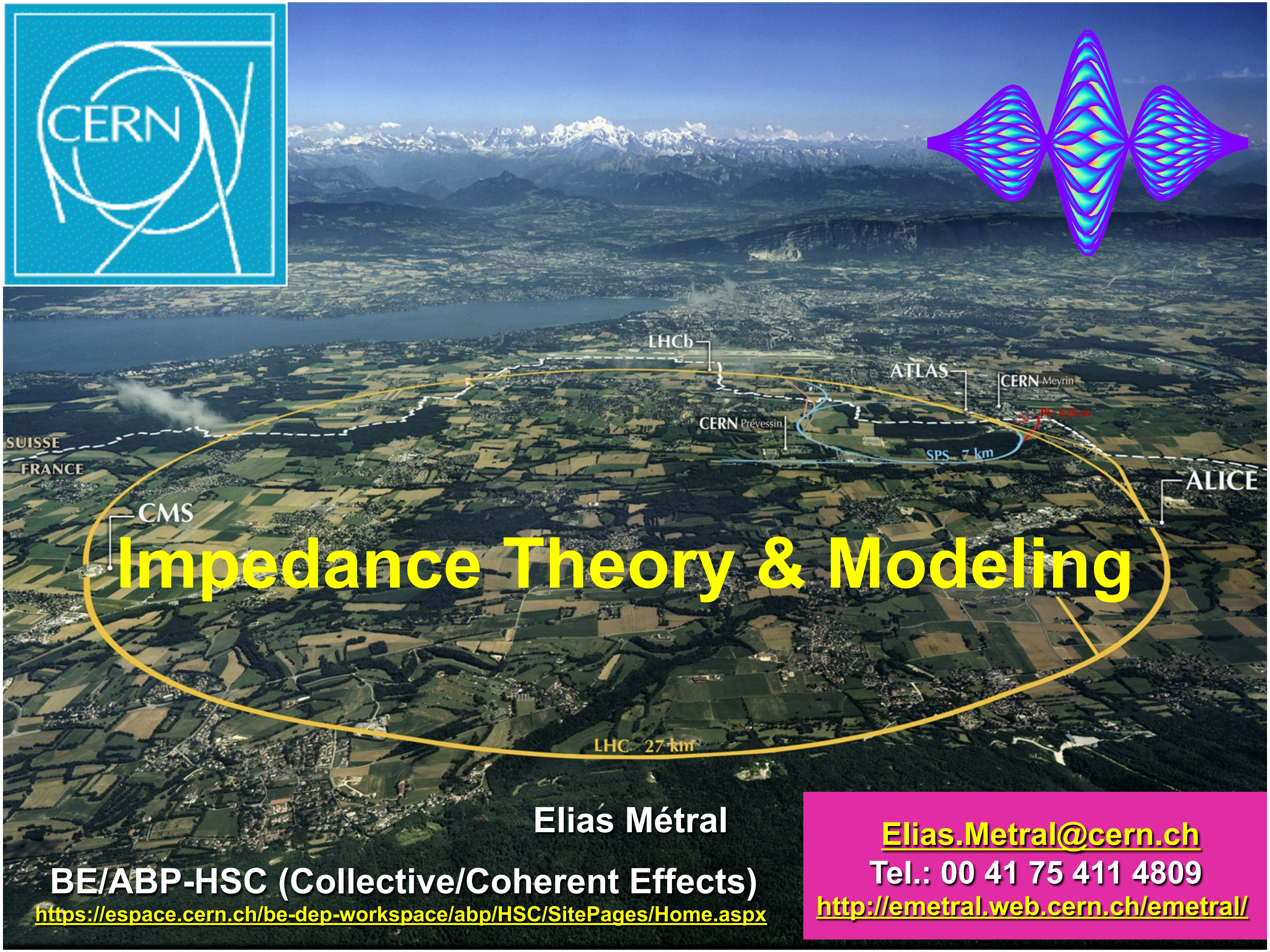



# Impedance Theory & Modeling

**Elias Métral**

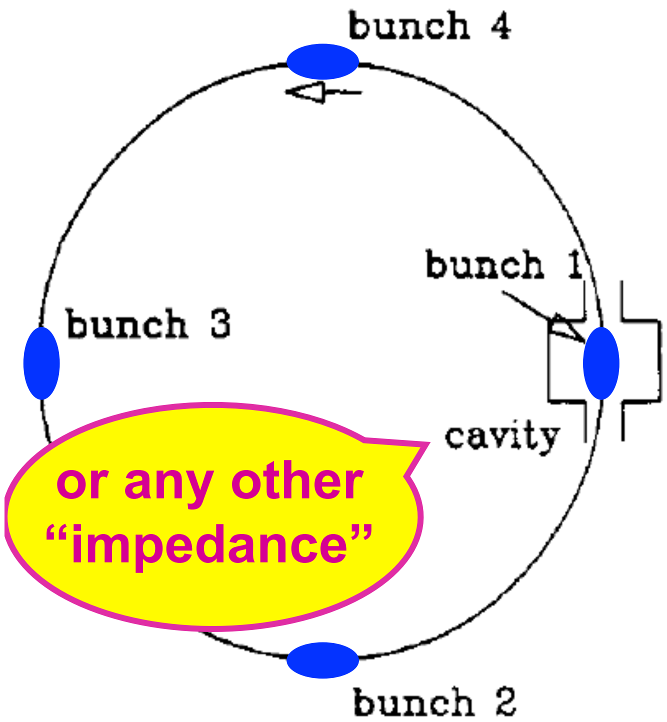
**BE/ABP-HSC (Collective/Coherent Effects)**

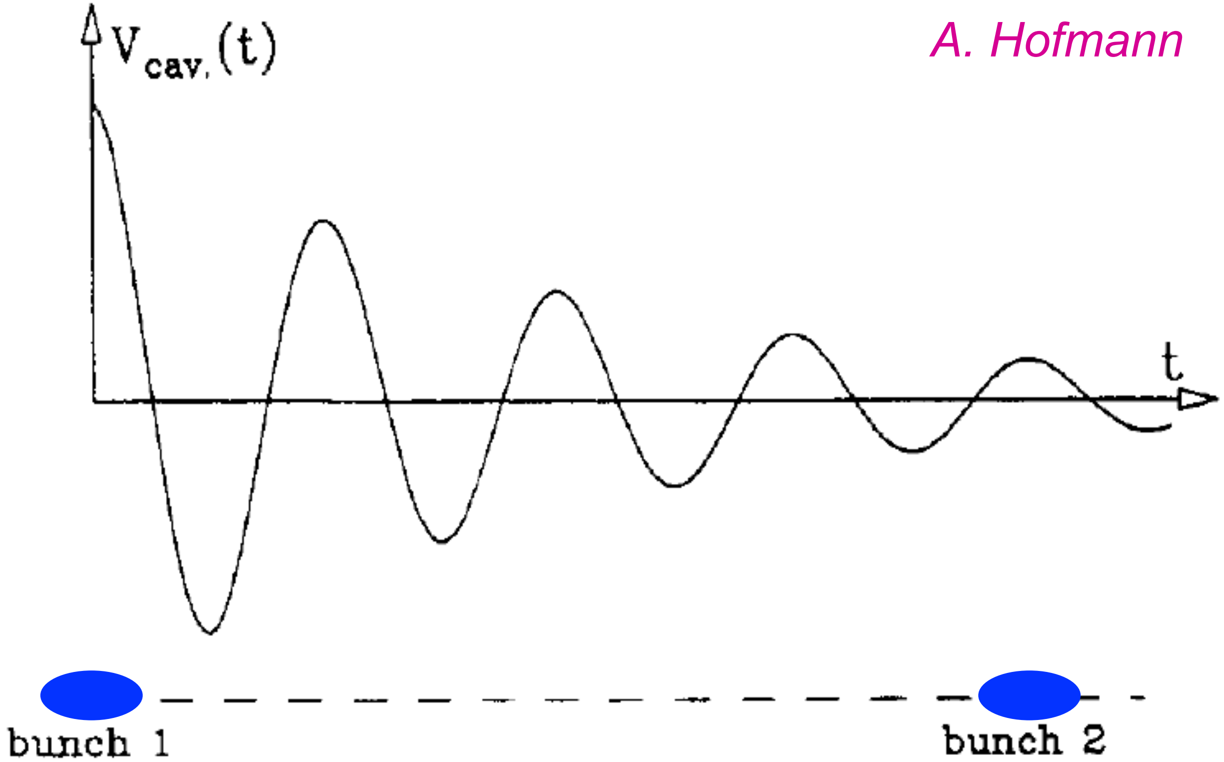
https://espace.cern.ch/be-dep-workspace/abp/HSC/SitePages/Home.aspx

Elias.Metral@cern.ch

**Tel.: 00 41 75 411 4809**

http://emetral.web.cern.ch/emetral/




*A. Hofmann*

- **"Impedances" limit performance of ALL machines**
  - **Beam instabilities => Increased beam size, beam losses**
  - **Excessive heating => Deformed / melted components, beam dumps**
- **Each equipment of each accelerator has an "impedance" => To be characterized and minimized!**

ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

# ICFA mini-Workshop on "Electromagnetic wake fields and impedances in particle accelerators"

23-28 April 2014
Europe/Zurich timezone

Search...

- Overview
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- Scientific programme and timeline
- International Advisory Committee (IAC)
- List of items to be discussed
- Contacts
- List of participants
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- Erice - Get there
- Excursions
- Application form
- Flyer
- Picture of the workshop

Support
Delphine.rivoiron...
004122 767 25 23

ICFA mini-Workshop on "Electromagnetic wake fields and impedances in particle accelerators" to be held in Erice, Sicily, in 2014 from April 24th to April 28th. The Workshop will be hosted by "ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE".

**THE ROOTS OF WESTERN CIVILIZATION**

**The quadrilingual gravestone in Ziza Museum in Palermo, Sicily. The languages are Latin, Greek, Arabic and Hebrew. The dates appearing in the four languages, each computed in its own calendar, correspond to 1148 a.d. .**

**Starts** 23 Apr 2014 21:00
**Ends** 28 Apr 2014 18:00
Europe/Zurich

Elias Metral
Vittorio Giorgio Vaccaro

# Scientific programme and timeline

**Wednesday 23/04/2014: Arrival**

21:00 - 23:00: Get-Together-Party

**Thursday 24/04/2014:**

Session 1: Impedance theory and related effects
Session 2: Impedance numerical simulations
Session 3: Impedance bench and beam-based measurements

**Friday 25/04/2014:**

Session 4: Extensions of the impedance concept
Session 5: Impedance challenges for new projects
Session 6: Building the impedance model of a machine
Banquet in the evening

**Saturday 26/04/2014:**

Session 7: Space charge and resistive-wall impedances
Session 8: Geometrical impedance
Session 9: Impedance of diagnostics structures
Poster session at the end of the afternoon

**Sunday 27/04/2014:** Full-day excursion

**Monday 28/04/2014:**

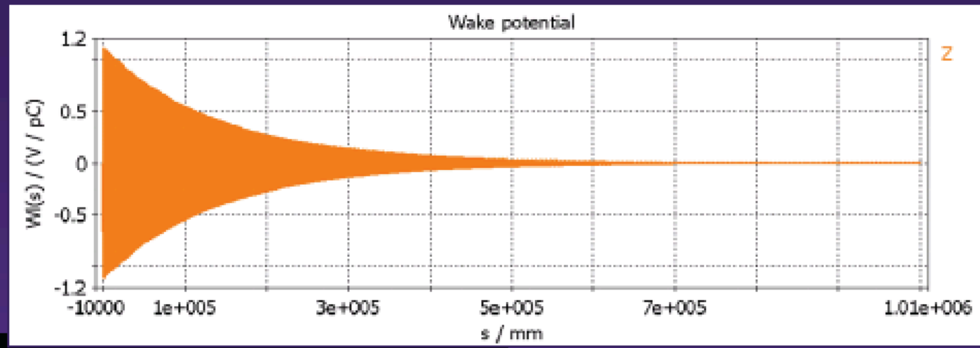
Session 10: Impedance of collimators and kickers
Session 11: Summaries

**Tuesday 29/04/2014: Departure**

$$E_z = - \frac{Z \; I}{2\pi R}$$

**A. Sessler and V. Vaccaro**

# February 6, 1967




**The very 1st paper on impedance was written in November, 1966**

**Many thanks again for all Vittorio!**
**(and let's celebrate the ½ century in 2016-2017)**

- "Known" 1st introduction of the beam coupling impedance concept for particle accelerators => A. Sessler and V. Vaccaro (1967)

$$U = Z\, I$$

Ohm's law in electricity

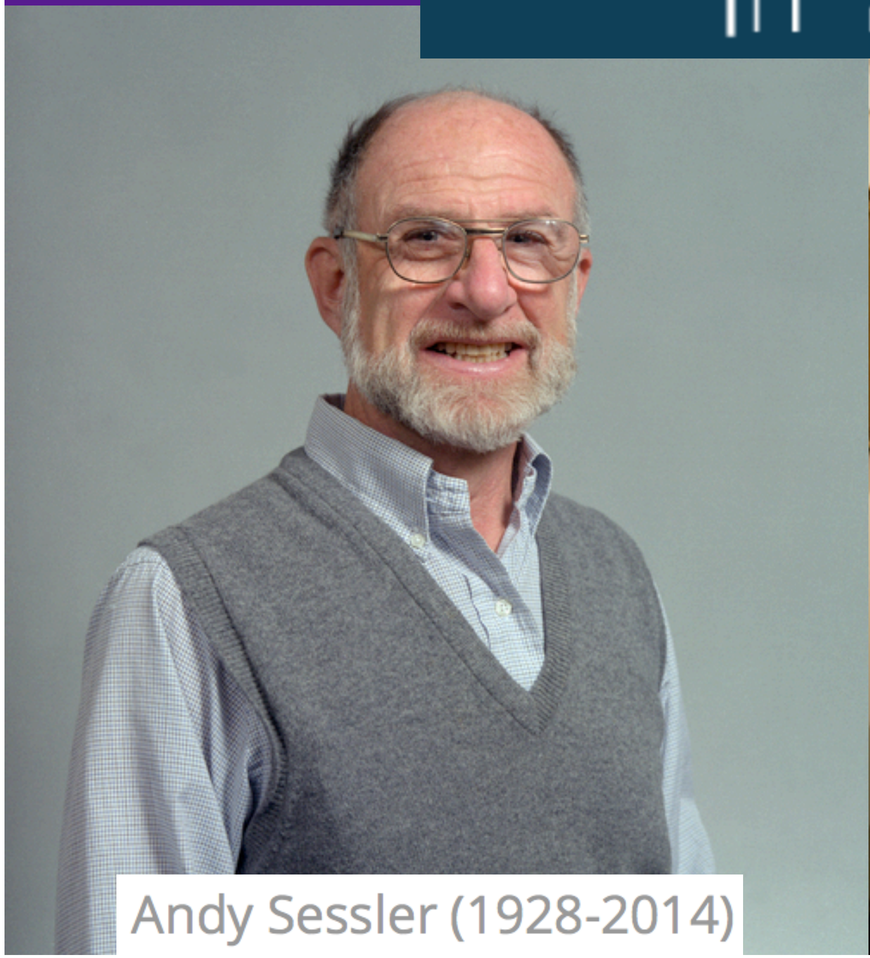
~ Integrated force

=> $$Z = -\frac{E_z\, 2\,\pi\, R}{I}$$

Longitudinal impedance (frequency domain)

# In Memoriam: Andrew Sessler, Former Laboratory Director, Acclaimed Physicist and Humanitarian

BERKELEY LAB
Bringing Science Solutions to the World



Andy Sessler (1928-2014)

## ◆ …There was another paper in 1966…which could not be known…

Distribution: (closed) AR and ISR Scientific Staff.

ARCHIVES CERN

ISR-RF/66-35
November 18, 1966

LONGITUDINAL INSTABILITY OF A COASTING BEAM ABOVE TRANSITION, DUE TO THE ACTION OF LUMPED DISCONTINUITIES.

by V.G. Vaccaro

1. Generalities

We assume that the electrical action on an ion beam, of a discontinuity in a tank is that of an impedance. We still consider the

where a is the beam radius. The passage of an ion beam induces a field in the discontinuity, which is given by:

$$E_d = -Z\ I/d, \quad (4)$$

where d is the magnitude of the discontinuity, and Z is the impedance of the discontinuity.

REFERENCES


1) V.K. Neil and A.M. Sessler
Longitudinal Resistive Instabilities of Intense Coasting Beams in Particle Accelerator
Rev. Sci. Instr. 36, 429 (1965)

1) A.M. Sessler and V.G. Vaccaro
Longitudinal Instabilities of Azimuthally Uniform Beams in Circular Vacuum Chambers of Arbitrary Electrical Proprieties (in preparation).

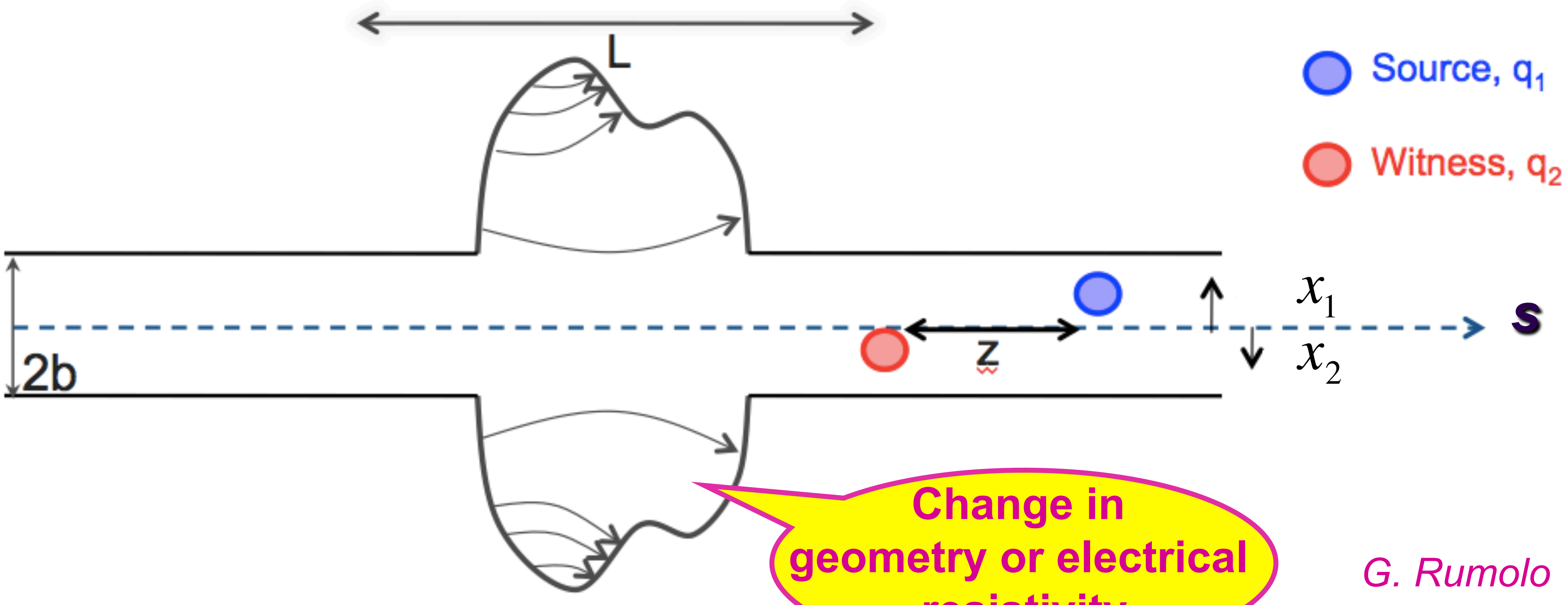
- **Wake field (wake function)** = concept in space / time domain (came few years later => 1969)

