REVIEW OF RECENT LHC IMPEDANCE ACTIVITIES

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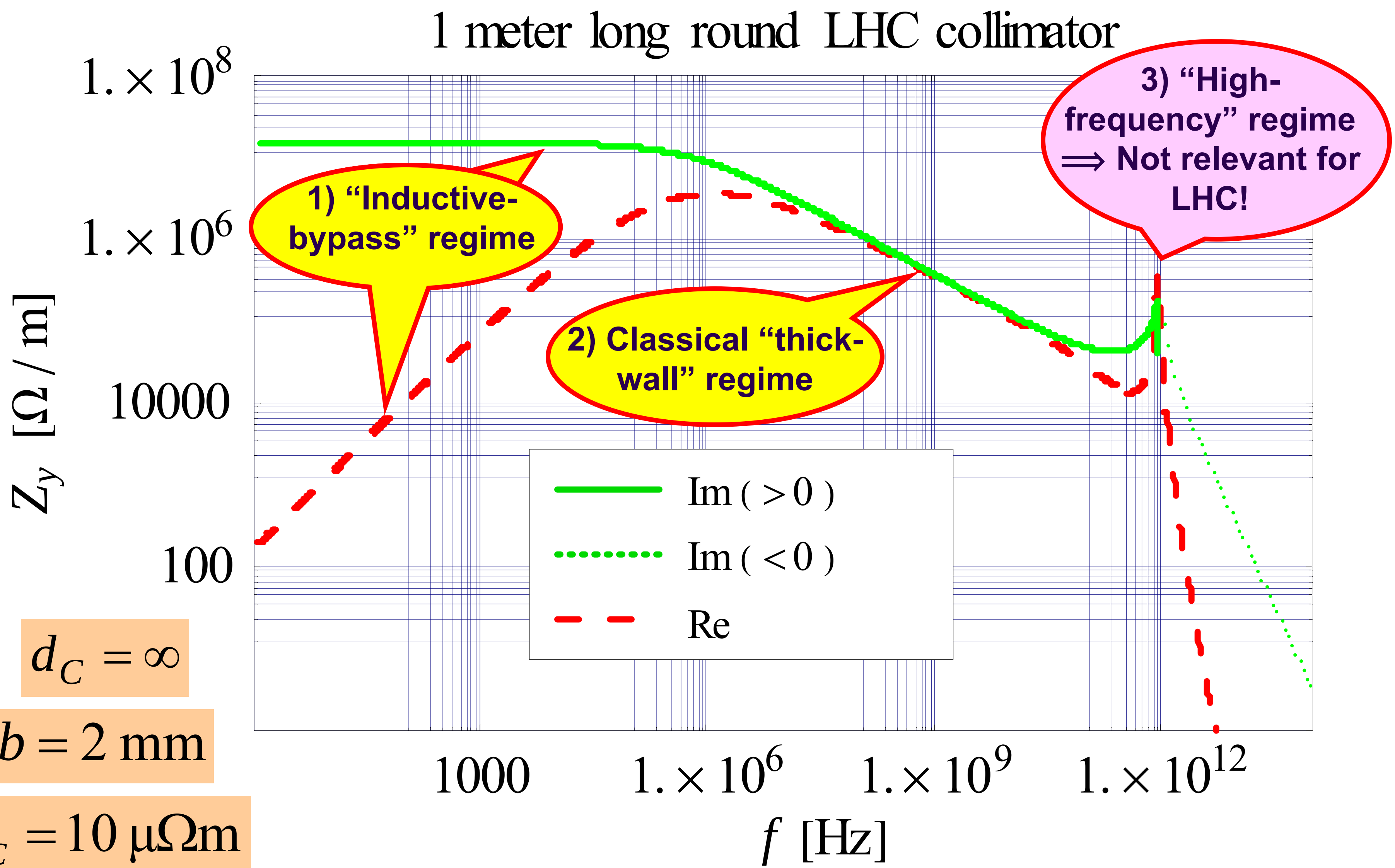
CONTENTS

- Some more infos about the transverse impedance of a LHC collimator and of the LHC
- Question from Ralph: EM fields near a collimator (for SPS MD in 2004)
- Studies for the collimators' phase 2 $\Longrightarrow$ Theory, simulations (HFSS and GdFidL) and first measurements for ceramics
- EPAC08 papers:
  - 1) Federico et al. $\Longrightarrow$ LHC collimator
  - 2) Benoit et al. $\Longrightarrow$ PIM
- CMS experimental chamber
- Collaboration with Rainer Wanzenberg from DESY
- Question from Stephane & Ranko: Impedance of 4 new triplets vs. warm pipe

ZOTTER2005'S THEORY FOR 1 GRAPHITE COLLIMATOR



$d_C = \infty$

$b = 2$ mm

$\rho_C = 10\ \mu\Omega\mathrm{m}$

Interesting frequency range for LHC
⟹ From few kHz to few GHz

SIMPLEST FORMULA FOR THE LHC COLLIMATOR TRANSVERSE IMPEDANCE (round case) (1/2)

Valid for any relatively good conductor with μ_r real and $\epsilon_r = 1$

$$Z_t^{RW1}(\omega) = \frac{j\,L\,Z_0}{\pi\,b^2} \times \frac{1}{1 - \frac{x_2}{\mu_r}\,\frac{K_1'(x_2)}{K_1(x_2)}}$$

with $\delta = \sqrt{\frac{2}{\mu_0\,\sigma\,\omega}}$, $x_2 = (1 + j)\frac{b}{\delta}$, $\mu_r = \frac{\mu}{\mu_0}$

Modified Bessel function

$$\frac{K_1'(x_2)}{K_1(x_2)} = \begin{cases} -\frac{1}{x_2} & \text{if } |x_2| << 1 \\ -1 & \text{if } |x_2| >> 1 \end{cases}$$

$\Rightarrow$

$$Z_t^{RW1}(\omega) \xrightarrow[\omega \to 0]{} \frac{j\,L\,Z_0}{\pi\,b^2} \times \frac{1}{1 + \frac{1}{\mu_r}}$$

$\Rightarrow$

$$Z_t^{RW1}(\omega) = (1 + j)\,\frac{L\,Z_0\,\mu_r\,\delta}{2\,\pi\,b^3}$$

Classical "thick-wall" regime

There are Yokoya's factors to go from round to flat (π^2 / 12 and π^2 / 24)

SIMPLEST FORMULA FOR THE LHC COLLIMATOR TRANSVERSE IMPEDANCE (round case) (2/2)

The maximum of the real part is reached when $\mathrm{Re}\left[x_2 \right] \approx 1$

It is a broad maximum

$\Leftrightarrow$ $\delta \approx b$

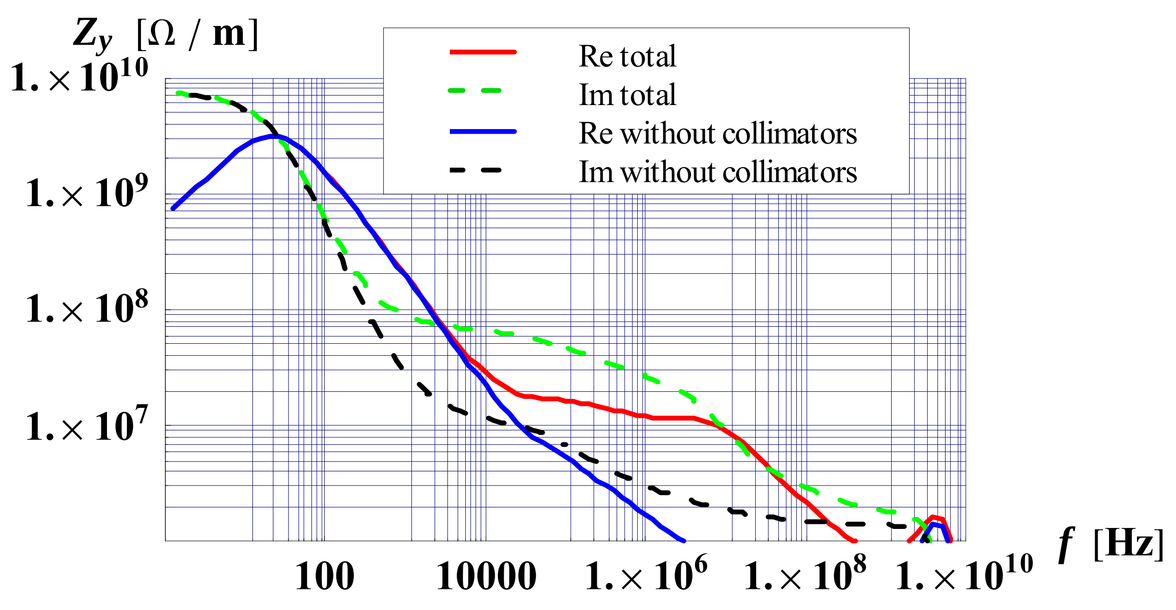
$\Longrightarrow$ $f_{\max \mathrm{Re}} \approx \dfrac{\rho}{b^2} \times \dfrac{1}{\pi \, \mu_0}$

This scaling was also found analytically using the approximated model of L. Vos (as said in the LHC Design Report, p. 100)

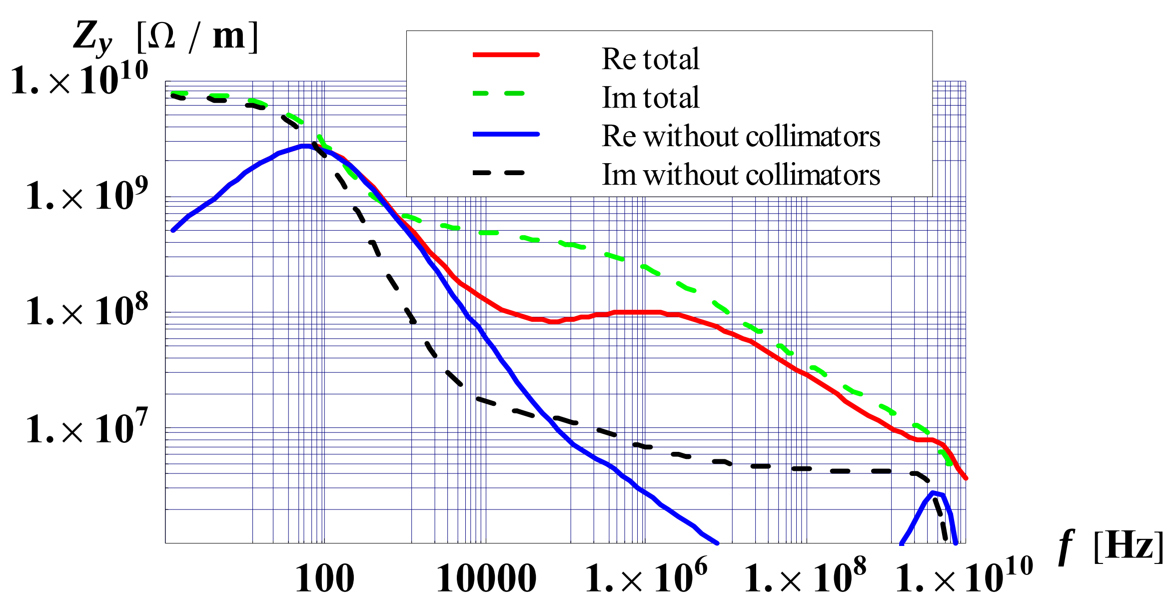
N.A.: $f_{\max \mathrm{Re}} \approx 0.6 \mathrm{\ MHz}$

LHC TRANSVERSE IMPEDANCE

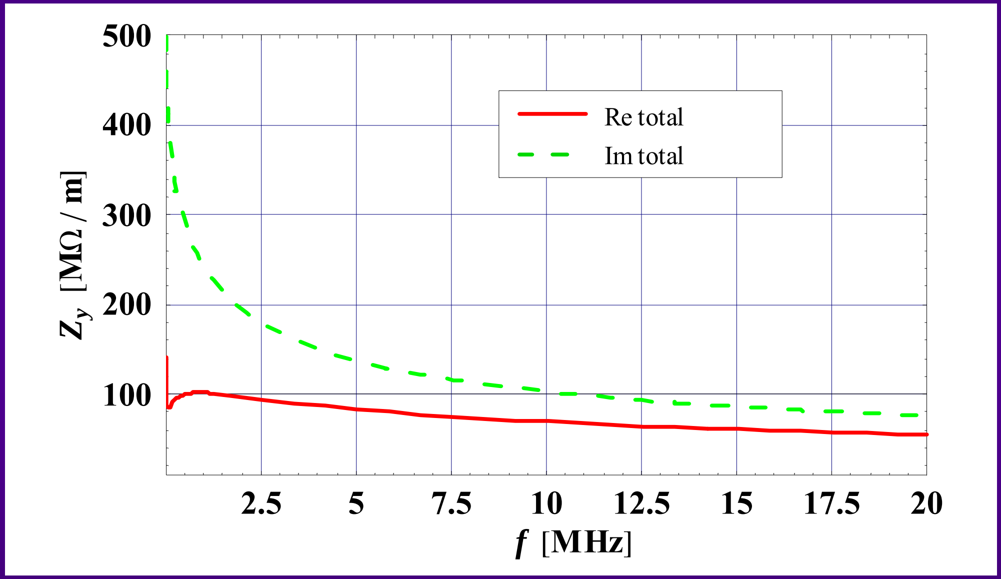
INJECTION



TOP ENERGY (after squeeze)



ZOOM (between 8 kHz and 20 MHz) OF THE LHC TRANSVERSE IMPEDANCE AT TOP ENERGY (AFTER THE SQUEEZE)



