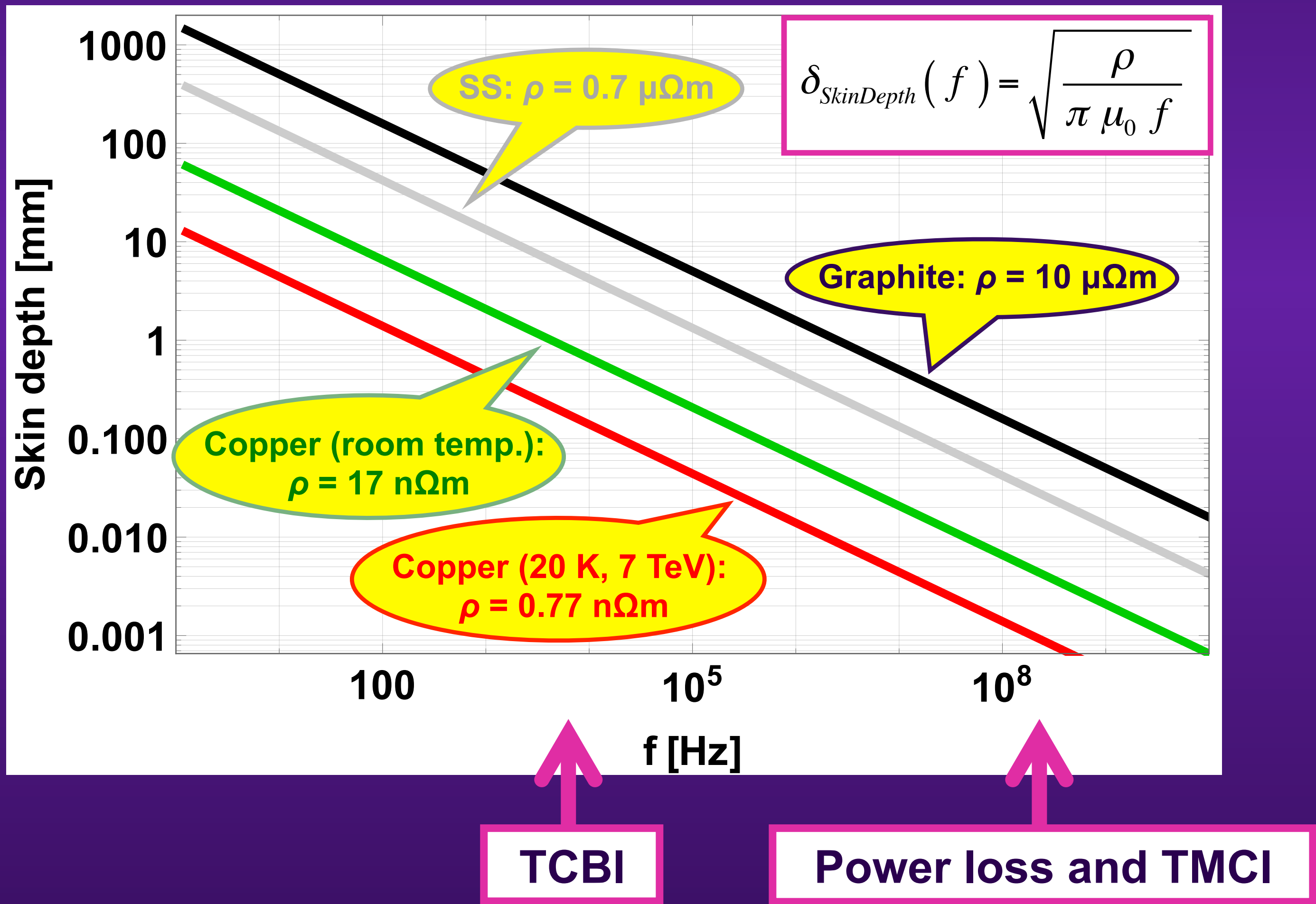

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$$\tau_y \approx \frac{\gamma \, Q_y \, \mu_0}{M \, N_b \, r_p \, \mathrm{Re}\left[\dfrac{Z_y \left(2 \, \pi \, f_{FUBL} \right)}{2 \, \pi \, R} \right]}$$

Instability rise-time (in the thick-wall regime)

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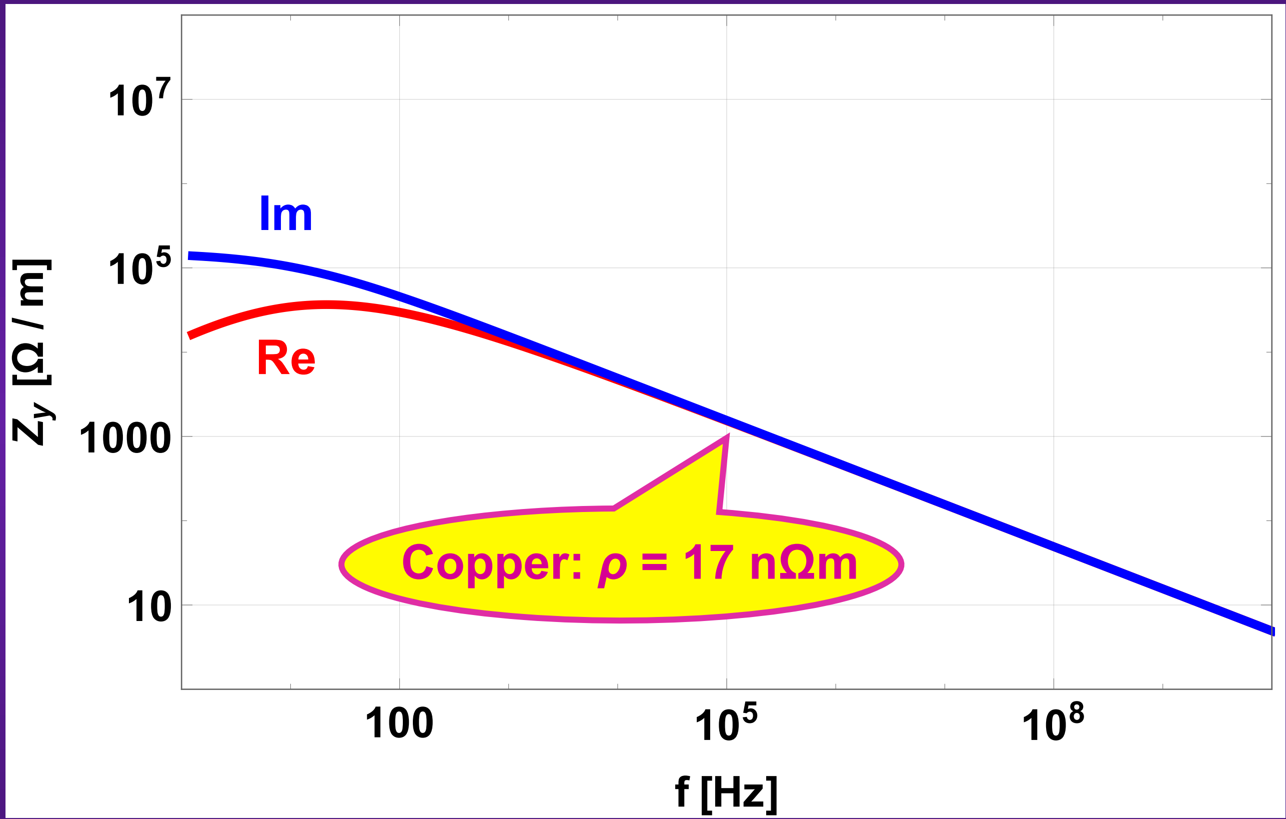
Instability rise-time (in the thick-wall regime)

- Previous plot reveals why in this case few tens / hundreds of µm are needed (at low frequency, IF we are in the thick-wall regime)
- This thick-wall regime is for instance not the case with the LHC collimators…

LHC beam pipe: round, 20 mm radius, 1 m long



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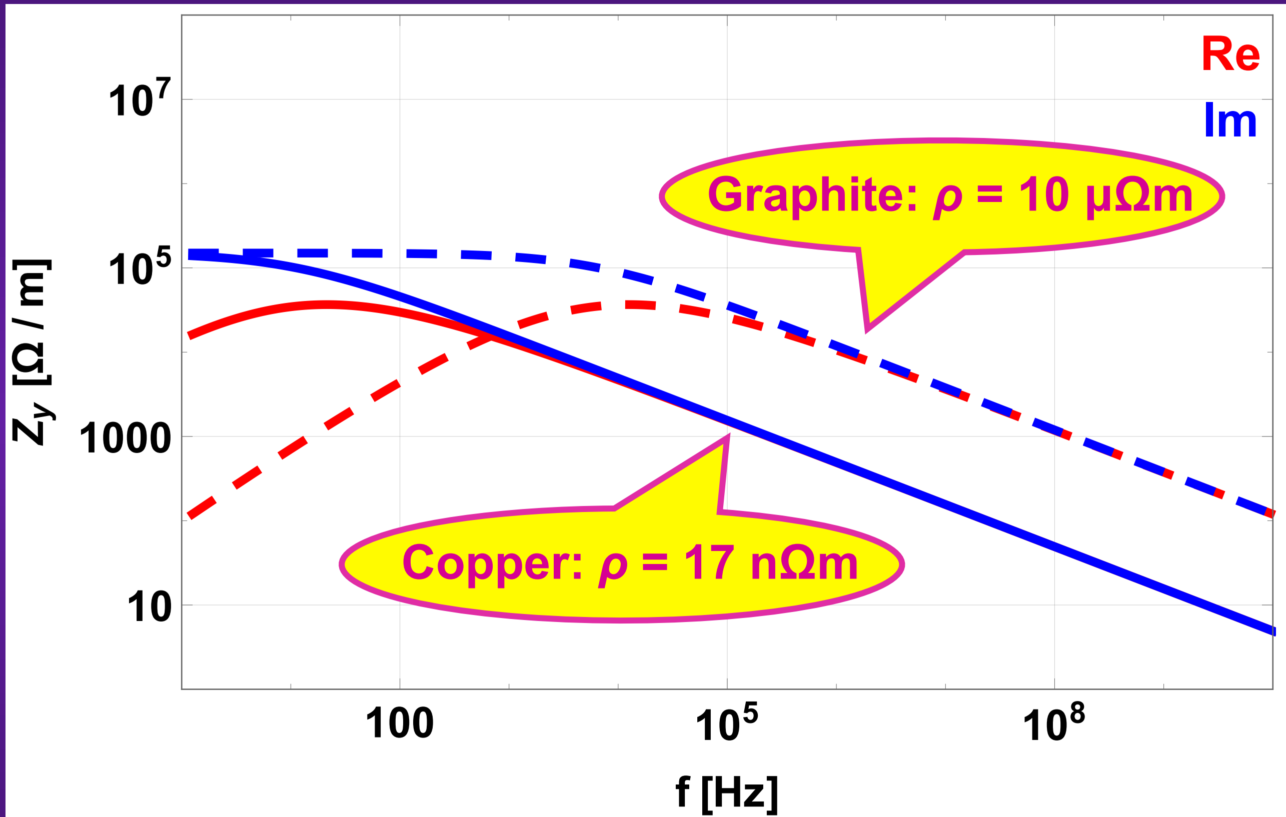

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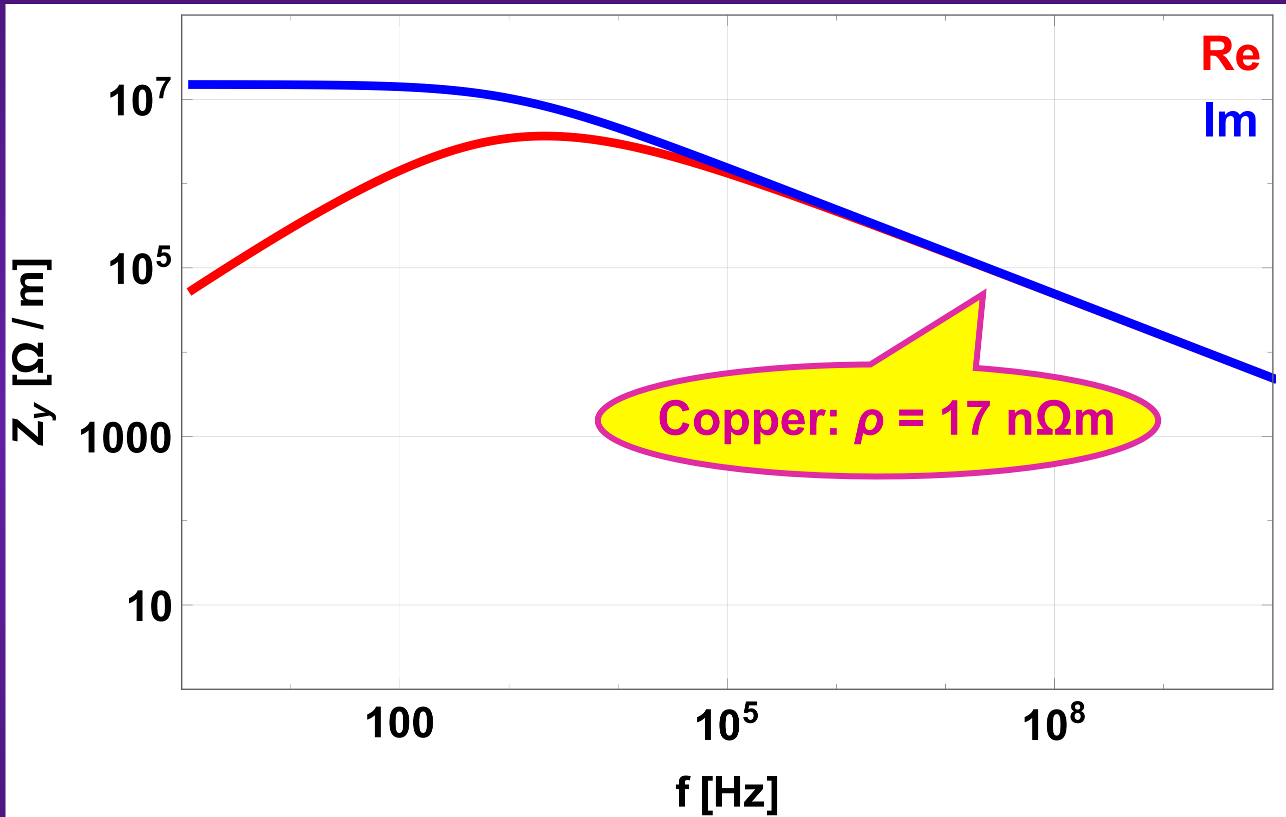

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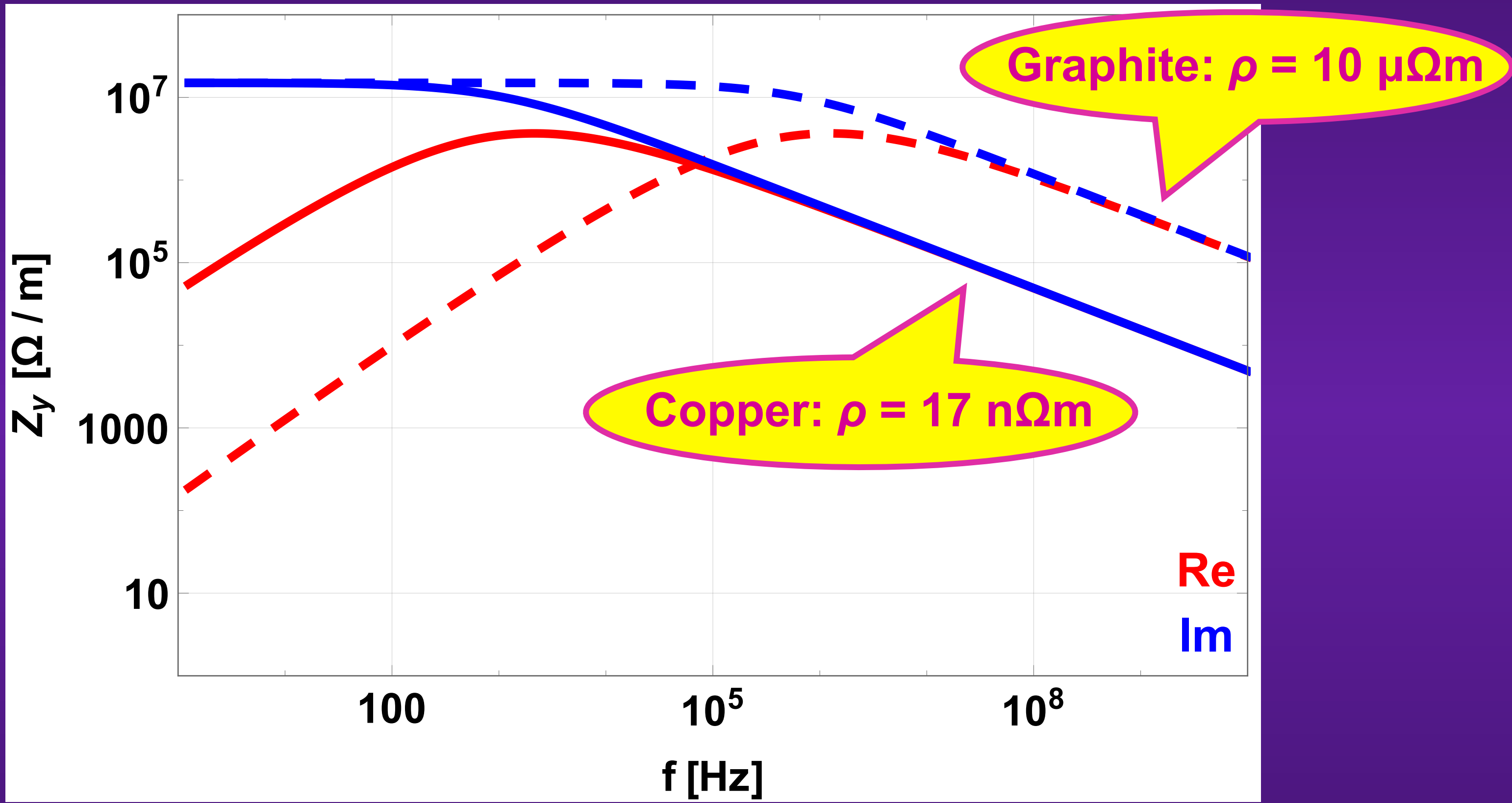

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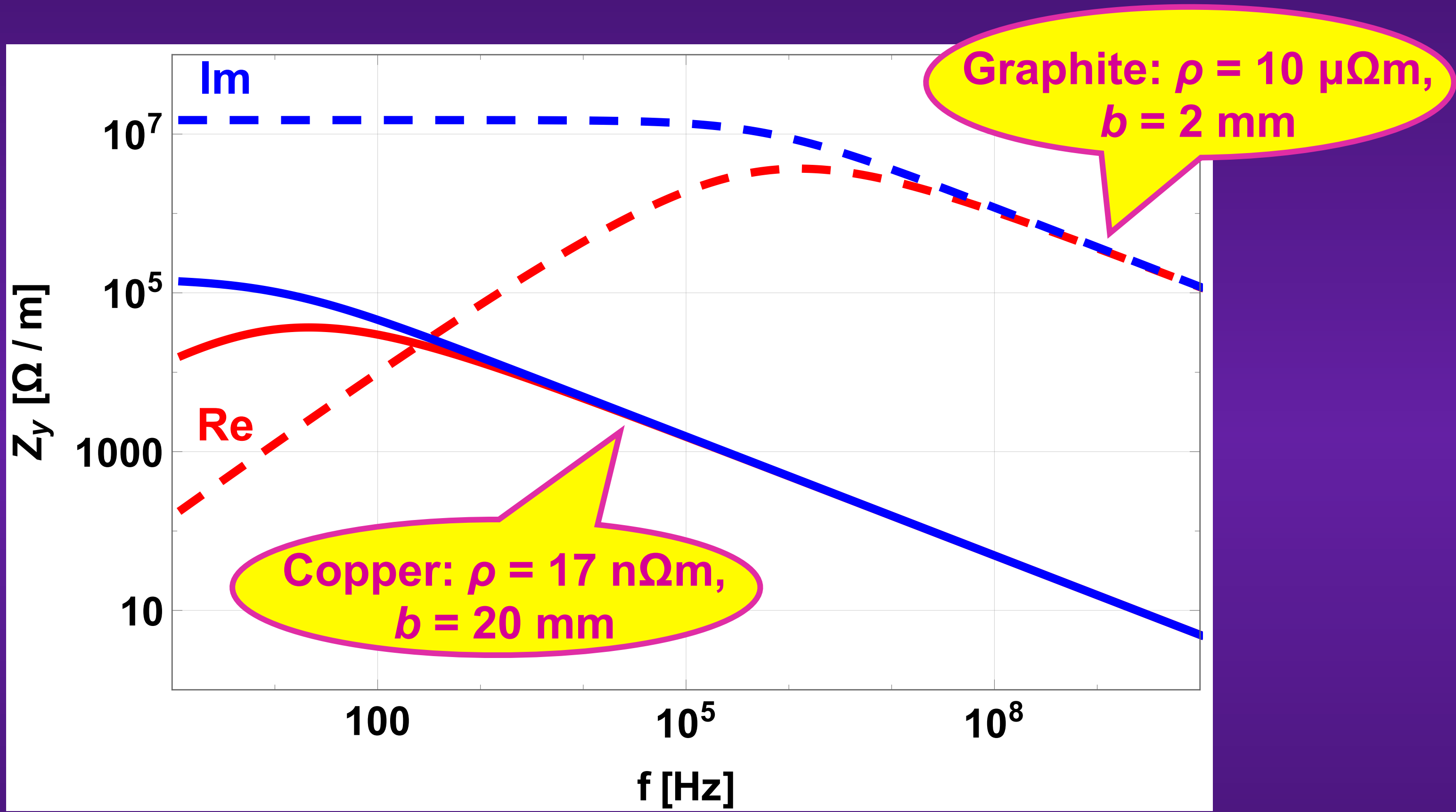