  => The 2 are linked by Fourier transforms

LNF - 69/80

23 Dicembre 1969

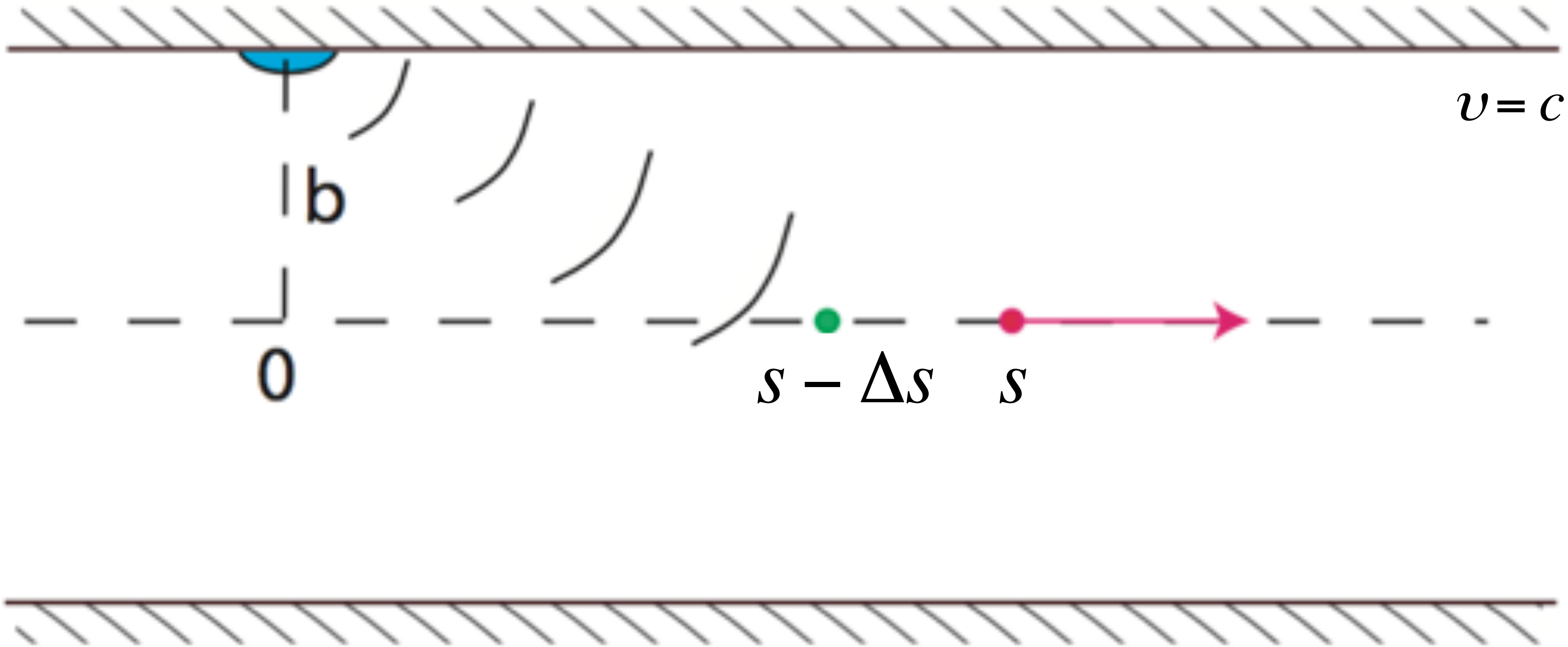
A. G. Ruggiero and V. G. Vaccaro : THE WAKE FIELD OF AN OSCILLATING PARTICLE IN THE PRESENCE OF CONDUCTIVE PLATES WITH RESISTIVE TERMINATIONS AT BOTH ENDS. -




- **2 fundamental approximations behind the "conventional impedances / wakes"**
  - **Rigid-beam approximation =>** $z = s_{witness} - s_{source} = \text{Constant}$
  - **Impulse approximation =>** $v \, \Delta p = \int_0^L F \, ds$

**Wake potential**

# "Catch-up" distance




K. Bane and G. Stupakov

$$s^2 = (c\,t)^2 = (s - \Delta s)^2 + b^2$$

If $\Delta s << b$ => $s \approx \dfrac{b^2}{2\,\Delta s}$

- **Maxwell equations => Panofsky-Wenzel theorem**

$$\vec{\nabla} \times \Delta \vec{p} = 0$$

For $\beta$ = constant

$$\beta = \frac{v}{c}$$

- **If** $\beta = 1$ **=>** $\vec{\nabla}_{\perp} \, . \Delta \, \vec{p}_{\perp} = 0$

- **Considering the case of a cylindrically symmetric chamber**

$$\upsilon \, \Delta p_s\left(r,\theta,z\right) = \int_0^L F_s \, ds = - \, q_1 \, q_2 \, x_1^m \, r^m \cos m\theta \;\; W_m'\left(z\right)$$

Longitudinal wake function ($m$ = 0)

Transverse wake function ($m$ = 1)

$$\upsilon \, \Delta p_r\left(r,\theta,z\right) = \int_0^L F_r \, ds = - \, q_1 \, q_2 \, x_1^m \, m \, r^{m-1} \cos m\theta \;\; W_m\left(z\right)$$

$$\upsilon \, \Delta p_\theta\left(r,\theta,z\right) = \int_0^L F_\theta \, ds = q_1 \, q_2 \, x_1^m \, m \, r^{m-1} \sin m\theta \;\; W_m\left(z\right)$$

- **Impedances are related to wake functions by Fourier transforms**

$$Z_m^{//}(\omega) = -\int_{-\infty}^{+\infty} W_m'(z)\, e^{jkz} \frac{dz}{v}$$

$$Z_m^{\perp}(\omega) = j\int_{-\infty}^{+\infty} W_m(z)\, e^{jkz} \frac{dz}{v}$$

- **As the conductivity, permittivity and permeability of a material depend in general on frequency, it is usually better (or easier) to treat the problem in the frequency domain, i.e. compute the impedance instead of the wake function**

- **It is also easier to treat the case $\beta \neq 1$**

- **2 important properties of impedances**
  - As wake functions are real, it can be shown that

$$\left[ Z_m^{//}(\omega) \right]^* = Z_m^{//}(-\omega)$$

$$-\left[ Z_m^{\perp}(\omega) \right]^* = Z_m^{\perp}(-\omega)$$

  - As consequence of Panofsky-Wenzel theorem

$$Z_m^{//}(\omega) = k \, Z_m^{\perp}(\omega)$$

- **Another interesting property of impedances is the directional symmetry (Lorentz reciprocity theorem): same impedance is obtained from both sides if entrance and exit are the same**

- Situation is more involved in the case of non axi-symmetric structures (or $\beta \neq 1$). Taking into account only linear terms

$$q_1 = q_2 = q$$

(or dipolar) (or quadrupolar)

$$\int_0^L F_x \, ds = -q^2 \left[ x_1 \, W_x^{\text{driving}}(z) - x_2 \, W^{\text{detuning}}(z) \right]$$

$$\int_0^L F_y \, ds = -q^2 \left[ y_1 \, W_y^{\text{driving}}(z) + y_2 \, W^{\text{detuning}}(z) \right]$$

$$Z_x \left[ \Omega \right] = x_1 \, Z_x^{\text{driving}} - x_2 \, Z^{\text{detuning}}$$

$$Z_y \left[ \Omega \right] = y_1 \, Z_y^{\text{driving}} + y_2 \, Z^{\text{detuning}}$$

- Analytical computations are possible only if structures are fairly simple

- In practice this is often not the case and one has to rely on numerical techniques

- First numerical wake field computations were performed in time domain (Balakin1978 and Weiland1980)

- For highly relativistic bunches, due to causality, wake fields can catch up with trailing particles only after traveling the catch-up distance => Compute wakes in linacs by using a mesh that moves together with the bunch (moving mesh technique introduced by Bane-Weiland1983)

- **Nowadays many methods are available for beam coupling impedance computation**
  - **Time Domain (TD) method**
  - **Frequency Domain (FD) method**
    - **Eigenmode methods**
    - **Methods based on beam excitation in FD**

- **Main ElectroMagnetic (EM) codes currently used**
  - **ABCI**
  - **Ansys HFSS**
  - **CST Studio (MAFIA)**
  - **GdfidL**
  - **ECHO2D**
  - **ACE3P**
  - **Etc.**

- **Time Domain (TD)**
  - Finite Differences Time Domain (FDTD) and Finite Integration Technique (FIT) with leapfrog algorithm for time stepping
  - More specialized techniques
    - Boundary element method (TD-BEM)
    - Finite volume method (FVTD)
    - Discontinuous Galerkin Finite Element (DG-FEM)
    - Implicit methods
  - Bunch length and wake length are the 2 important parameters for TD impedance computation
  - The criterion for the time step is also referred to as the Courant-Friedrichs-Lewy (CFL) criterion
  - Suitable at medium and high frequencies, and particularly in perfectly conducting structures

- **Frequency Domain (FD): Eigenmode methods**
  - **When high quality factor structures are under investigation and high accuracy is required**

$$Z_m^{//}(\omega) = \frac{R_s}{1 + j\,Q\left(\dfrac{\omega}{\omega_r} - \dfrac{\omega_r}{\omega}\right)}$$

$$Z_m^{\perp}(\omega) = \frac{\omega_r}{\omega}\,\frac{R_\perp}{1 + j\,Q\left(\dfrac{\omega}{\omega_r} - \dfrac{\omega_r}{\omega}\right)}$$

Shunt impedances

Quality factor

(Angular) resonance frequency

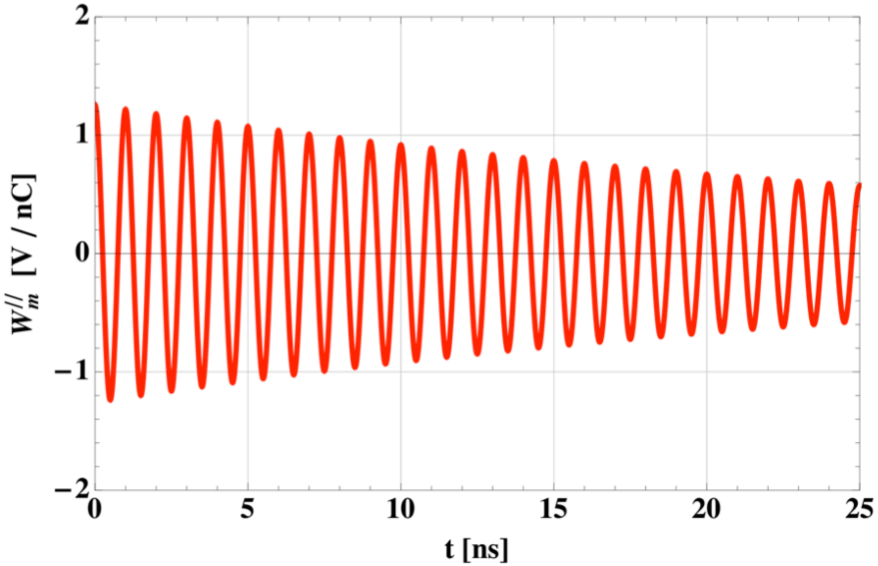
$$W_m^{//}(t) = \frac{\omega_r\,R_s}{Q}\,e^{-\alpha t}\left[\cos\left(\bar{\omega}_r\,t\right) - \frac{\alpha}{\bar{\omega}_r}\sin\left(\bar{\omega}_r\,t\right)\right]$$

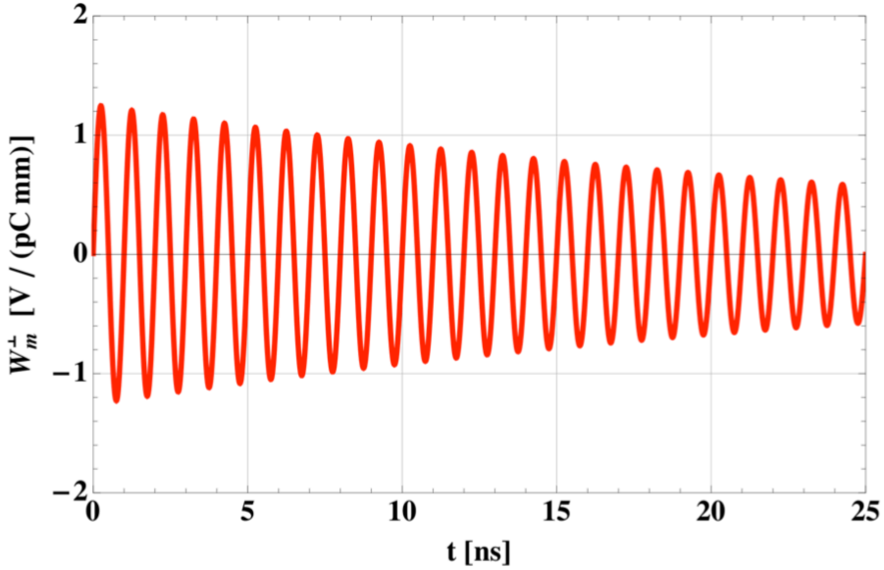
$$W_m^{\perp}(t) = \frac{\omega_r^2\,R_\perp}{Q\,\bar{\omega}_r}\,e^{-\alpha t}\,\sin\left(\bar{\omega}_r\,t\right)$$

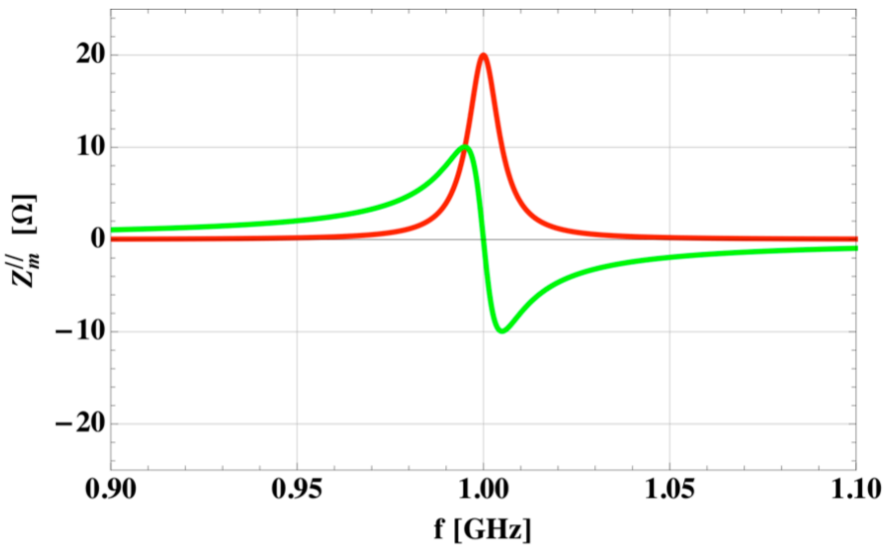
$$\bar{\omega}_r = \omega_r\sqrt{1 - \frac{1}{4\,Q^2}}$$

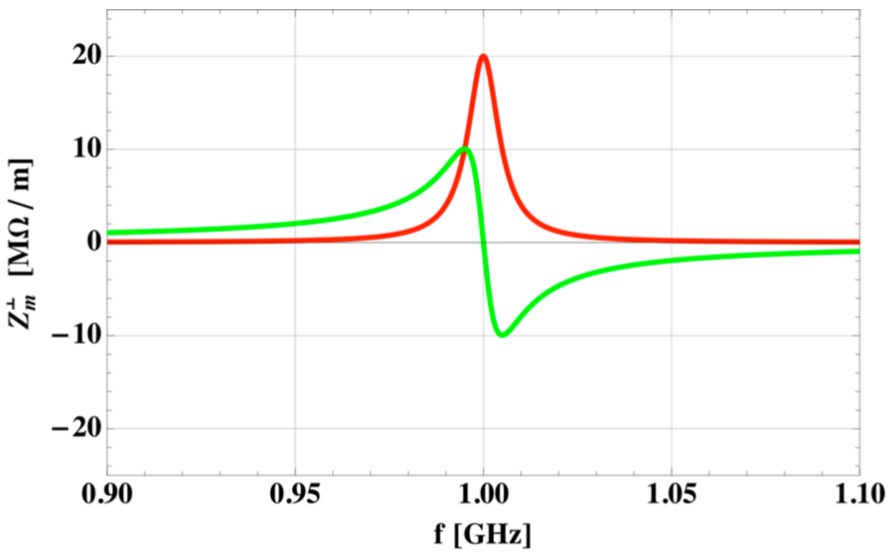
$$\alpha = \frac{\omega_r}{2\,Q}$$

$R_s = 20\ \Omega$ $R_\perp = 20\ \mathrm{M\Omega/m}$ $f_r = 1\ \mathrm{GHz}$ $Q = 100$



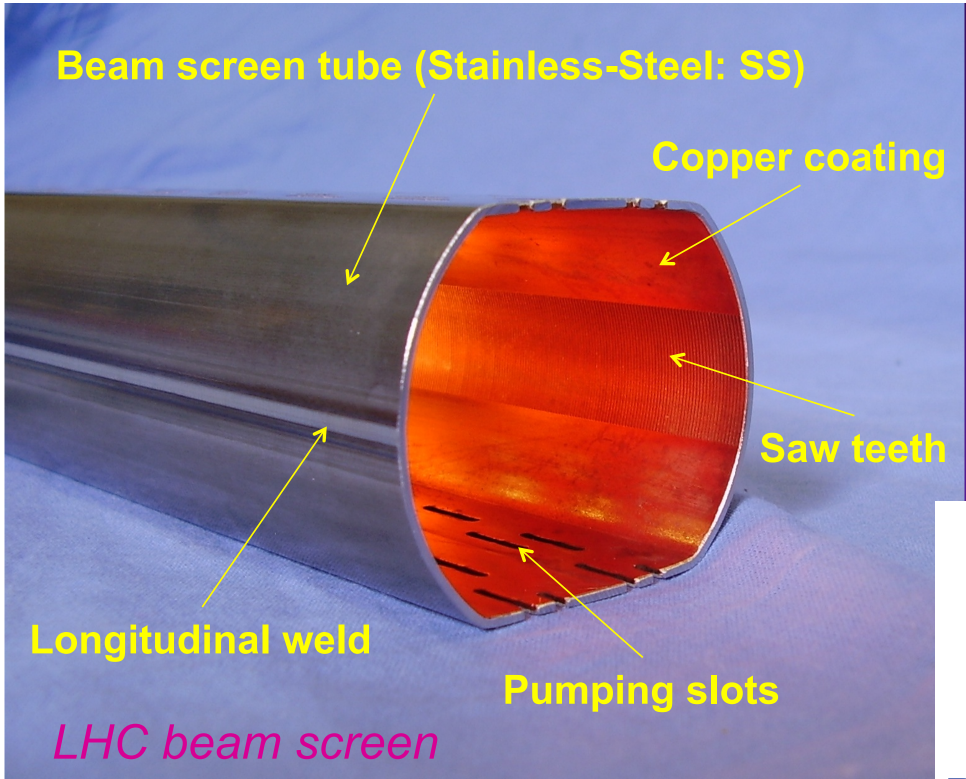



- **Frequency Domain (FD): Methods based on beam excitation in FD**
  - At low frequencies, the CFL criterion poses a strong requirement on the time step
  - Due to uncertainty principle, lower frequencies require computing longer wakes. As the time step is fixed by structure properties via the CFL criterion, this leads to the necessity to compute many time steps
  - FD methods prevail for
    - Low frequency
    - Low velocity of the beam
    - Dispersively lossy materials