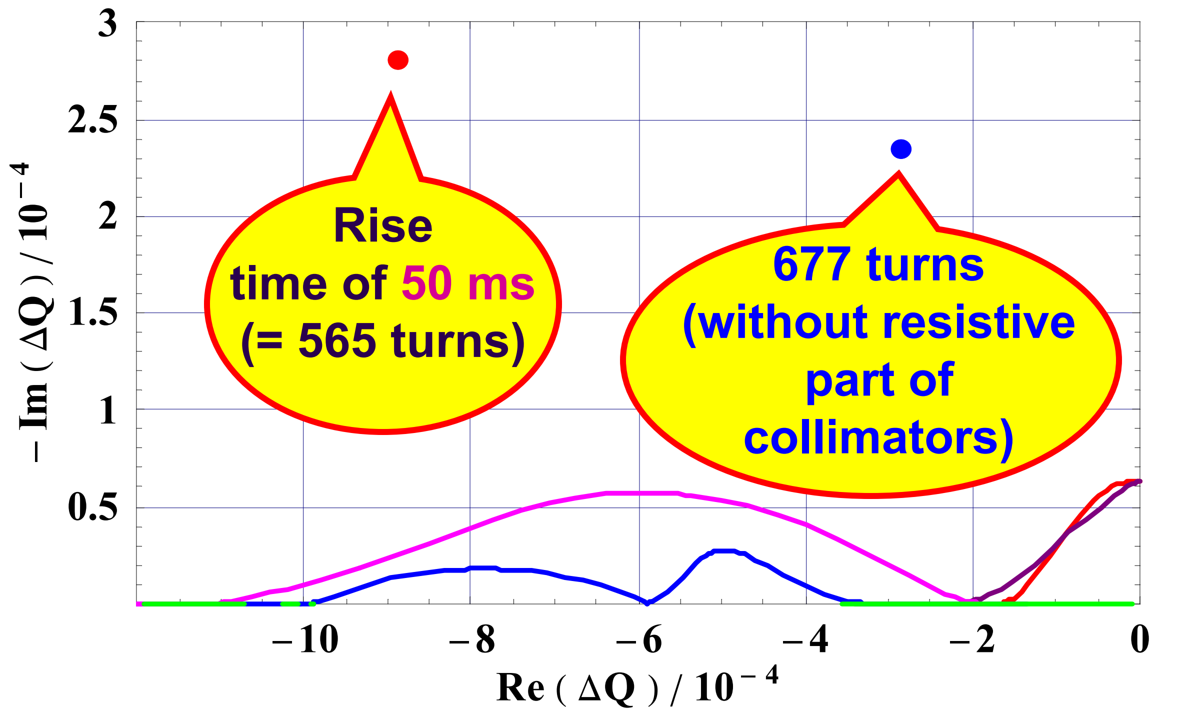
- The value of the real part of the impedance at 8 kHz (1st unstable betatron line) is ~ 141 MΩ/m
- The value of the real part of the impedance at 20 MHz (frequency limit of the transverse damper) is ~ 55 MΩ/m
- The ratio between the two values is only ~ 2.6 (it would have been 50 in the case of the classical resistive-wall theory!)

STABILITY DIAGRAM (1/3)

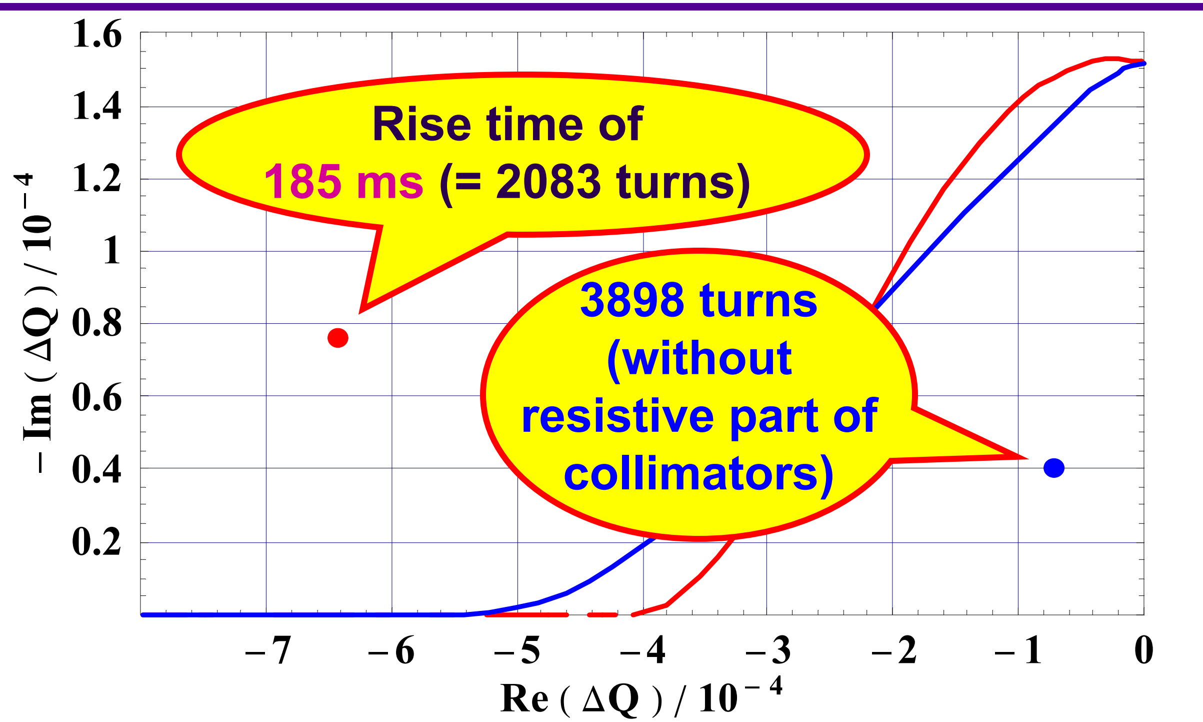
INJECTION

- Nominal case (25 ns bunch spacing and nominal intensity)

$T_{rev}^{LHC} \approx 89\ \mu s$



TOP ENERGY (after squeeze)

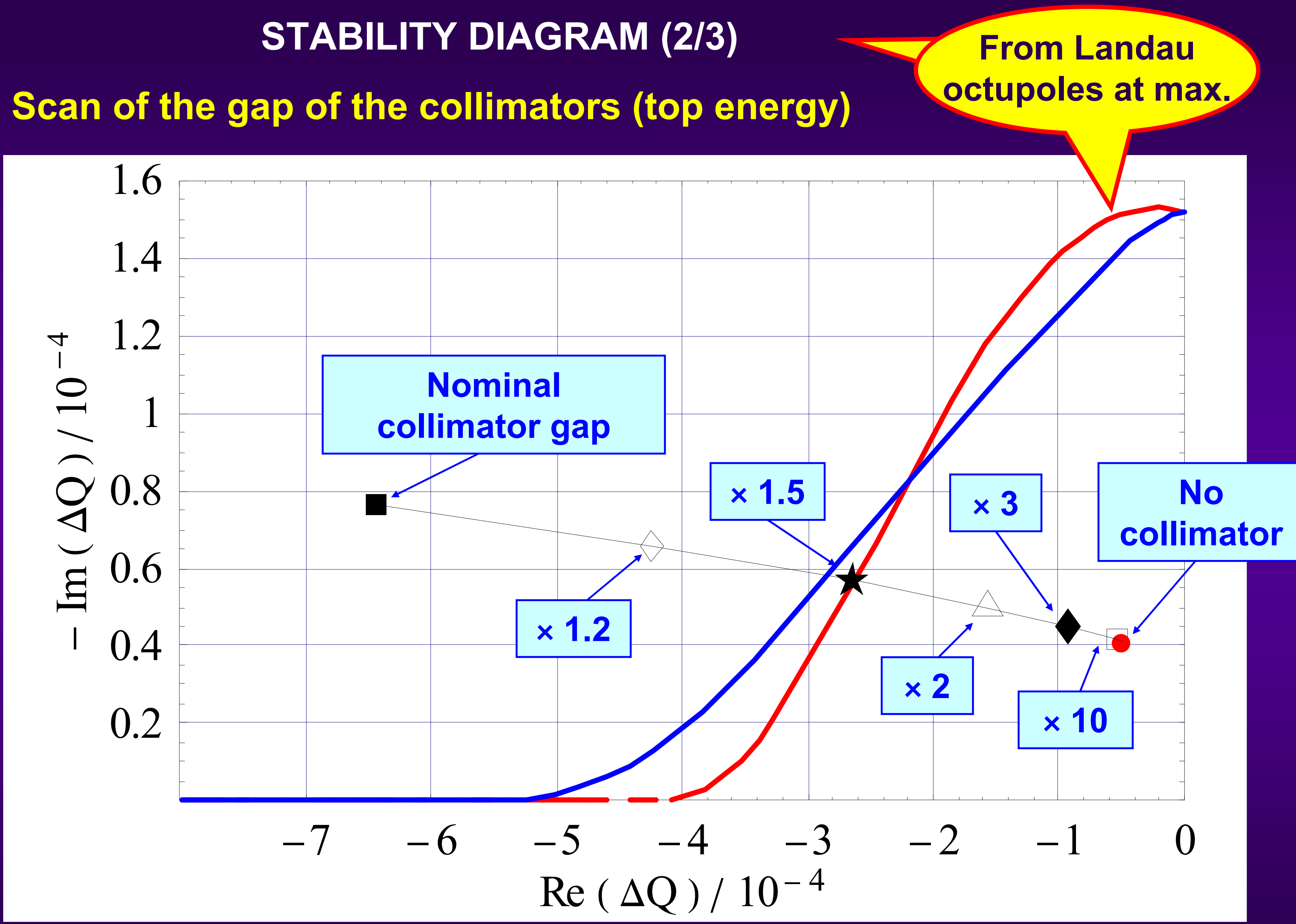


Reminder: $-\text{Im}(\Delta Q) / 10^{-4} = 1 \Longrightarrow$ Rise time $\approx$ 1600 turns $\approx$ 140 ms

Elias Métral, LCU meeting, 17/06/2008

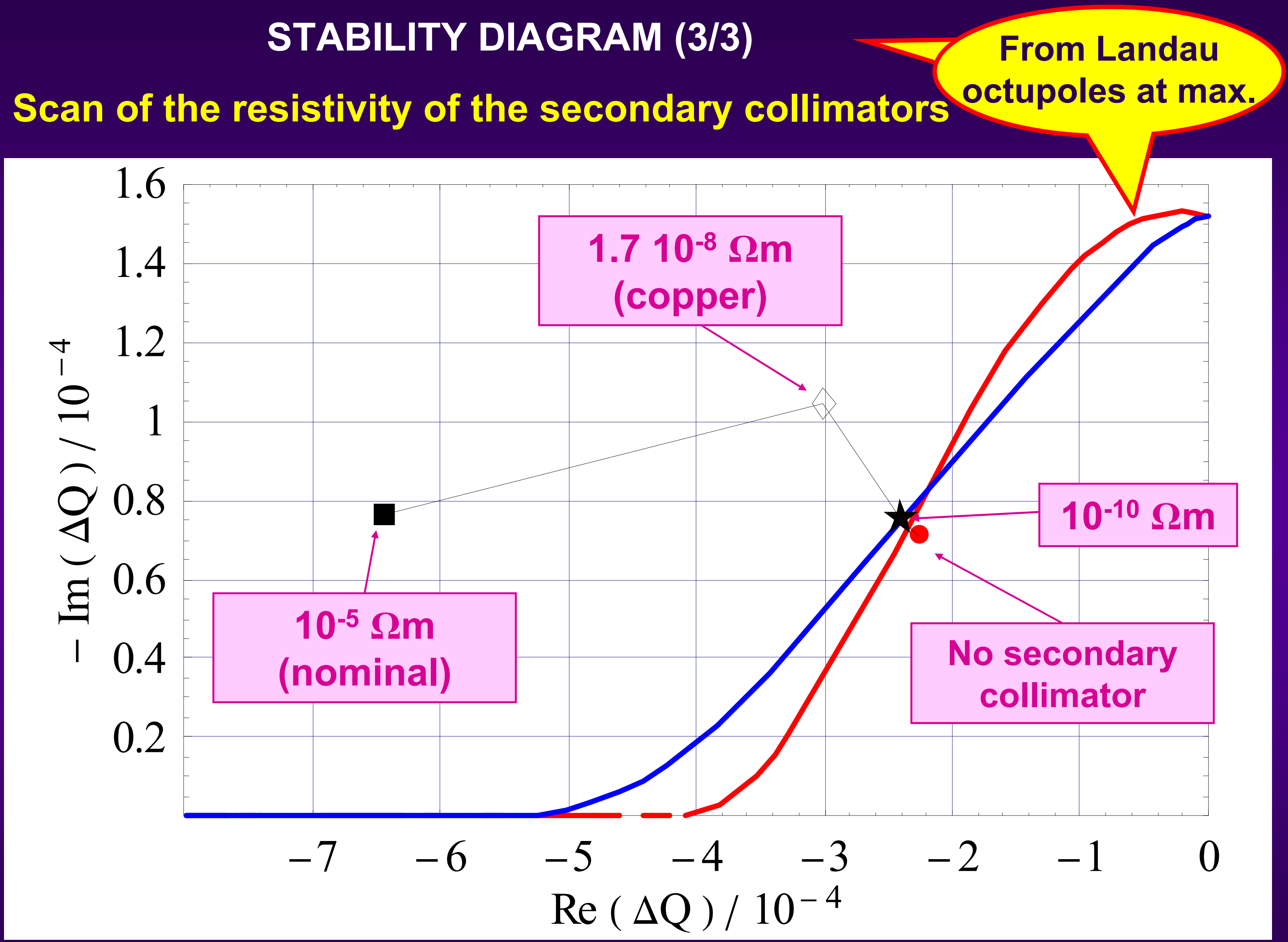
STABILITY DIAGRAM (2/3)

- **Scan of the gap of the collimators (top energy)**



STABILITY DIAGRAM (3/3)