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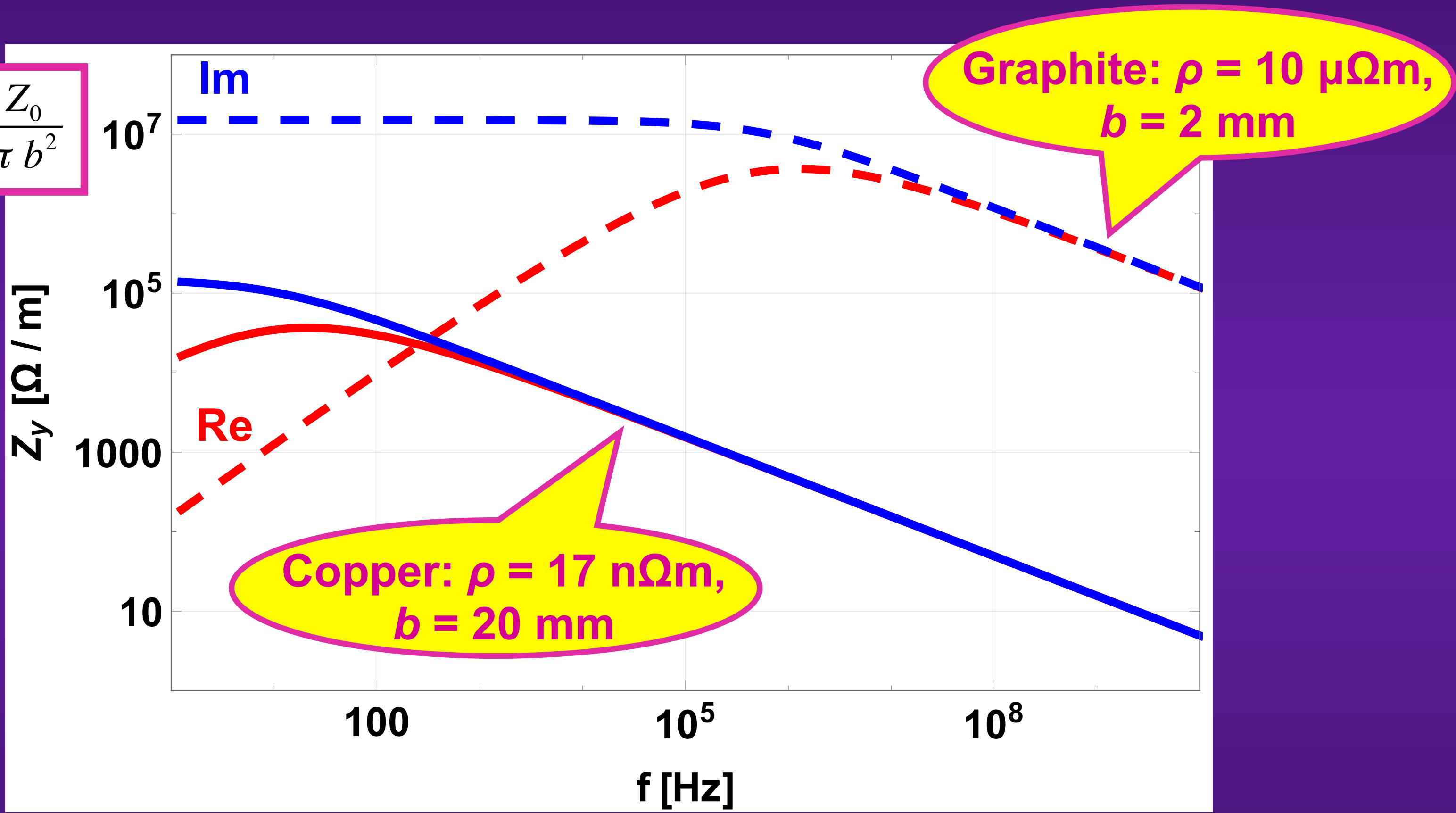
$$Z_y \left(f \rightarrow 0 \right) = \frac{j\, Z_0}{2\pi\, b^2}$$



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$$f_{\max,\mathrm{Re}} \approx \frac{\rho}{b^2} \times \frac{1}{\pi \mu_0}$$

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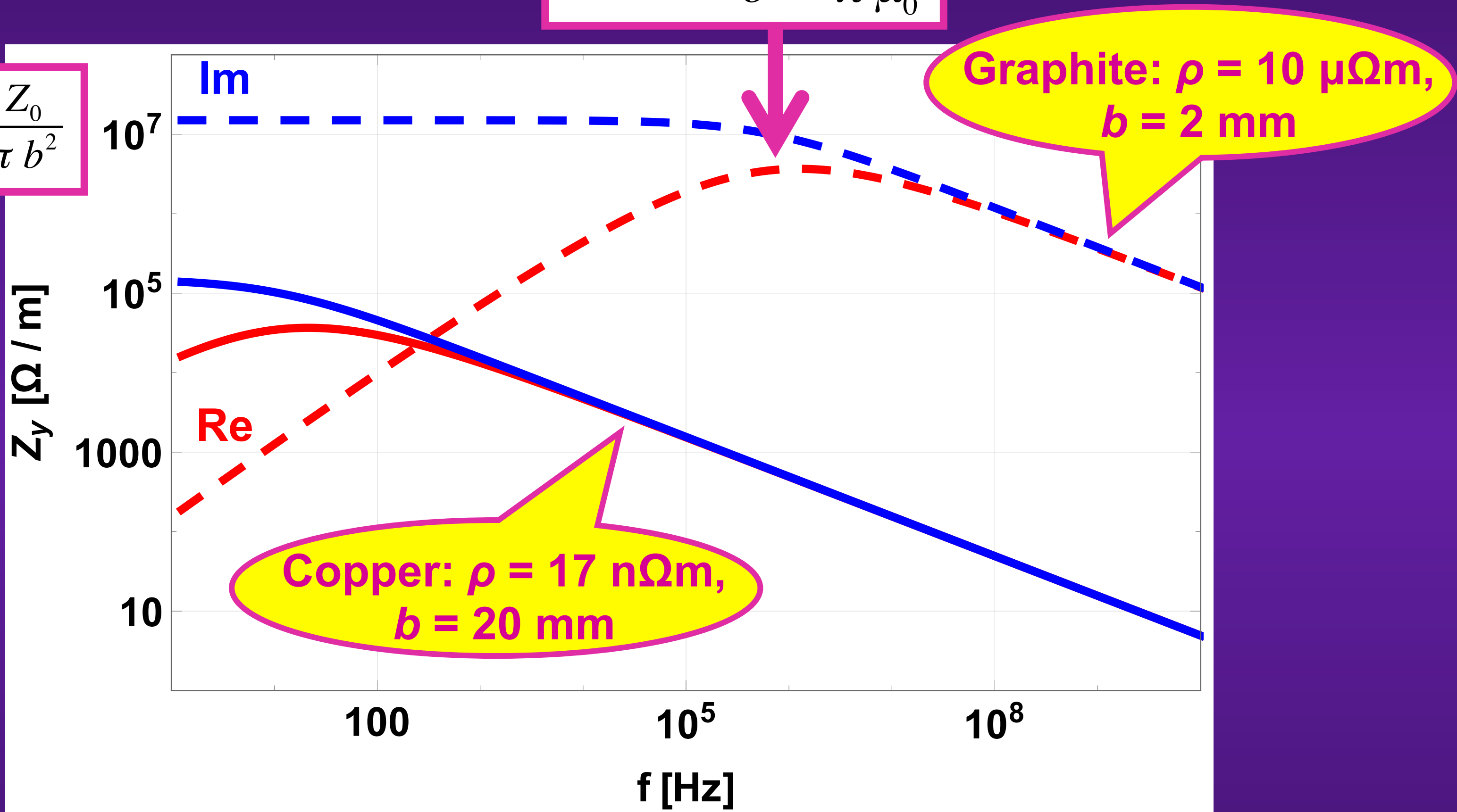

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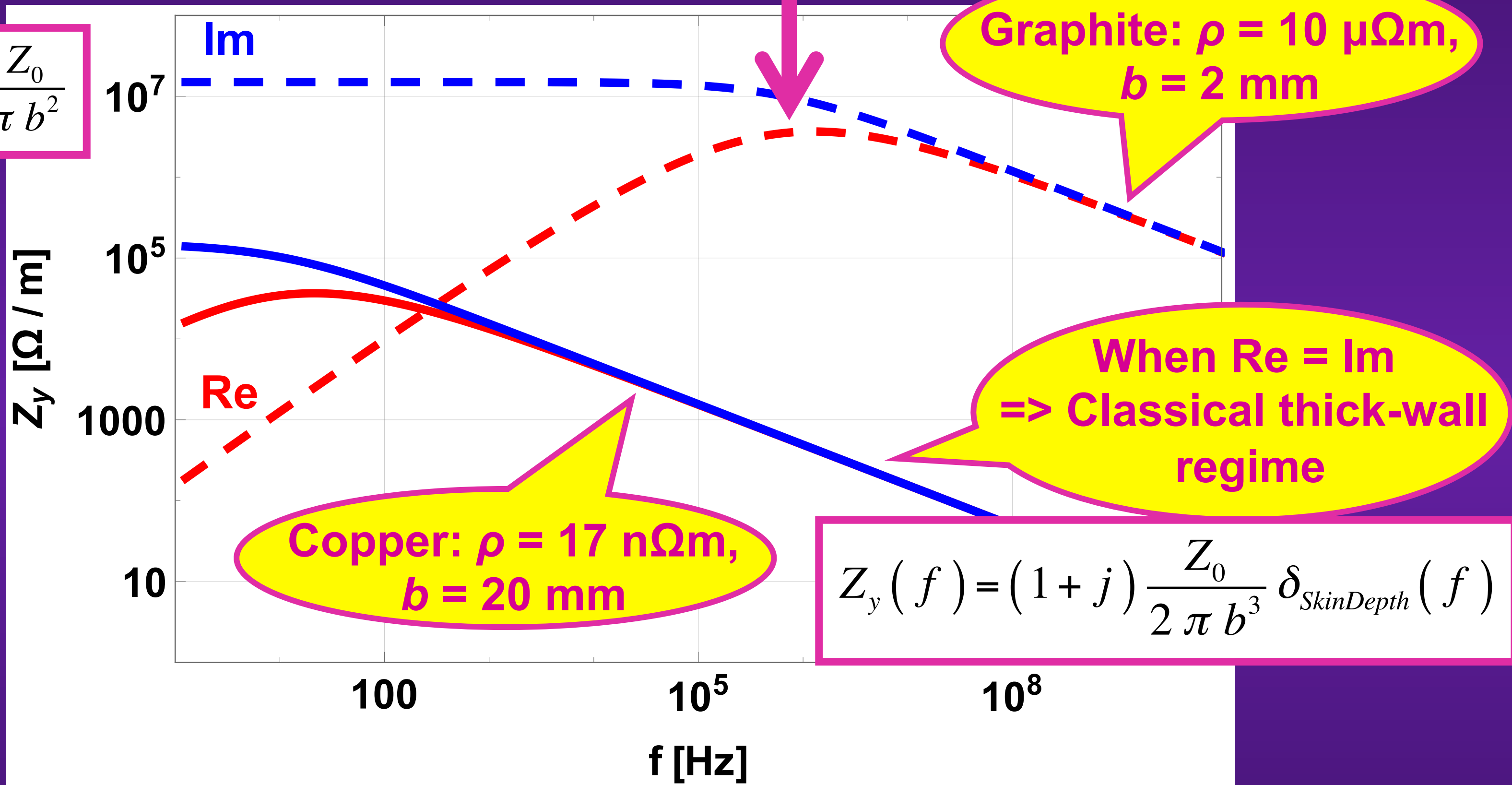
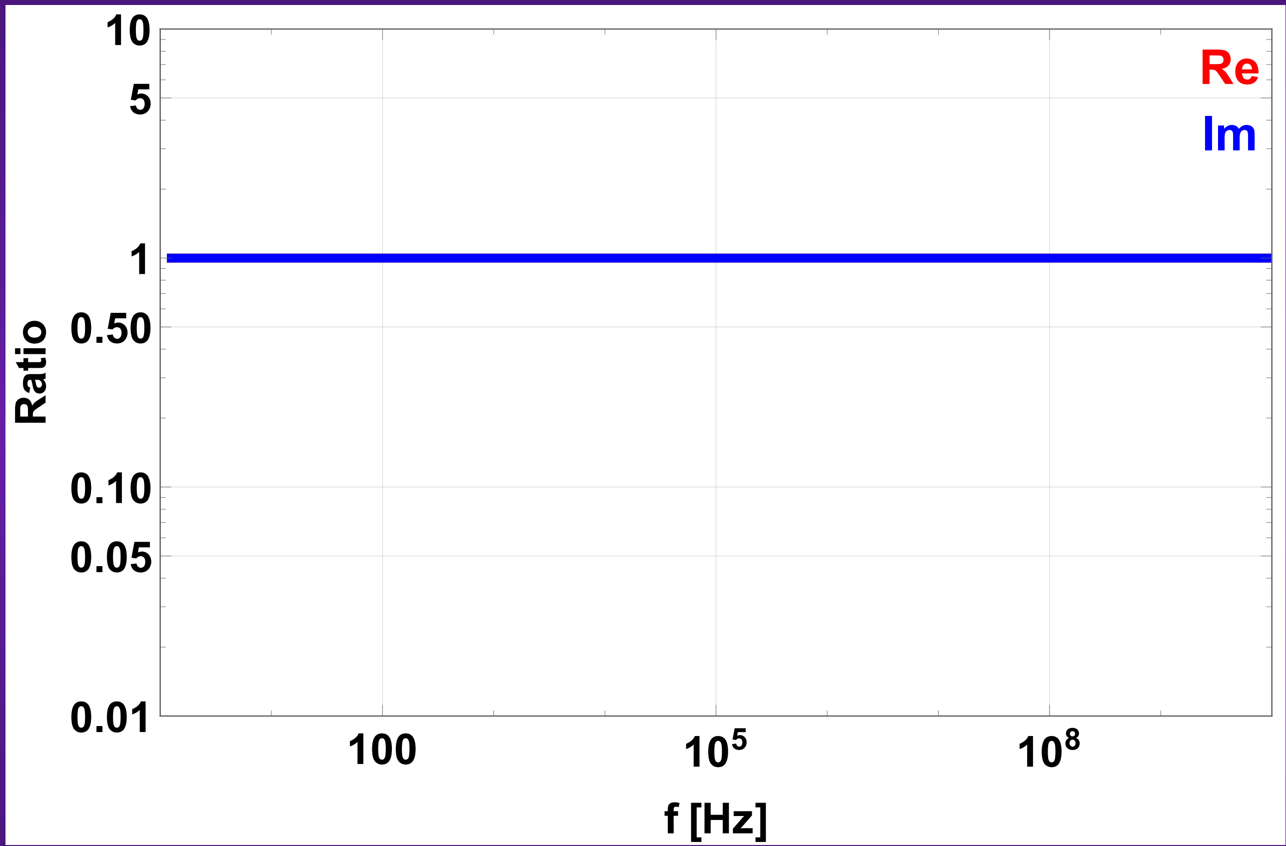
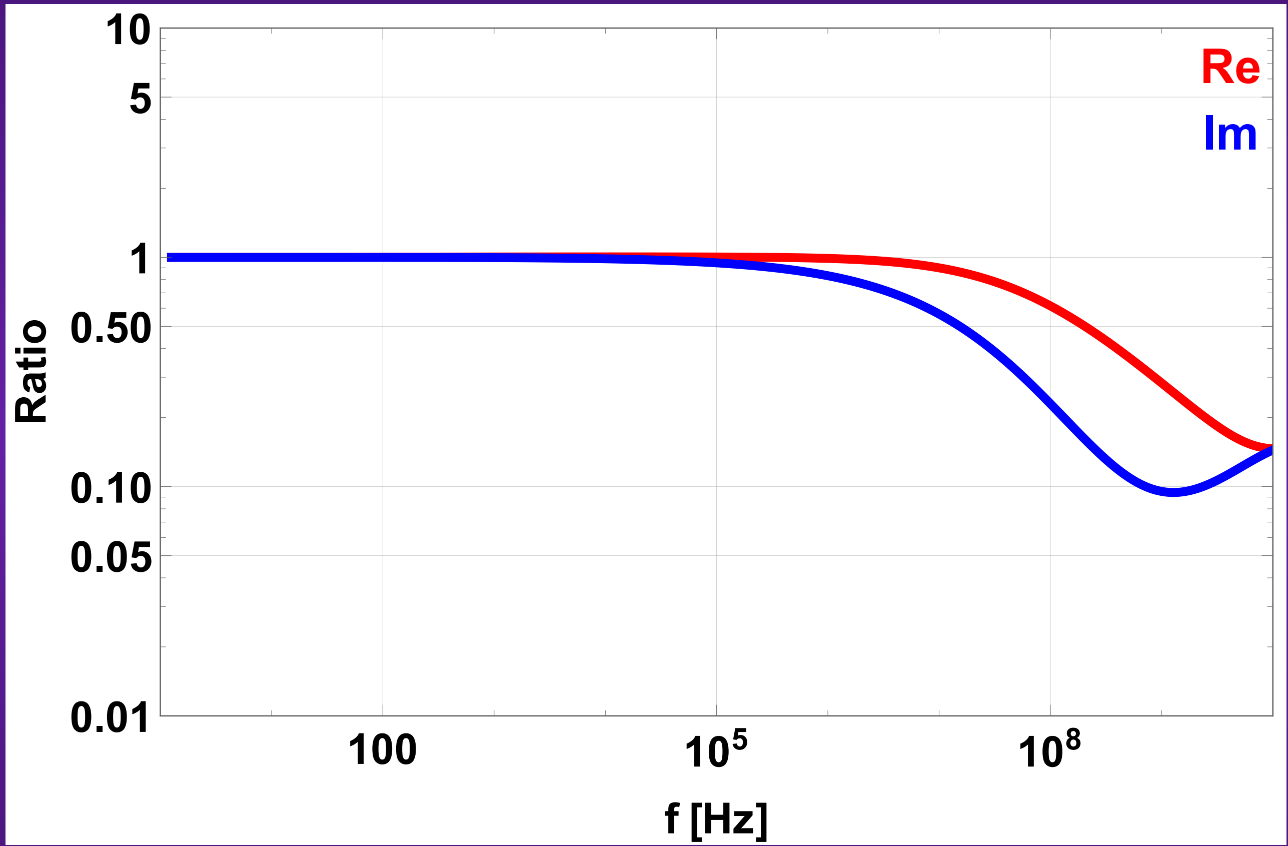