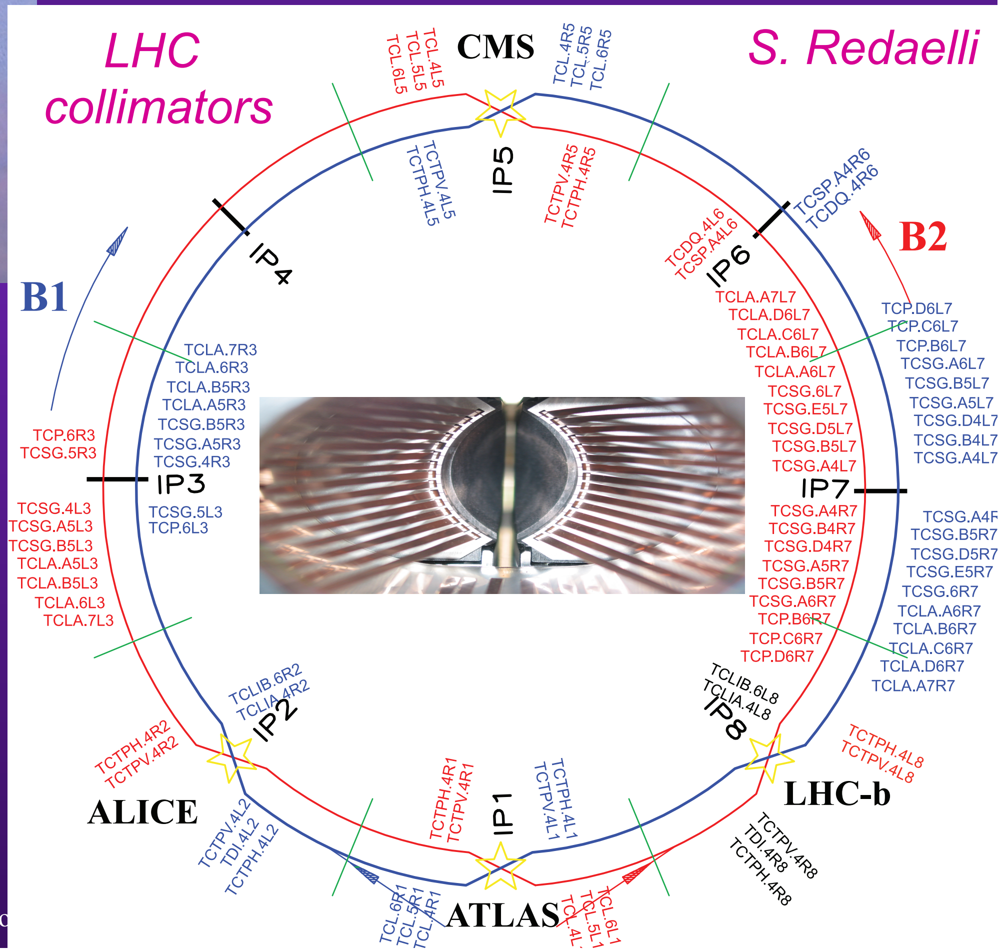
- Particularly difficult components are those which combine elements of geometric wake fields and resistive elements (like tapered collimators or dielectric structures)

- Impedances of surface roughness and of small random pumping slots (e.g. LHC beam screen) are difficult to model

- EM properties of some materials (vs. frequency) are not well known and should be measured with precision

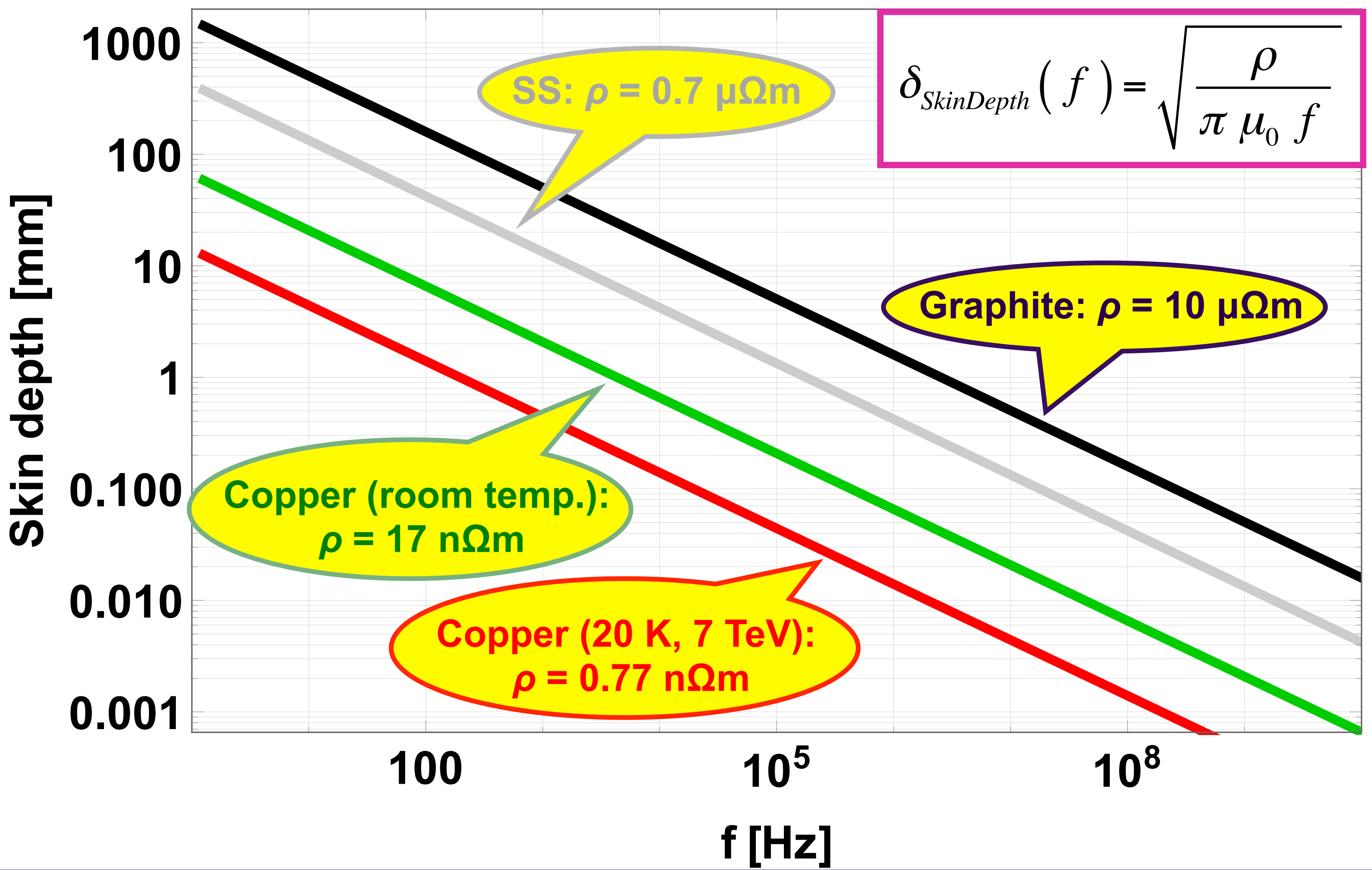


Beam screen tube (Stainless-Steel: SS)
Copper coating
Saw teeth
Longitudinal weld
Pumping slots
LHC beam screen

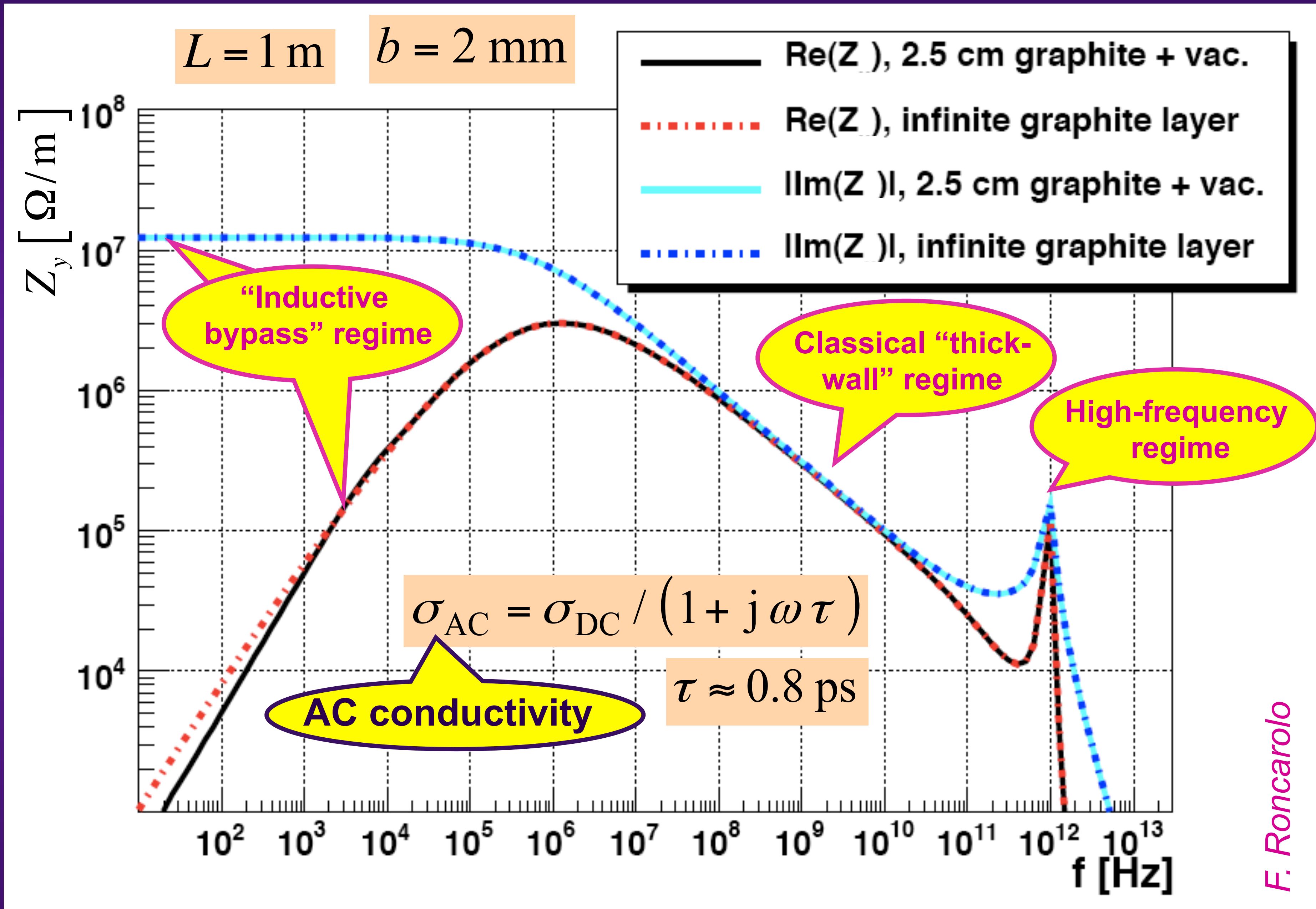



LHC collimators
S. Redaelli
CMS
IP5
TCL.4L5
TCL.5L5
TCL.6L5
TCL.4R5
TCL.5R5
TCL.6R5
TCTPV.4L5
TCTPH.4L5
TCTPV.4R5
TCTPH.4R5
IP4
IP6
TCSP.A4R6
TCDQ.4R6
TCDQ.4L6
TCSP.A4L6
B1
B2
TCLA.7R3
TCLA.6R3
TCLA.B5R3
TCLA.A5R3
TCSG.B5R3
TCSG.A5R3
TCSG.4R3
TCP.6R3
TCSG.5R3
IP3
TCSG.5L3
TCP.6L3
TCSG.4L3
TCSG.A5L3
TCSG.B5L3
TCLA.A5L3
TCLA.B5L3
TCLA.6L3
TCLA.7L3
TCLA.A7L7
TCLA.D6L7
TCLA.C6L7
TCLA.B6L7
TCLA.A6L7
TCSG.6L7
TCSG.E5L7
TCSG.D5L7
TCSG.B5L7
TCSG.A4L7
TCP.D6L7
TCP.C6L7
TCP.B6L7
TCSG.A6L7
TCSG.B5L7
TCSG.A5L7
TCSG.D4L7
TCSG.B4L7
TCSG.A4L7
IP7
TCSG.A4R7
TCSG.B4R7
TCSG.D4R7
TCSG.A5R7
TCSG.B5R7
TCSG.A6R7
TCP.B6R7
TCP.C6R7
TCP.D6R7
TCSG.B5R7
TCSG.D5R7
TCSG.E5R7
TCSG.6R7
TCLA.A6R7
TCLA.B6R7
TCLA.C6R7
TCLA.D6R7
TCLA.A7R7
TCLIB.6L8
TCLIA.4L8
IP8
TCTPH.4L8
TCTPV.4L8
LHC-b
TCTPV.4R8
TDI.4R8
TCTPH.4R8
TCLIB.6R2
TCLIA.4R2
IP2
TCTPH.4R2
TCTPV.4R2
ALICE
TCTPV.4L2
TDI.4L2
TCTPH.4L2
TCTPH.4R1
TCTPV.4R1
IP1
TCTPH.4L1
TCTPV.4L1
ATLAS
TCL.6R1
TCL.5R1
TCL.4R1
TCL.6L1
TCL.5L1

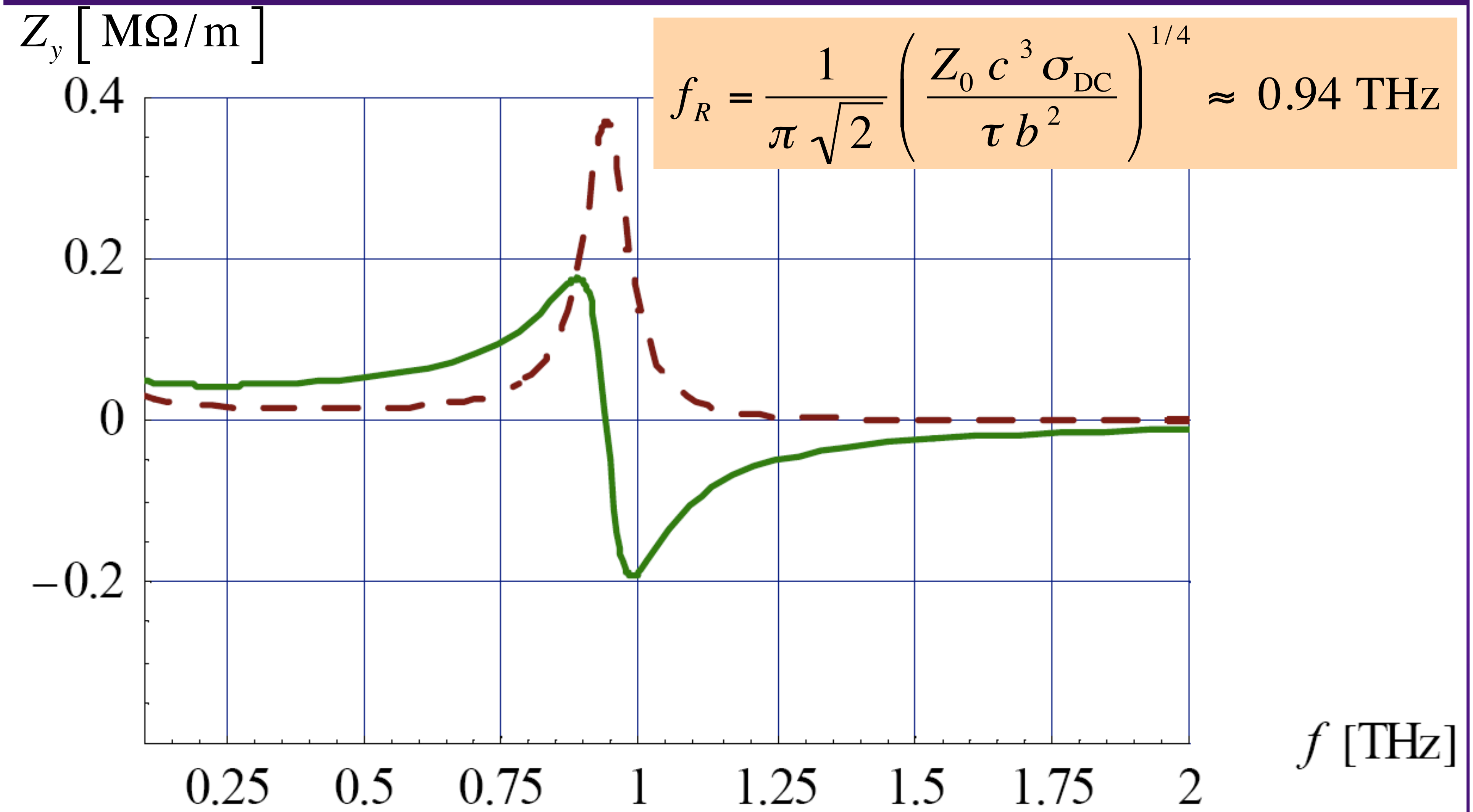
- **Analytical computations**
  - **FIELD MATCHING: Continuity of EM field components on separating surfaces**
    - **Many studies performed**
    - **IW2D code for round or // plates (N. Mounet)**
  - **MODE MATCHING: Decomposition of the fields in summation of modes and matching of each mode coefficient by proper field projection on the correspondent mode**
    - **Effect of finite length (N. Biancacci)**
    - **IW2D valid if $L$ >(>) $b$**



$$\delta_{SkinDepth}(f) = \sqrt{\frac{\rho}{\pi \mu_0 f}}$$
SS: ρ = 0.7 μΩm
Graphite: ρ = 10 μΩm
Copper (room temp.): ρ = 17 nΩm
Copper (20 K, 7 TeV): ρ = 0.77 nΩm
Skin depth [mm]
1000
100
10
1
0.100
0.010
0.001
100
10^5
10^8
f [Hz]

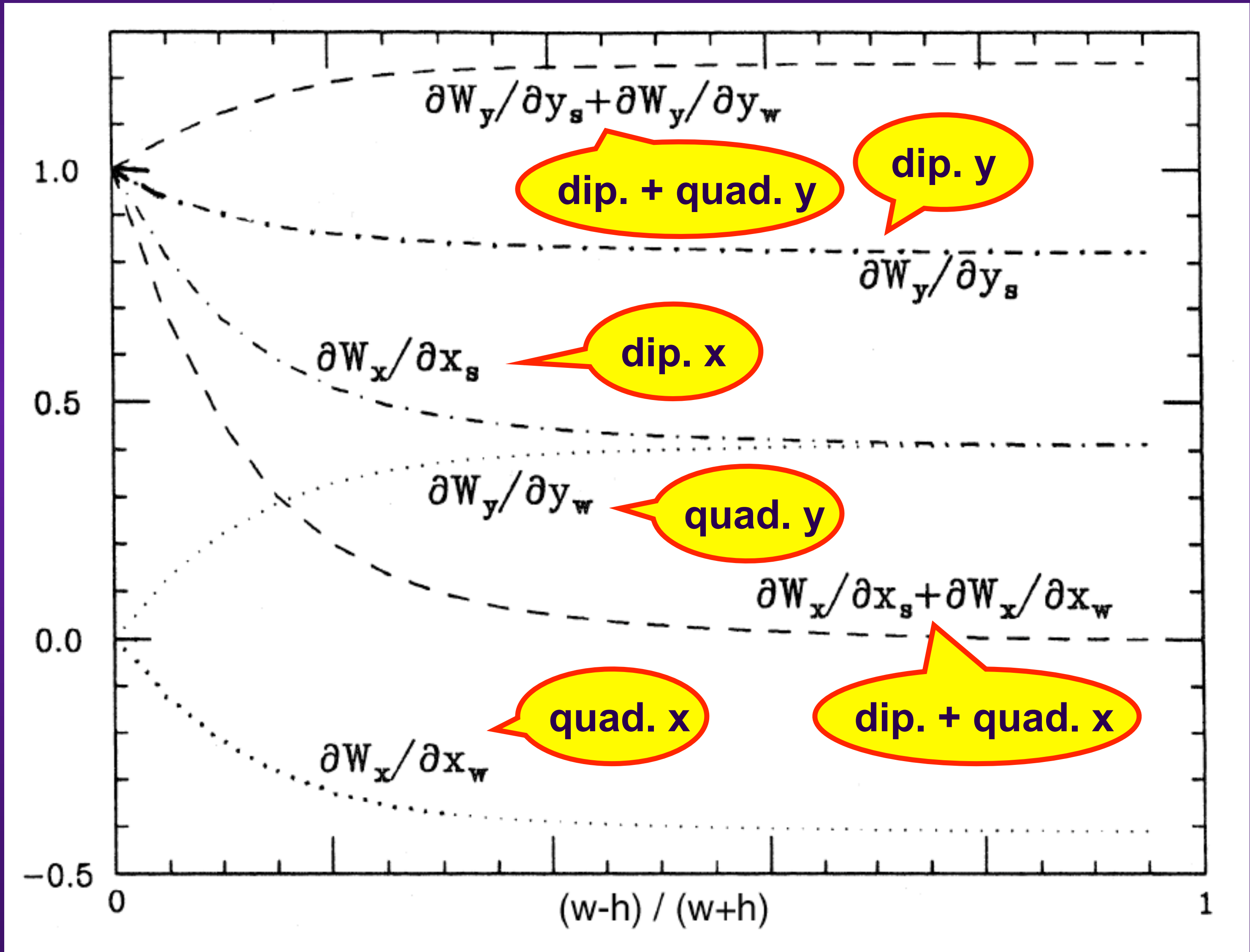


$L = 1\,\mathrm{m}$
$b = 2\,\mathrm{mm}$
Re(Z ), 2.5 cm graphite + vac.
Re(Z ), infinite graphite layer
|Im(Z )|, 2.5 cm graphite + vac.
|Im(Z )|, infinite graphite layer
$Z_y\ [\Omega/\mathrm{m}]$
$10^8$
$10^7$
$10^6$
$10^5$
$10^4$
"Inductive bypass" regime
Classical "thick-wall" regime
High-frequency regime
$\sigma_{AC} = \sigma_{DC} / (1 + j\,\omega\,\tau)$
$\tau \approx 0.8$ ps
AC conductivity
$10^2$ $10^3$ $10^4$ $10^5$ $10^6$ $10^7$ $10^8$ $10^9$ $10^{10}$ $10^{11}$ $10^{12}$ $10^{13}$
f [Hz]
F. Roncarolo




$$f_R = \frac{1}{\pi\sqrt{2}}\left(\frac{Z_0\, c^3\, \sigma_{DC}}{\tau\, b^2}\right)^{1/4} \approx 0.94\ \mathrm{THz}$$