- **Scan of the resistivity of the secondary collimators**



TRANSVERSE FEEDBACK (1/3)

- **The transverse feedback system should be able to damp instability rise-times of (I take a safety margin of a factor 2 compared to what was computed in the previous slides)**

  - **AT INJECTION ENERGY**

    - **~ 280 turns (i.e. ~ 25 ms) at injection for nominal intensity**
    - **~ 190 turns (i.e. ~ 17 ms) at injection for ultimate intensity**

  - **AT TOP ENERGY (AFTER THE SQUEEZE)**

    - **~ 1040 turns (i.e. ~ 93 ms) at injection for nominal intensity**
    - **~ 705 turns (i.e. ~ 63 ms) at injection for ultimate intensity**

TRANSVERSE FEEDBACK (2/3)

- According to W. Hofle:
  - In the SPS ~ 20 turns damping is achieved in the vertical plane on a regular basis
  - The normal operating mode of the feedback should be at gains corresponding to 20-40 turns damping

    $\Longrightarrow$ It seems therefore feasible to damp the foreseen instability rise-times both at injection and top energy
  - The issue of the noise at top energy: K. Ohmi et al. (PAC 2007, LHC Project Report 1048) has estimated from numerical calculations that we can run in the LHC at a gain of 0.1 (10 turns damping) with a monitor resolution of 0.6% of σ and still have a luminosity life-time of one day. The corresponding required resolution is 7.2 μm at 450 GeV (σ = 1.2 mm) and 1.8 mm at 7 TeV (σ proportional to $\gamma^{-1/2}$). If the gain can be reduced, then the requirement for the monitor resolution can be relaxed. The improvement in monitor resolution required for LHC when compared with the SPS can be achieved due to the increased number of bits used and the higher signal power available from the coupler type pick-up

TRANSVERSE FEEDBACK (3/3)

- The transverse impedance (both RE and IM parts) of the LHC can be decreased by increasing the gap of the collimators
- The RE part of the transverse impedance of the LHC is increased by reducing the resistivity of the secondary collimators
- The beam will be stabilized at injection by a transverse feedback
- At top energy:
  - If one wants to stabilize the beam at top energy by Landau damping $\Longrightarrow$ One should try and reduce the IMAGINARY part of the collimator impedance (this has a huge effect compared to the rest of the machine!)
  - If one wants to (can) stabilize the beam at top energy by transverse feedback $\Longrightarrow$ It seems that it should be possible. In this case one can help the feedback system even more by reducing the REAL part of the collimator impedance (in particular until ~ 20 MHz)

SOURCE CHARGE DENSITY USED FOR THE COMPUTATIONS

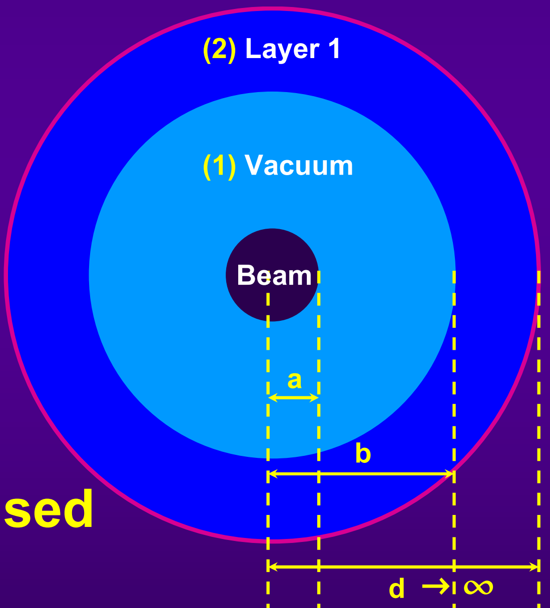
- A macro-particle of charge $Q = N_b \, e$ is assumed to move along the pipe (in the *s* - direction) with an offset $r = a$ in the $\vartheta = 0$ direction and with velocity $\upsilon = \beta \, c$

A cos mθ beam generates EM fields in cos mθ and sin mθ $\Longrightarrow$ Different multipoles are decoupled (consequence of the axial symmetry)

$\Longrightarrow$ The charge density can be written

$$\rho(r, \vartheta, s; t) = \sum_{m=0}^{\infty} \frac{P_m \cos(m \vartheta)}{\pi \, a^{m+1} (1 + \delta_{m0})} \delta(r - a) \, \delta(s - \upsilon t)$$

where $P_m = Q \, a^m$ is the m^{th} multipole moment



- The cylindrical coordinate system $(\vec{r}, \vec{\vartheta}, \vec{s})$ is used

- Numerical values are given for the 2004 SPS experiment $N_b = 1.15 \times 10^{11}$ p/b $r = b = 2$ mm $\vartheta = 0$

REMINDER: Perfectly Conducting wall (1/3)

***m* = 0**	***m* = 1**
Used to compute the longitudinal impedance	Used to compute the transverse impedance

$$E_\vartheta^{PC0} = B_r^{PC0} = B_s^{PC0} = 0$$

$$E_s^{PC0} = \frac{Q}{2\pi\varepsilon_0\gamma^2}\ln\left(\frac{b}{r}\right)\delta'(s-\upsilon t) \xrightarrow[\gamma\to\infty]{} 0$$

$$E_s^{PC0} = 0$$

$$E_r^{PC0} = \frac{Q}{2\pi\varepsilon_0 r}\delta(s-\upsilon t)$$

$$E_r^{PC0} \approx 1.7\times10^5\ \delta(s-\upsilon t)$$

$$B_\vartheta^{PC0} = \frac{\beta}{c}E_r^{PC0}$$

$$B_\vartheta^{PC0} \approx 6\times10^{-4}\ \delta(s-\upsilon t)$$

$$B_s^{PC1} = 0$$

$$E_s^{PC1} = \frac{P_1\cos(\vartheta)}{2\pi\varepsilon_0\gamma^2}\left[\frac{1}{r}-\frac{r}{b^2}\right]\delta'(s-\upsilon t) \xrightarrow[\gamma\to\infty]{} 0$$

$$E_s^{PC1} = 0$$

$$E_r^{PC1} = \frac{P_1\cos(\vartheta)}{2\pi\varepsilon_0}\left[\frac{1}{r^2}+\frac{1}{b^2}\right]\delta(s-\upsilon t)$$

$$E_r^{PC1} \approx 0.9\times10^5\ \delta(s-\upsilon t)$$

$$E_\vartheta^{PC1} = \frac{P_1\sin(\vartheta)}{2\pi\varepsilon_0}\left[\frac{1}{r^2}-\frac{1}{b^2}\right]\delta(s-\upsilon t)$$

$$E_\vartheta^{PC1} = 0$$

$$B_\vartheta^{PC1} = \frac{\beta}{c}E_r^{PC1} \qquad B_r^{PC1} = -\frac{\beta}{c}E_\vartheta^{PC1}$$

$$B_\vartheta^{PC1} \approx 3\times10^{-4}\ \delta(s-\upsilon t) \qquad B_r^{PC1} = 0$$

REMINDER: Perfectly Conducting wall (2/3)

Force on a particle with charge *q*

$$\vec{F} = q \left[E_s \, \vec{s} + \left(E_r - \upsilon \, B_\vartheta \right) \vec{r} + \left(E_\vartheta + \upsilon \, B_r \right) \vec{\vartheta} \right]$$

***m* = 0**

$$F_s^{PC0} = \frac{q \, Q}{2 \pi \varepsilon_0 \gamma^2} \ln\left(\frac{b}{r} \right) \delta'\left(s - \upsilon t \right) \xrightarrow[\gamma \to \infty]{} 0$$

$$F_r^{PC0} = \frac{q \, Q}{2 \pi \varepsilon_0 \, r \, \gamma^2} \delta\left(s - \upsilon t \right)$$

$$F_\vartheta^{PC0} = 0$$

***m* = 1**

$$F_s^{PC1} = \frac{q \, P_1 \cos\left(\vartheta \right)}{2 \pi \varepsilon_0 \gamma^2} \left[\frac{1}{r} - \frac{r}{b^2} \right] \delta'\left(s - \upsilon t \right) \xrightarrow[\gamma \to \infty]{} 0$$

$$F_r^{PC1} = \frac{q \, P_1 \cos\left(\vartheta \right)}{2 \pi \varepsilon_0 \gamma^2} \left[\frac{1}{r^2} + \frac{1}{b^2} \right] \delta\left(s - \upsilon t \right)$$

$$F_\vartheta^{PC1} = \frac{q \, P_1 \sin\left(\vartheta \right)}{2 \pi \varepsilon_0 \gamma^2} \left[\frac{1}{r^2} - \frac{1}{b^2} \right] \delta\left(s - \upsilon t \right)$$

REMINDER: Perfectly Conducting wall (3/3)

m = 0

$$Z_l^{PC0}(\omega) = -j \, \frac{L \, \omega \, Z_0}{2 \pi c \, \beta^2 \gamma^2} \ln\left(\frac{b}{a}\right)$$

$$W_l^{PC0}(\tau) = -\frac{L \, Z_0}{2 \pi c \, \beta^2 \gamma^2} \ln\left(\frac{b}{a}\right) \delta'(\tau)$$

Behind the bunch

For L = 2 π R

$$Z_l^{PC0}(\omega) = -j \, \frac{\omega \, Z_0}{\omega_0 \, \beta \, \gamma^2} \ln\left(\frac{b}{a}\right)$$

$$W_l^{PC0}(\tau) = -\frac{Z_0}{\omega_0 \, \beta \, \gamma^2} \ln\left(\frac{b}{a}\right) \delta'(\tau)$$

m = 1

$$Z_t^{PC1}(\omega) = -j \, \frac{L \, Z_0}{2 \pi \, \beta \, \gamma^2} \left(\frac{1}{a^2} - \frac{1}{b^2}\right)$$

$$W_t^{PC1}(\tau) = -\frac{L \, Z_0}{2 \pi \, \beta \, \gamma^2} \left(\frac{1}{a^2} - \frac{1}{b^2}\right) \delta(\tau)$$

For L = 2 π R

$$Z_t^{PC1}(\omega) = -j \, \frac{R \, Z_0}{\beta \, \gamma^2} \left(\frac{1}{a^2} - \frac{1}{b^2}\right)$$

$$W_t^{PC1}(\tau) = -\frac{R \, Z_0}{\beta \, \gamma^2} \left(\frac{1}{a^2} - \frac{1}{b^2}\right) \delta(\tau)$$

CASE OF A RESISTIVE OBJECT (1/4)

$\gamma \to \infty$

$z = s - c\,t$

⟹ z > 0 is ahead of the beam and z < 0 is behind the beam

m = 0

$$E_\vartheta^{RW0} = B_r^{RW0} = B_s^{RW0} = 0$$

$$E_s^{RW0} = \frac{Q\,c\,\sqrt{Z_0}}{4\,\pi^{3/2}\,b\,\sqrt{\sigma}\,|z|^{3/2}}$$

$$E_s^{RW0} \approx \frac{8}{|z|^{3/2}}$$

$$E_r^{RW0} = -\frac{3\,Q\,r\,c\,\sqrt{Z_0}}{16\,\pi^{3/2}\,b\,\sqrt{\sigma}\,|z|^{5/2}}$$

$$E_r^{RW0} \approx -\frac{0.01}{|z|^{5/2}}$$

$$B_\vartheta^{RW0} = \frac{E_r^{RW0}}{c}$$

$$c\,B_\vartheta^{RW0} \approx -\frac{0.01}{|z|^{5/2}}$$

m = 1

$$E_s^{RW1} \approx \frac{4}{|z|^{3/2}}$$

$$E_s^{RW1} = \frac{P_1 \cos(\vartheta)\,c\,r\,\mu_r\,\sqrt{Z_0}}{2\,\pi^{3/2}\,b^3\,\sqrt{\sigma}\,|z|^{3/2}}$$

E_r^{RW1} E_ϑ^{RW1}

Different from Chao page 54 (see next slide)!

$$B_s^{RW1} = -\frac{P_1 \sin(\vartheta)\,r\,\mu_r\,\sqrt{Z_0}}{2\,\pi^{3/2}\,b^3\,\sqrt{\sigma}\,|z|^{3/2}}$$

$$B_s^{RW1} = 0$$

$$E_\vartheta^{RW1} + c\,B_r^{RW1} = -\frac{P_1 \sin(\vartheta)\,c\,\mu_r\,\sqrt{Z_0}}{\pi^{3/2}\,b^3\,\sqrt{\sigma}\,|z|^{1/2}}$$

$$E_\vartheta^{RW1} + c\,B_r^{RW1} = 0$$

$$E_r^{RW1} - c\,B_\vartheta^{RW1} = \frac{P_1 \cos(\vartheta)\,c\,\mu_r\,\sqrt{Z_0}}{\pi^{3/2}\,b^3\,\sqrt{\sigma}\,|z|^{1/2}}$$

$$E_r^{RW1} - c\,B_\vartheta^{RW1} \approx \frac{4\times 10^3}{|z|^{1/2}}$$

CASE OF A RESISTIVE OBJECT (2/4)

I have (at the moment…) for *m* = 1

Chao finds the same result for *r* = *b* and *θ* = 0

μ_r = 1 for Chao

$$E_{\vartheta}^{RW1} = 0$$

$$E_{\vartheta}^{RW1} = -\frac{3\,P_1 \sin\left(\vartheta\right) c\, \mu_r \sqrt{Z_0}}{16\,\pi^{3/2}\, b^3 \sqrt{\sigma} \left| z \right|^{5/2}}\, r^2$$

Chao has ($r^2 - b^2$) instead of r^2

Chao finds a result 2 times bigger

$$E_r^{RW1} \approx \frac{3 \times 10^{-3}}{\left| z \right|^{5/2}}$$

$$E_r^{RW1} = -\frac{3\,P_1 \cos\left(\vartheta\right) c\, \mu_r \sqrt{Z_0}}{16\,\pi^{3/2}\, b^3 \sqrt{\sigma} \left| z \right|^{5/2}}\, r^2$$