$$Z_y(f) = (1 + j) \frac{Z_0}{2 \pi b^3} \delta_{SkinDepth}(f)$$

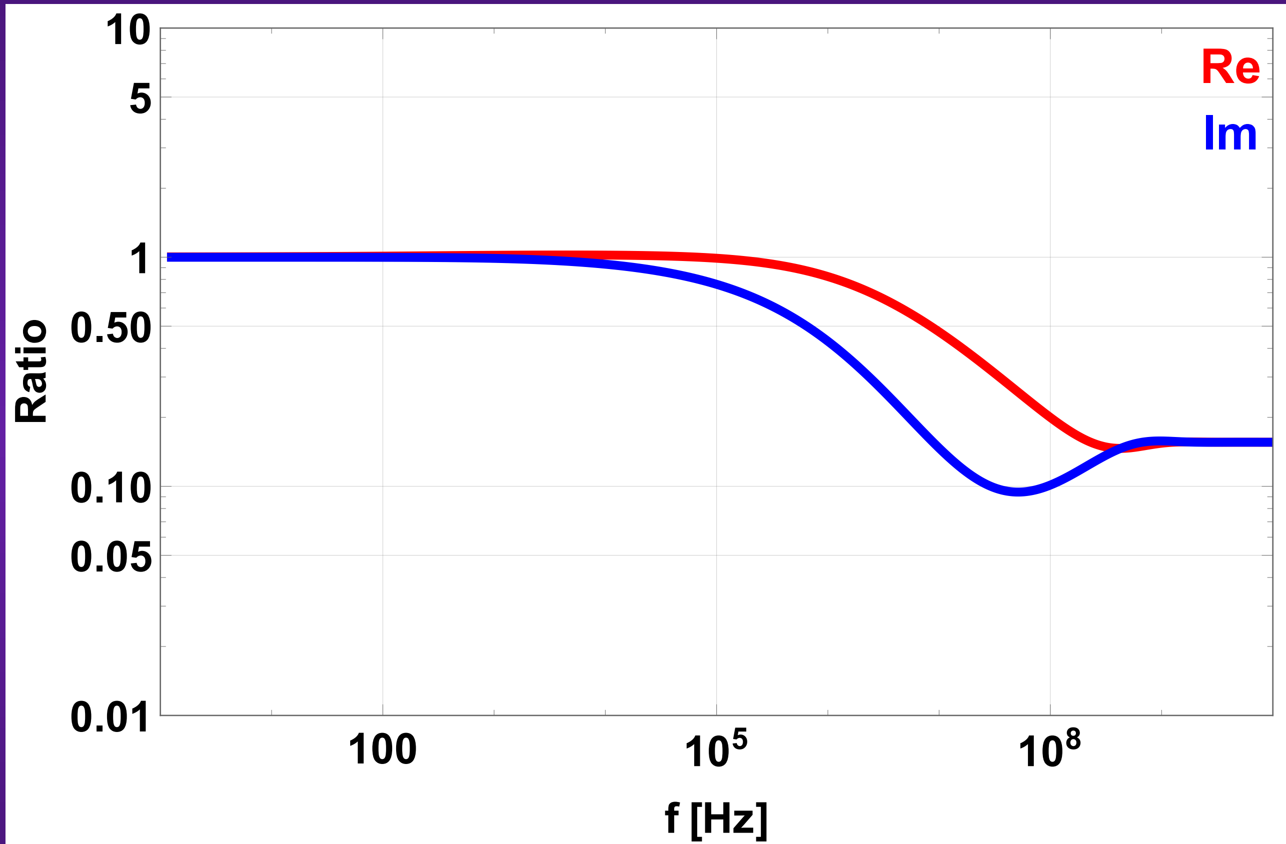
SS beam pipe with 20 mm radius and 0 µm copper coating (room temp.)



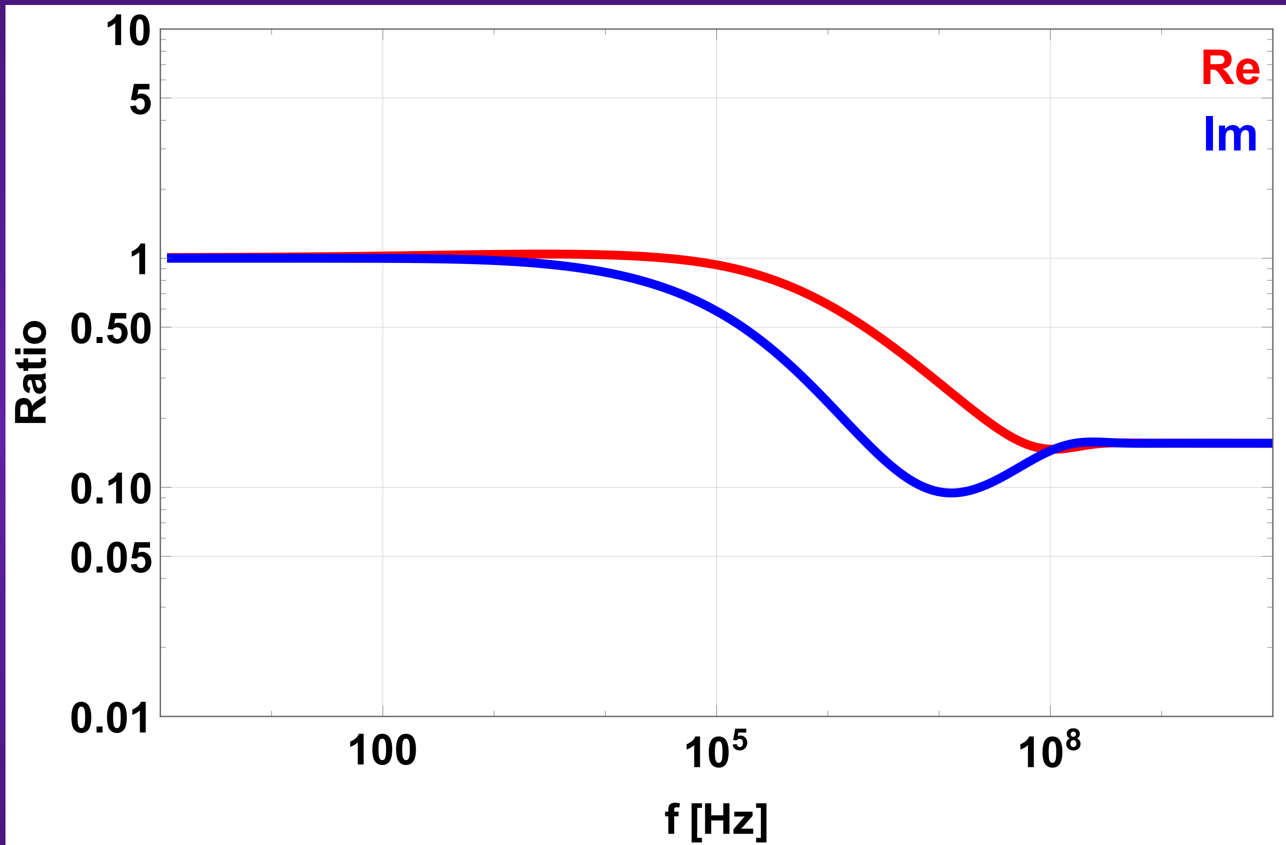
SS beam pipe with 20 mm radius and 1 µm copper coating (room temp.)



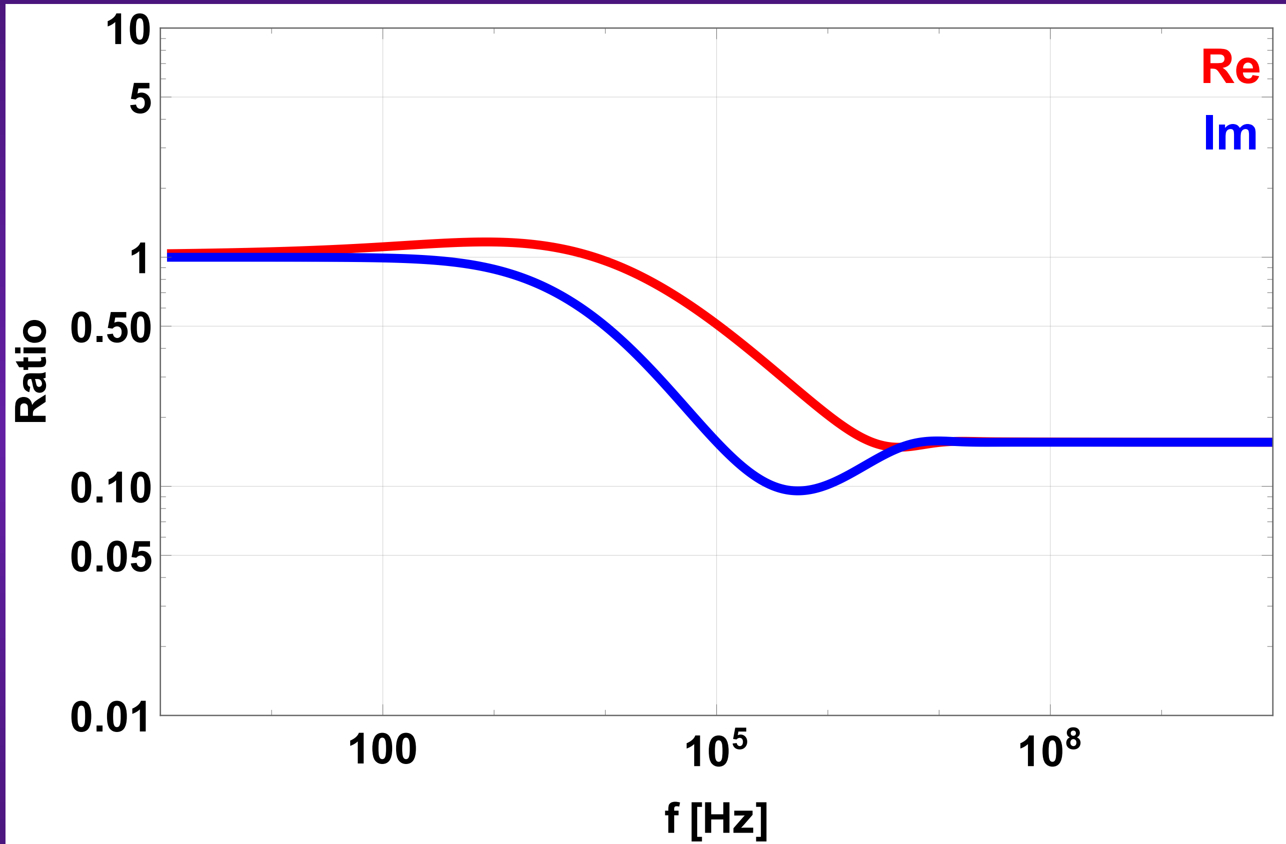
SS beam pipe with 20 mm radius and 5 μm copper coating (room temp.)



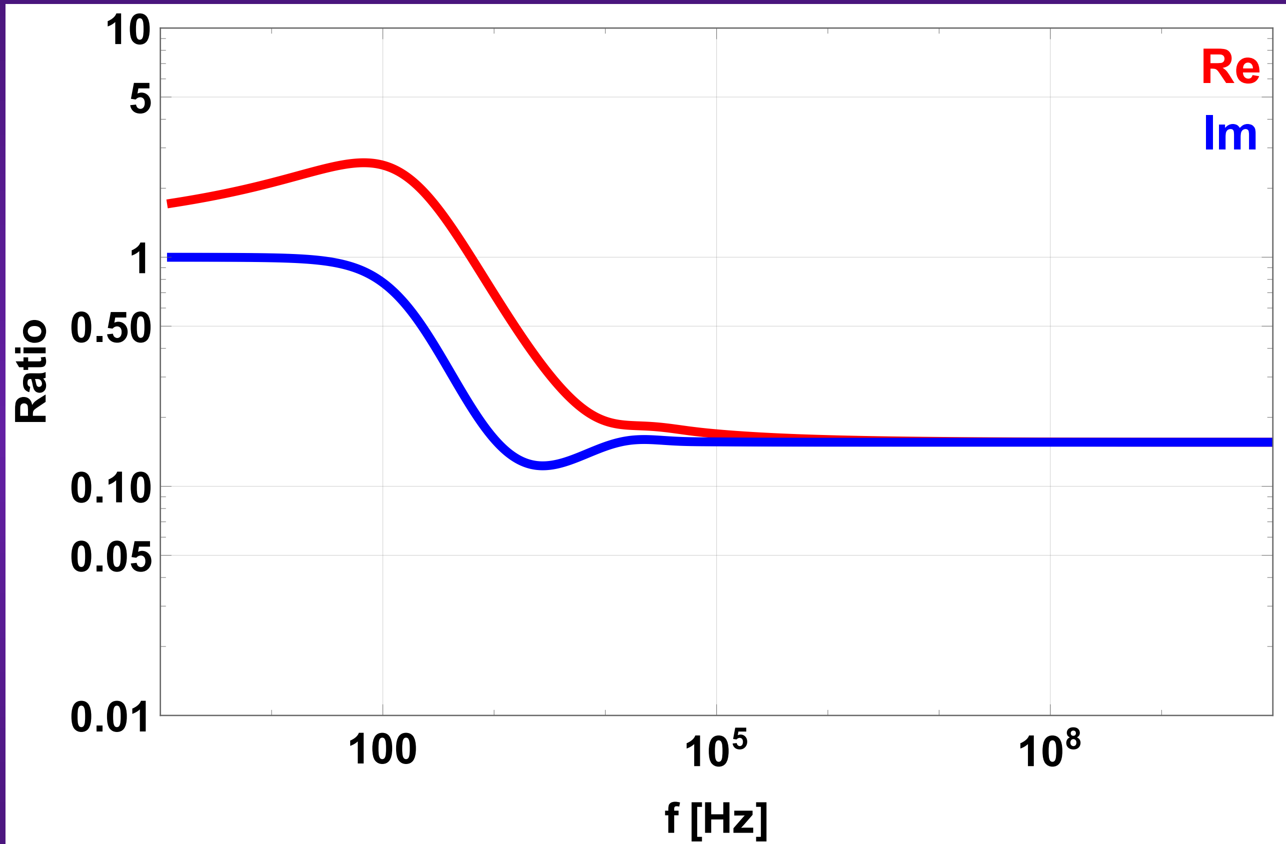
SS beam pipe with 20 mm radius and 10 μm copper coating (room temp.)



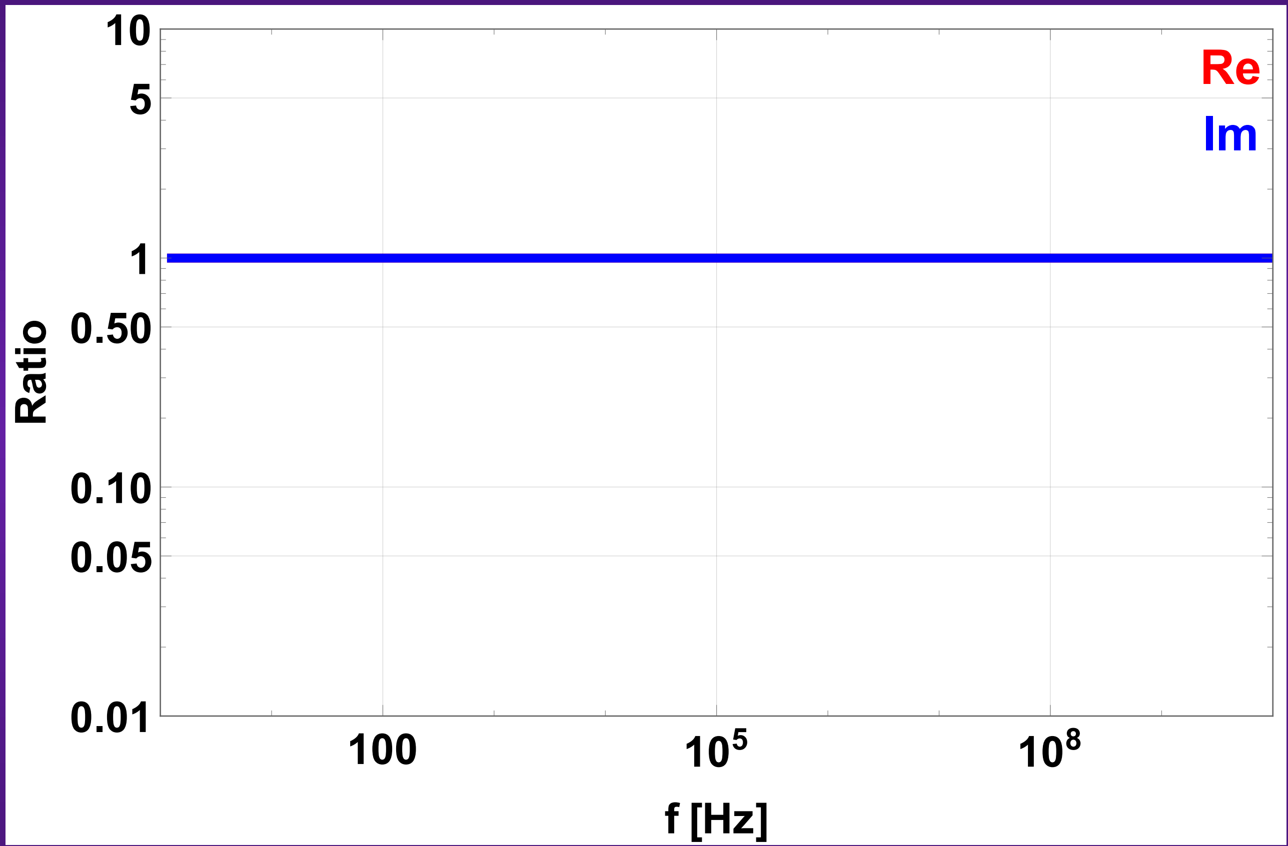
SS beam pipe with 20 mm radius and 50 µm copper coating (room temp.)



SS beam pipe with 20 mm radius and 1000 μm = 1 mm copper coating (room temp.)



Graphite beam pipe with 2 mm radius and 0 µm copper coating (room temp.)