## Yokoya form factors for dipolar and quadrupolar impedances in resistive elliptical pipes (compared to circular)

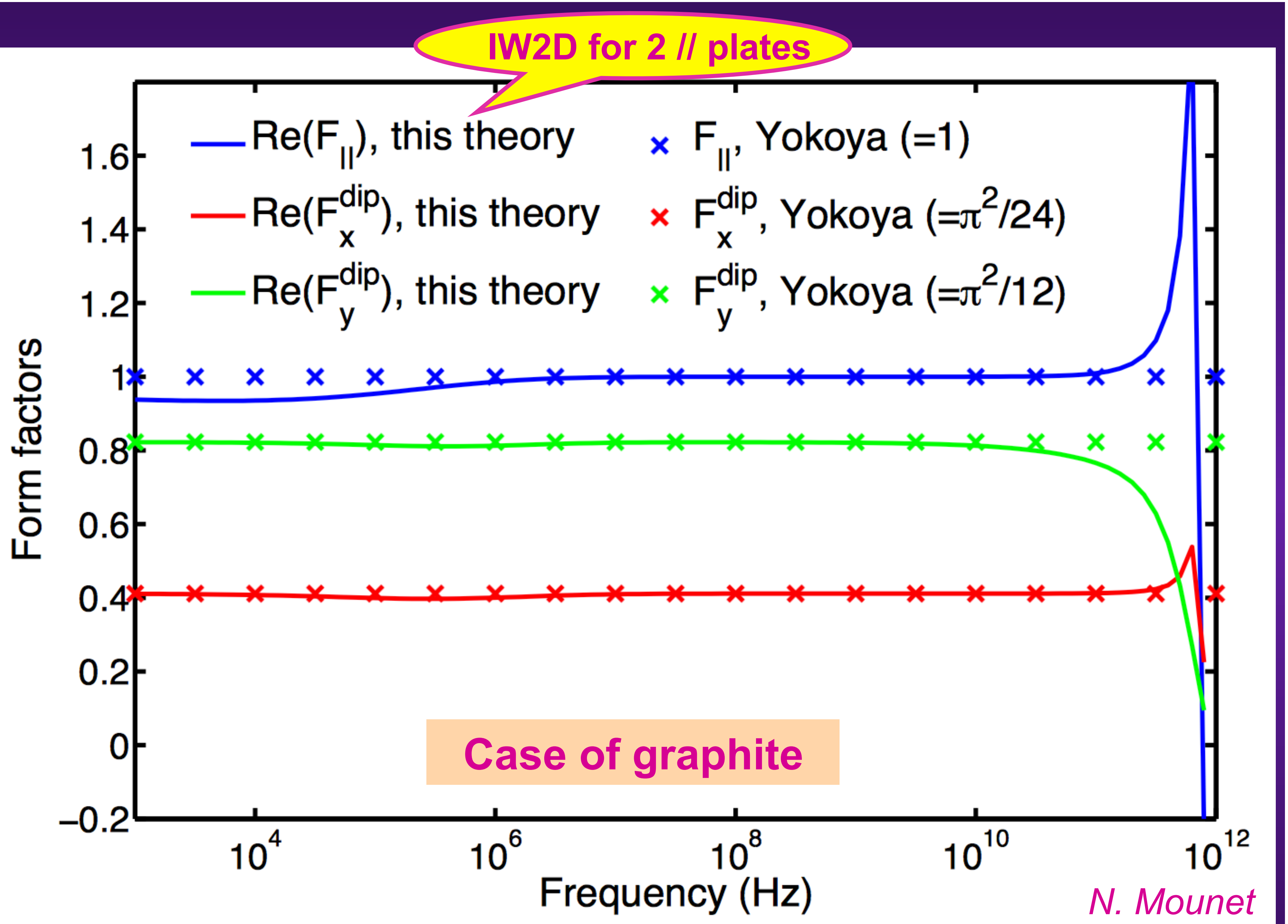



$$\frac{\pi^2}{8}$$

$$\frac{\pi^2}{12}$$

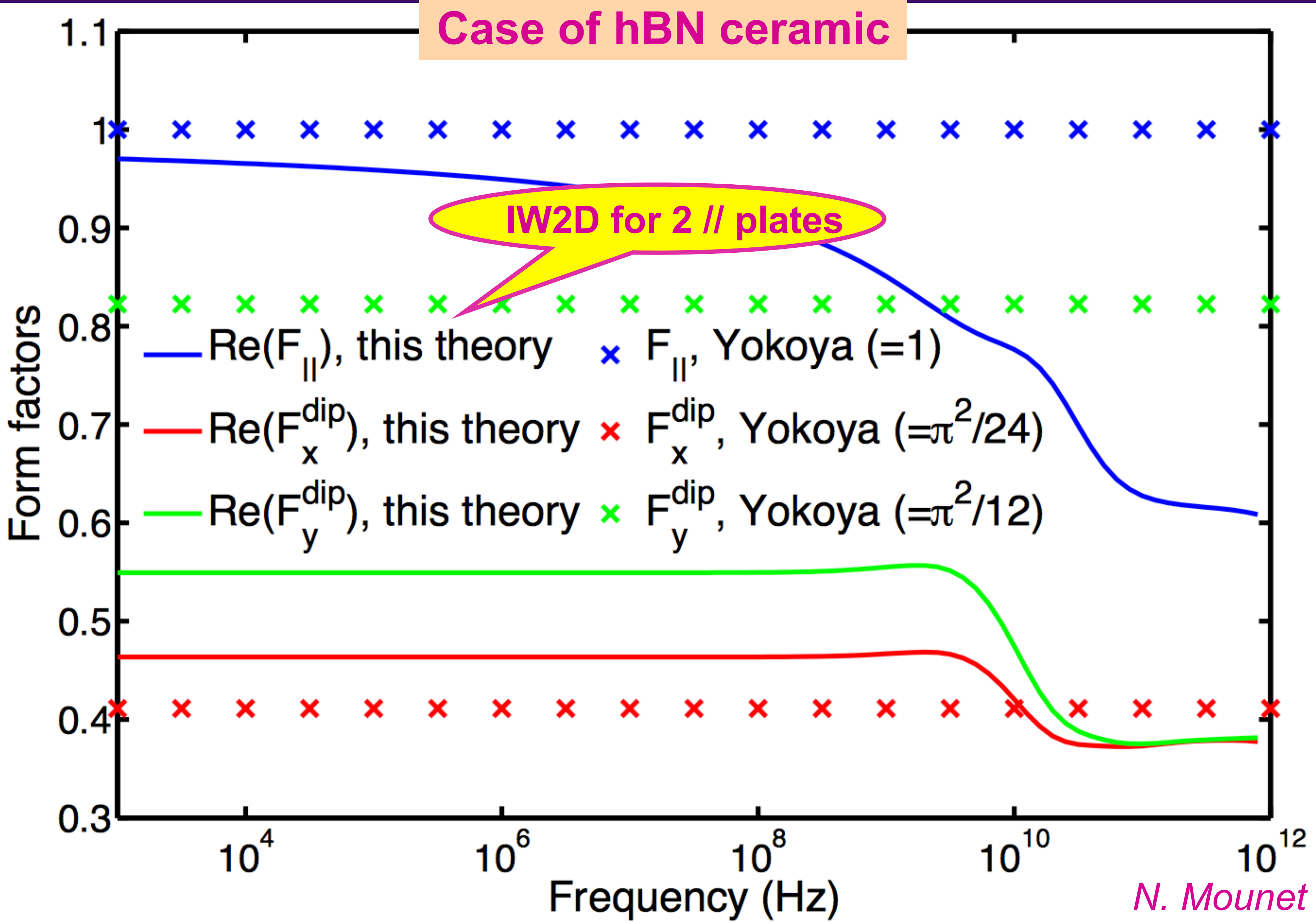
$$\frac{\pi^2}{24}$$

$$-\frac{\pi^2}{24}$$



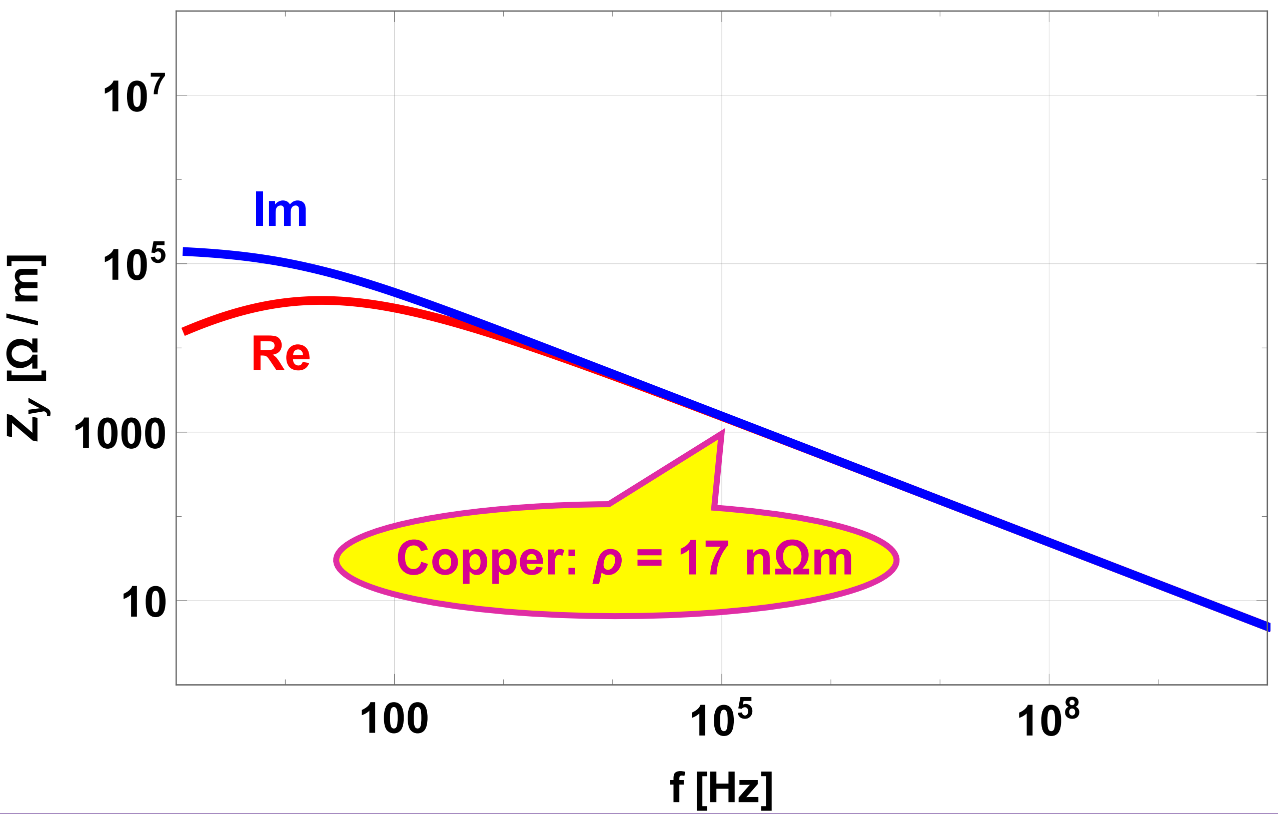
IW2D for 2 // plates
Re(F||), this theory
Re(Fxdip), this theory
Re(Fydip), this theory
F||, Yokoya (=1)
Fxdip, Yokoya (=π2/24)
Fydip, Yokoya (=π2/12)
Case of graphite
Form factors
Frequency (Hz)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
10^4
10^6
10^8
10^10
10^12
N. Mounet

# Case of hBN ceramic

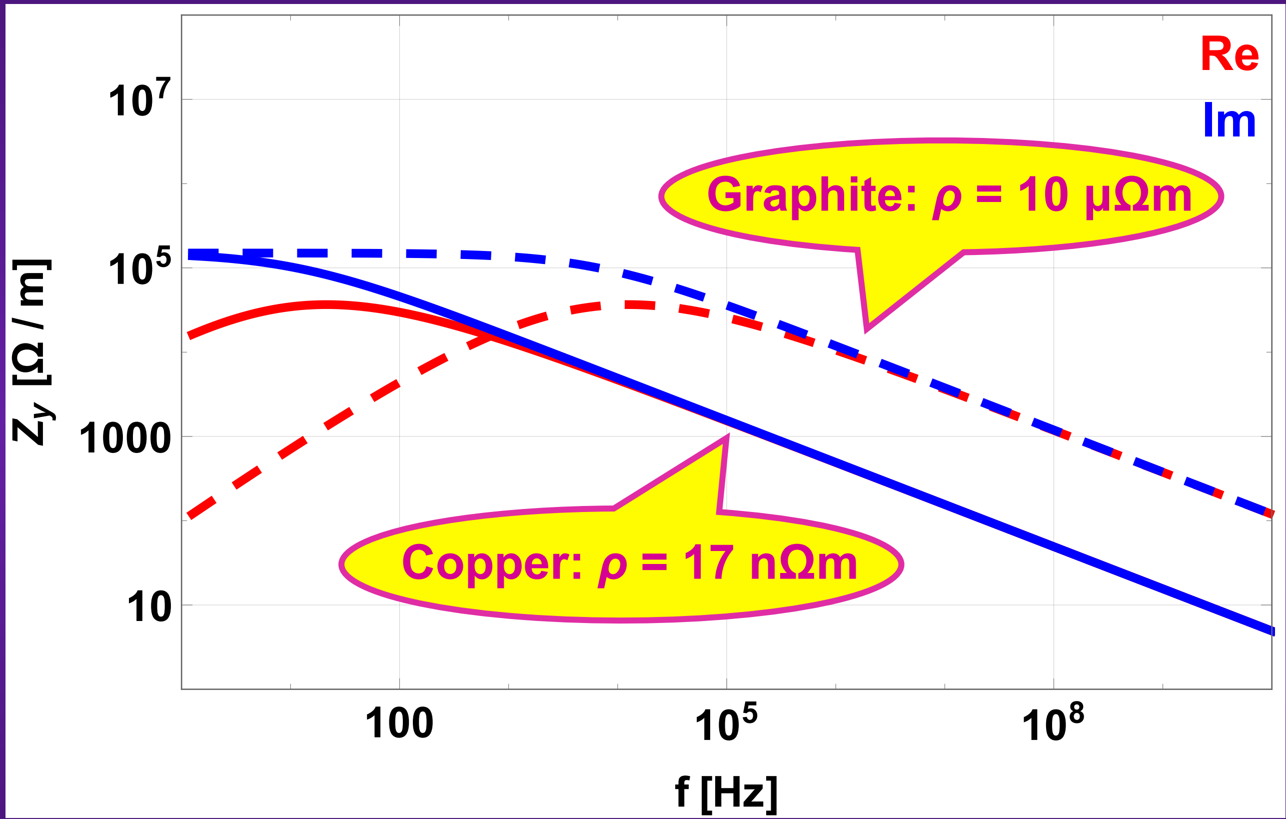



*N. Mounet*

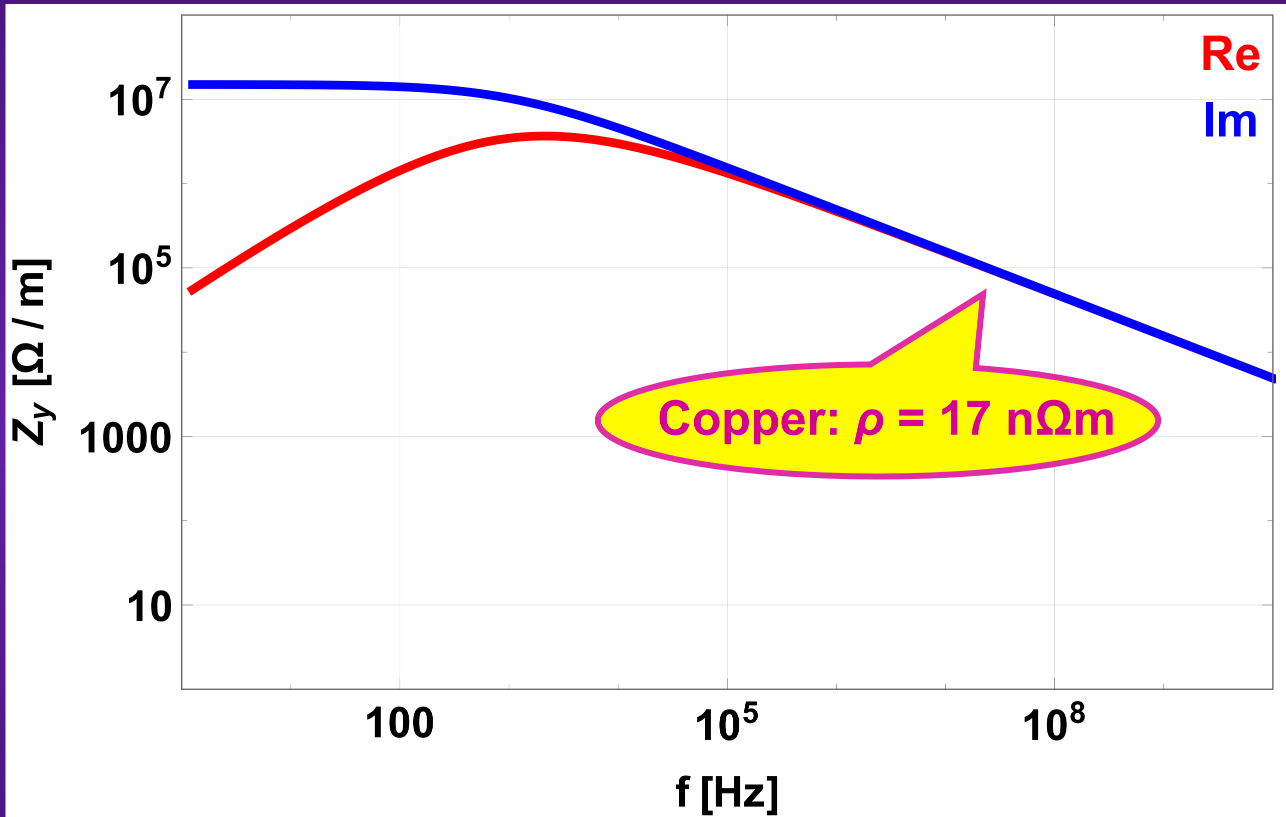
# LHC beam pipe: round, 20 mm radius, 1 m long