Chao has ($r^2 + b^2$) instead of r^2

CASE OF A RESISTIVE OBJECT (3/4)

***m* = 0**

$$F_s^{RW0} = \frac{q\, Q\, c \sqrt{Z_0}}{4\, \pi^{3/2}\, b \sqrt{\sigma}\, |z|^{3/2}}$$

$$F_r^{RW0} = F_\vartheta^{RW0} = 0$$

***m* = 1**

$$F_s^{RW1} = \frac{q\, P_1 \cos(\vartheta)\, c\, r\, \mu_r \sqrt{Z_0}}{2\, \pi^{3/2}\, b^3 \sqrt{\sigma}\, |z|^{3/2}}$$

$$F_r^{RW1} = \frac{q\, P_1 \cos(\vartheta)\, c\, \mu_r \sqrt{Z_0}}{\pi^{3/2}\, b^3 \sqrt{\sigma}\, |z|^{1/2}}$$

$$F_\vartheta^{RW1} = -\frac{q\, P_1 \sin(\vartheta)\, c\, \mu_r \sqrt{Z_0}}{\pi^{3/2}\, b^3 \sqrt{\sigma}\, |z|^{1/2}}$$

CASE OF A RESISTIVE OBJECT (4/4)

m = 0

$$Z_l^{RW0}(\omega) = (1 + j)\frac{L}{2\pi b}\sqrt{\frac{\omega Z_0}{2 c \sigma}}$$

$$W_l^{RW0}(\tau) = -\frac{L}{4\pi^{3/2} b}\sqrt{\frac{Z_0}{c \sigma}} \times \frac{1}{\tau^{3/2}}$$

m = 1

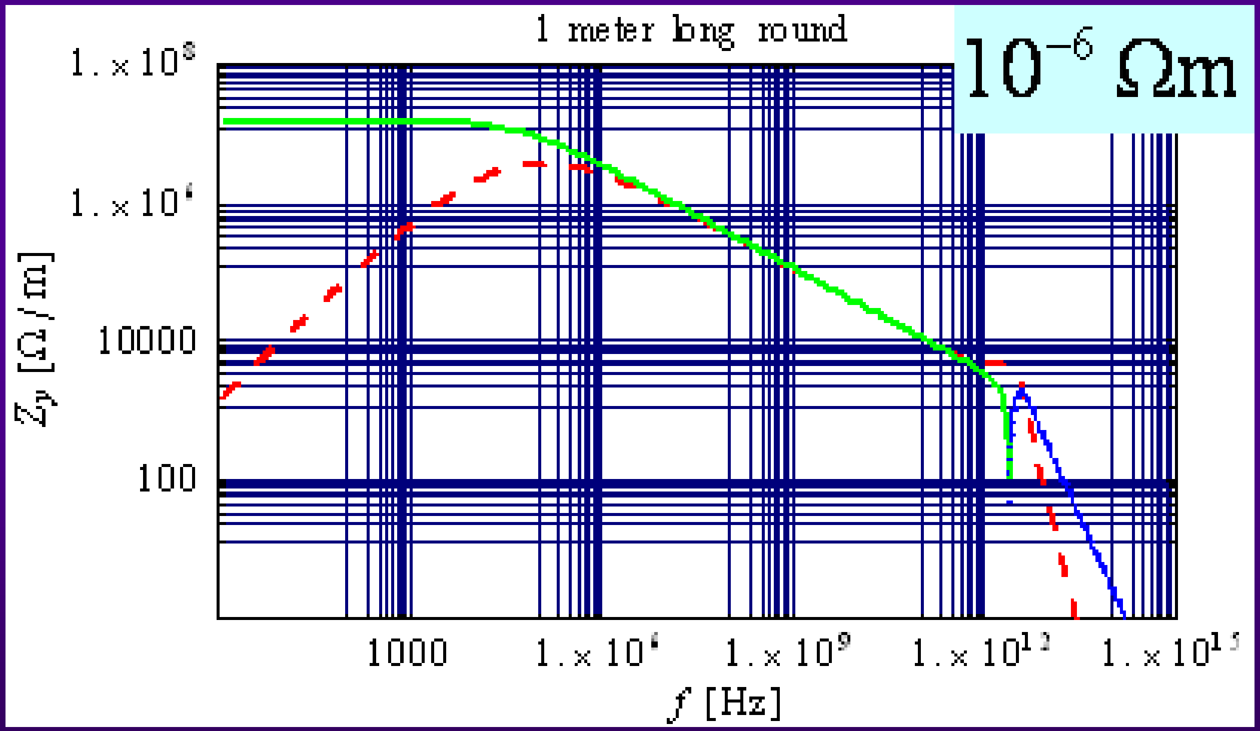
$$Z_t^{RW1}(\omega) = (1 + j)\frac{L Z_0}{\pi b^3}\frac{\mu_r}{\sqrt{2 \mu_0 \sigma \omega}}$$

$$W_t^{RW1}(\tau) = \frac{L \mu_r}{\pi^{3/2} b^3}\sqrt{\frac{c Z_0}{\sigma}} \times \frac{1}{\tau^{1/2}}$$

STUDIES ONGOING FOR A CERAMIC COLLIMATOR (1/10)

ANALYTICAL PREDICTIONS

$\Longrightarrow$ **Scan in resistivity ρ from 10^{-6} to 10^{20} Ωm and** $\varepsilon_r = 5$

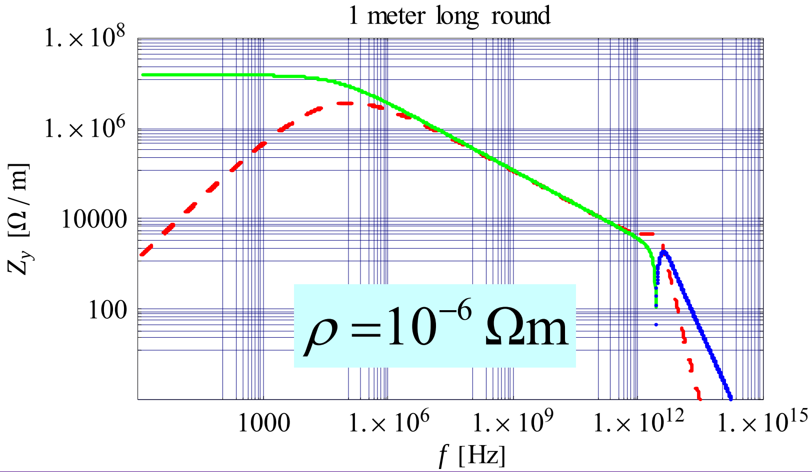


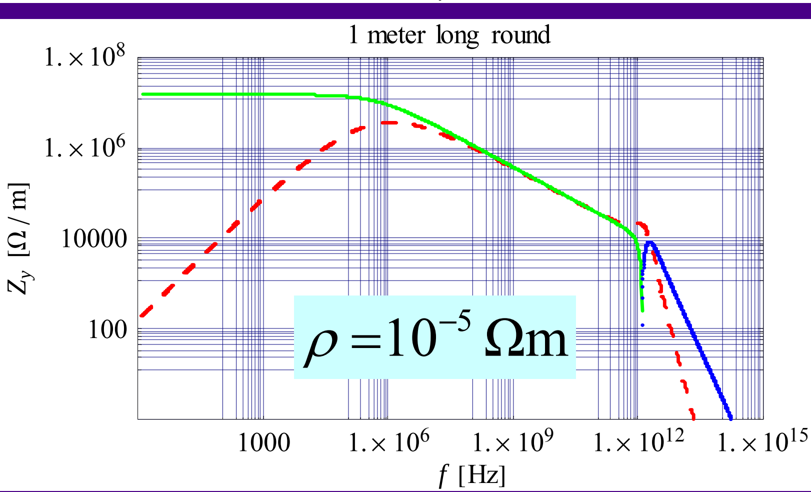
$f_{\text{1st peak}} \propto \rho$

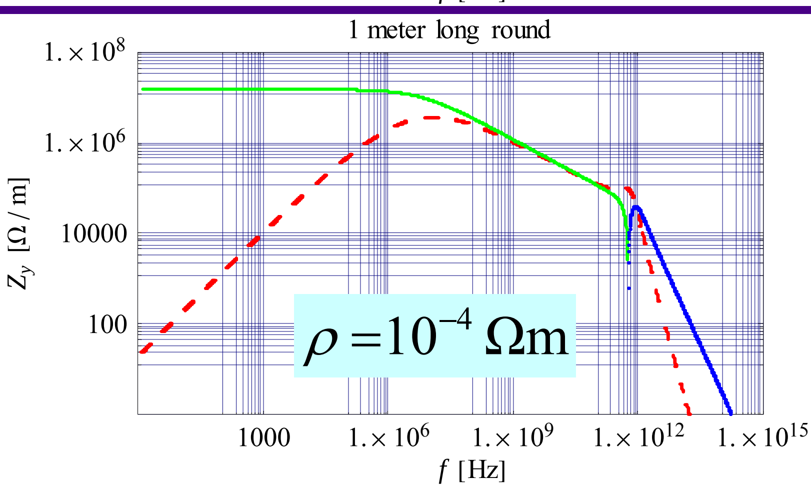
$f_{\text{2nd peak}} \propto 1/\rho$

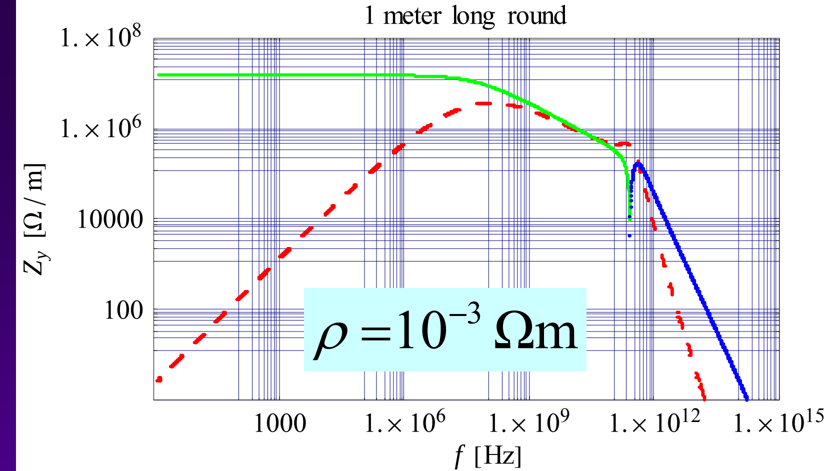
$\varepsilon_r = 5$

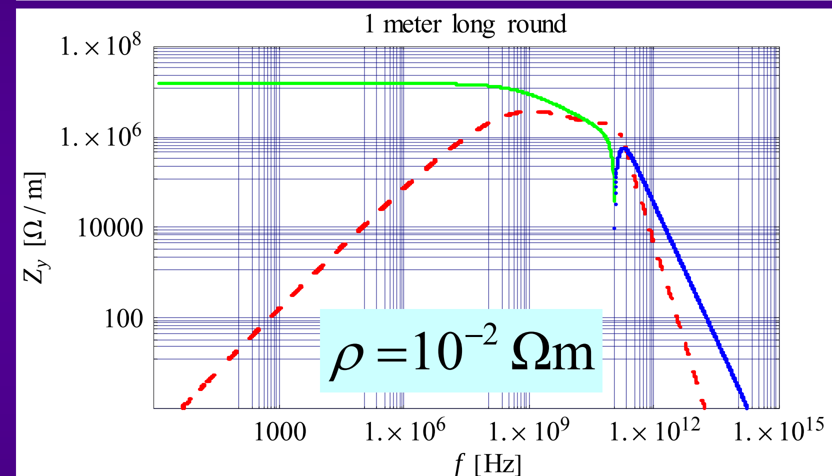
(2/10)