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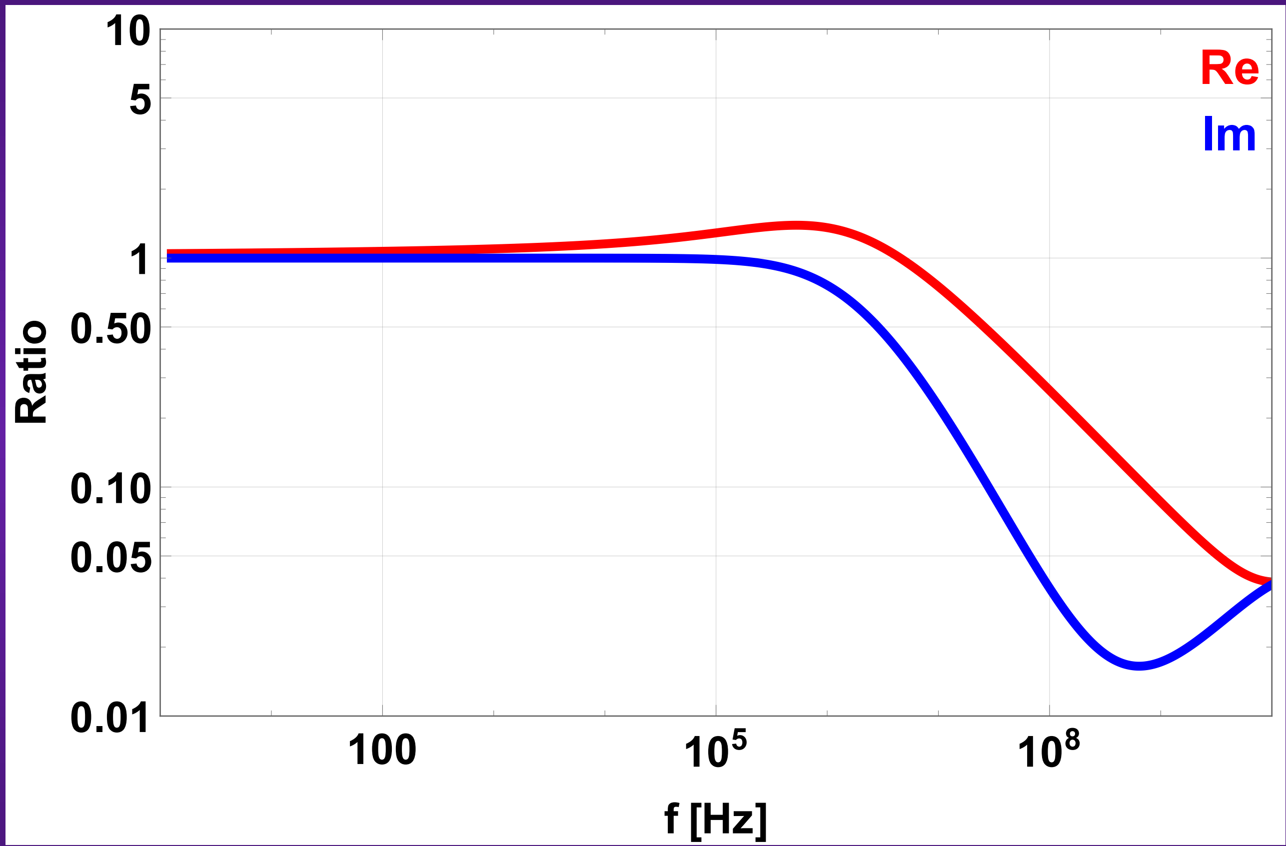
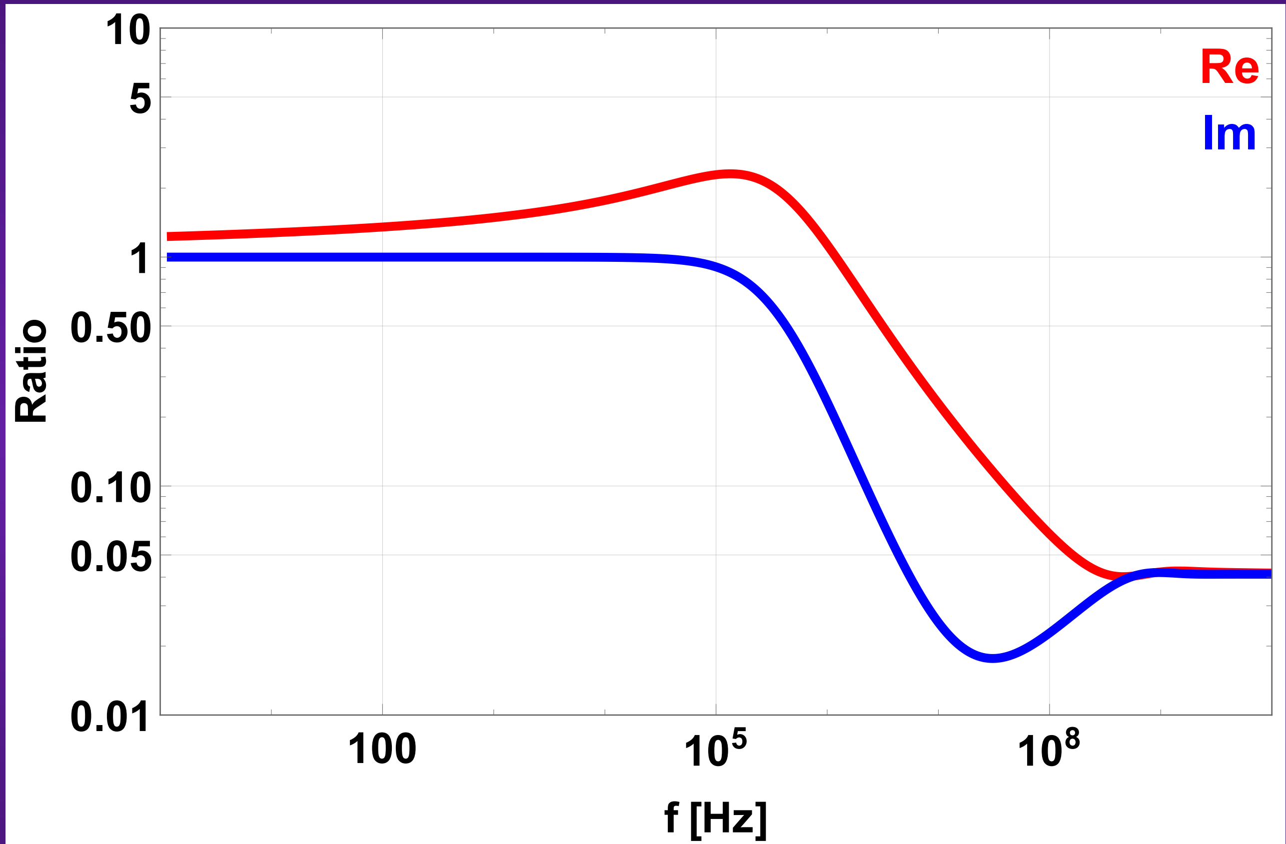


Graphite beam pipe with 2 mm radius and 5 µm copper coating (room temp.)



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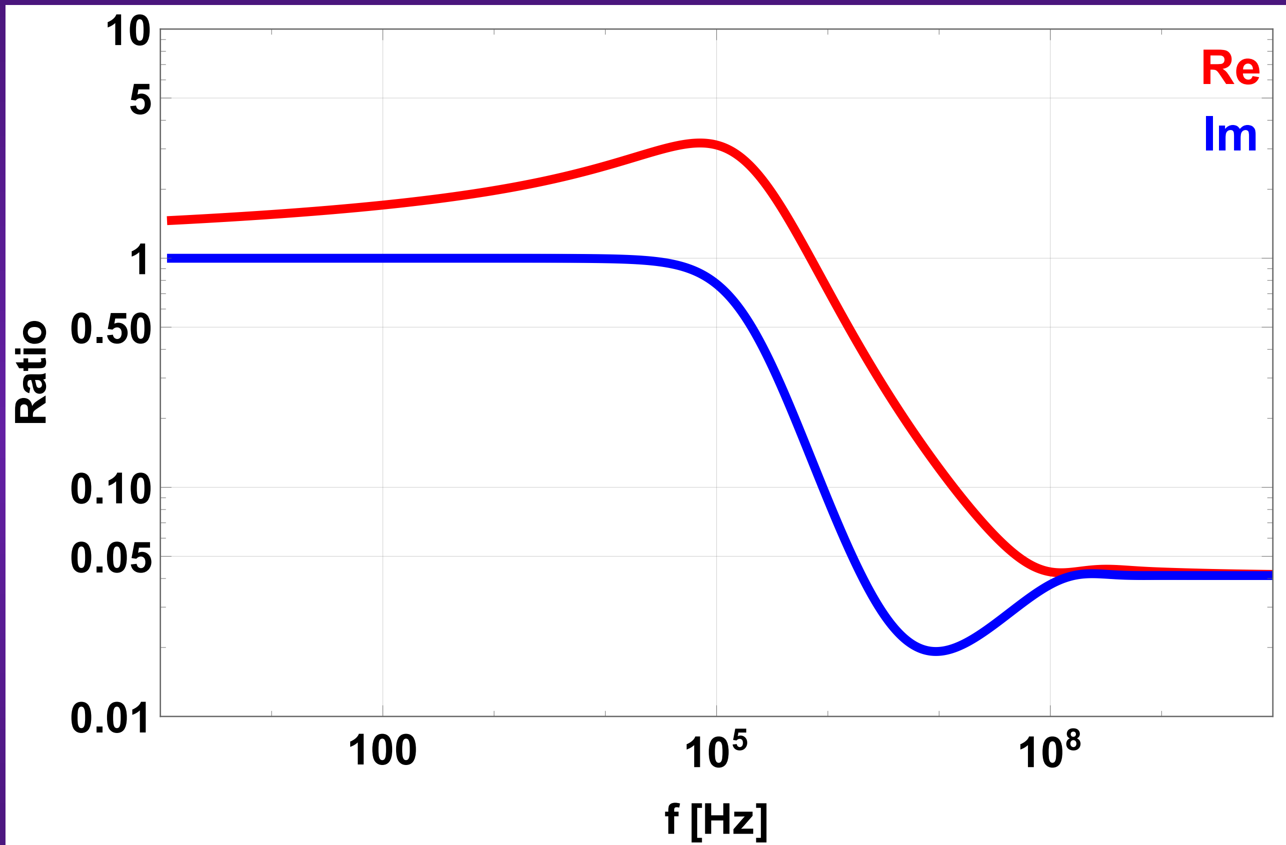

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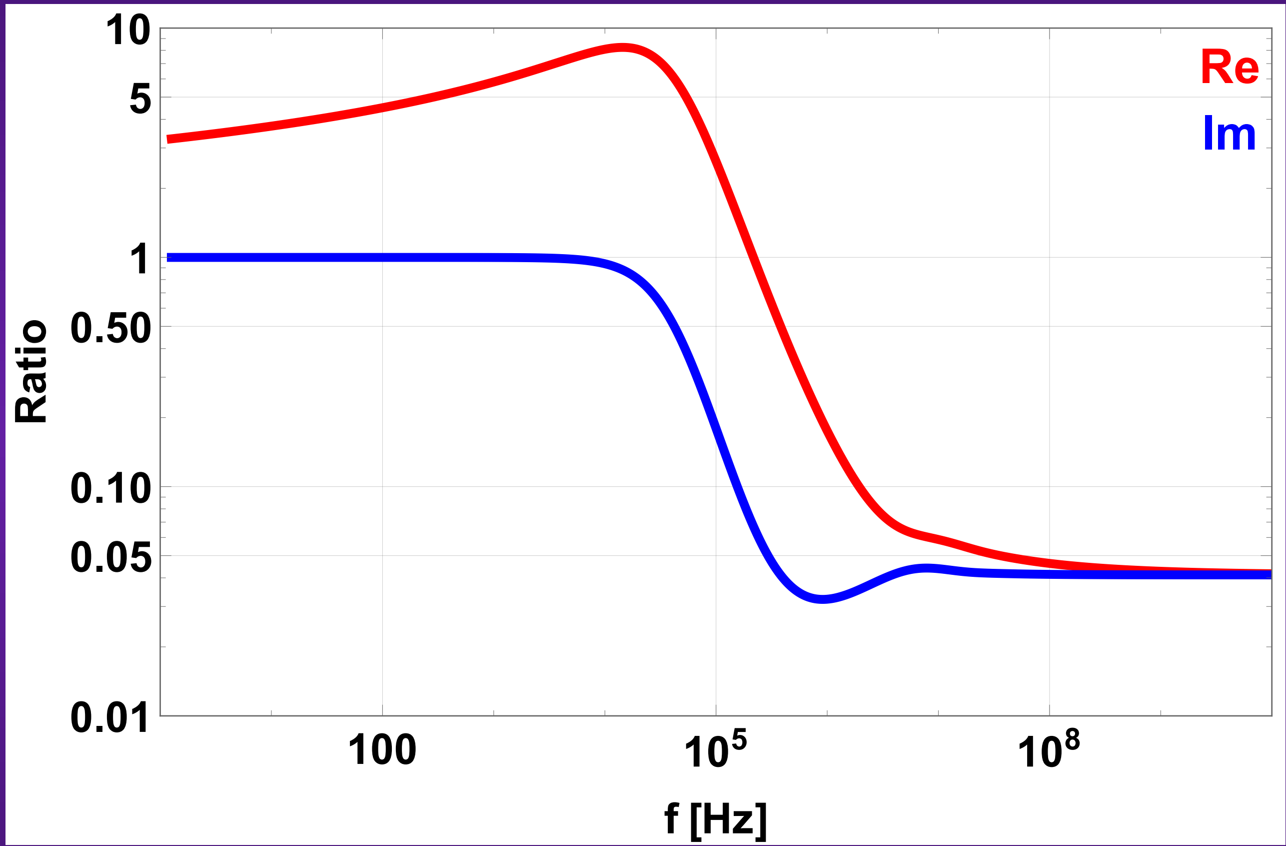
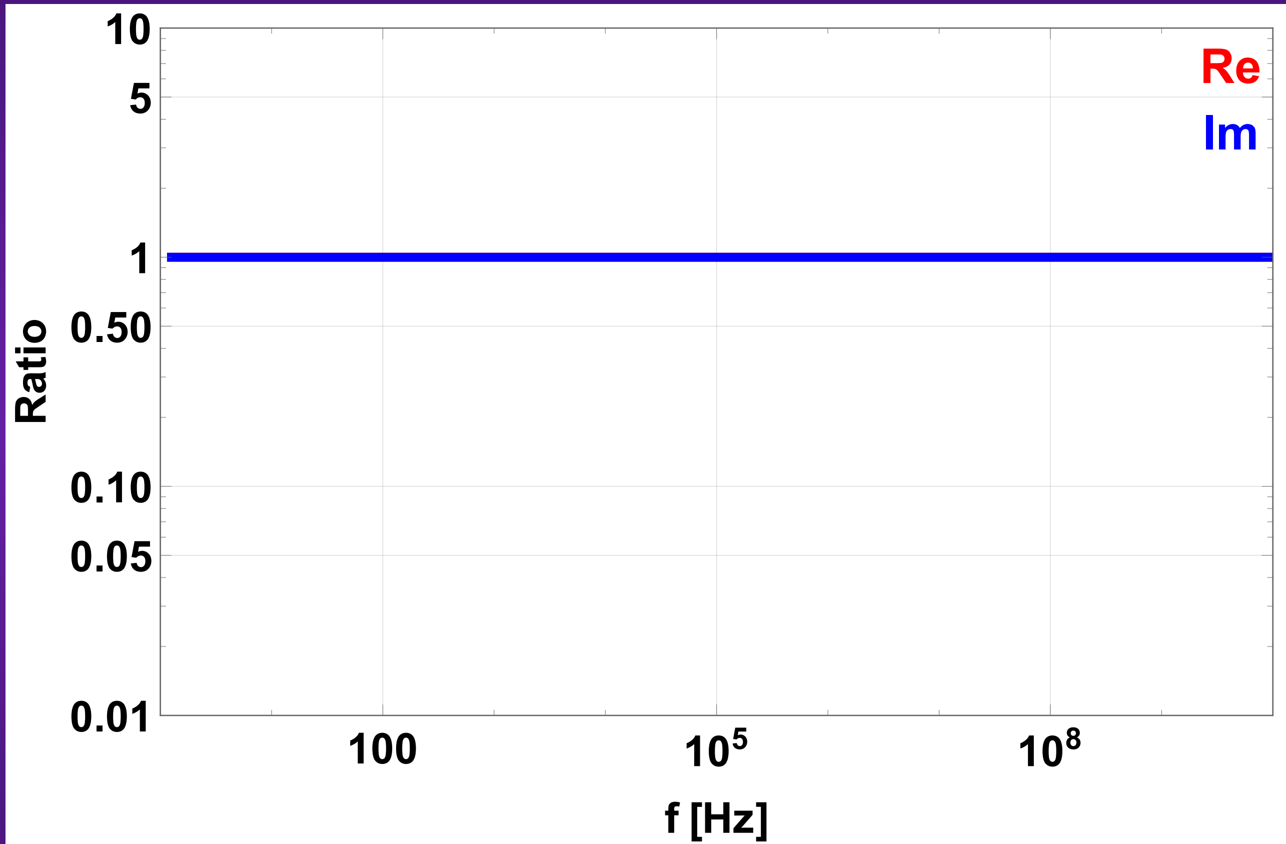
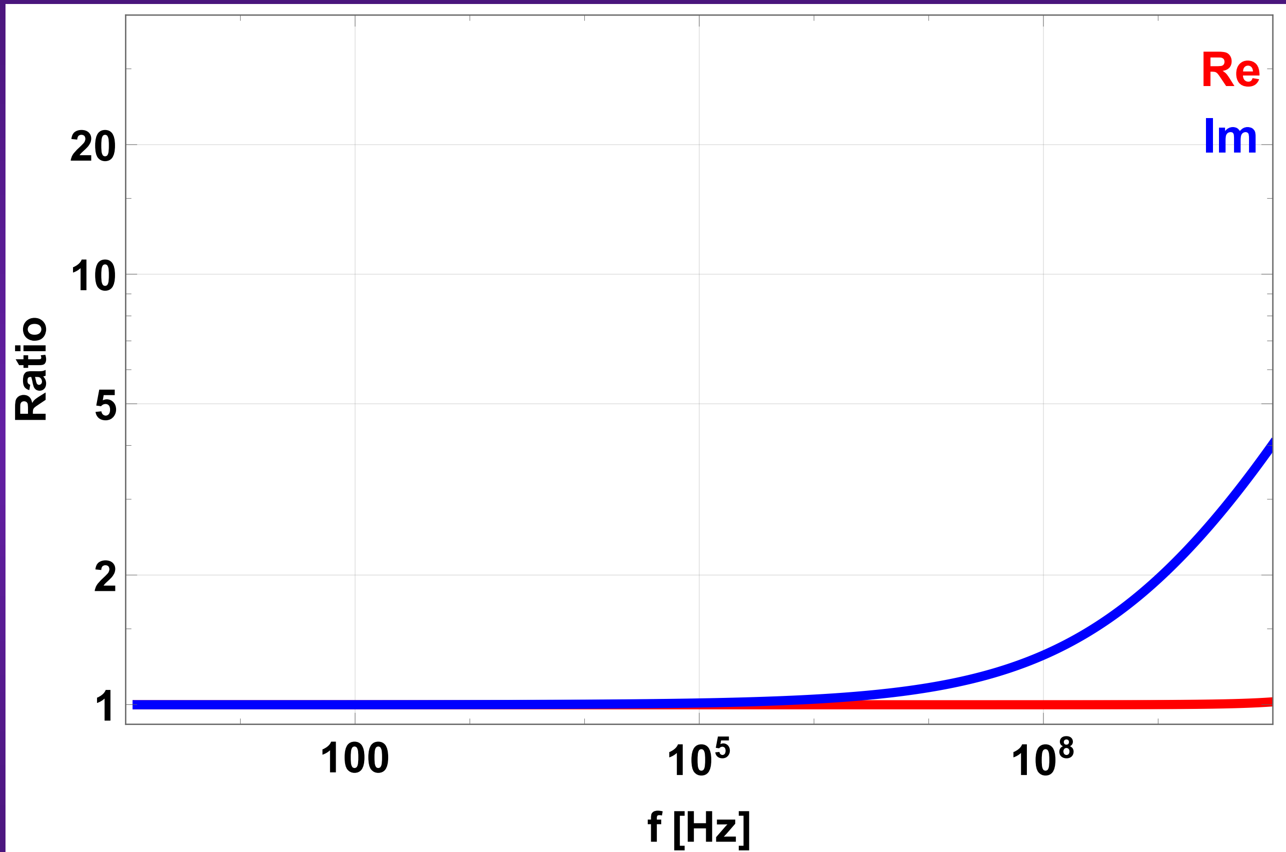


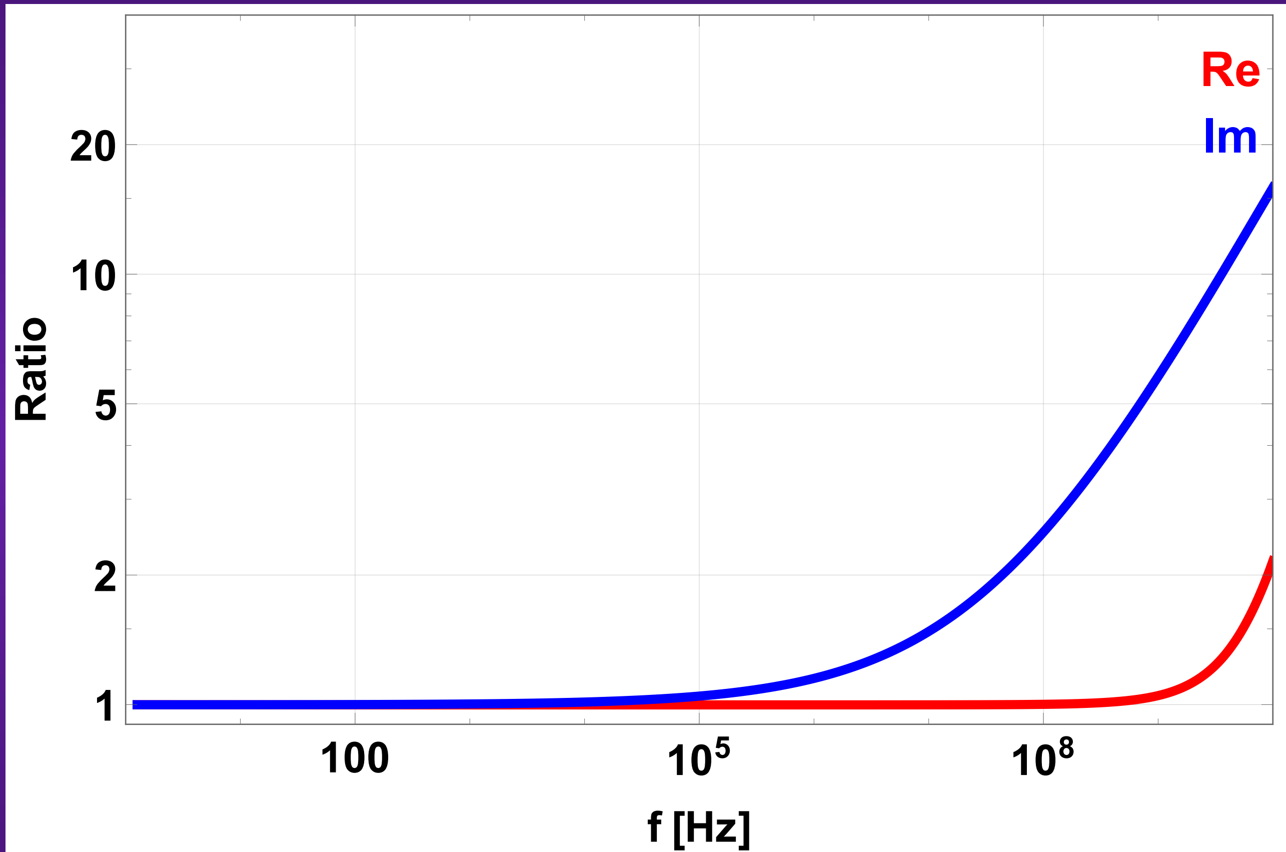
Copper (room temp.) beam pipe with 20 mm radius and 0 μm graphite coating