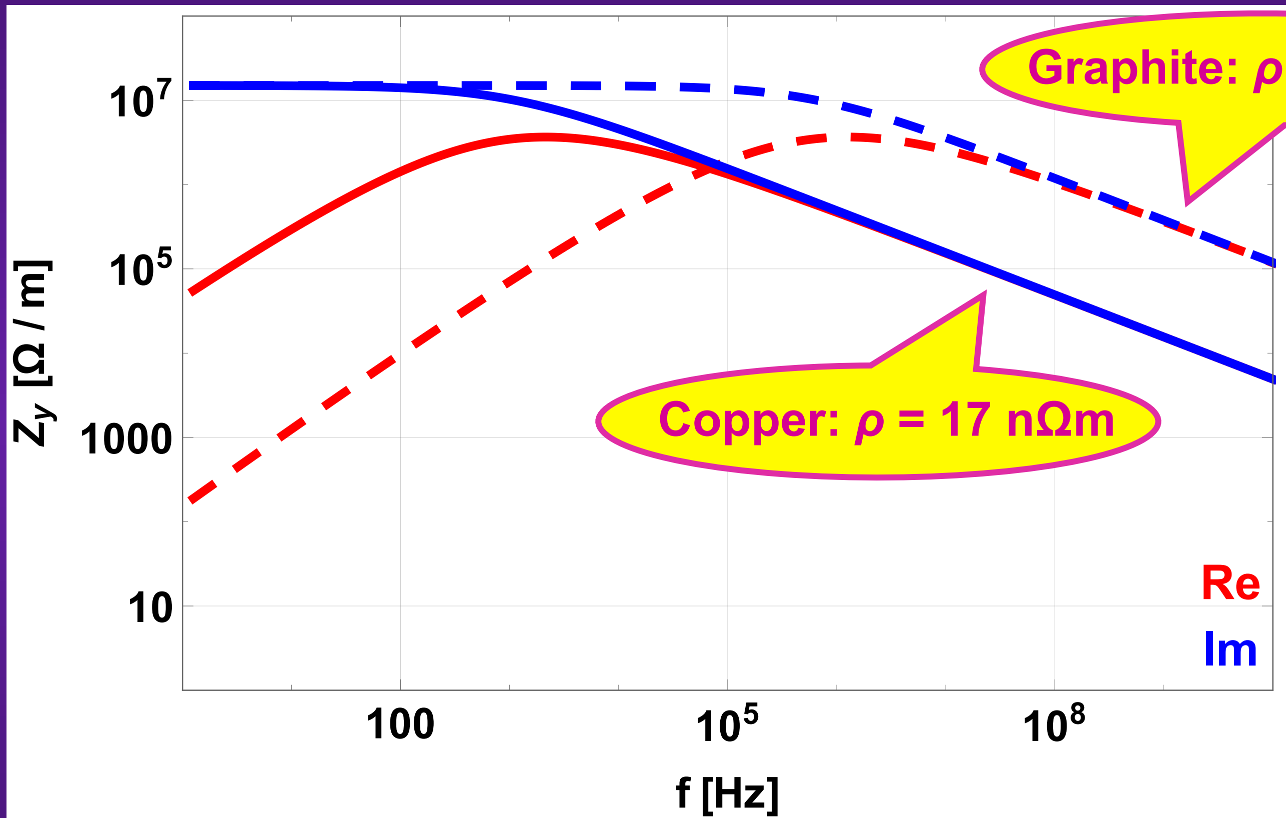
# LHC beam pipe: round, 20 mm radius, 1 m long



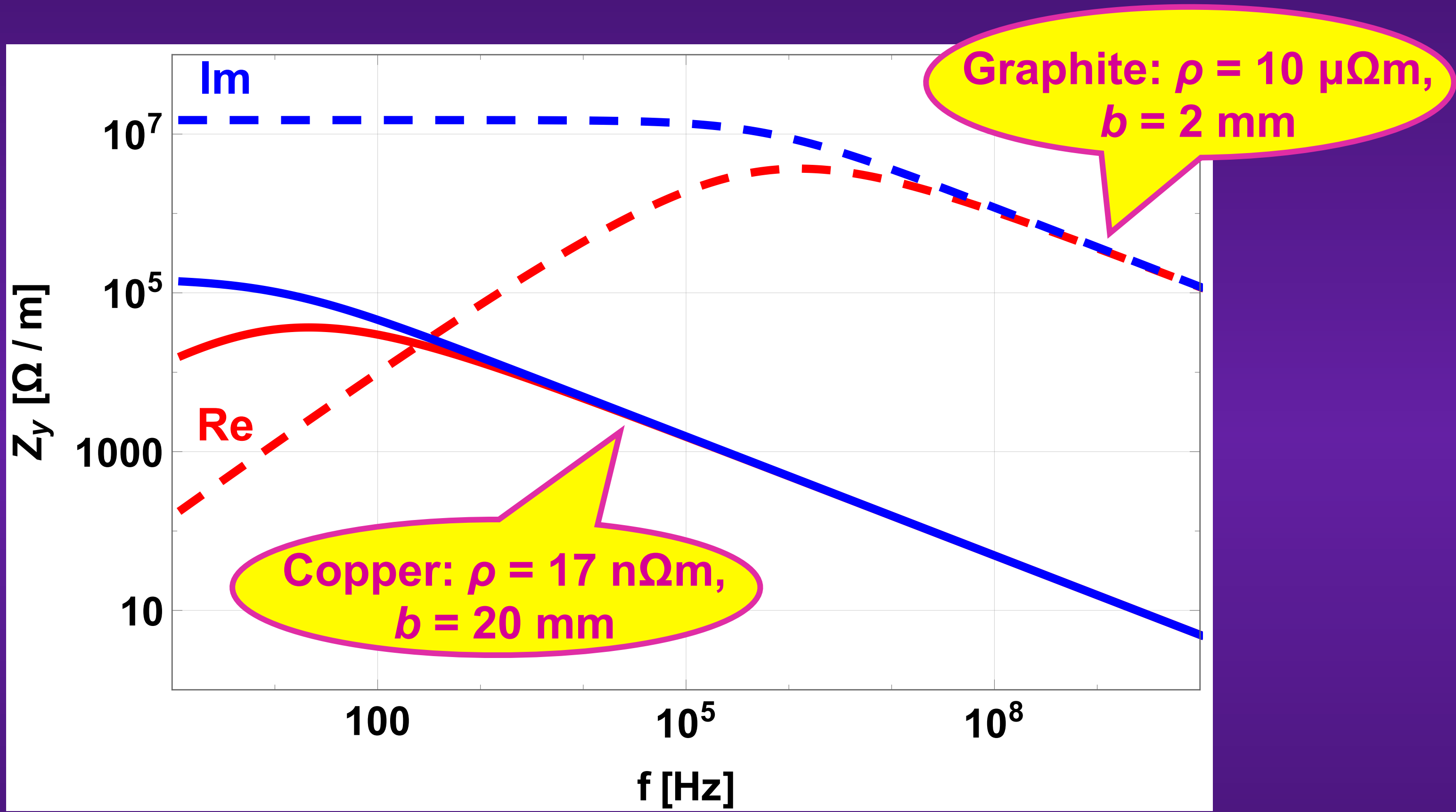
# LHC beam pipe: round, 2 mm radius, 1 m long



# LHC beam pipe: round, 2 mm radius, 1 m long

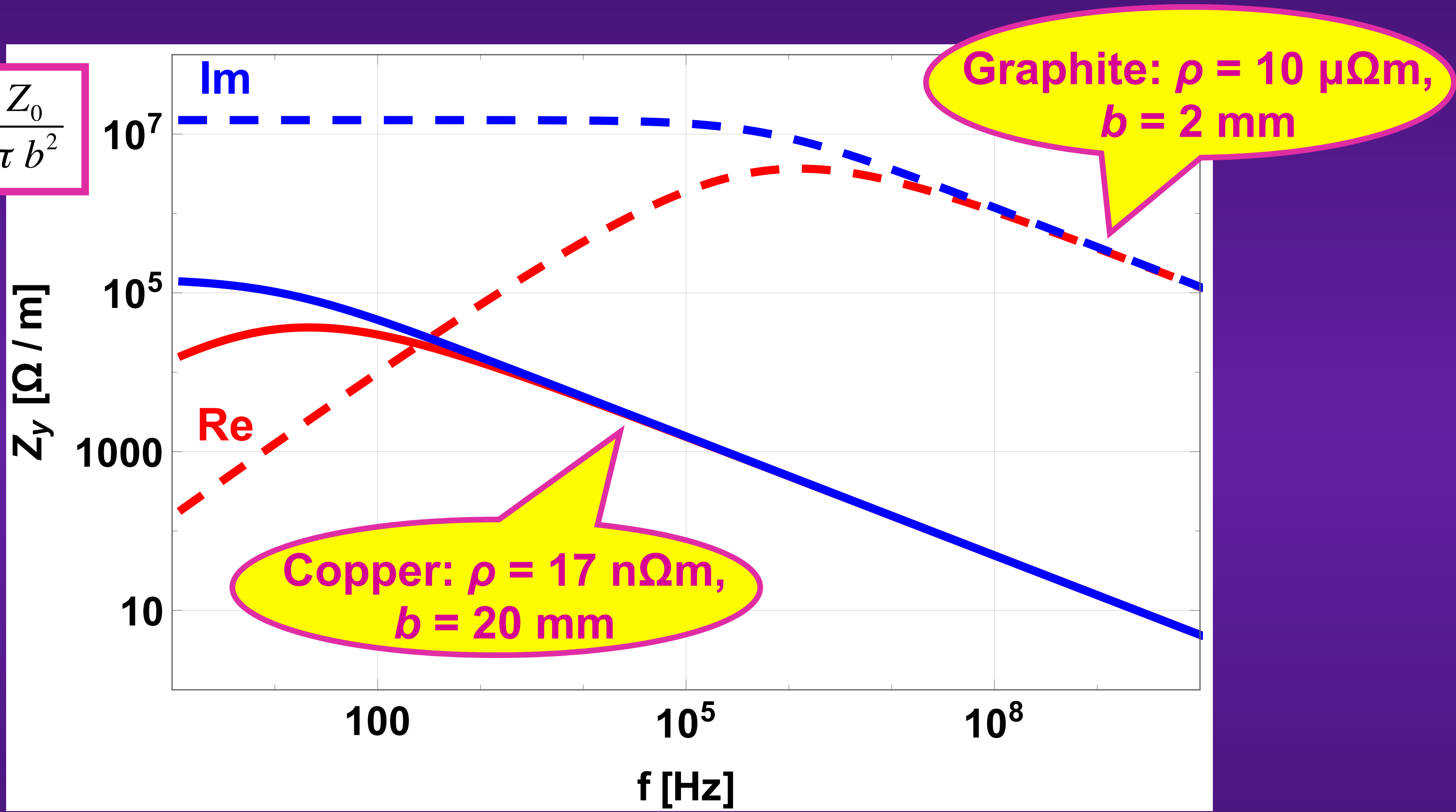


# LHC beam pipe: round, 1 m long



# LHC beam pipe: round, 1 m long

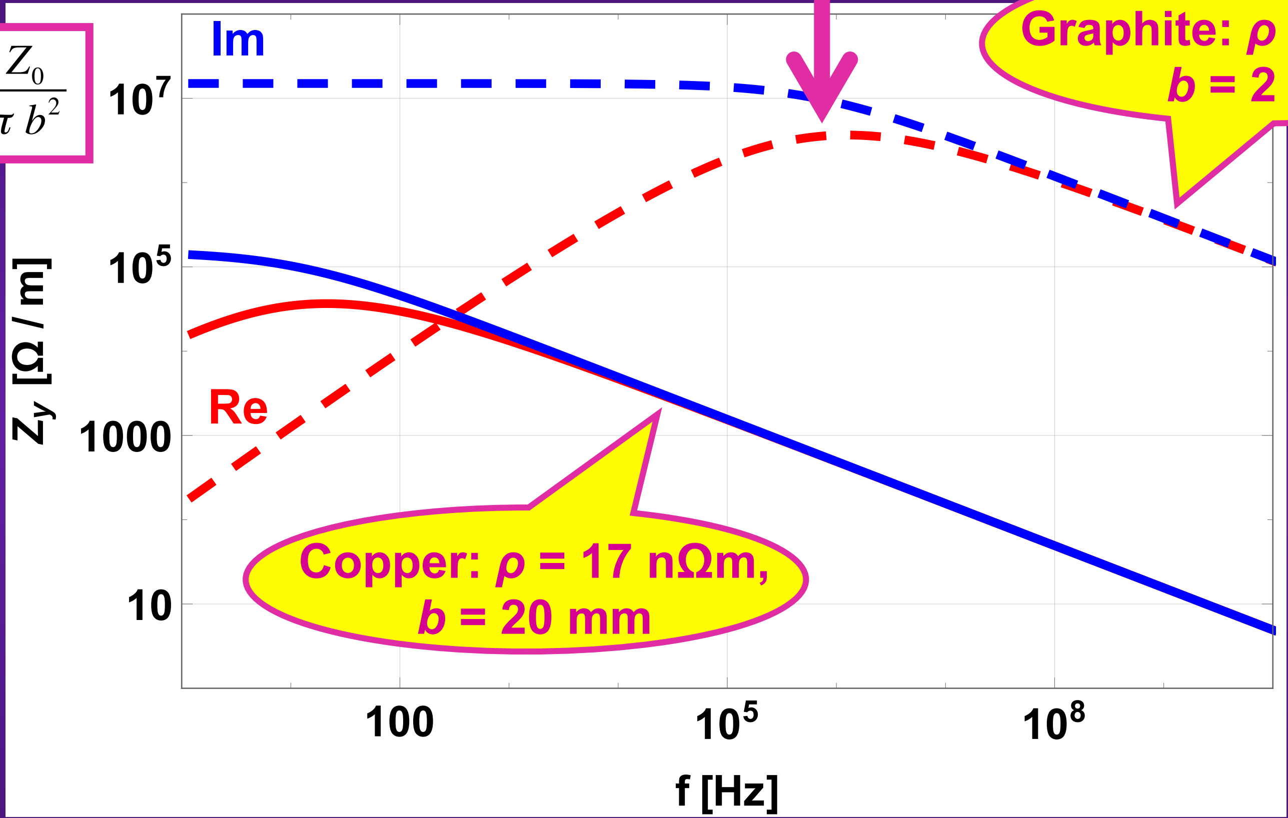
$$Z_y\left(f \rightarrow 0\right) = \frac{j\,Z_0}{2\,\pi\,b^2}$$



# LHC beam pipe: round, 1 m long

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

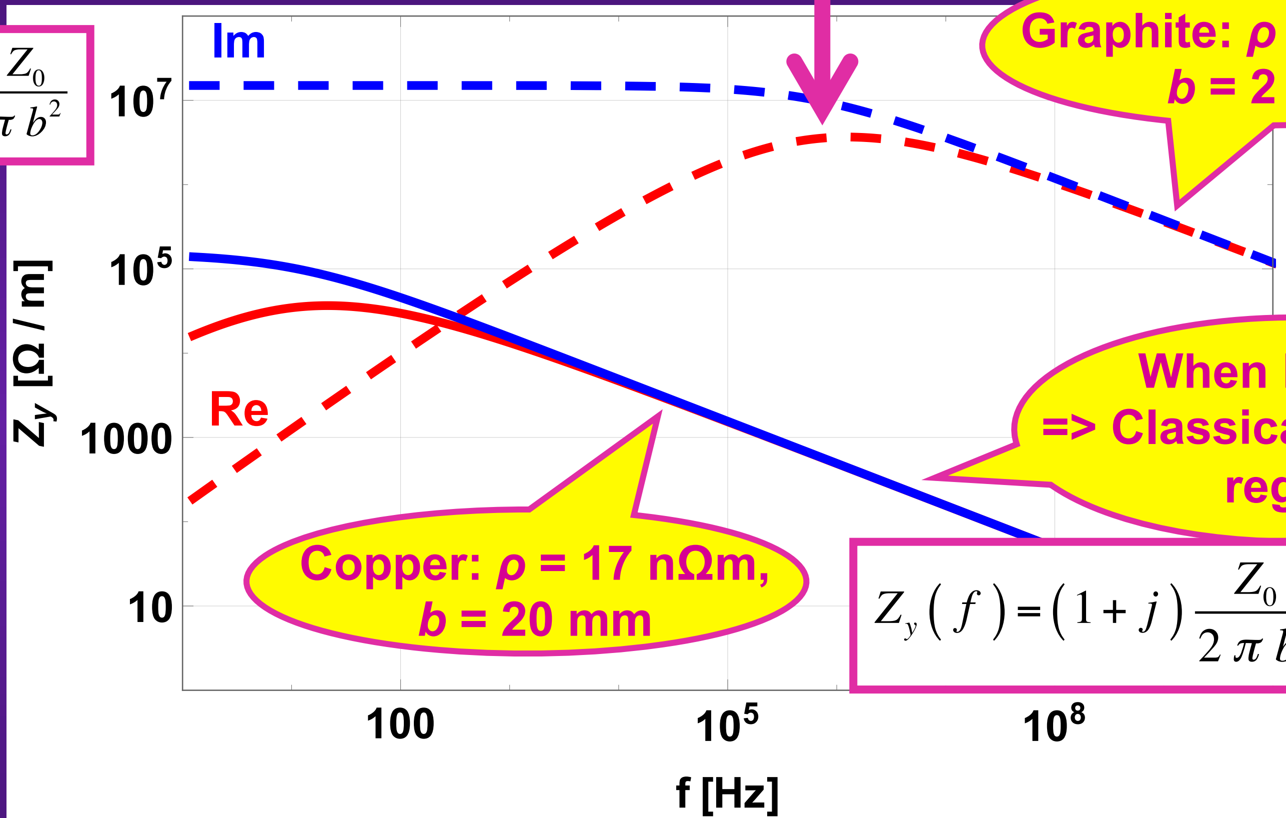
$$Z_y(f \to 0) = \frac{j Z_0}{2\pi b^2}$$



# LHC beam pipe: round, 1 m long

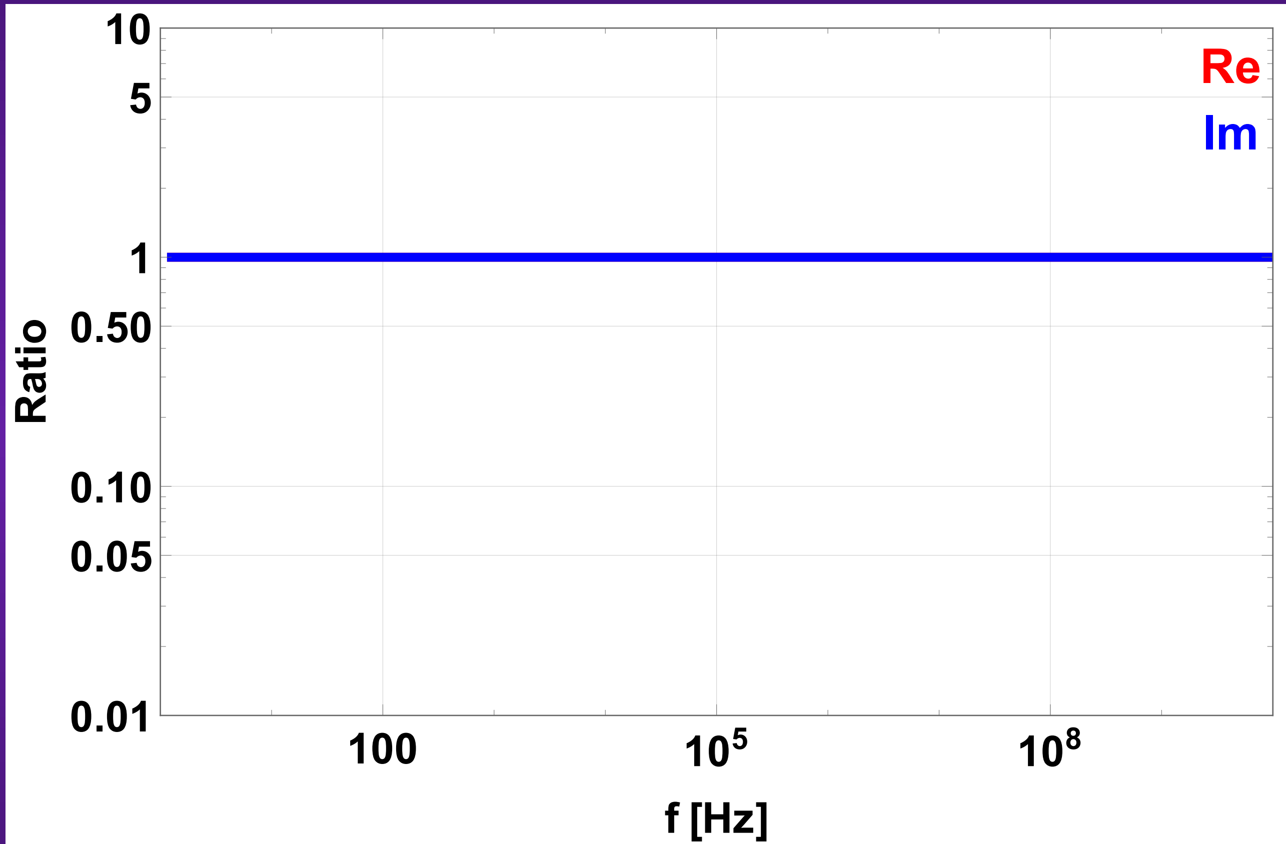
$$f_{\max,\mathrm{Re}} \approx \frac{\rho}{b^2} \times \frac{1}{\pi \mu_0}$$