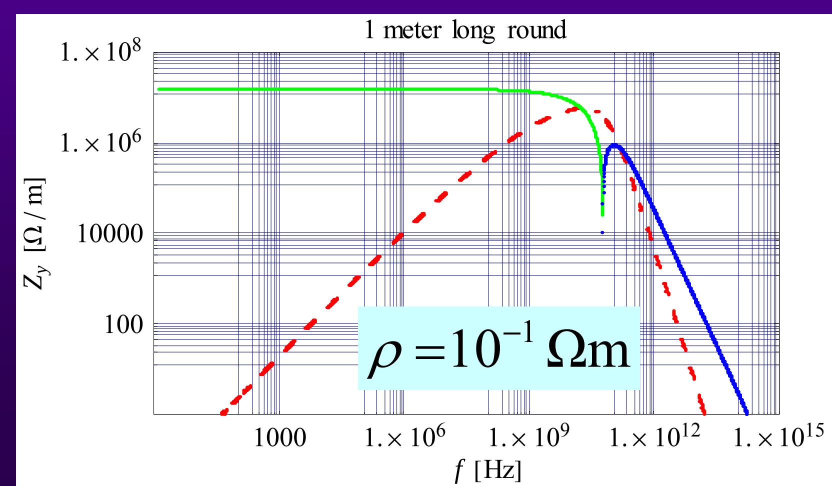




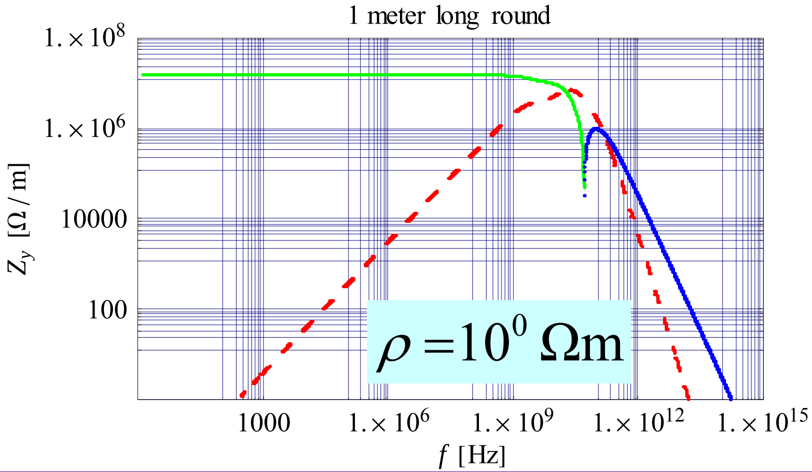


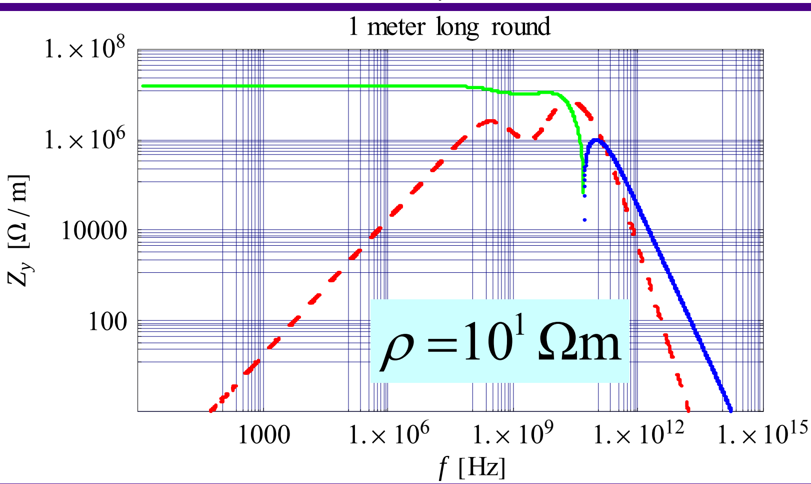


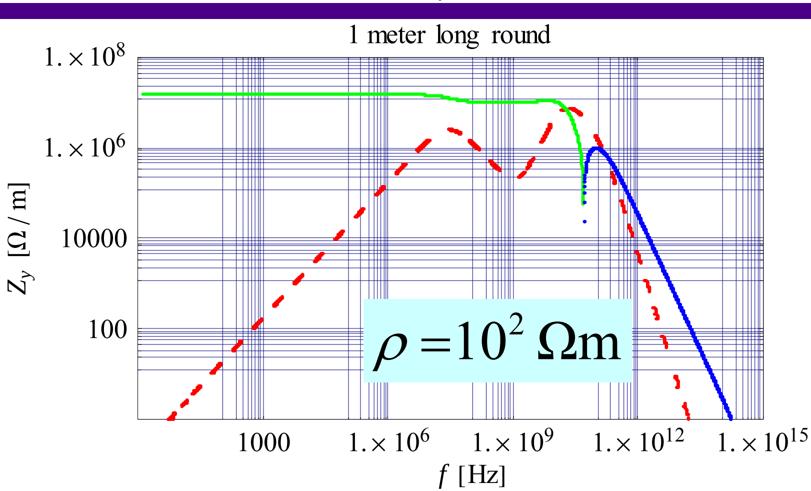


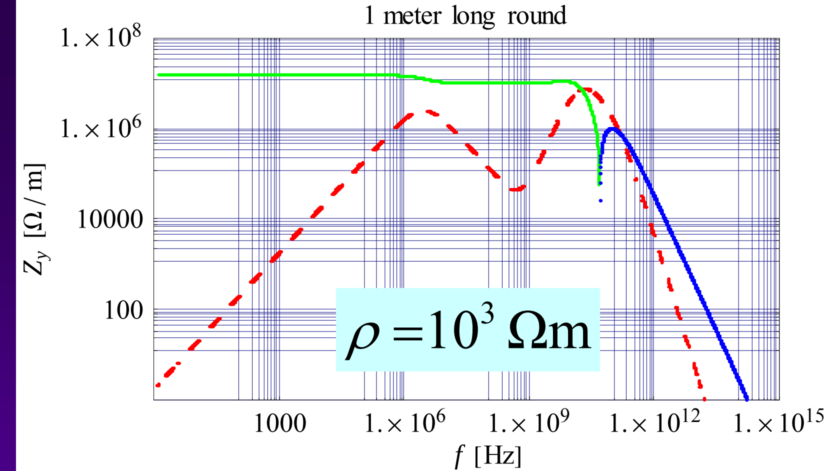


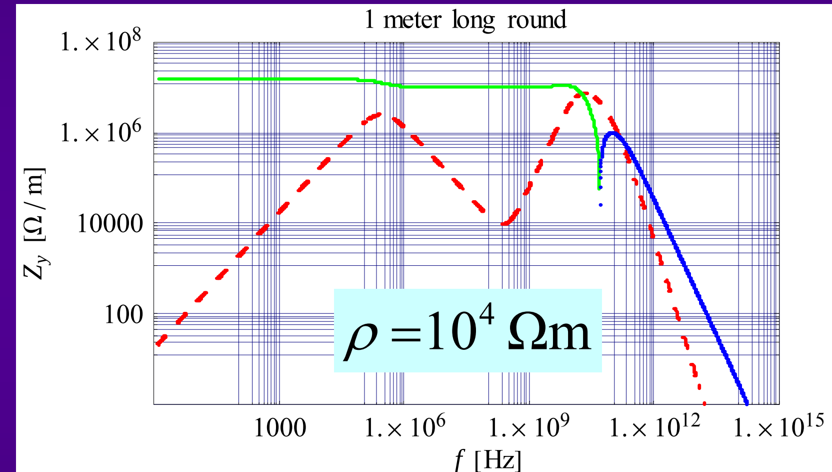
(3/10)

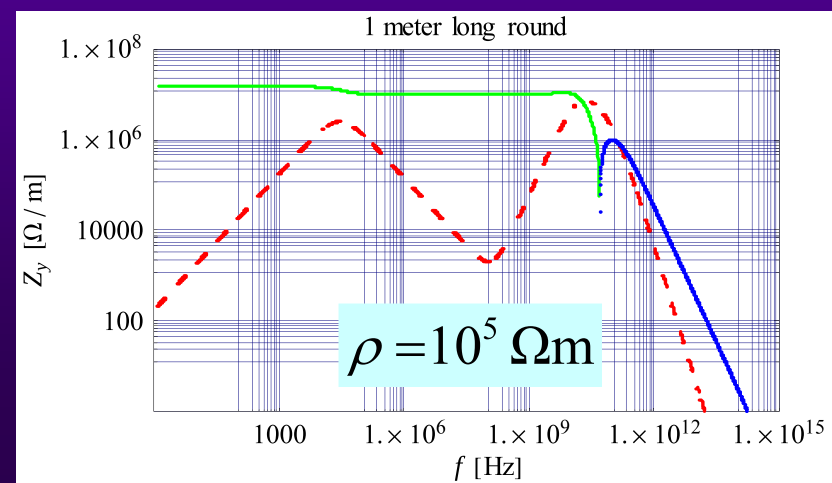

1 meter long round
1. × 10^8
1. × 10^6
10000
100
Z_y [Ω / m]
1000
1. × 10^6
1. × 10^9
1. × 10^12
1. × 10^15
f [Hz]
ρ = 10^0 Ωm


1 meter long round
1. × 10^8
1. × 10^6
10000
100
Z_y [Ω / m]
1000
1. × 10^6
1. × 10^9
1. × 10^12
1. × 10^15
f [Hz]
ρ = 10^1 Ωm

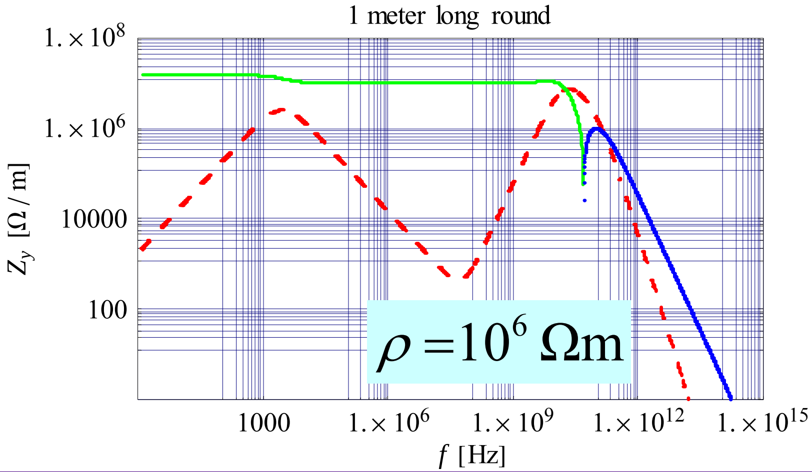

1 meter long round
1. × 10^8
1. × 10^6
10000
100
Z_y [Ω / m]
1000
1. × 10^6
1. × 10^9
1. × 10^12
1. × 10^15
f [Hz]
ρ = 10^2 Ωm

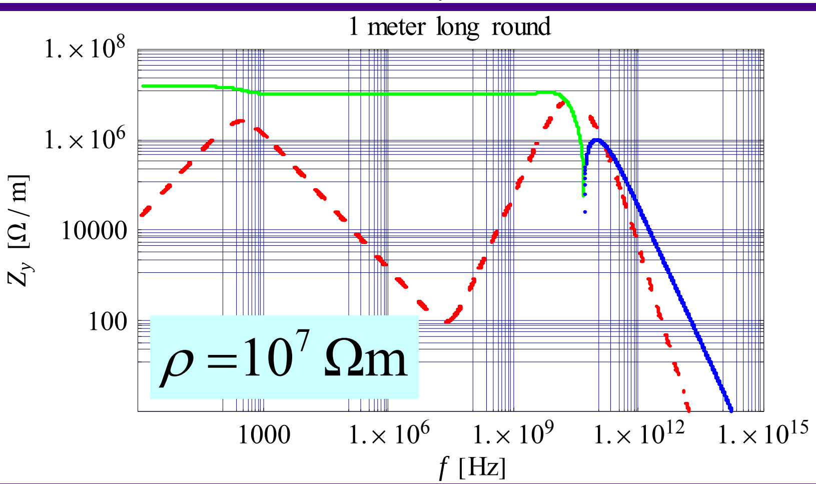

1 meter long round
1. × 10^8
1. × 10^6
10000
100
Z_y [Ω / m]
1000
1. × 10^6
1. × 10^9
1. × 10^12
1. × 10^15
f [Hz]
ρ = 10^3 Ωm

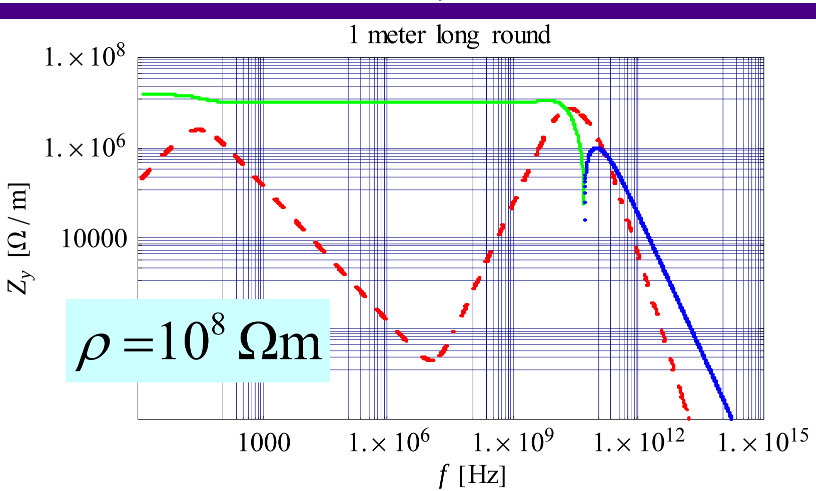

1 meter long round
1. × 10^8
1. × 10^6
10000
100
Z_y [Ω / m]
1000
1. × 10^6
1. × 10^9
1. × 10^12
1. × 10^15
f [Hz]
ρ = 10^4 Ωm

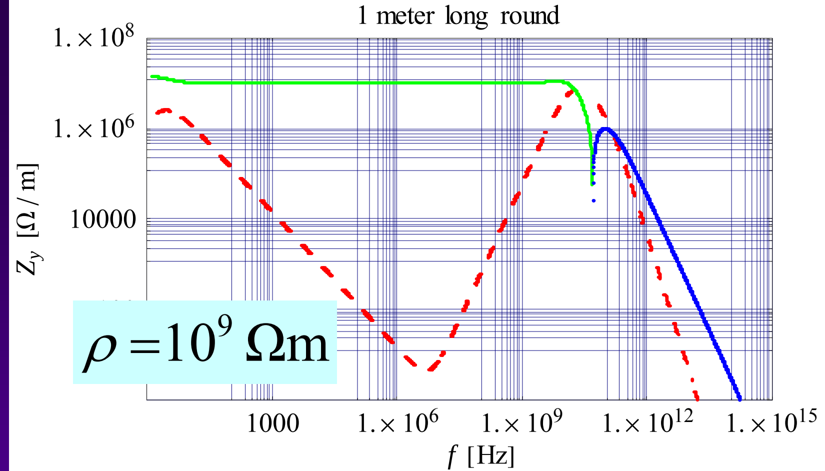

1 meter long round
1. × 10^8
1. × 10^6
10000
100
Z_y [Ω / m]
1000
1. × 10^6
1. × 10^9
1. × 10^12
1. × 10^15
f [Hz]
ρ = 10^5 Ωm