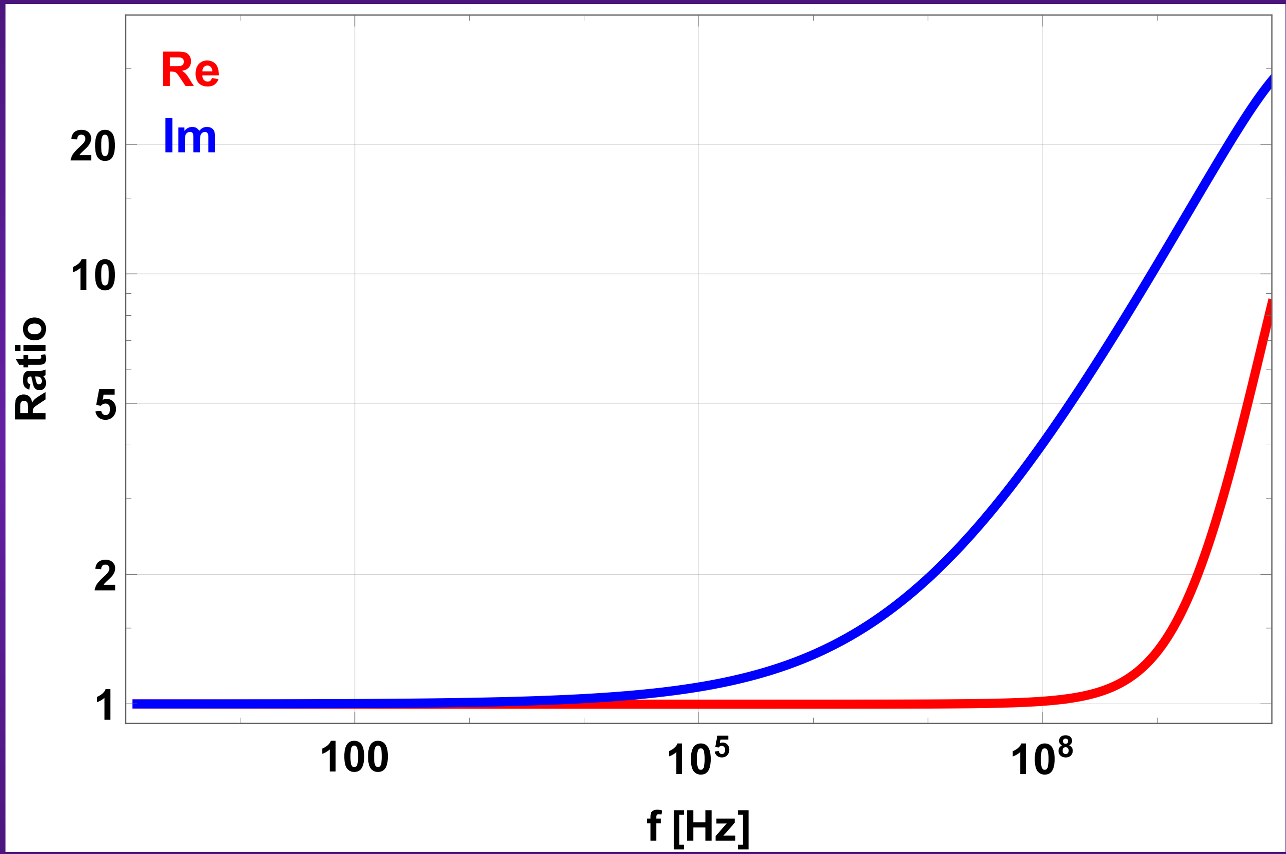
Copper (room temp.) beam pipe with 20 mm radius and 1 µm graphite coating



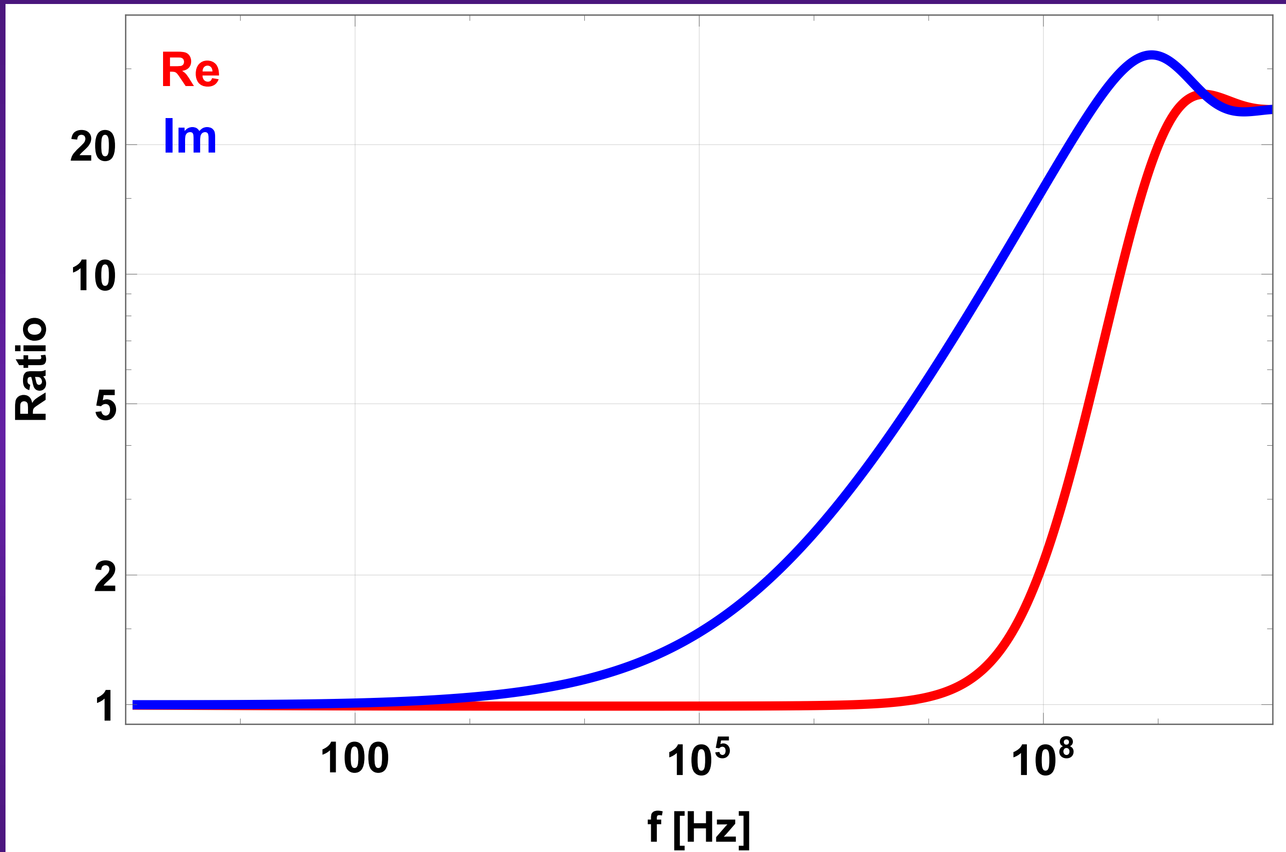
Copper (room temp.) beam pipe with 20 mm radius and 5 μm graphite coating



Copper (room temp.) beam pipe with 20 mm radius and 10 μm graphite coating



Copper (room temp.) beam pipe with 20 mm radius and 50 µm graphite coating



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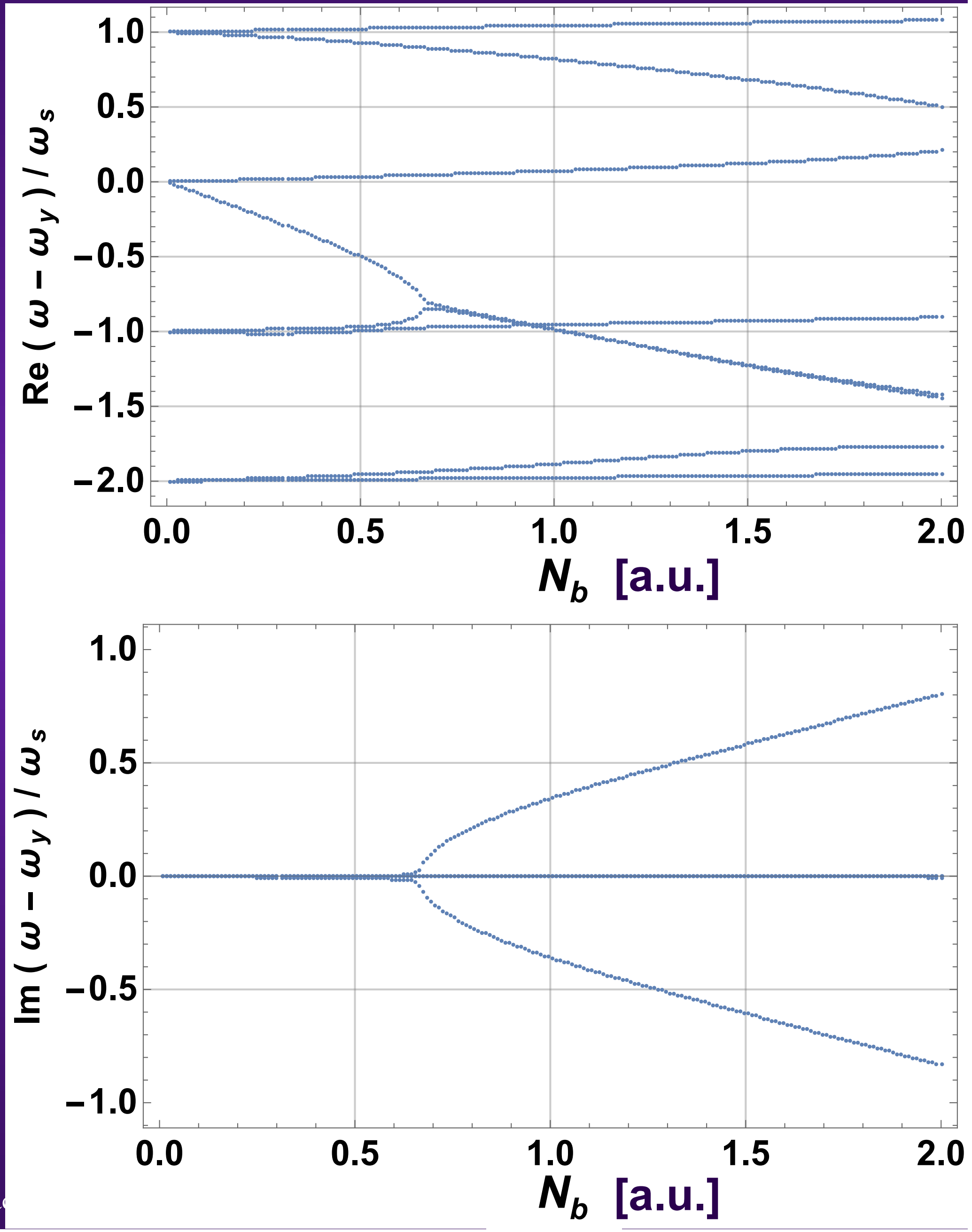

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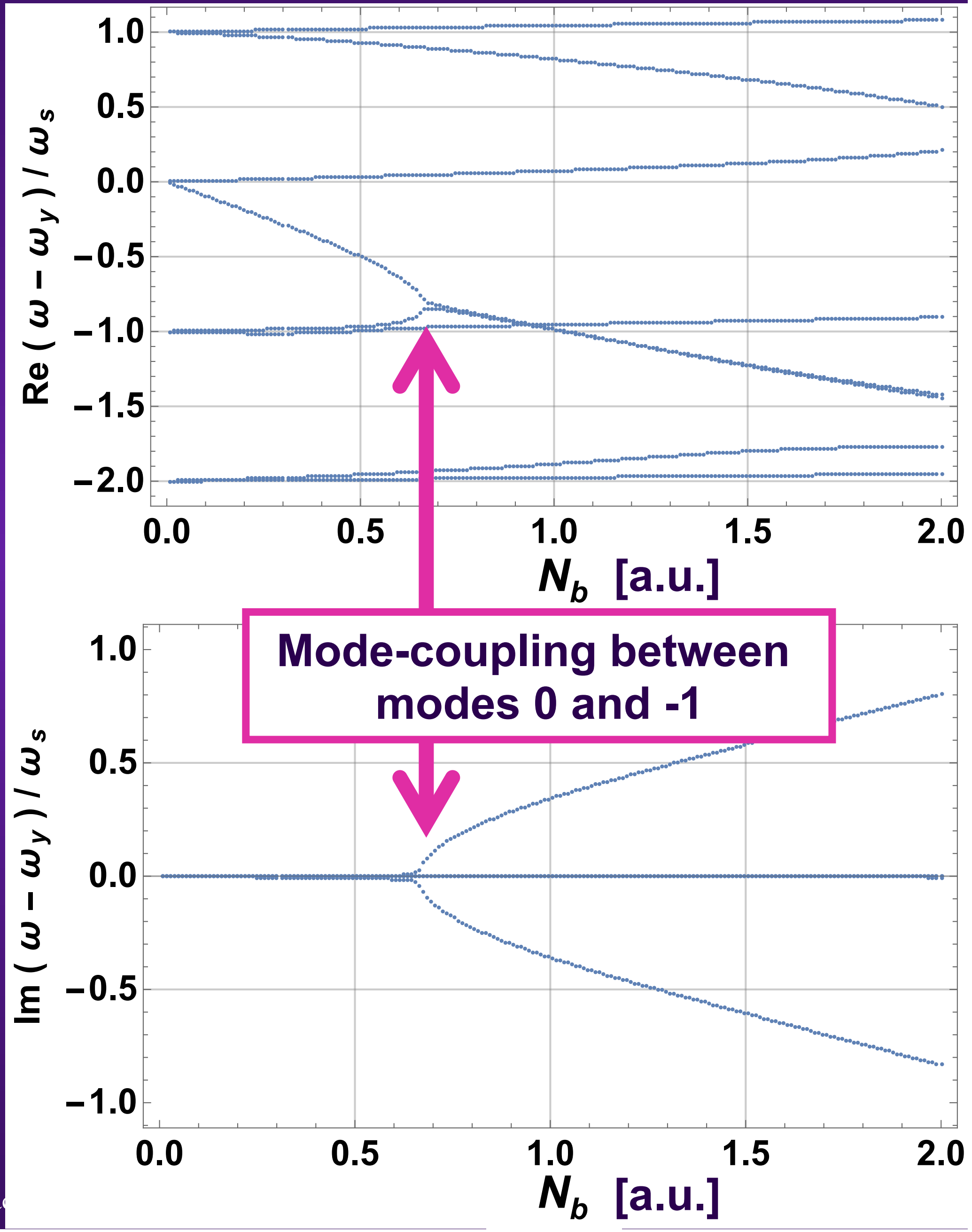

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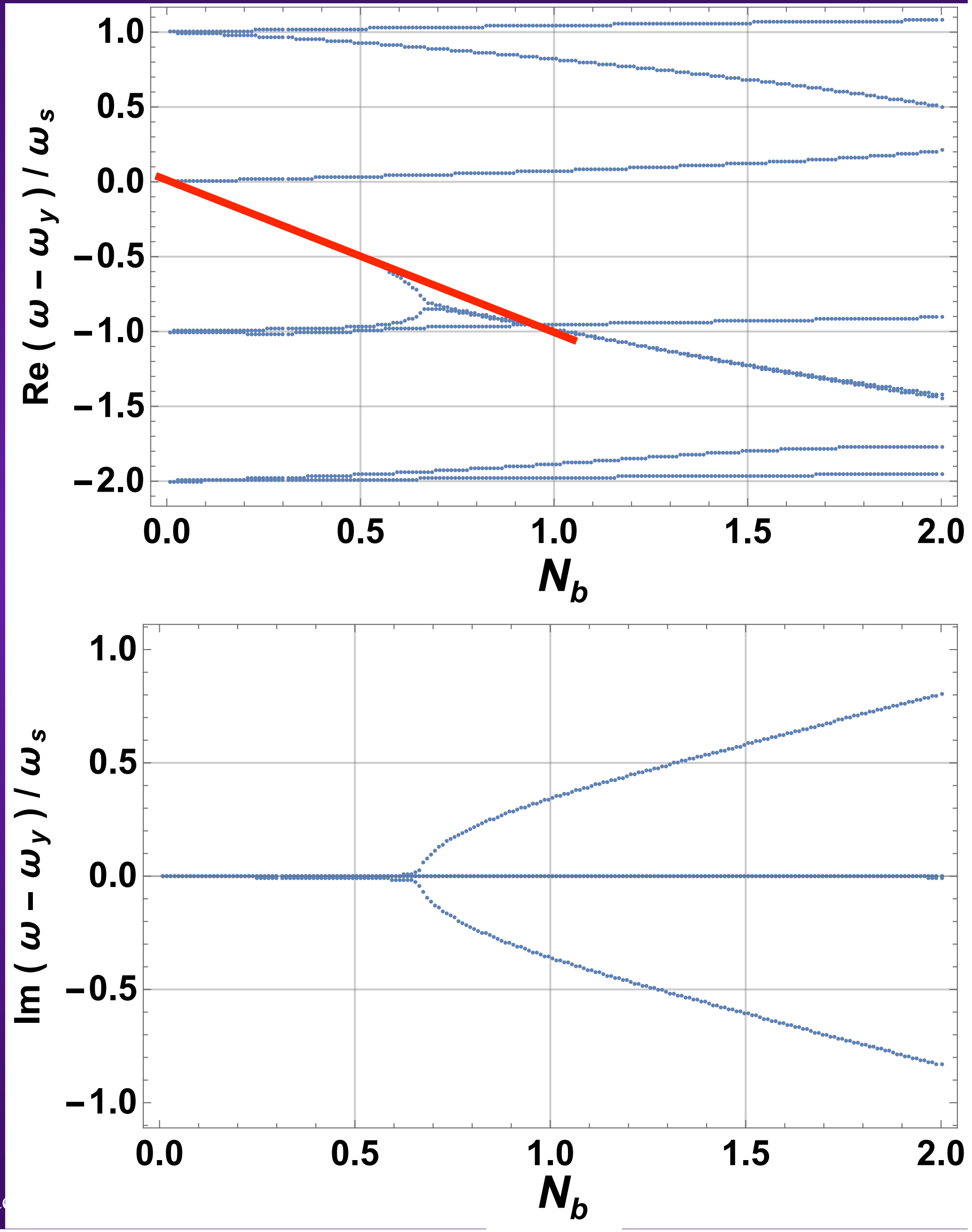
From Sacherer formula



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Weighted by the bunch spectrum (mode 0), which also depends on bunch length…

$\tau_b = 1\ \text{ns}$

$= 7E12$

$= 2E-3$

$$\text{Im}\left(Z_y^{eff}\right) < \text{Im}\left(Z_y^{eff}\right)_{\max} = \frac{4\,\pi\,\left(E_t / e\right)\tau_b\,Q_s}{N_b\;e\;\beta_y^{av}}$$

$$\approx 134\ \text{M}\Omega/\text{m}$$

1.15E11 p/b

$= R / Q_y = 71.5\ \text{m}$

EFFECT OF THE (RESISTIVE) TRANSVERSE DAMPER

- **A (bunch by bunch) resistive transverse damper is usually used to damp the TCBI => IF instability rise-time is longer than ~ 10 turns**