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



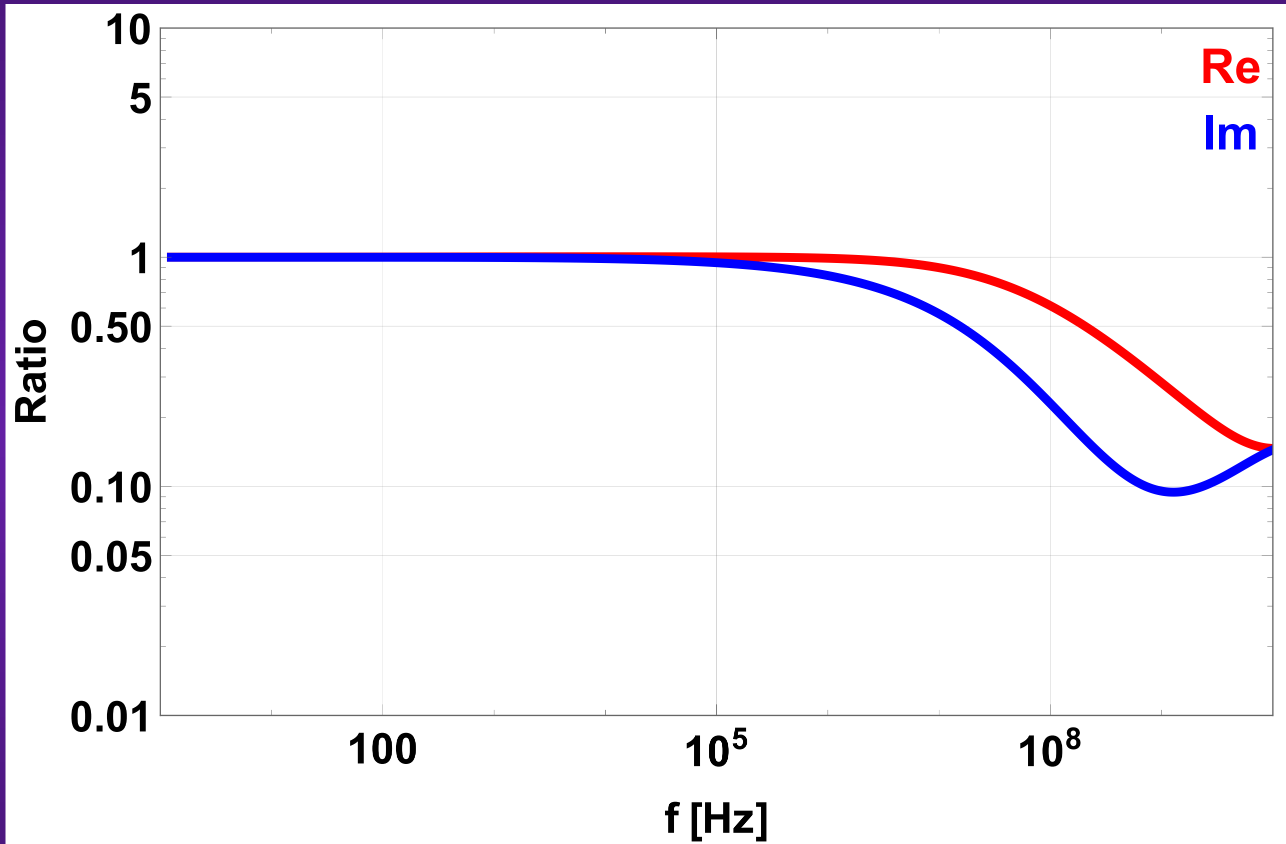

$$Z_y\left(f\right) = \left(1 + j\right) \frac{Z_0}{2\, \pi\, b^3}\, \delta_{SkinDepth}\left(f\right)$$

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



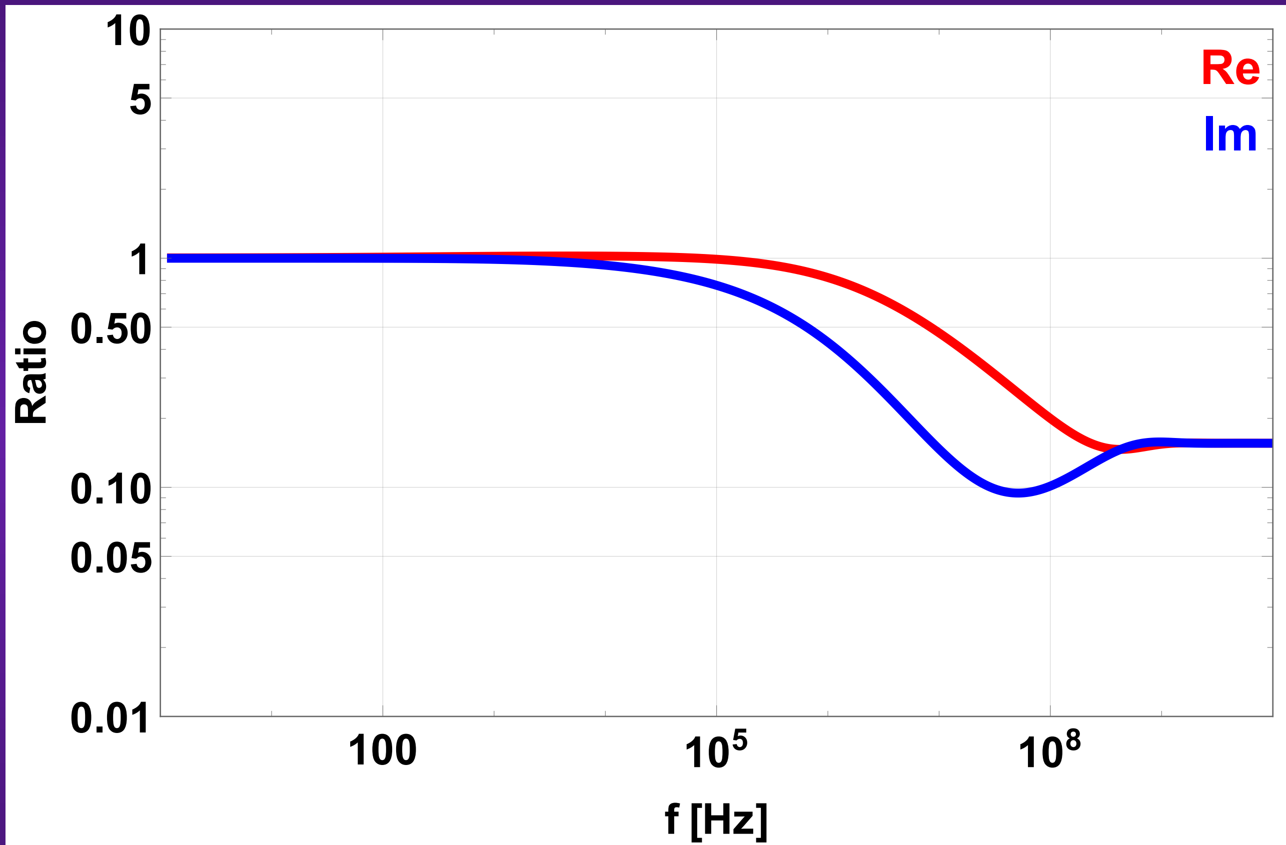

$$\text{Ratio} = \frac{Z_y(\text{ with coating })}{Z_y(\text{ without coating })}$$

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



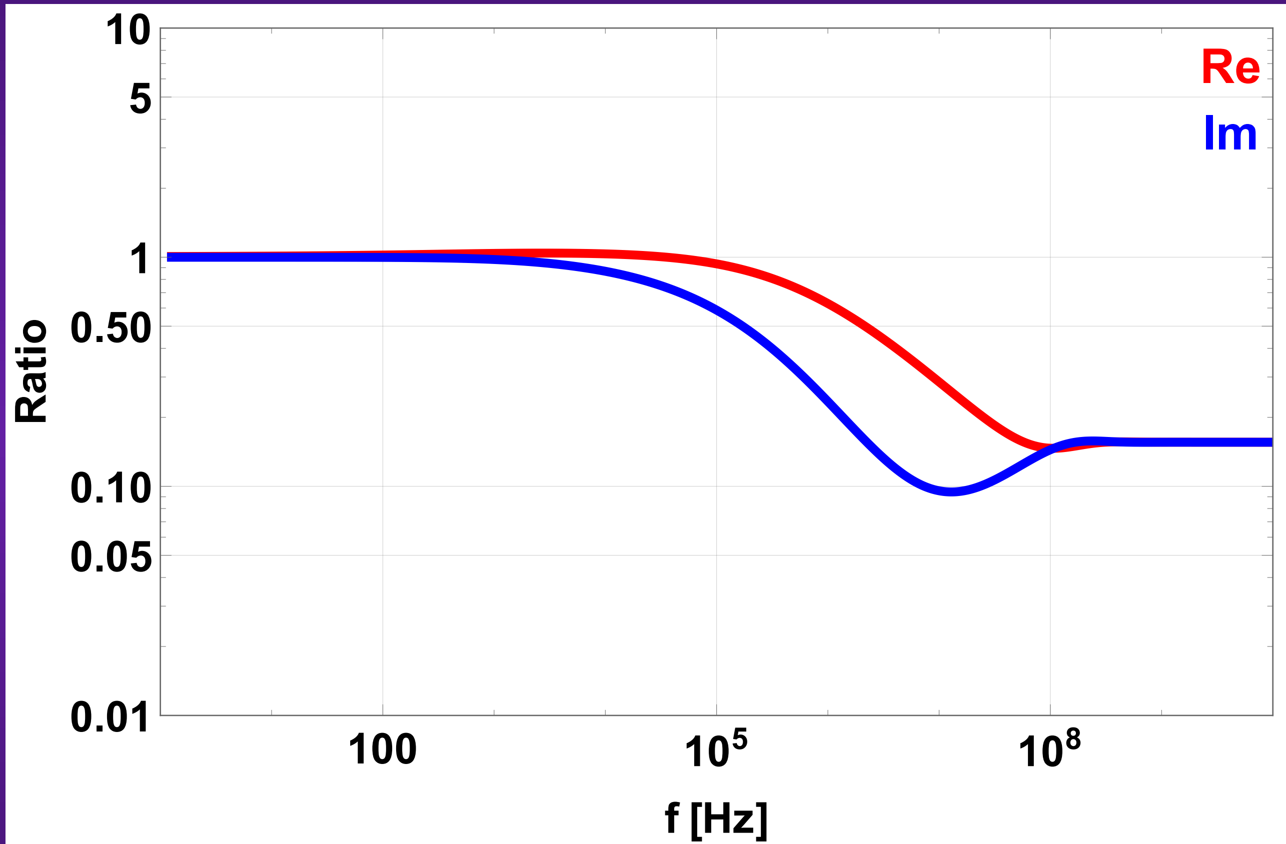

$$\text{Ratio} = \frac{Z_y\left(\text{with coating}\right)}{Z_y\left(\text{without coating}\right)}$$

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



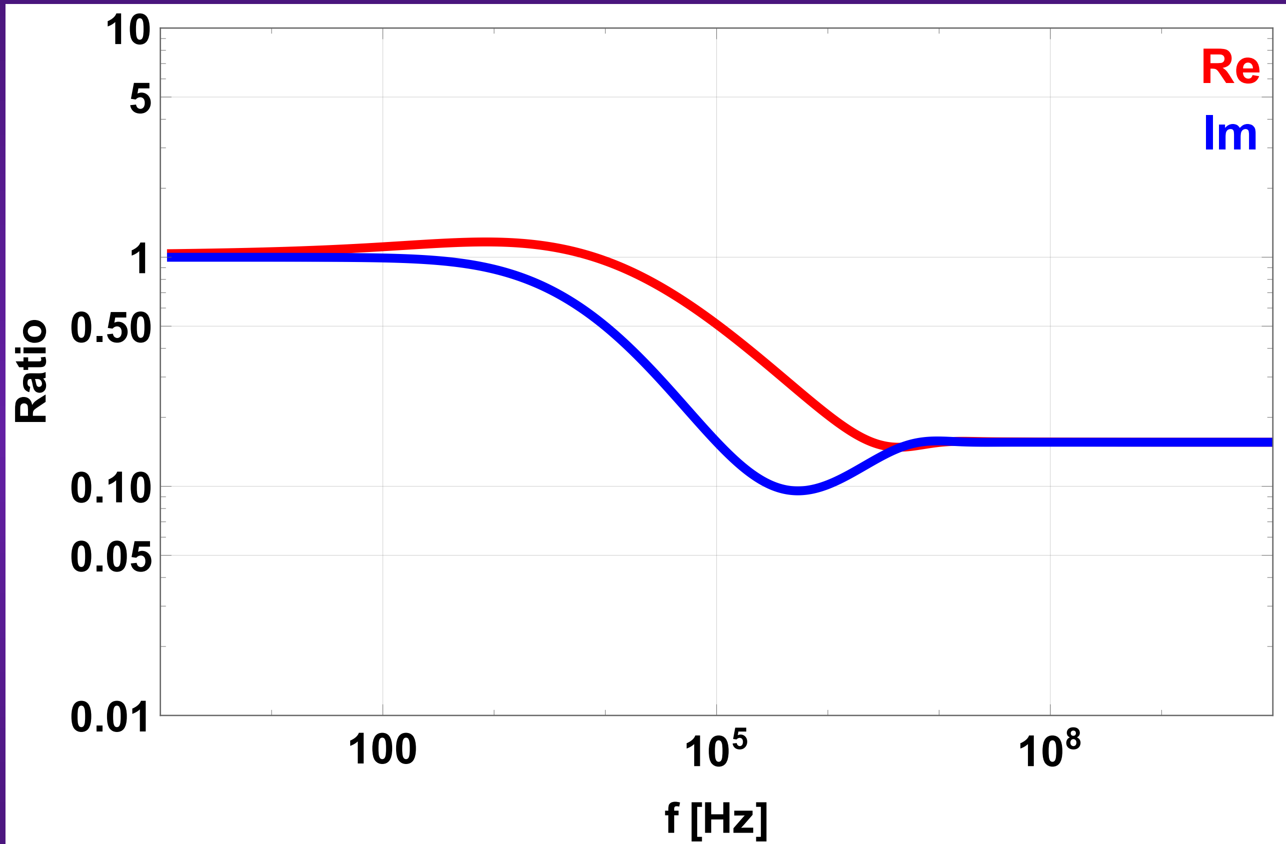

$$\text{Ratio} = \frac{Z_y\left(\text{ with coating }\right)}{Z_y\left(\text{ without coating }\right)}$$

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



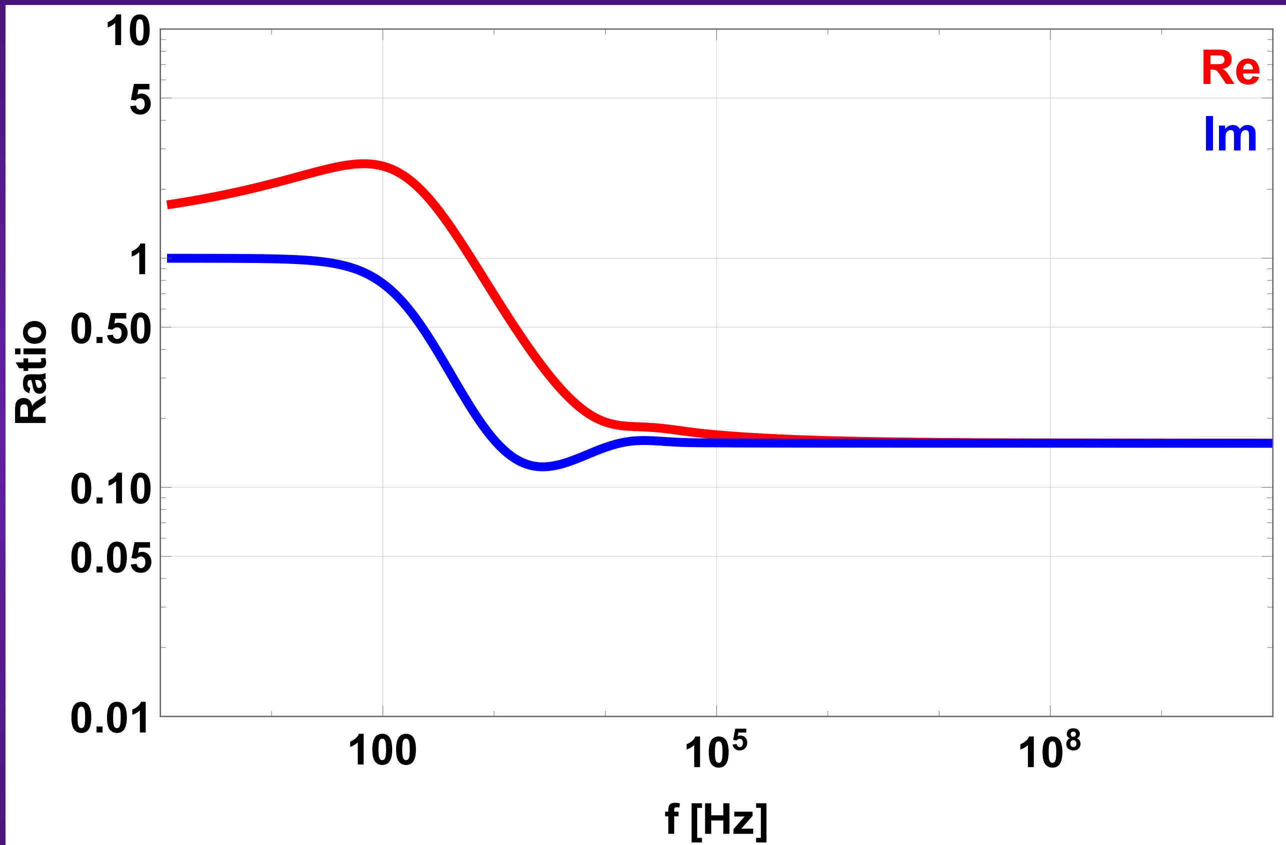

$$\text{Ratio} = \frac{Z_y(\text{ with coating })}{Z_y(\text{ without coating })}$$