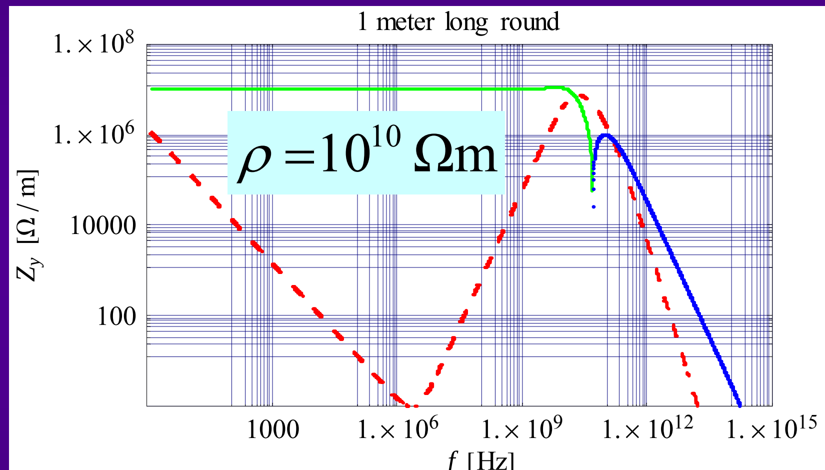
(4/10)

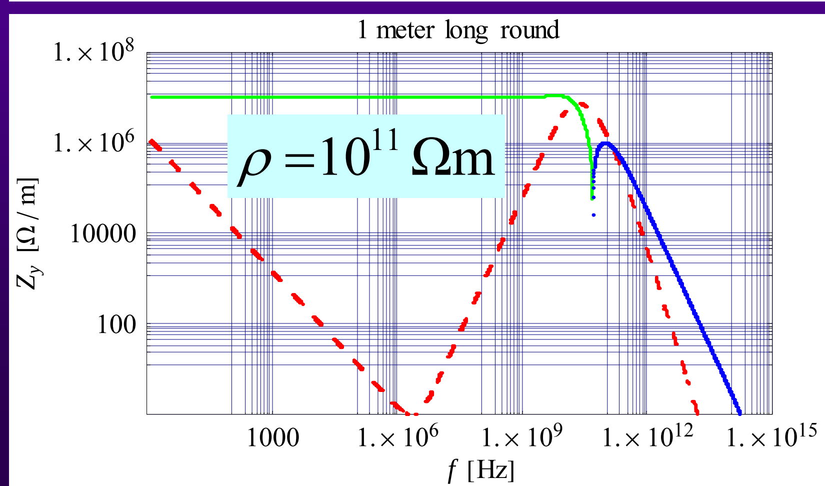

1 meter long round
$1.\times10^{8}$
$1.\times10^{6}$
10000
100
Z_y [Ω / m]
1000
$1.\times10^{6}$
$1.\times10^{9}$
$1.\times10^{12}$
$1.\times10^{15}$
f [Hz]
$\rho = 10^{6}\ \Omega\text{m}$

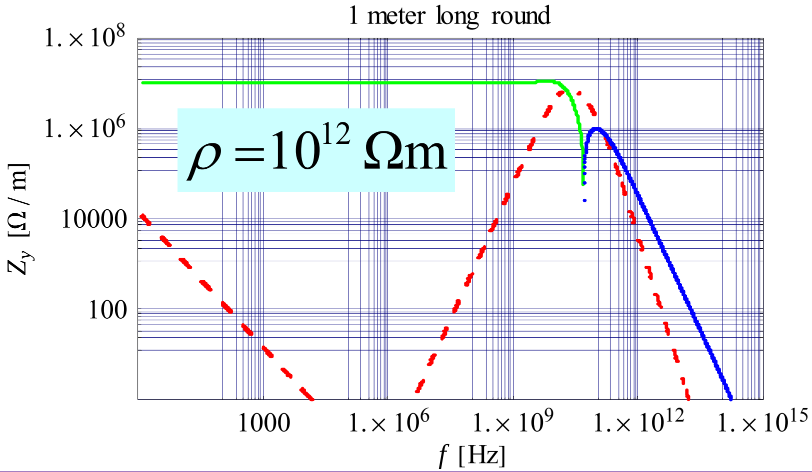

1 meter long round
$1.\times10^{8}$
$1.\times10^{6}$
10000
100
Z_y [Ω / m]
1000
$1.\times10^{6}$
$1.\times10^{9}$
$1.\times10^{12}$
$1.\times10^{15}$
f [Hz]
$\rho = 10^{7}\ \Omega\text{m}$

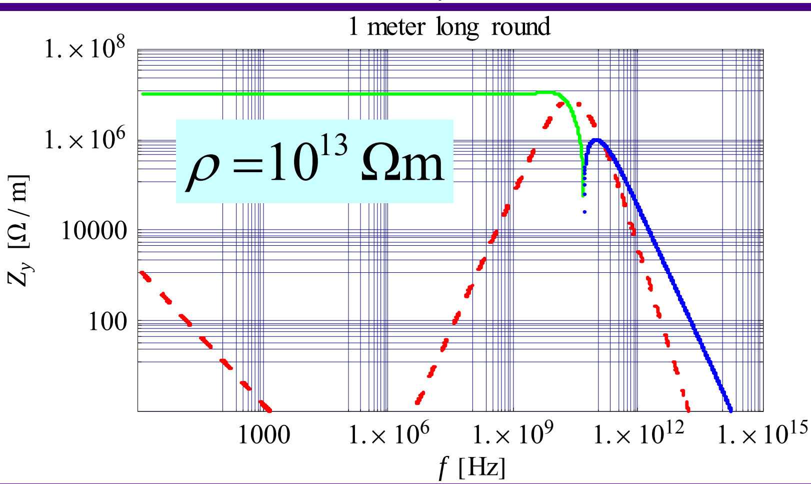

1 meter long round
$1.\times10^{8}$
$1.\times10^{6}$
10000
Z_y [Ω / m]
1000
$1.\times10^{6}$
$1.\times10^{9}$
$1.\times10^{12}$
$1.\times10^{15}$
f [Hz]
$\rho = 10^{8}\ \Omega\text{m}$

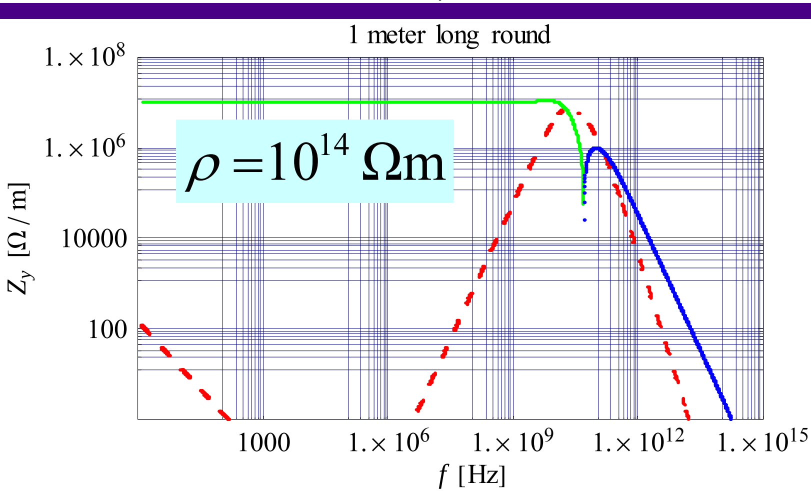

1 meter long round
$1.\times10^{8}$
$1.\times10^{6}$
10000
Z_y [Ω / m]
1000
$1.\times10^{6}$
$1.\times10^{9}$
$1.\times10^{12}$
$1.\times10^{15}$
f [Hz]
$\rho = 10^{9}\ \Omega\text{m}$


1 meter long round
$1.\times10^{8}$
$1.\times10^{6}$
10000
100
Z_y [Ω / m]
1000
$1.\times10^{6}$
$1.\times10^{9}$
$1.\times10^{12}$
$1.\times10^{15}$
f [Hz]
$\rho = 10^{10}\ \Omega\text{m}$

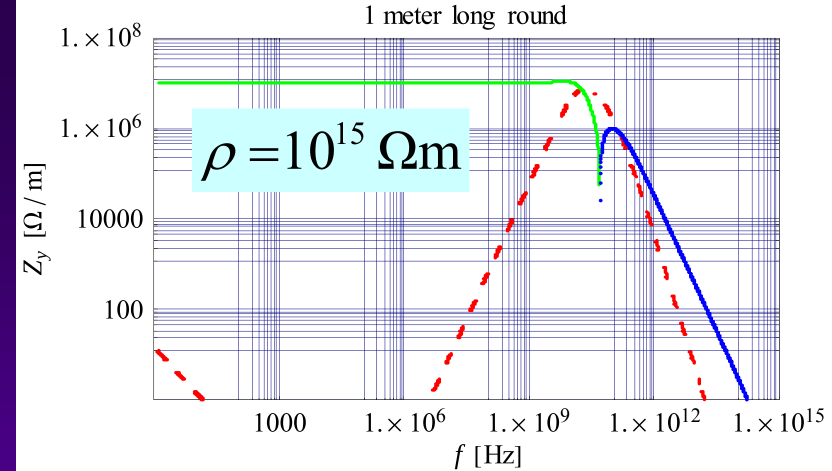

1 meter long round
$1.\times10^{8}$
$1.\times10^{6}$
10000
100
Z_y [Ω / m]
1000
$1.\times10^{6}$
$1.\times10^{9}$
$1.\times10^{12}$
$1.\times10^{15}$
f [Hz]
$\rho = 10^{11}\ \Omega\text{m}$

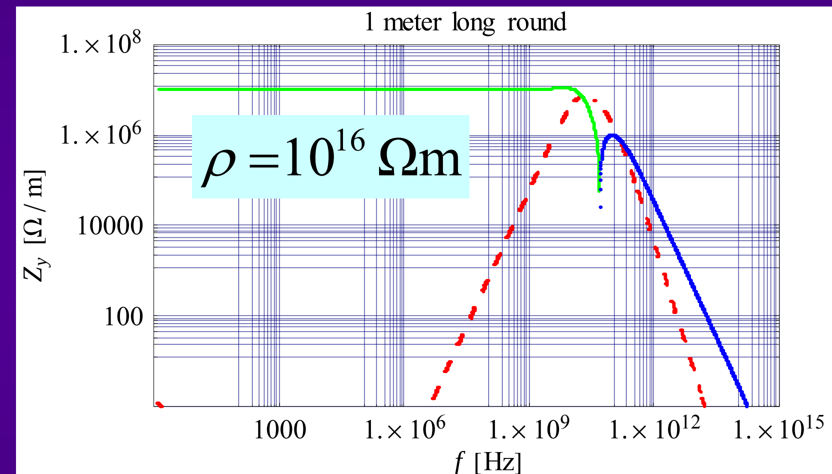

1 meter long round
$\rho = 10^{12}\ \Omega\text{m}$
Z_y [Ω / m]
1. × 10^8
1. × 10^6
10000
100
1000
1. × 10^6
1. × 10^9
1. × 10^12
1. × 10^15
f [Hz]

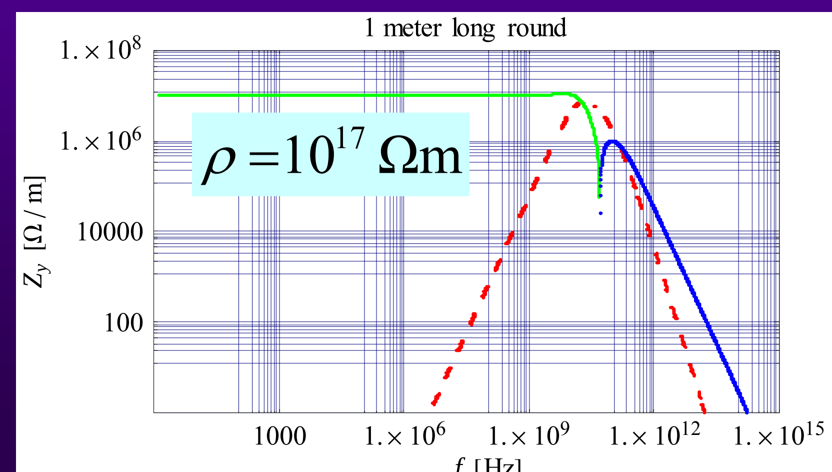

1 meter long round
$\rho = 10^{13}\ \Omega\text{m}$
Z_y [Ω / m]
1. × 10^8
1. × 10^6
10000
100
1000
1. × 10^6
1. × 10^9
1. × 10^12
1. × 10^15
f [Hz]

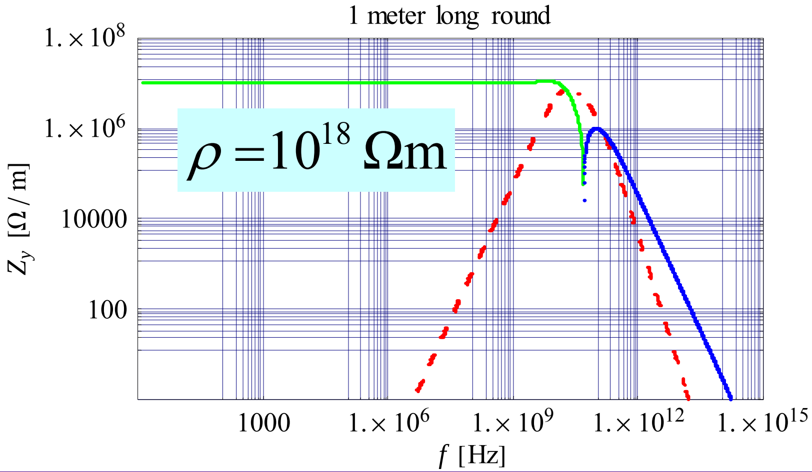

1 meter long round
$\rho = 10^{14}\ \Omega\text{m}$
Z_y [Ω / m]
1. × 10^8
1. × 10^6
10000
100
1000
1. × 10^6
1. × 10^9
1. × 10^12
1. × 10^15
f [Hz]