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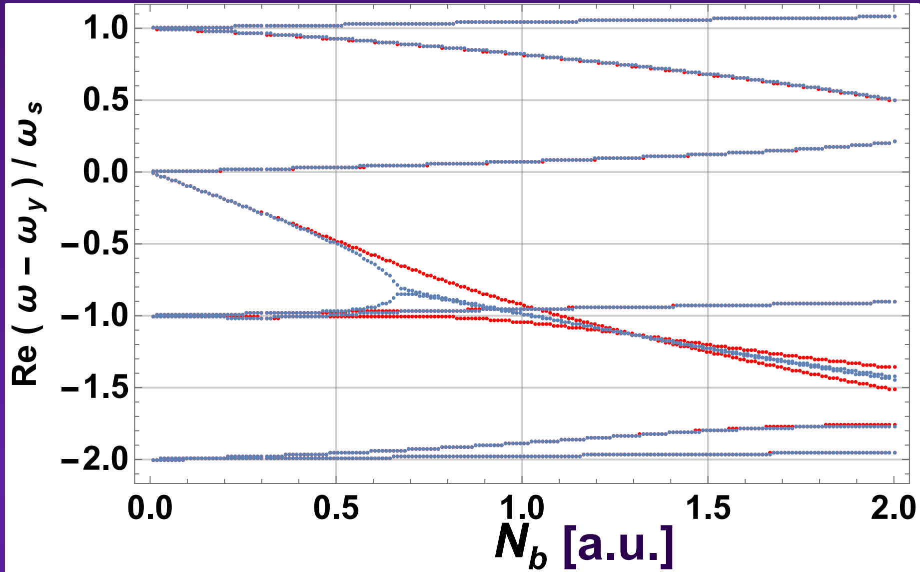
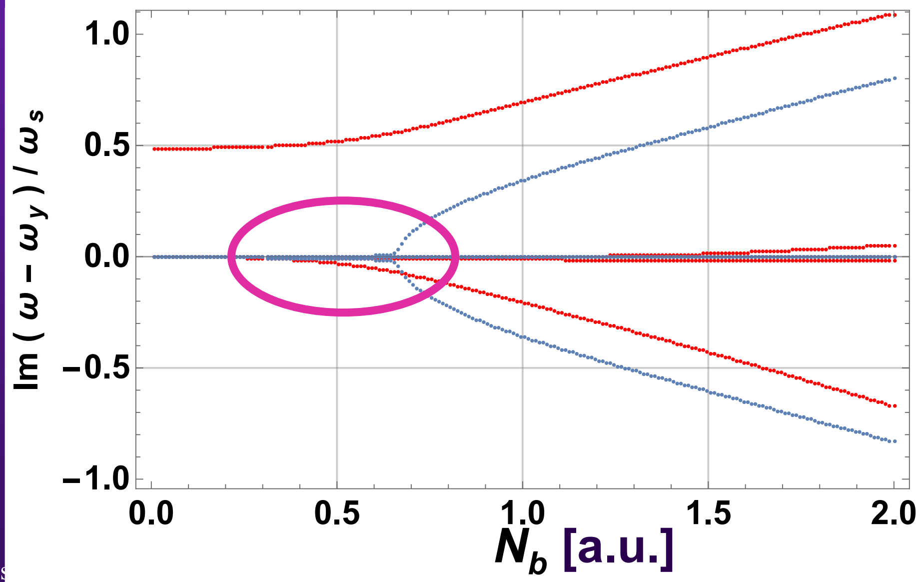
- **Recent studies revealed that for Q' = 0 the resistive transverse damper is destabilising (for the single bunch) and shed a light on the physical mechanism**

EFFECT OF THE (RESISTIVE) TRANSVERSE DAMPER

- **Destabilising effect of the resistive transverse damper (in red below)**





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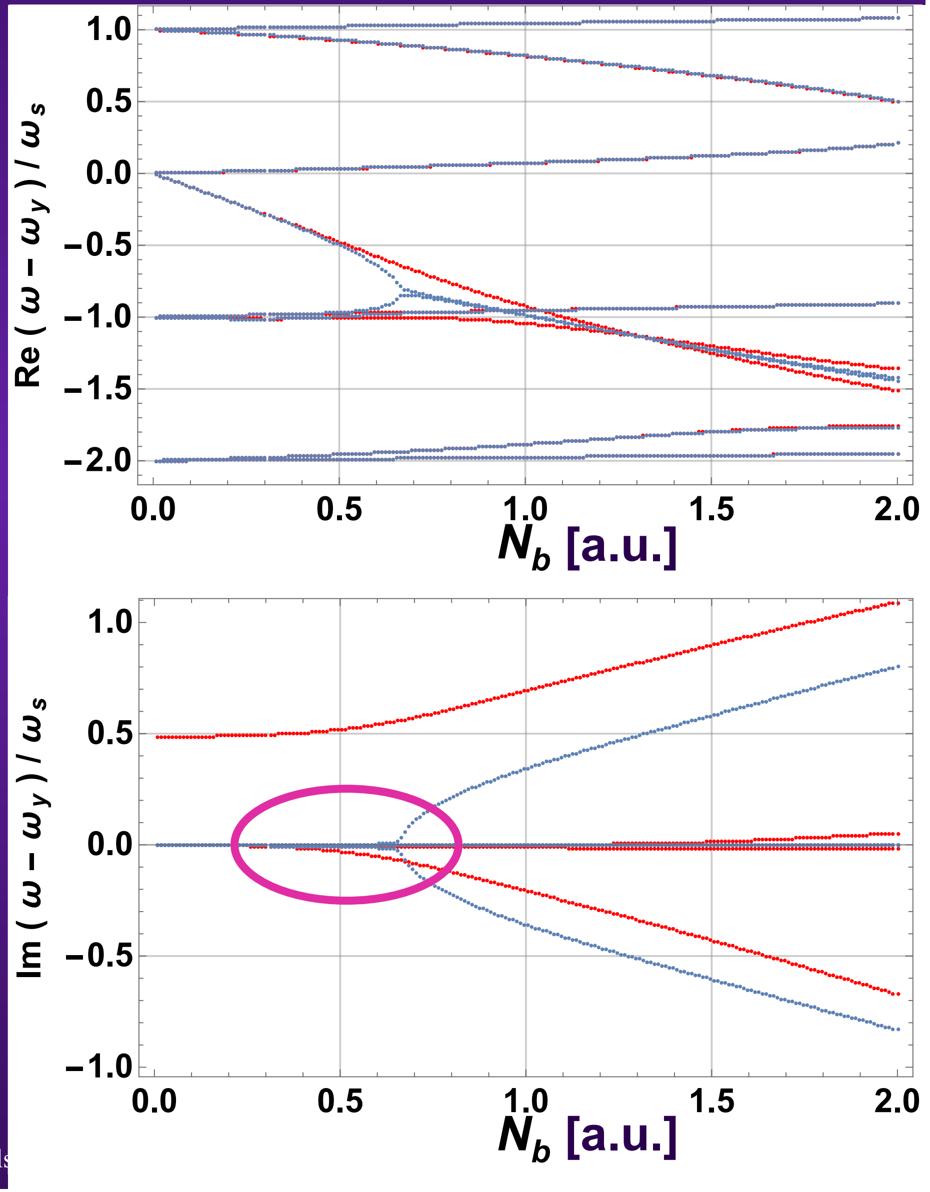

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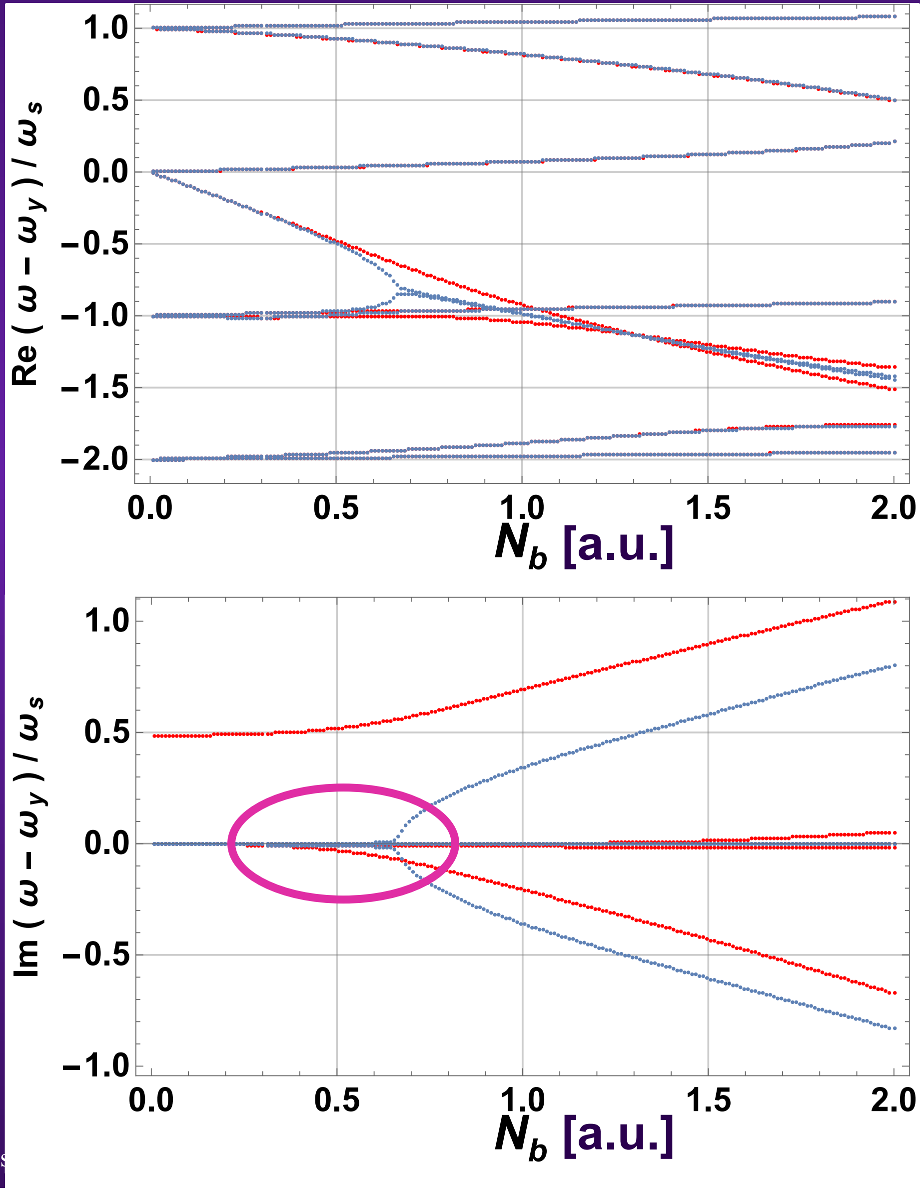
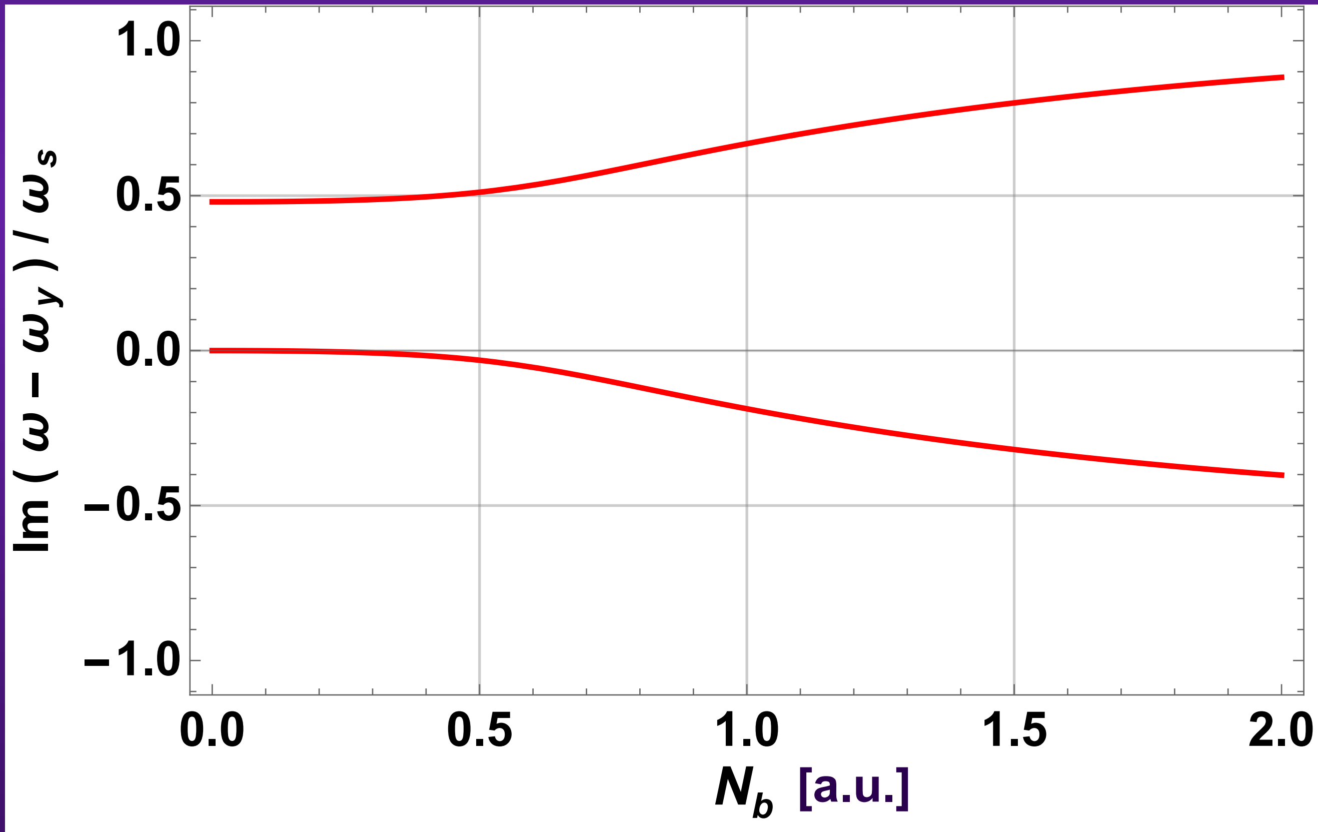
  - **The “coupling” between the 2 modes pushes apart the instability growth rates and as the lowest one is 0, it becomes negative**



EFFECT OF THE (RESISTIVE) TRANSVERSE DAMPER

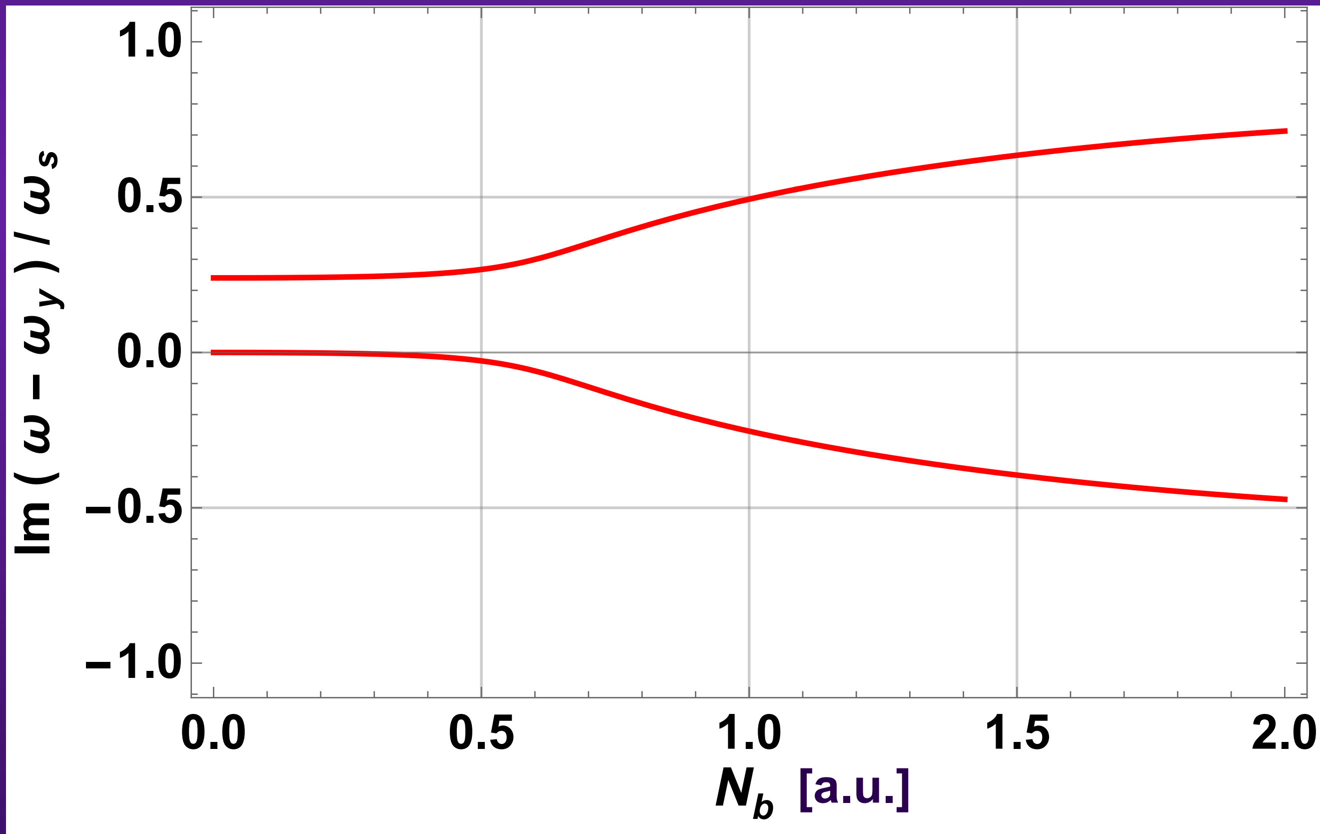
- **Considering only the 2 modes 0 and - 1 yields**