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



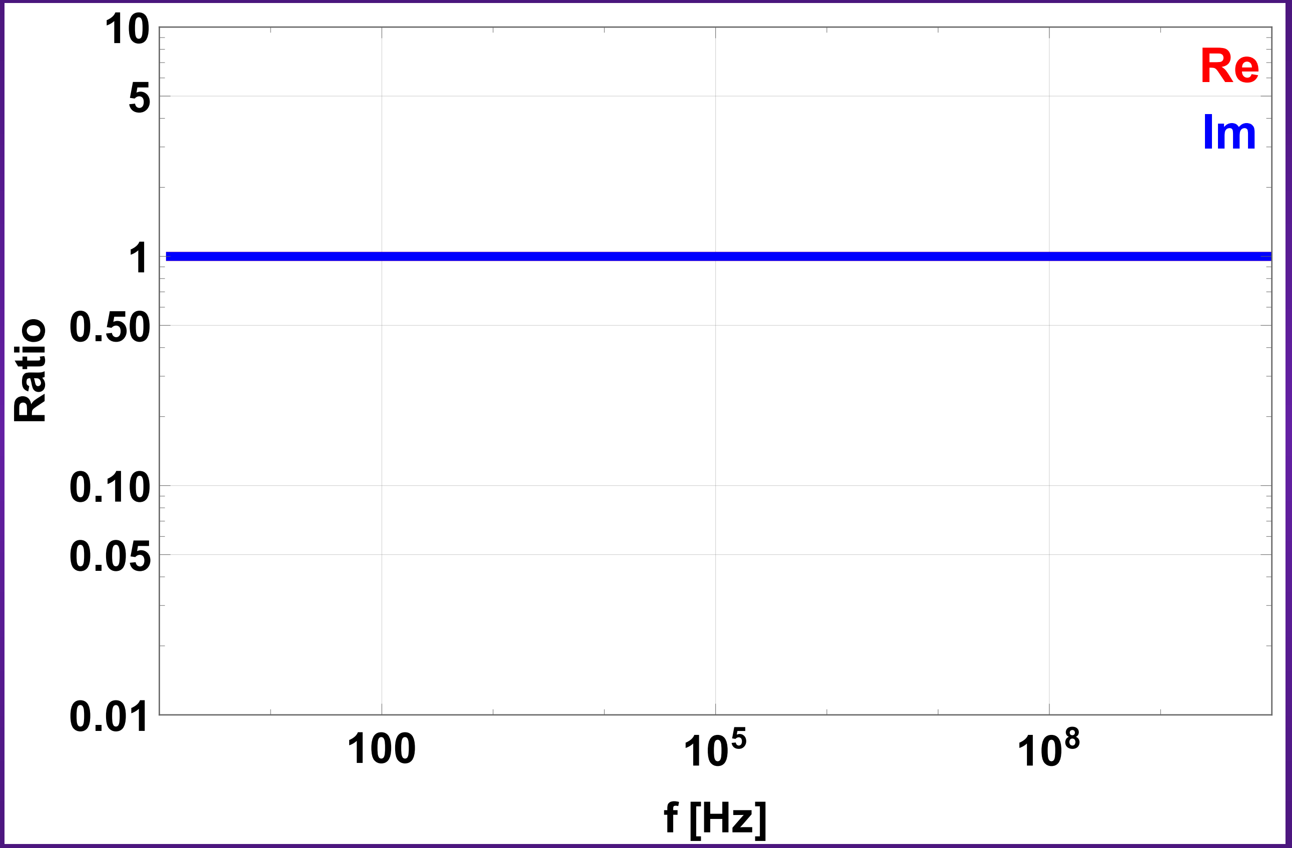

$$\text{Ratio} = \frac{Z_y\left(\text{with coating}\right)}{Z_y\left(\text{without coating}\right)}$$

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



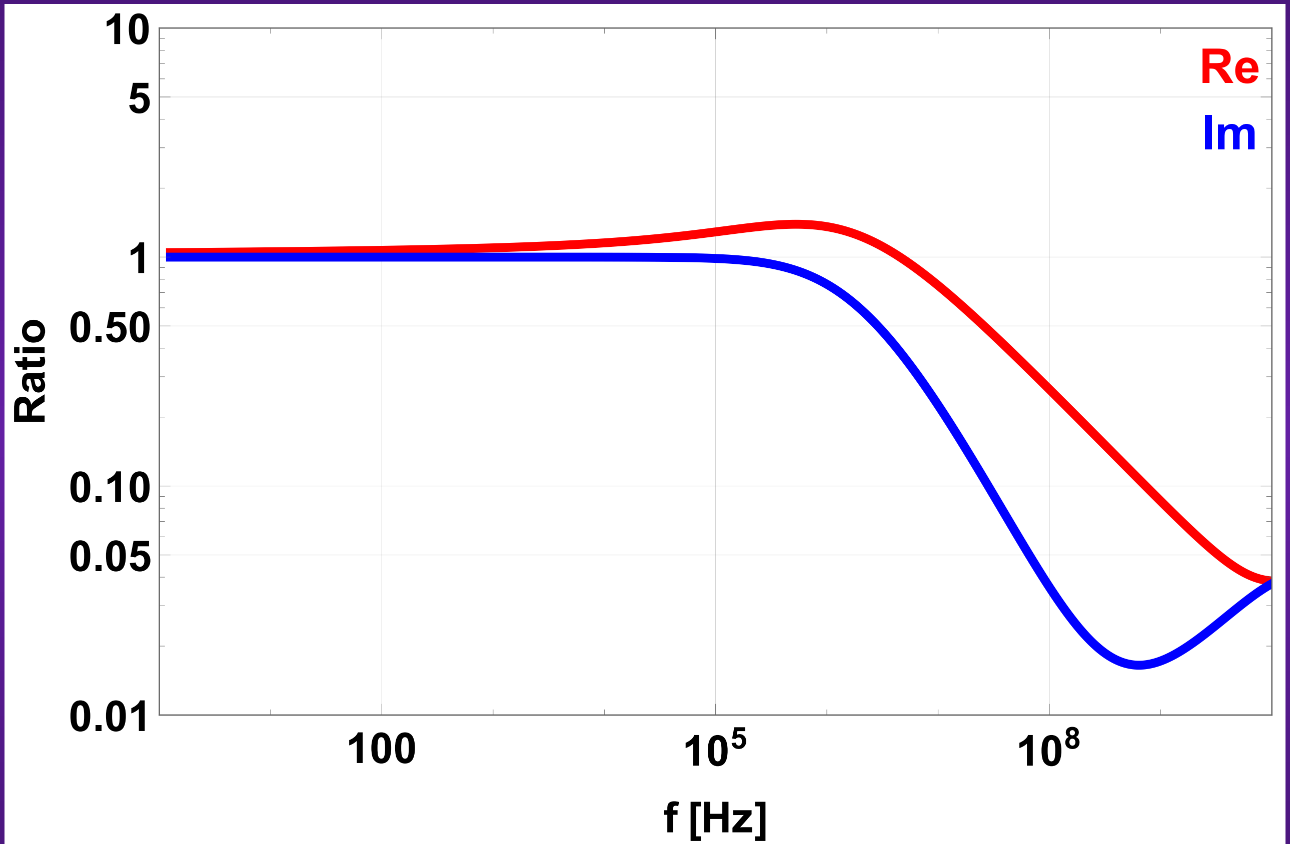

$$\text{Ratio} = \frac{Z_y(\text{ with coating })}{Z_y(\text{ without coating })}$$

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



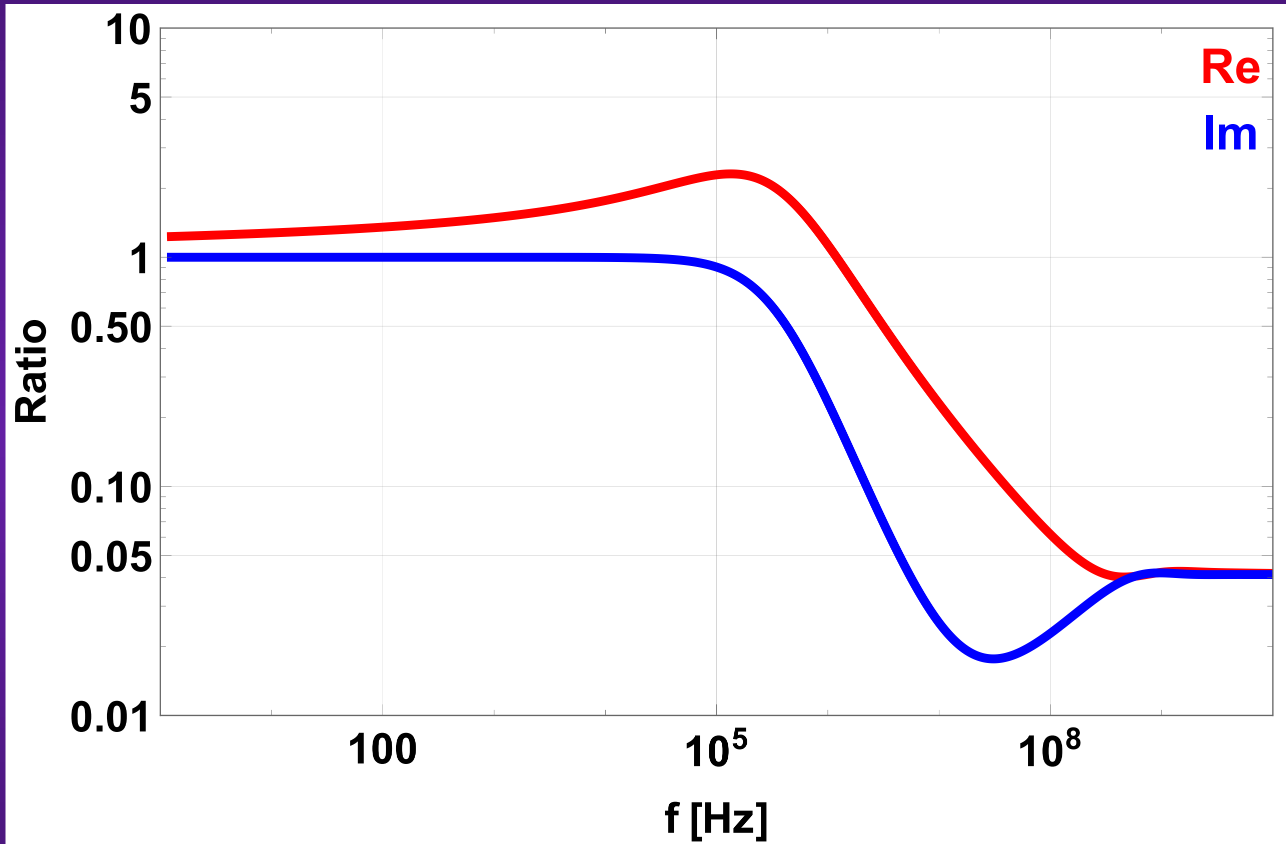

$$\text{Ratio} = \frac{Z_y(\text{ with coating })}{Z_y(\text{ without coating })}$$

# Graphite beam pipe with 2 mm radius and 1 μm copper coating (room temp.)



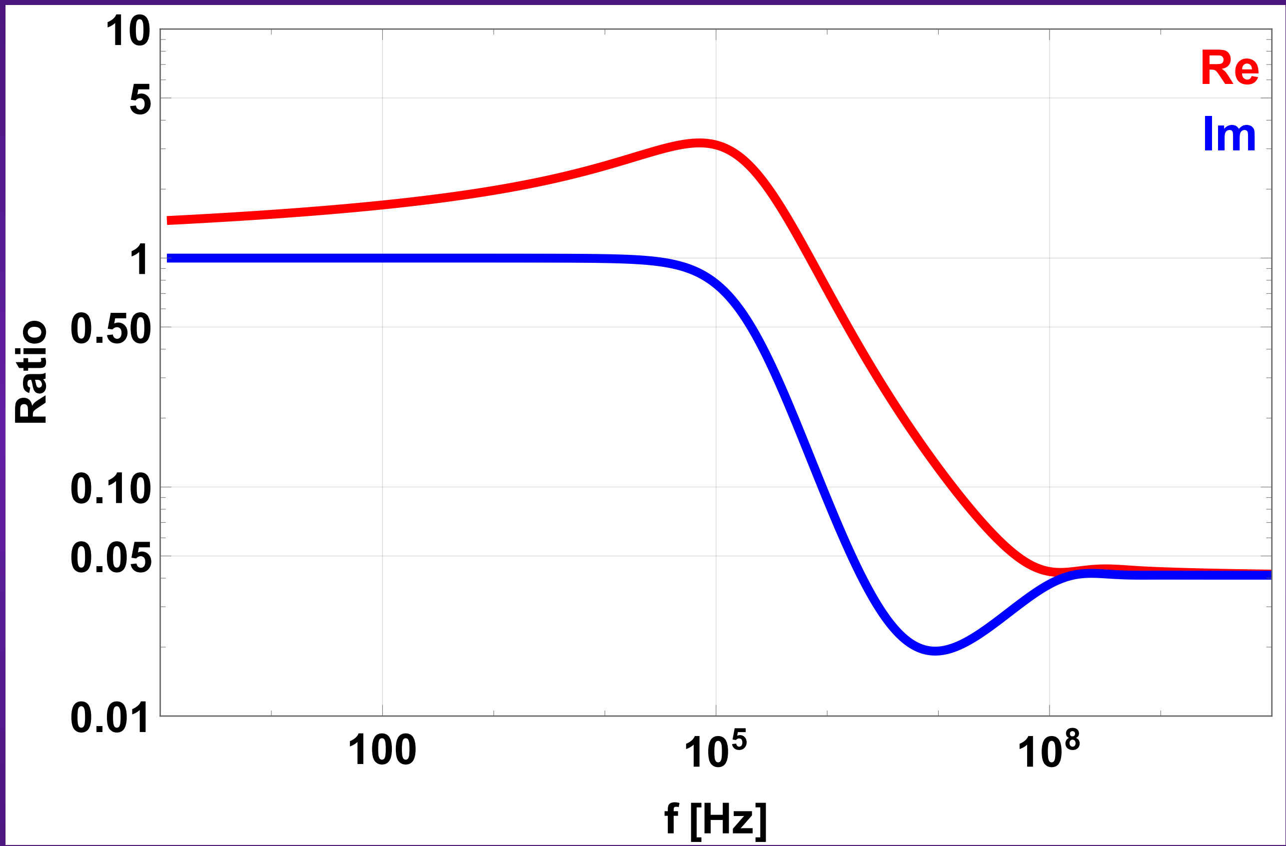

$$\text{Ratio} = \frac{Z_y(\text{ with coating })}{Z_y(\text{ without coating })}$$

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



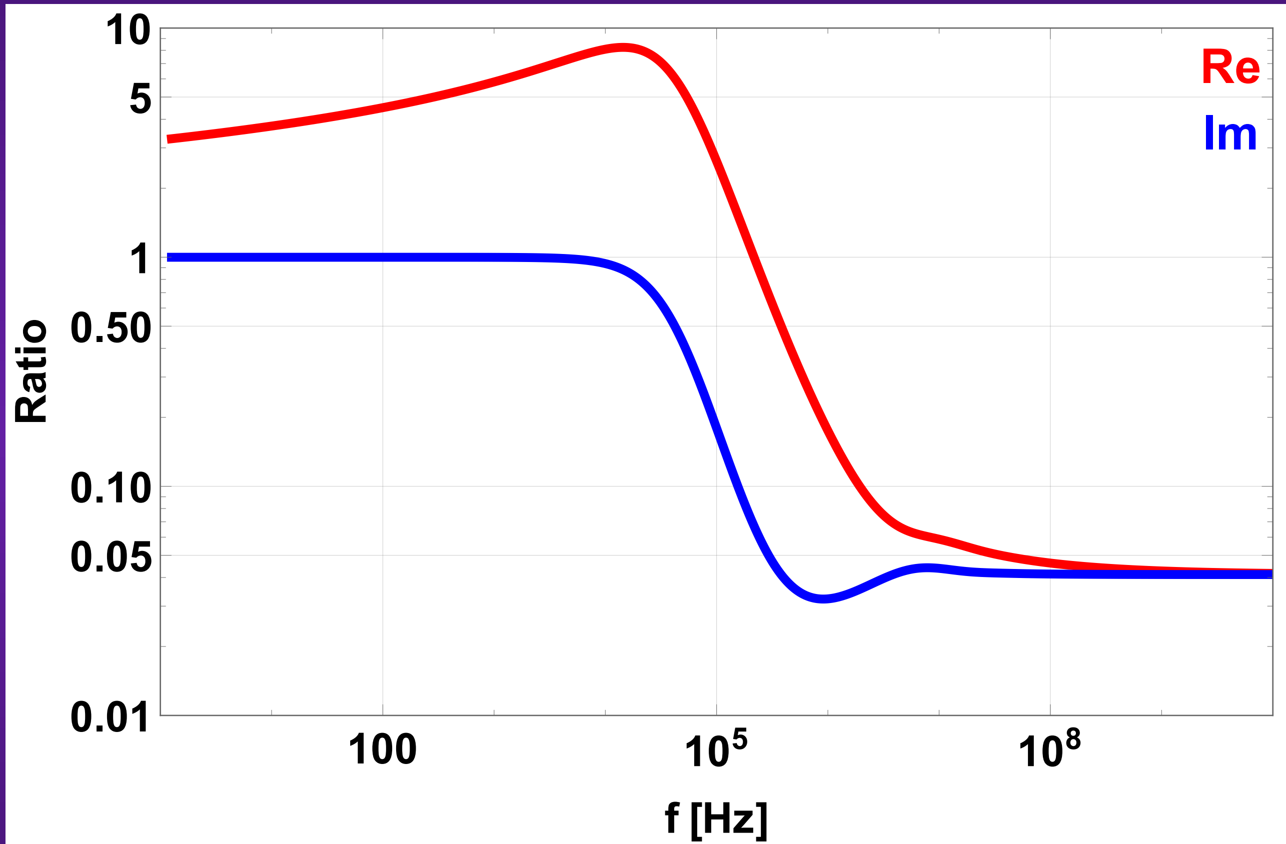

$$\text{Ratio} = \frac{Z_y(\text{ with coating })}{Z_y(\text{ without coating })}$$

# Graphite beam pipe with 2 mm radius and 10 µm copper coating (room temp.)



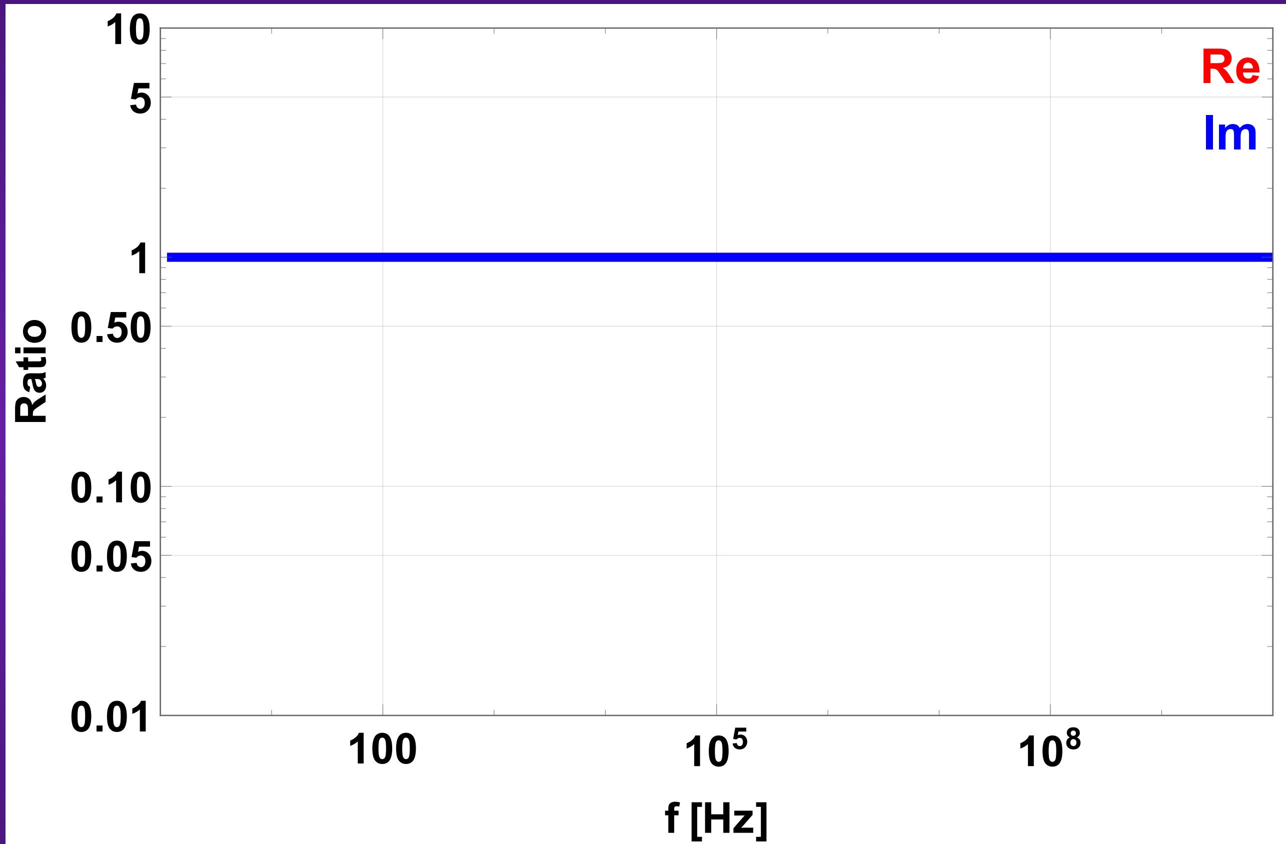

$$\text{Ratio} = \frac{Z_y(\text{ with coating })}{Z_y(\text{ without coating })}$$