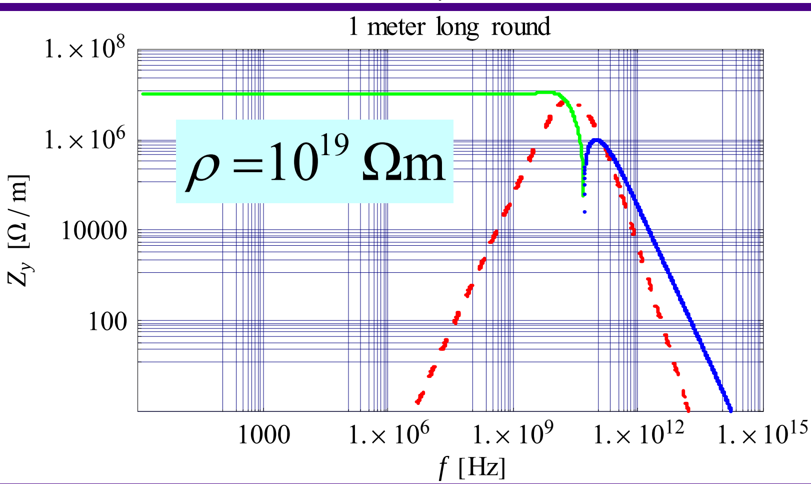
(5/10)

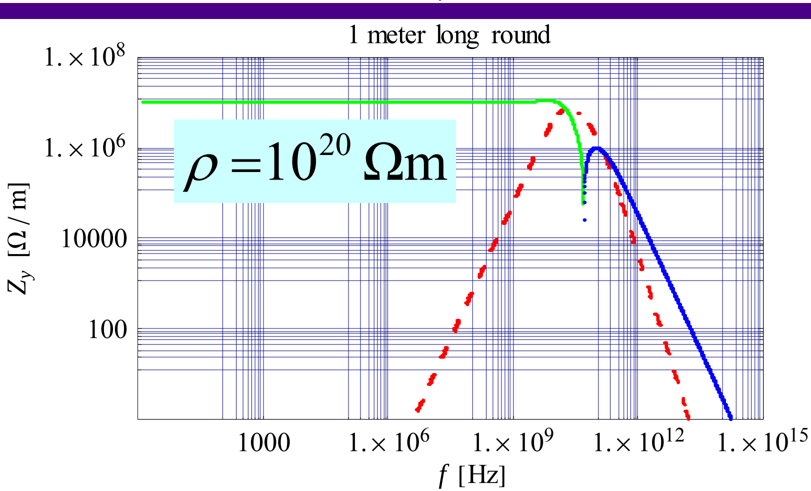

1 meter long round
$\rho = 10^{15}\ \Omega\text{m}$
Z_y [Ω / m]
1. × 10^8
1. × 10^6
10000
100
1000
1. × 10^6
1. × 10^9
1. × 10^12
1. × 10^15
f [Hz]


1 meter long round
$\rho = 10^{16}\ \Omega\text{m}$
Z_y [Ω / m]
1. × 10^8
1. × 10^6
10000
100
1000
1. × 10^6
1. × 10^9
1. × 10^12
1. × 10^15
f [Hz]


1 meter long round
$\rho = 10^{17}\ \Omega\text{m}$
Z_y [Ω / m]
1. × 10^8
1. × 10^6
10000
100
1000
1. × 10^6
1. × 10^9
1. × 10^12
1. × 10^15
f [Hz]


1 meter long round
$\rho = 10^{18}\ \Omega\text{m}$
$1.\times10^{8}$
$1.\times10^{6}$
10000
100
$Z_y\ [\Omega\ /\ \text{m}]$
1000
$1.\times10^{6}$
$1.\times10^{9}$
$1.\times10^{12}$
$1.\times10^{15}$
f [Hz]


1 meter long round
$\rho = 10^{19}\ \Omega\text{m}$
$1.\times10^{8}$
$1.\times10^{6}$
10000
100
$Z_y\ [\Omega\ /\ \text{m}]$
1000
$1.\times10^{6}$
$1.\times10^{9}$
$1.\times10^{12}$
$1.\times10^{15}$
f [Hz]

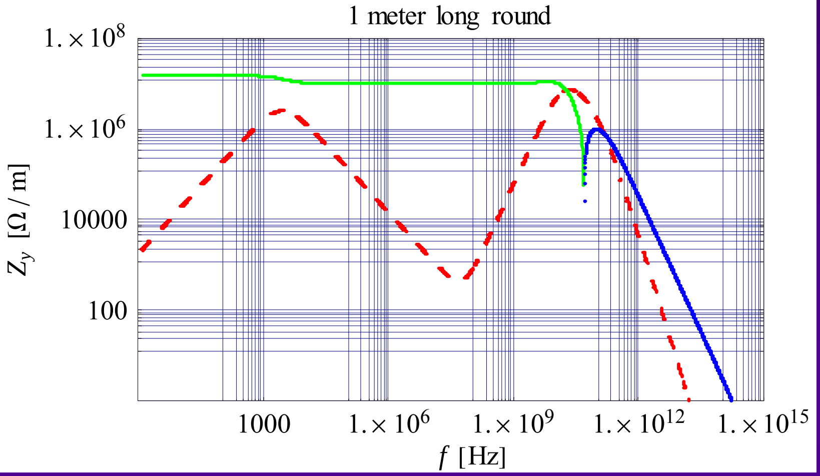

1 meter long round
$\rho = 10^{20}\ \Omega\text{m}$
$1.\times10^{8}$
$1.\times10^{6}$
10000
100
$Z_y\ [\Omega\ /\ \text{m}]$
1000
$1.\times10^{6}$
$1.\times10^{9}$
$1.\times10^{12}$
$1.\times10^{15}$
f [Hz]

(6/10)

STUDIES ONGOING FOR A CERAMIC COLLIMATOR (7/10)

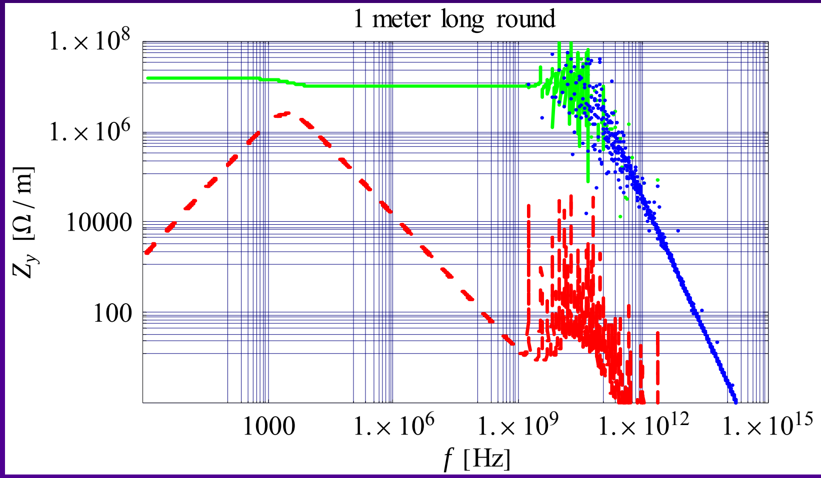
$\rho = 10^6\ \Omega\text{m}$

1 layer of infinite thickness

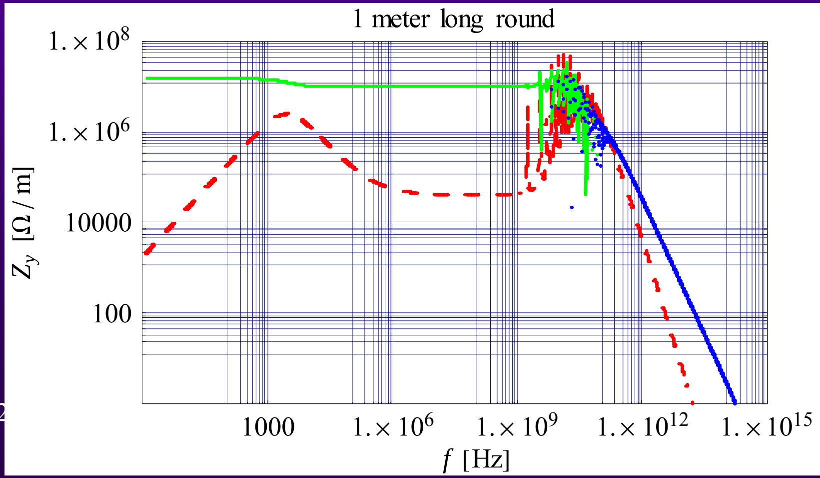


$\varepsilon_r = 5$

1 layer of thickness 2.5 cm and then Perfect Conductor



1 layer of thickness 2.5 cm and then Perfect Conductor + $\varepsilon_r = 5 \times \left[1 - j \tan\left(0.01\right)\right]$



Lossy dielectric

STUDIES ONGOING FOR A CERAMIC COLLIMATOR (8/10)

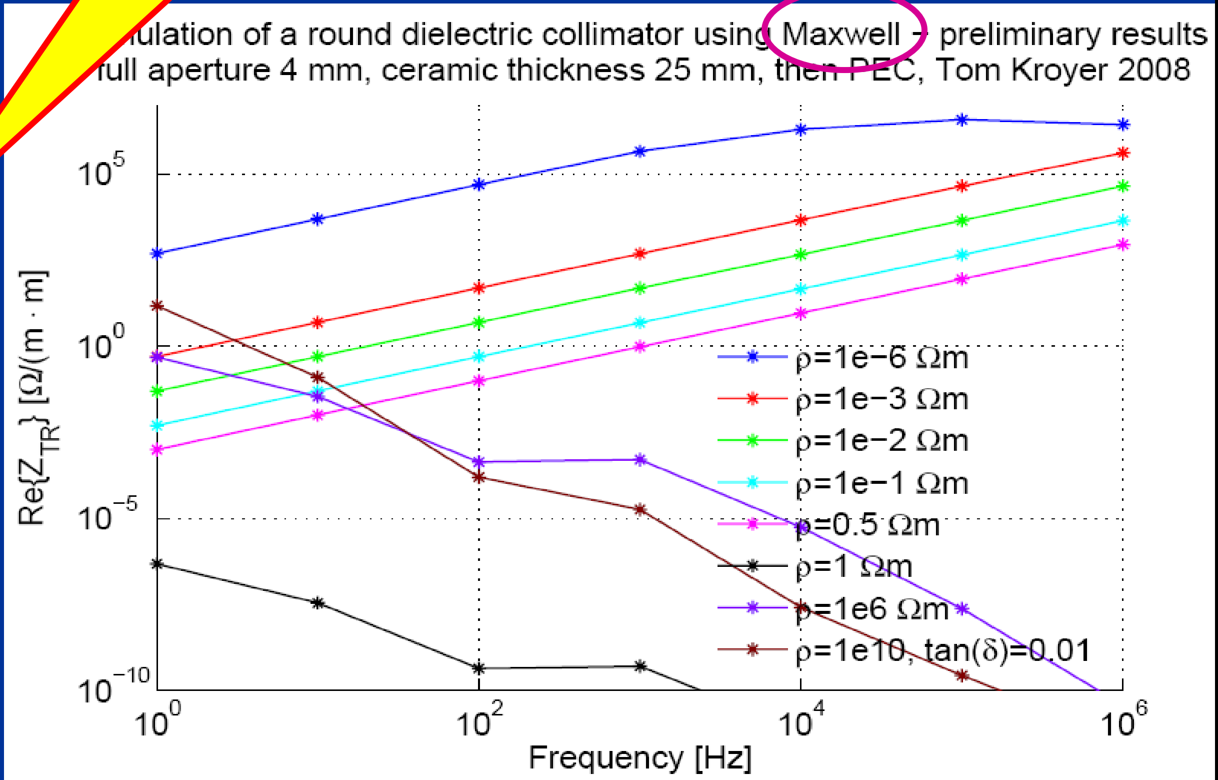
SIMULATIONS

Dielectric collimator - Results

Typo ⟹ "below"

Typo ⟹ "above"

- Data for resistivities above 1 Ohm*m in agreement with Elias' calculations
- For resistivities below 1 Ohm*m no reasonable results obtained so far

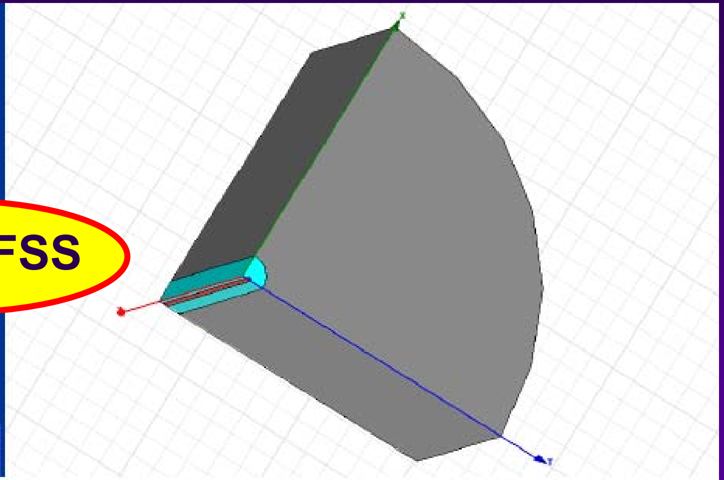


STUDIES ONGOING FOR A CERAMIC COLLIMATOR (9/10)