With the transverse damper gain used before



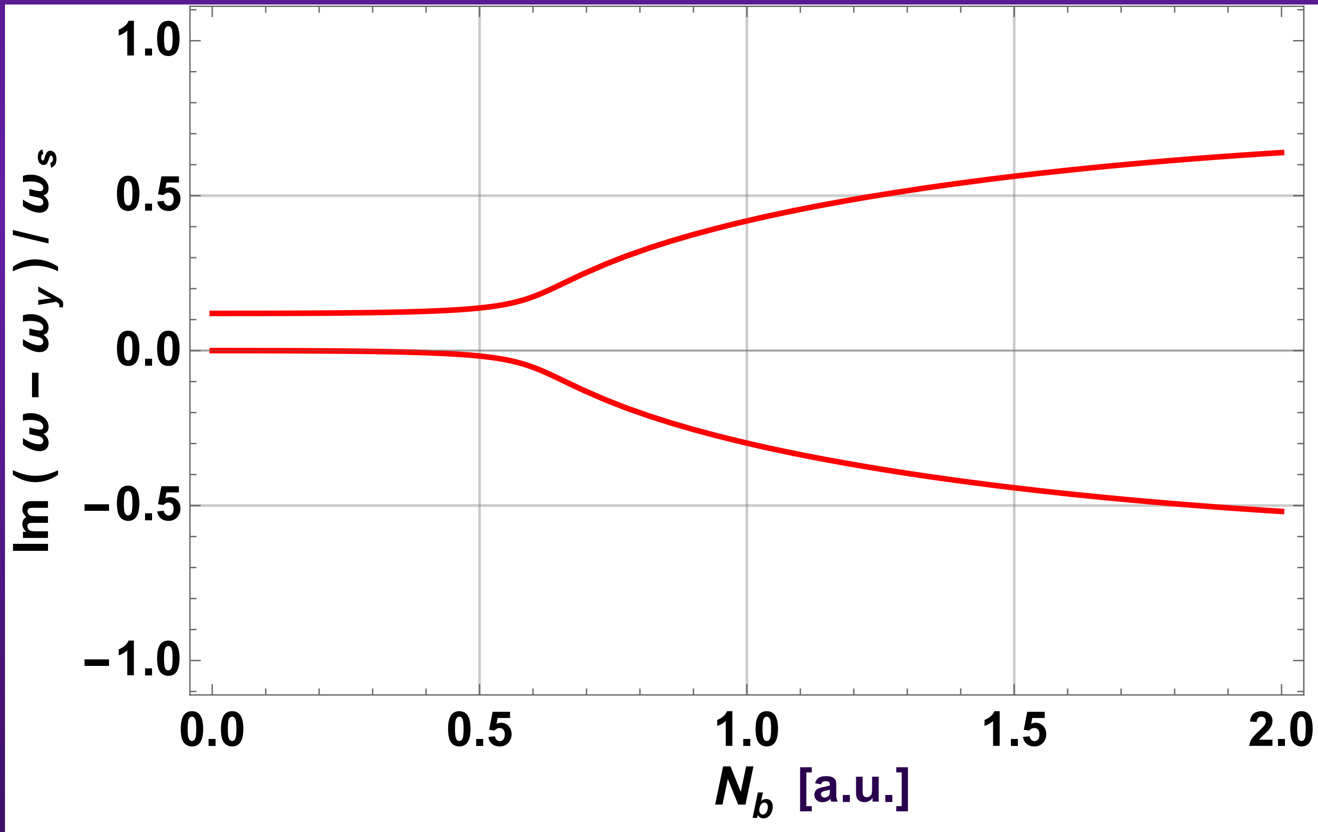
EFFECT OF THE (RESISTIVE) TRANSVERSE DAMPER

With the transverse damper gain used before / 2



EFFECT OF THE (RESISTIVE) TRANSVERSE DAMPER

With the transverse damper gain used before / 4



EFFECT OF THE (RESISTIVE) TRANSVERSE DAMPER

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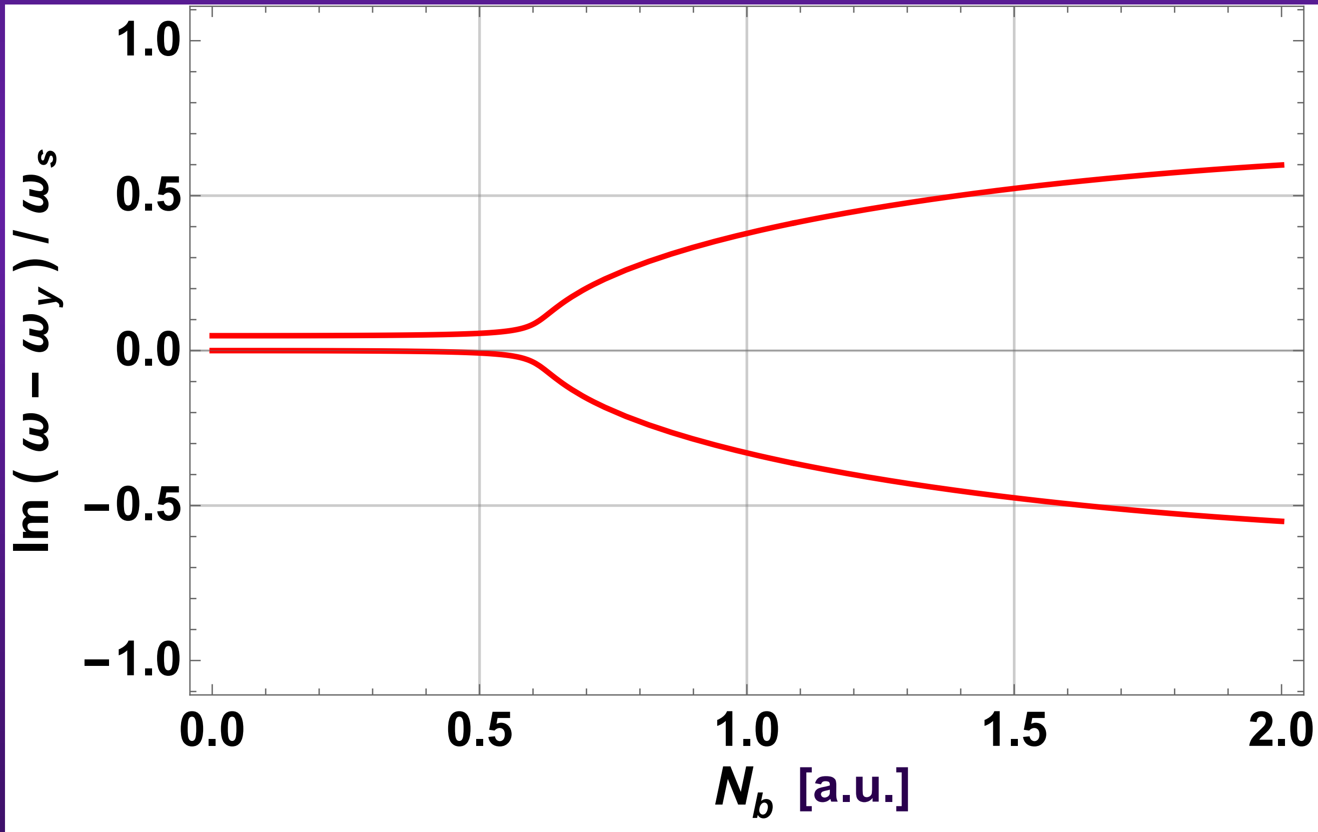
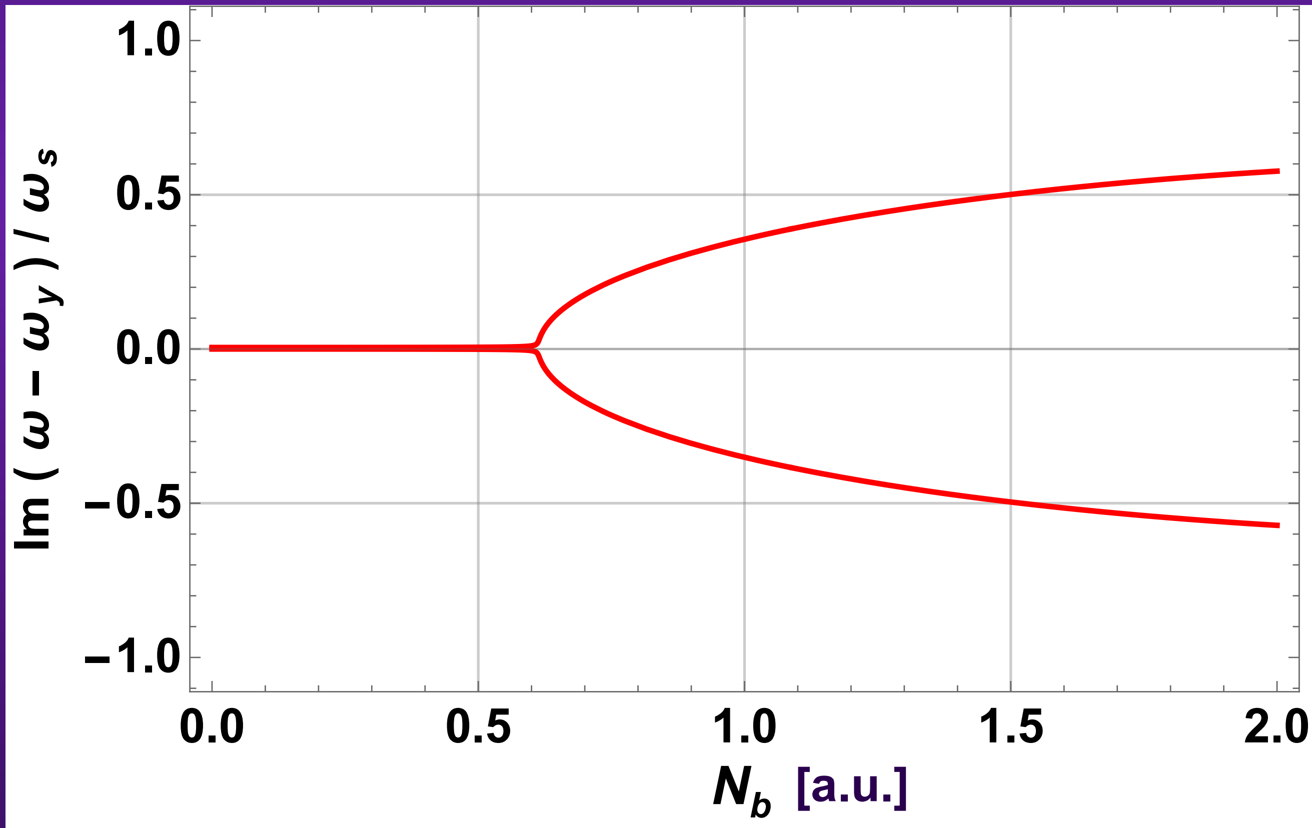


EFFECT OF THE (RESISTIVE) TRANSVERSE DAMPER

With the transverse damper gain used before / 100



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- **The consequences on the Landau damping are currently under investigation (as the assumption of independent modes cannot be made anymore)**

- **However, with a sufficiently strong (and low noise) transverse damper, the TCBI (low frequency) should not be a problem anymore => Particular attention should be paid to the high frequency (single-bunch) regime**

COATING (e.g. a-C) OR SURFACE TREATMENT (e.g. LESS) TO FIGHT AGAINST E-CLOUD

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$$= \tau_b \, f_{rev} = 1\,\text{ns} \times 11245.5\,\text{Hz}$$

35640

16 MV

$$\left| \frac{Z_l(n)}{n} \right|_{eff} \leq \left| \frac{Z_l(n)}{n} \right|_{eff}^{\max} \propto \frac{h^3 \, \hat{V}_{RF} \, B_0^5}{N_b \, e \, f_{rev}}$$

$n = f \,/\, f_{rev}$

Weighted by the bunch spectrum

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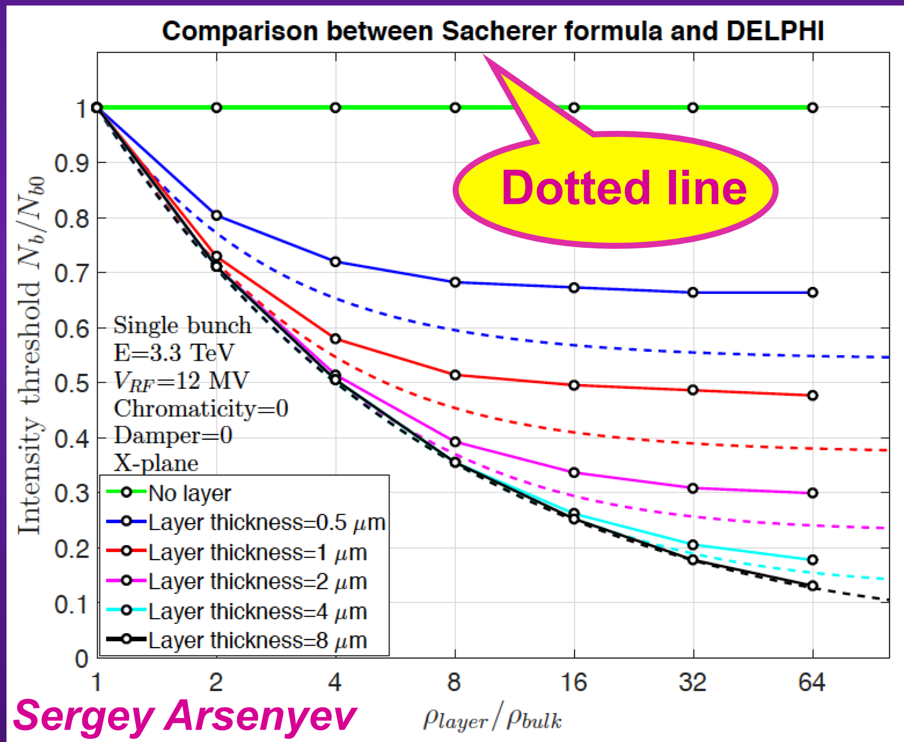

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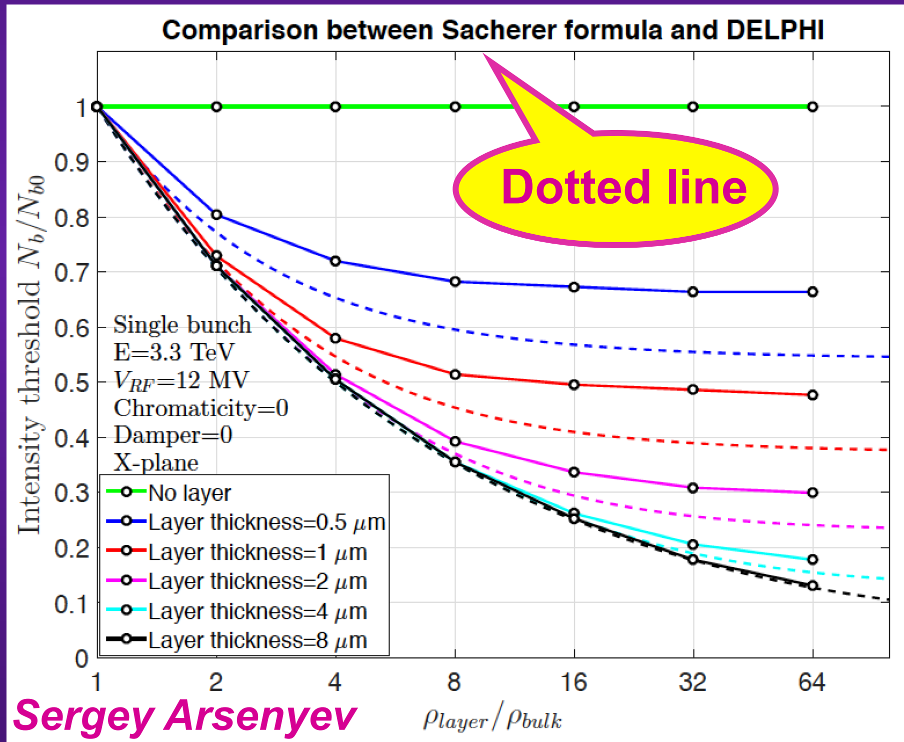

=> Measurements at low temperature and high magnetic field are required (and planned)

HTS COATING for FCC-hh: YBCO (from Sergio Calatroni)

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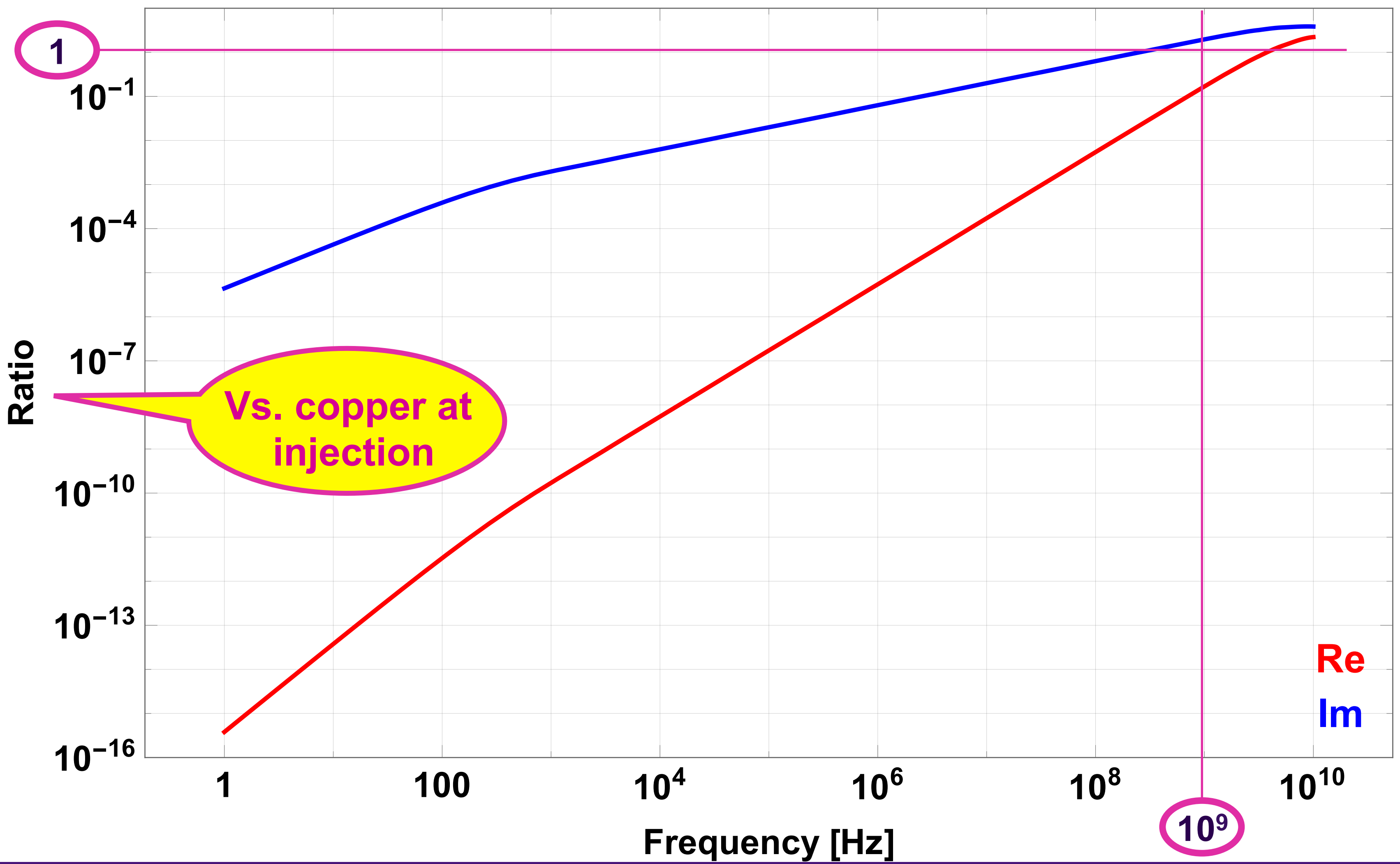

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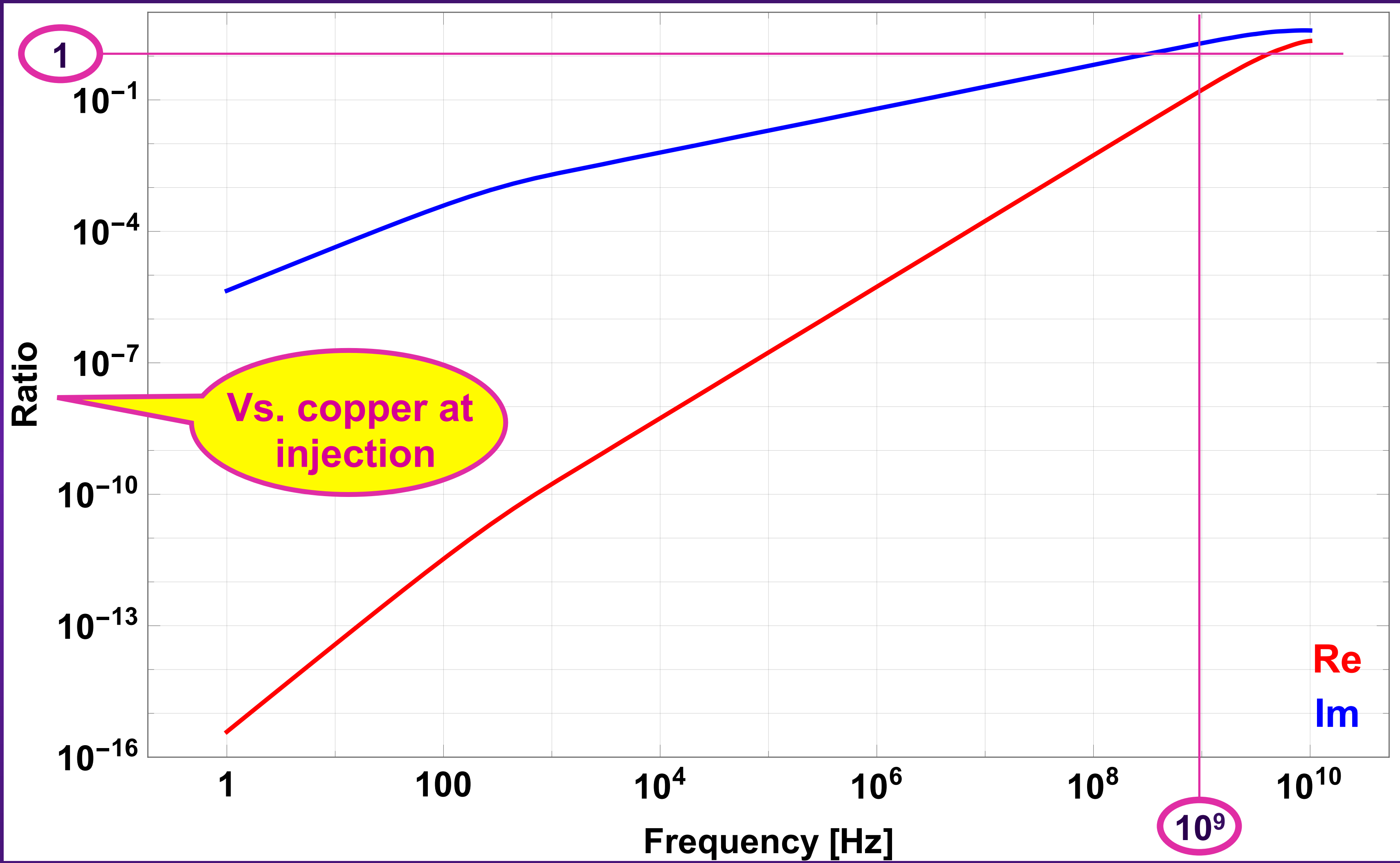