# Graphite beam pipe with 2 mm radius and 50 µm copper coating (room temp.)



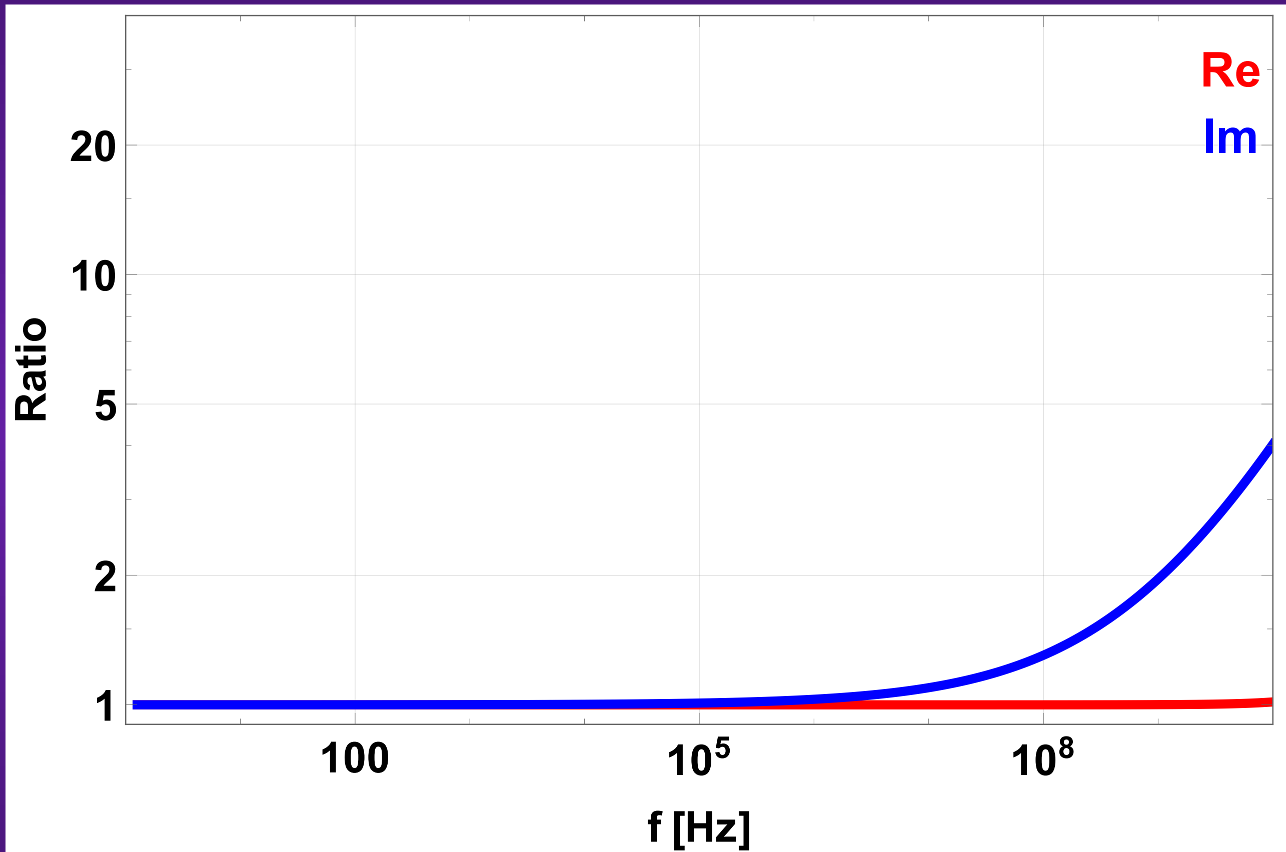

$$\text{Ratio} = \frac{Z_y(\text{with coating})}{Z_y(\text{without coating})}$$

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



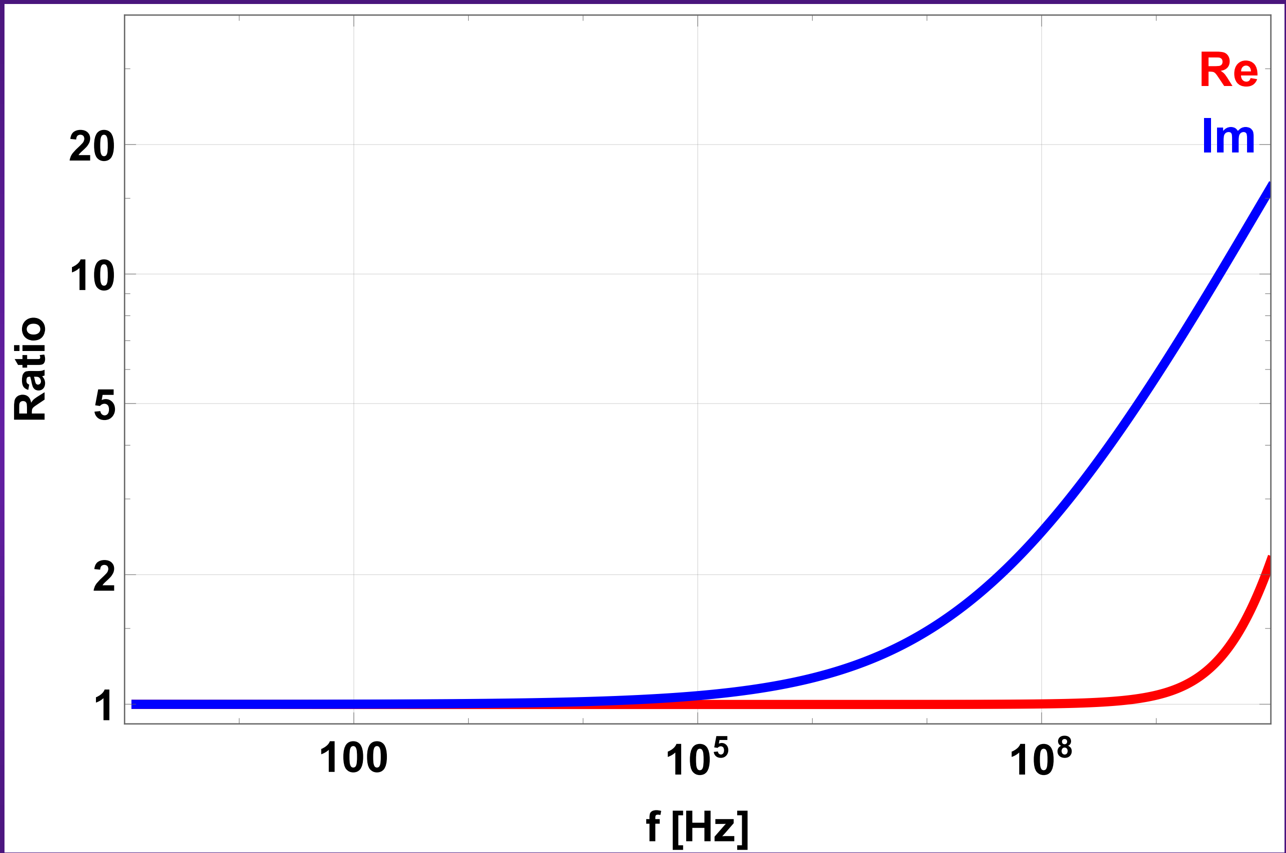

$$\text{Ratio} = \frac{Z_y(\text{with coating})}{Z_y(\text{without coating})}$$

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



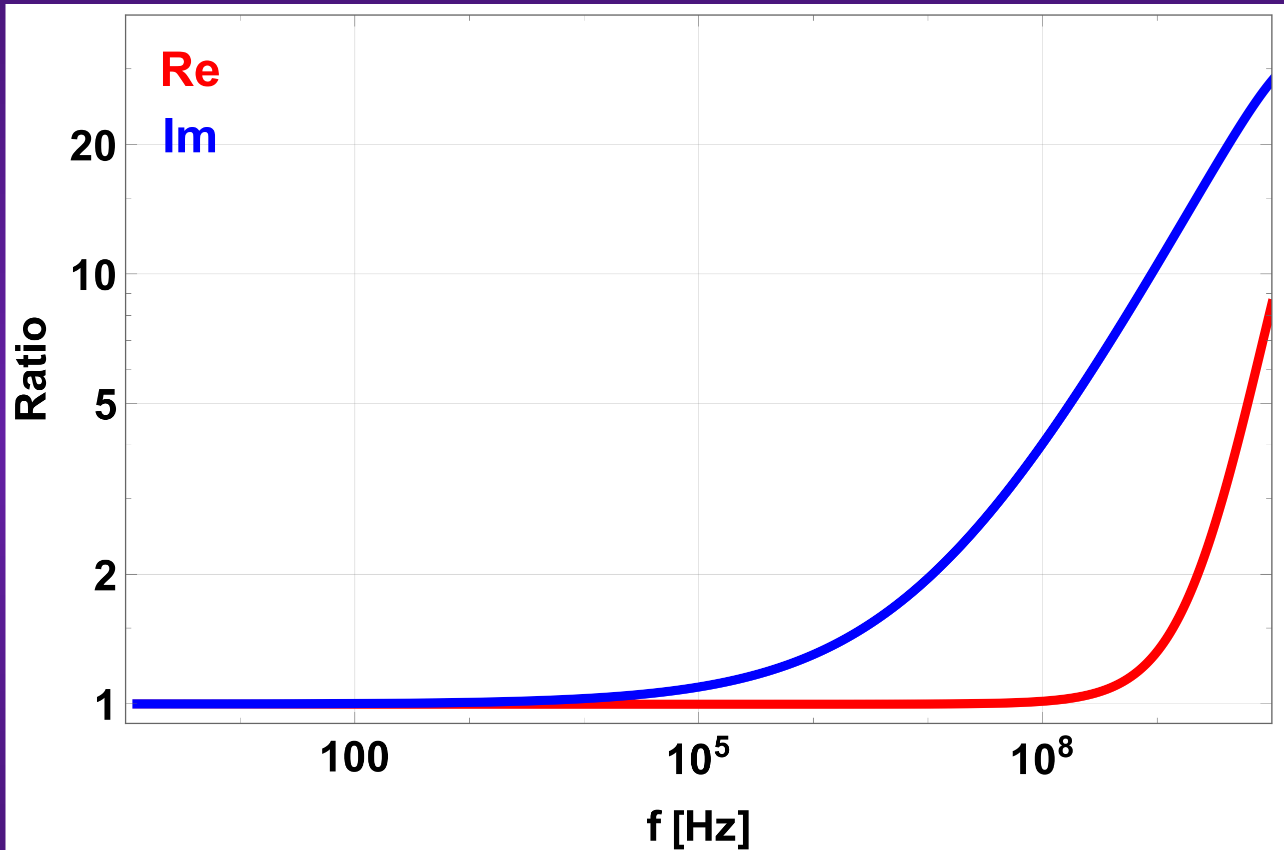

$$\text{Ratio} = \frac{Z_y(\text{ with coating })}{Z_y(\text{ without coating })}$$

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



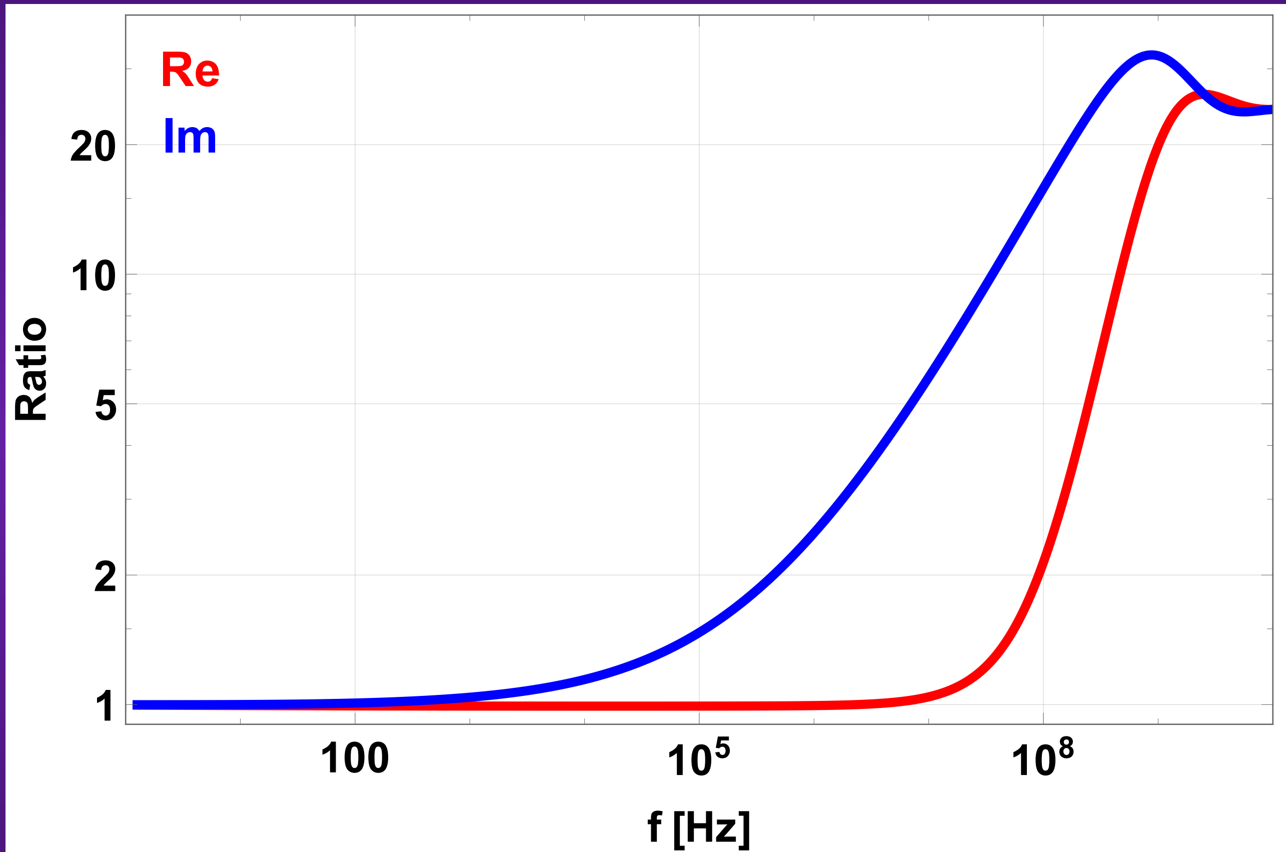

$$\text{Ratio} = \frac{Z_y(\text{ with coating })}{Z_y(\text{ without coating })}$$

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




$$\text{Ratio} = \frac{Z_y(\text{ with coating })}{Z_y(\text{ without coating })}$$

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

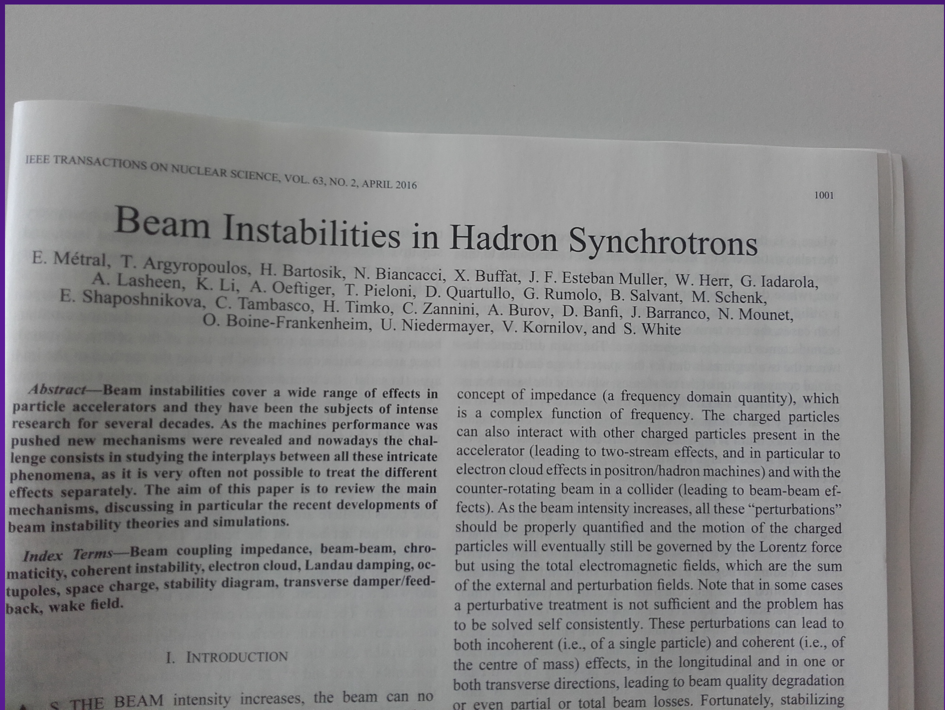



$$\text{Ratio} = \frac{Z_y(\text{ with coating })}{Z_y(\text{ without coating })}$$


## CONCLUSION

- **50 years of studies:** happy birthday!
- **Several extensions of impedance concept:** space charge, e-cloud, CSR
- **Still challenges for the future**…(e.g. due to surface treatments to fight e-cloud)

# 2 recent reviews with many references therein


IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 63, NO. 2, APRIL 2016 1001

Beam Instabilities in Hadron Synchrotrons

E. Métral, T. Argyropoulos, H. Bartosik, N. Biancacci, X. Buffat, J. F. Esteban Muller, W. Herr, G. Iadarola, A. Lasheen, K. Li, A. Oeftiger, T. Pieloni, D. Quartullo, G. Rumolo, B. Salvant, M. Schenk, E. Shaposhnikova, C. Tambasco, H. Timko, C. Zannini, A. Burov, D. Banfi, J. Barranco, N. Mounet, O. Boine-Frankenheim, U. Niedermayer, V. Kornilov, and S. White

*Abstract*—Beam instabilities cover a wide range of effects in particle accelerators and they have been the subjects of intense research for several decades. As the machines performance was pushed new mechanisms were revealed and nowadays the challenge consists in studying the interplays between all these intricate phenomena, as it is very often not possible to treat the different effects separately. The aim of this paper is to review the main mechanisms, discussing in particular the recent developments of beam instability theories and simulations.

*Index Terms*—Beam coupling impedance, beam-beam, chromaticity, coherent instability, electron cloud, Landau damping, octupoles, space charge, stability diagram, transverse damper/feedback, wake field.

I. INTRODUCTION

AS THE BEAM intensity increases, the beam can no

concept of impedance (a frequency domain quantity), which is a complex function of frequency. The charged particles can also interact with other charged particles present in the accelerator (leading to two-stream effects, and in particular to electron cloud effects in positron/hadron machines) and with the counter-rotating beam in a collider (leading to beam-beam effects). As the beam intensity increases, all these "perturbations" should be properly quantified and the motion of the charged particles will eventually still be governed by the Lorentz force but using the total electromagnetic fields, which are the sum of the external and perturbation fields. Note that in some cases a perturbative treatment is not sufficient and the problem has to be solved self consistently. These perturbations can lead to both incoherent (i.e., of a single particle) and coherent (i.e., of the centre of mass) effects, in the longitudinal and in one or both transverse directions, leading to beam quality degradation or even partial or total beam losses. Fortunately, stabilizing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December 2016

Article for special edition of IEEE TNS for 50th anniversary of PAC conference, originally launched by IEEE in 1965 (50 pages)

Theme: Collective Effects in Particle Accelerators => 26 articles (310 pages)

- First one by F. Zimmermann on Introduction to Collective Effects
- Last one by F. Antoniou et al. on Mitigation of Collective Effects by Optics Optimization