- **Much better at low and intermediate frequencies**

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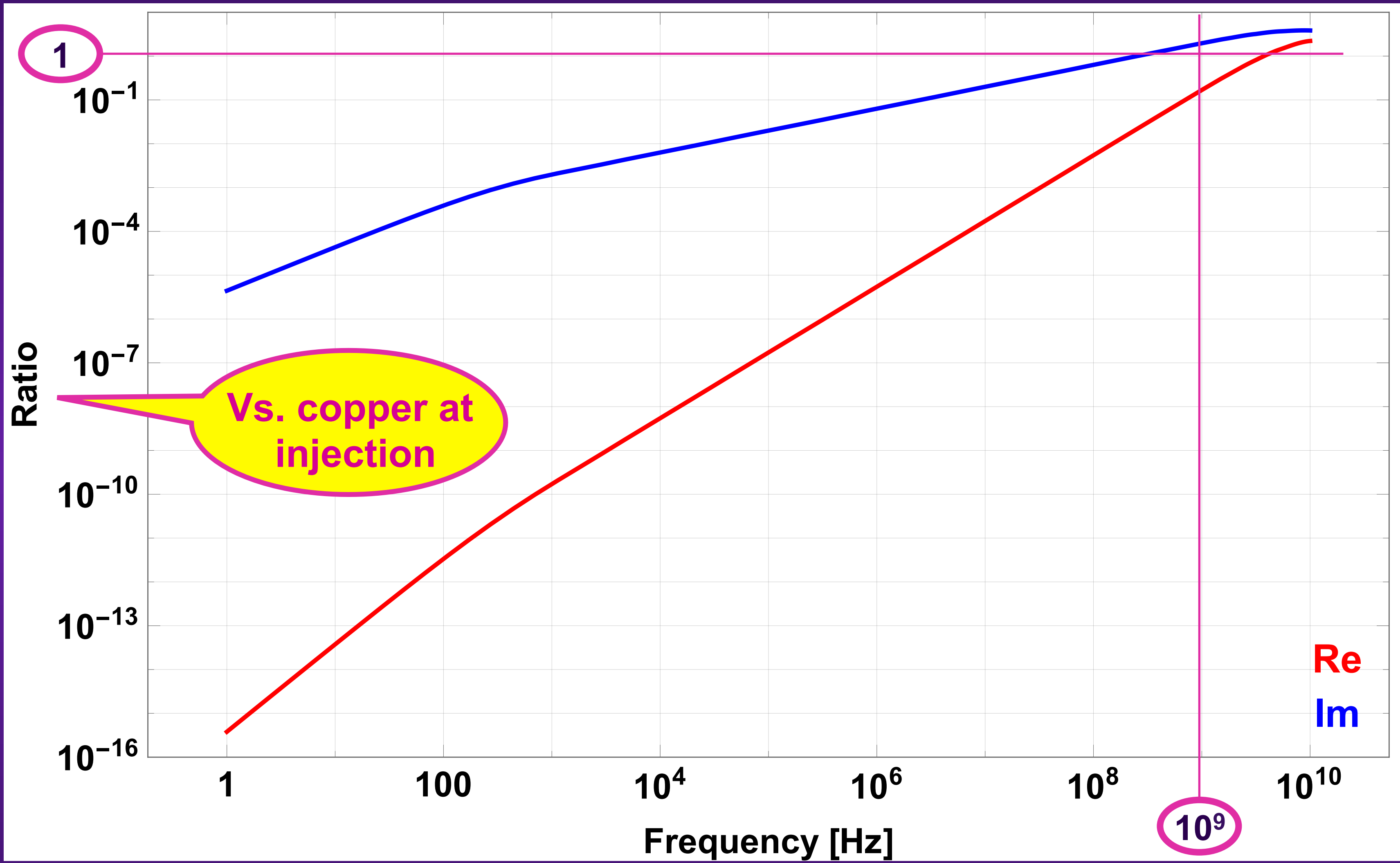
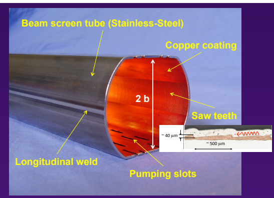


- Much better at low and intermediate frequencies
- Pay attention to higher frequencies as it could impact TMCI

Longitudinal weld



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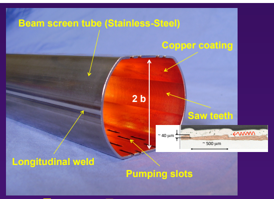

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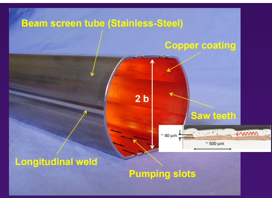

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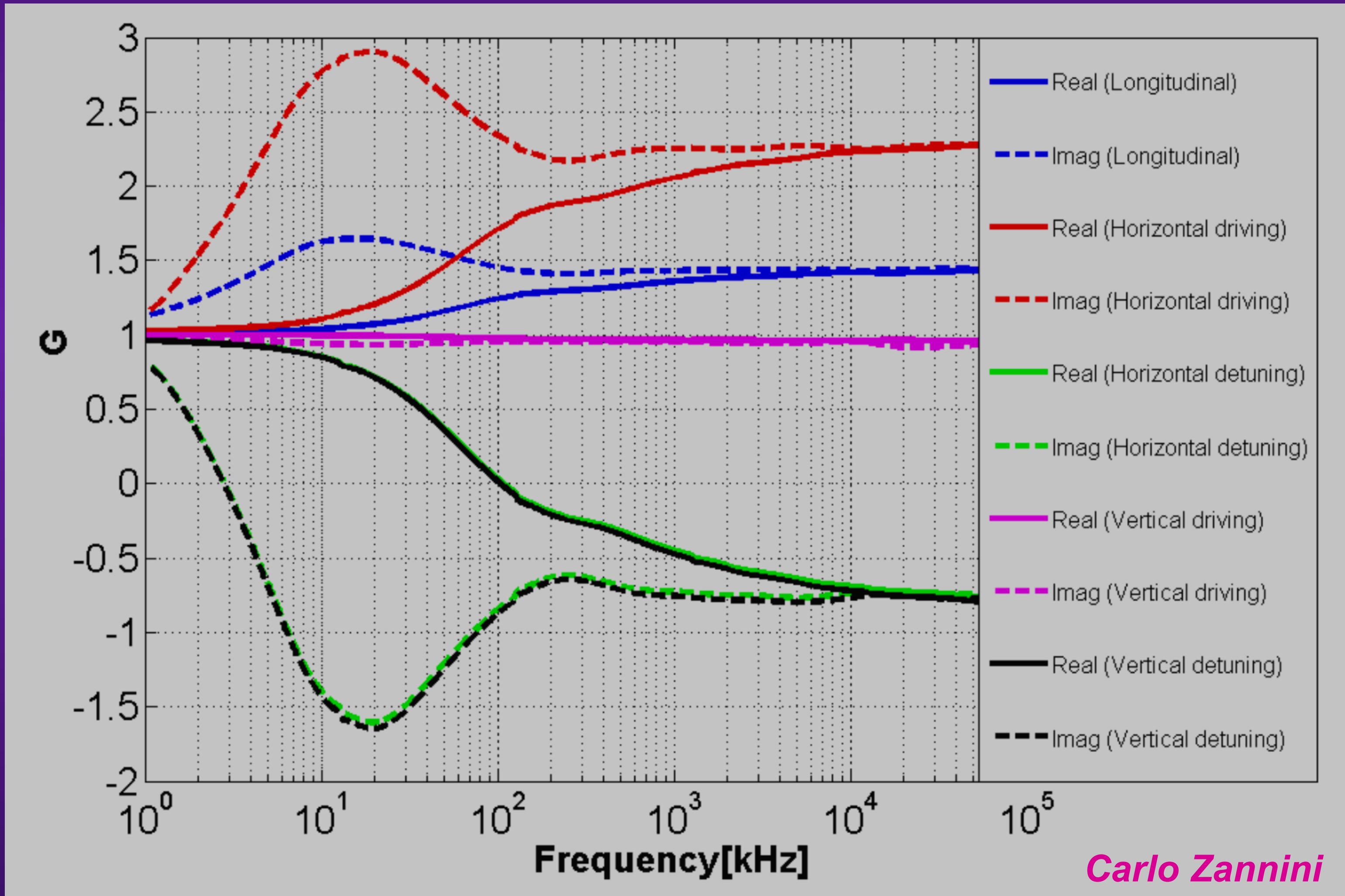

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$$\frac{\Delta_l^{Weld}}{2\,\pi\,b} = \frac{2}{2\,\pi \times 18.4} = \frac{1}{\pi \times 18.4} \approx \frac{1}{60}$$

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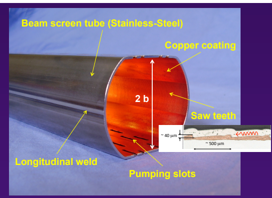
=> The estimated increase of the power loss by ~ 50% is in agreement with the previous simulations (high frequency effect)

Pumping slots



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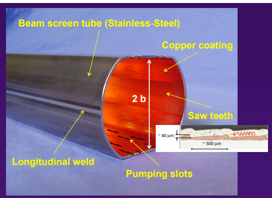

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  - **In the arcs: η = 4.0%**
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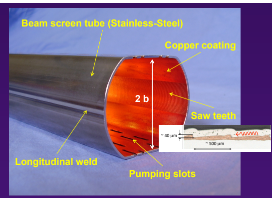

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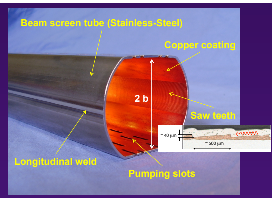
Pumping slots



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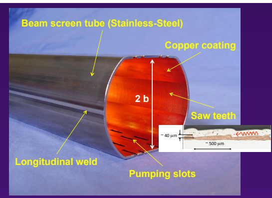

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- **In addition, some trapped modes could be created => Randomization of the slots lengths (between 6,7,8,9,10 mm with average at 8 mm) + randomization of the slot spacing**

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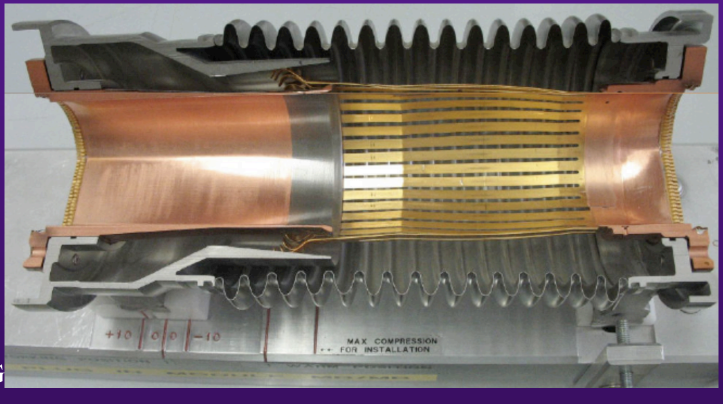
Example of RF fingers:

PIMs = Plug-In Modules



Many thanks for your attention!

APPENDIX A: LHC BEAM SCREENS

Arc beam screens:

Inner dimension between flats:	36.8 mm
Inner dimension between radii:	46.4 mm
SS thickness:	1.0 mm
Cu thickness:	0.075 mm

LSS beam screens:

Inner dimension between flats:	varying from 37.6 until 61.0 mm
Inner dimension between radii:	varying from 47.2 until 70.7 mm
SS thickness:	0.6 mm
Cu thickness:	0.075 mm

Courtesy of N. Kos

Resistance SS at room temp:	7E-7 ohm.m
RRR SS:	1.2
Low temp resistance SS:	7E-7/1.2 = 6E-7 ohm.m
Resistance copper at room temp:	2E-8 ohm.m
RRR Cu (co-laminated surface):	100
Low temp Cu resistance:	2E-8/100 = 2E-10 ohm.m

Courtesy of N. Kos

APPENDIX B: RRR (Residual Resistivity Ratio)

- **Reduction of the resistivity with temperature => The resistivity decreases with temperature towards a minimum (determined by purity) and the RRR is defined as the ratio of the DC resistivity at room temperature to its cold-DC lower limit**

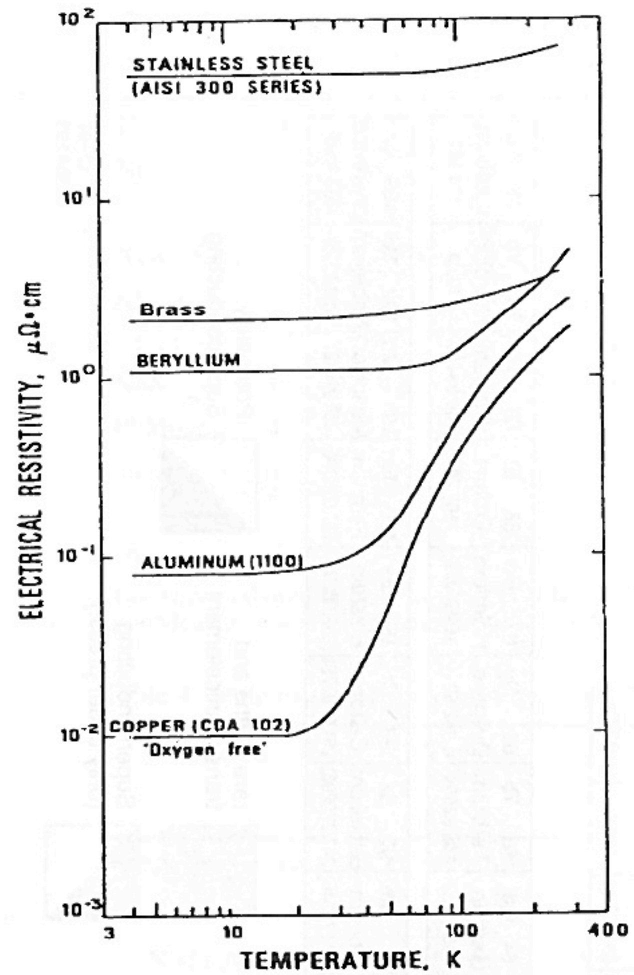
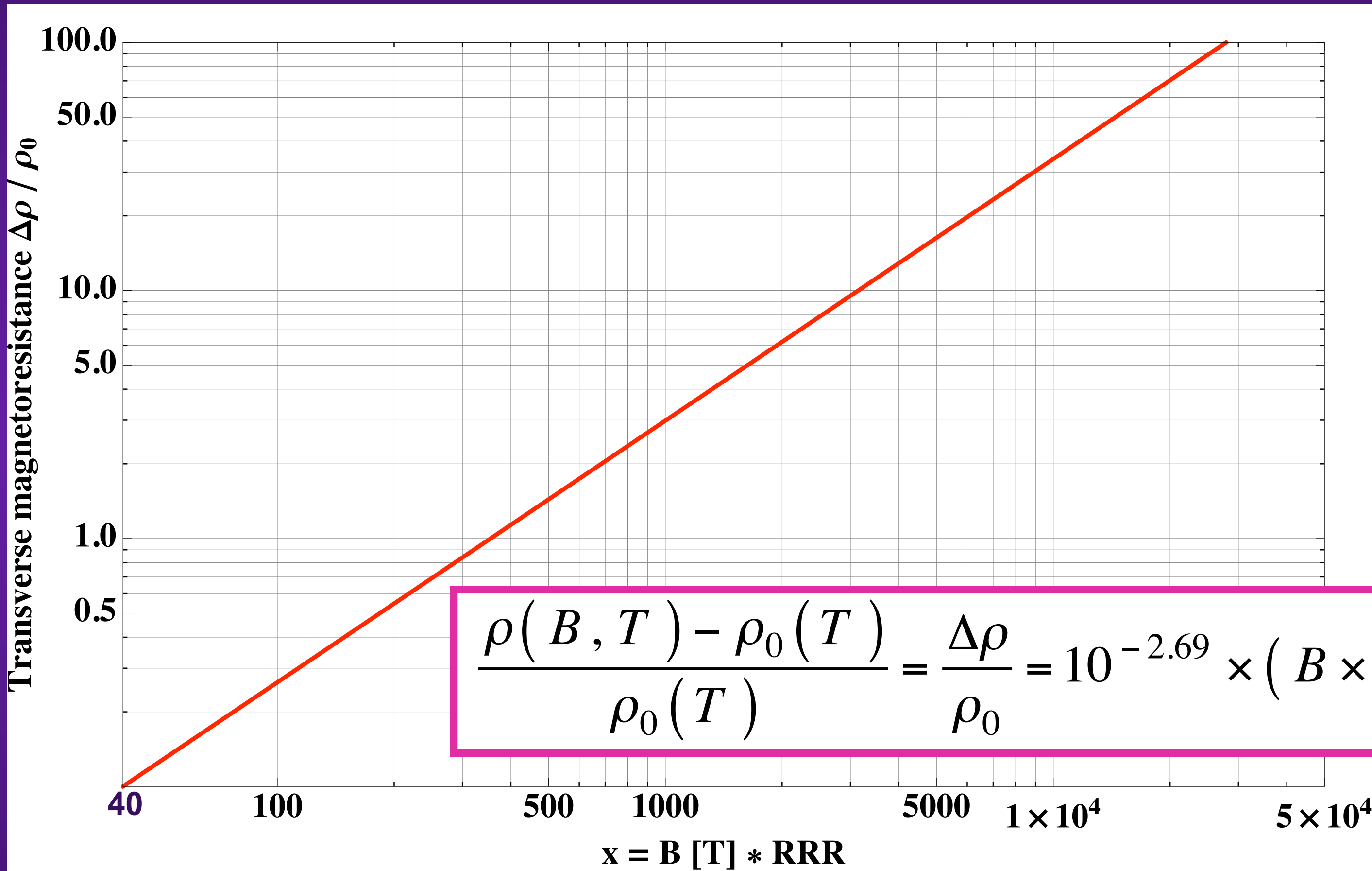


Figure 2: Resistivity of several metals vs T.

"Handbook of Accelerator Physics and Engineering", 2nd Printing, Edited by A.W. Chao and M. Tigner, p. 368

APPENDIX C: MAGNETO-RESISTANCE

- Increase of the resistivity with magnetic field => Kohler's rule



$$\frac{\rho(B,T)-\rho_0(T)}{\rho_0(T)} = \frac{\Delta\rho}{\rho_0} = 10^{-2.69} \times (B \times RRR)^{1.055}$$

- **0.535 T**

  $x = 53.5$

  $\Delta\rho / \rho_0 \approx 0.14$

- **8.33 T**

  $x = 833$

  $\Delta\rho / \rho_0 \approx 2.5$

- **20 T**

  $x = 2000$

  $\Delta\rho / \rho_0 \approx 6.2$

APPENDIX D: PUMPING HOLES

- The parameters for the current beam screen are
  - Length of the slots: L = 6,7,8,9 and 10 mm => Laverage = 8 mm
  - Width of the slots:
    - In the arcs: W = 1.5 mm
    - In the LSS: W = 1.0 mm
  - Beam screen thickness:
    - In the arcs: T = 1 mm SS + 0.075 mm Cu = 1.075 mm
    - In the LSS: T = 0.6 mm SS + 0.075 mm Cu = 0.675 mm