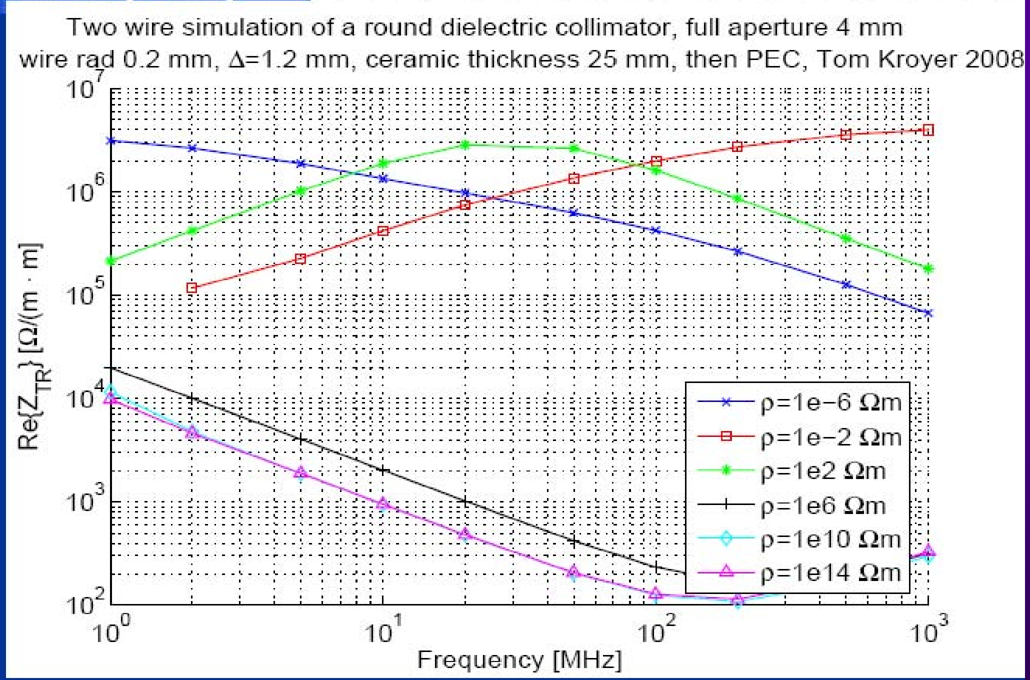
Dielectric collimator – HF Results

- Scan over resistivities rho=1e-6 to 1e14 Ohm*m
- Rotational symmetry, full beam aperture: 4 mm, dielectric thickness 23 mm, then PEC, eps_r=5, two wires with 0.4 mm diameter, spaced by 1.2 mm, structure length 5 mm
- Very good agreement with analytical results from Elias found up to 1e6 Ohm*m
- The peak at ~20 MHz for rho=1e2 Ohm*m was confirmed
- For higher resistivities (rho >= 1e10 Ohm*m) convergence not very good

With HFSS



Re(ZTR)

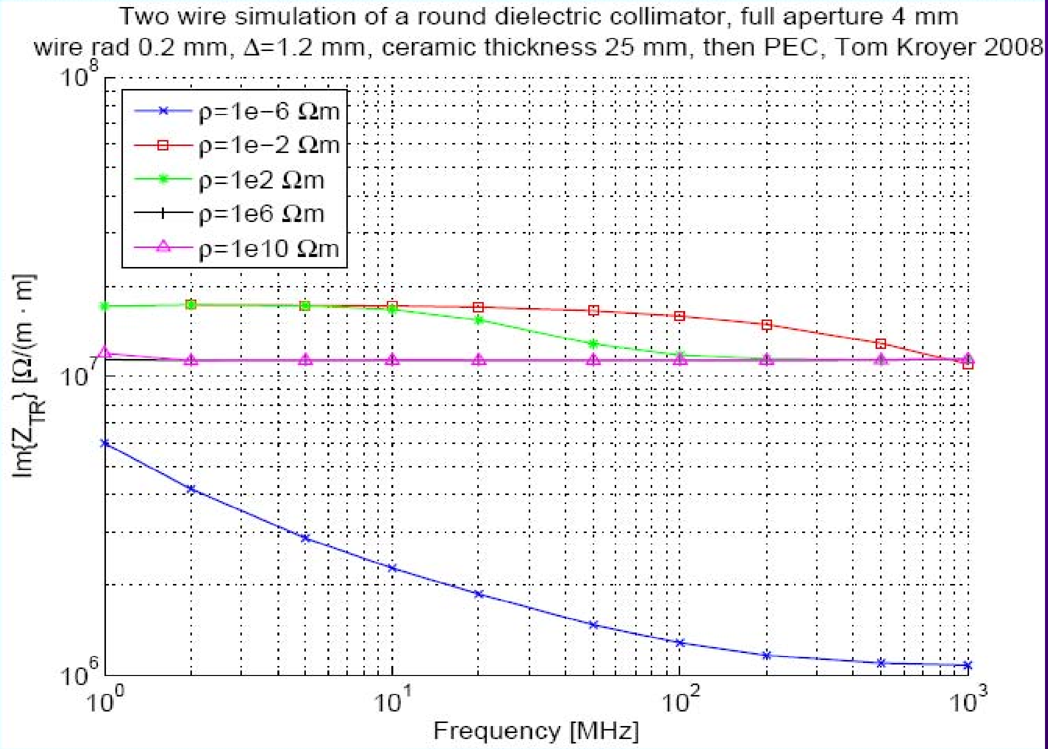


STUDIES ONGOING FOR A CERAMIC COLLIMATOR (10/10)

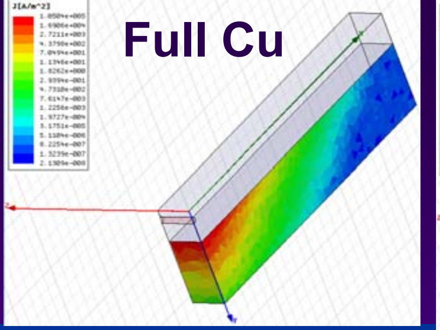
Dielectric collimator - HF Results

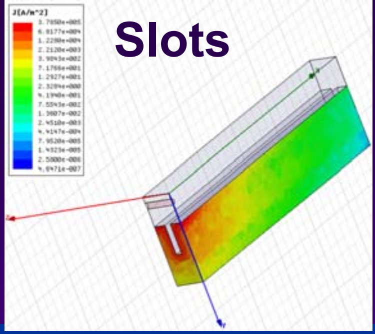
- The imaginary part of the transverse impedance also agrees well with the analytic results, except for rho=1e6 Ohm*m.

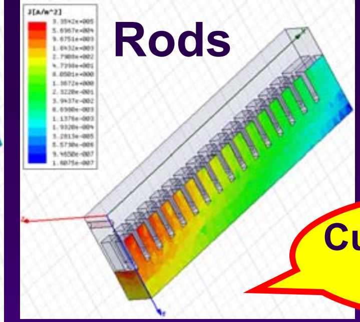
Im(ZTR)



NEWS ABOUT COLLIMATOR WITH SLOTS & RODS

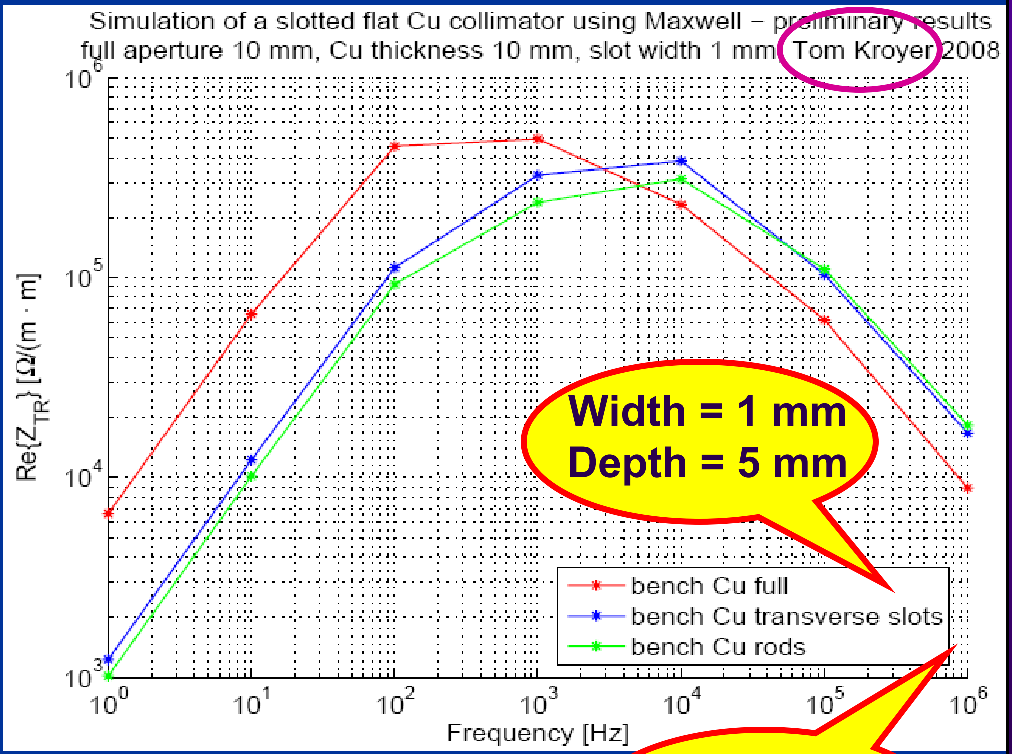






Collimator with slots and rods - ZTR

- A full Cu collimator compared to 5 mm deep slots and 5 mm long rods.
- Slots and rods have about the same impedance
- At low frequencies (<3 kHz) Re(ZTR) of rods and slots is smaller than of a full copper jaw, because the currents are forced to flow farther from the surface
- At larger frequencies Re(ZTR) is larger due to the longer path the current have to follow. Im(ZTR) should be increased at all frequencies
- Rods and slots act similar as a material with larger resistivity



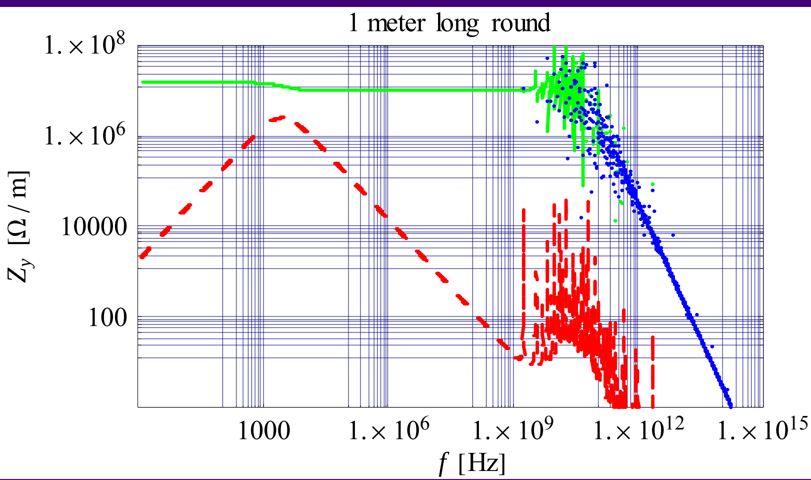
MEASUREMENTS

- **Preliminary measurements with the nail board ("planche a clous") from Fritz were performed by Benoit and Federico $\Longrightarrow$ Data still to be analyzed, but it seems to behave as anticipated by Fritz (low impedance at low frequency)…**

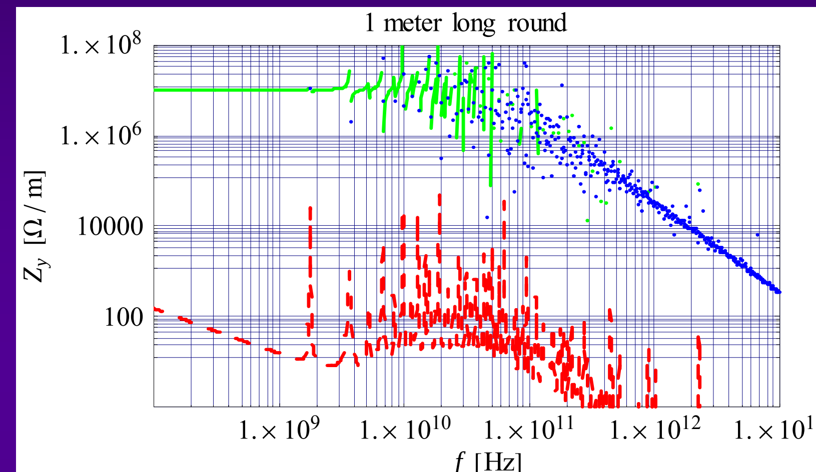
MORE DETAILED ANALYSIS OF THE THEORETICAL PREDICTIONS AT HIGH FREQUENCY (1/6)

1 layer of thickness 2.5 cm and then Perfect Conductor (PC)

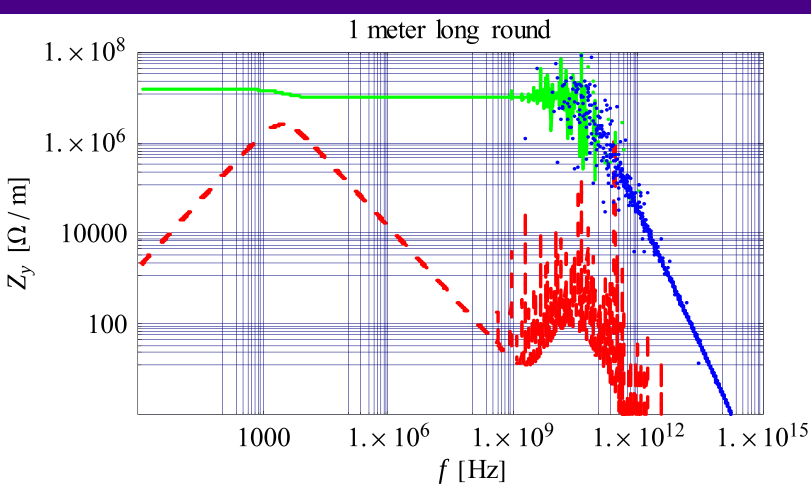
$\rho = 10^6\ \Omega\mathrm{m}$ $\varepsilon_r = 5$



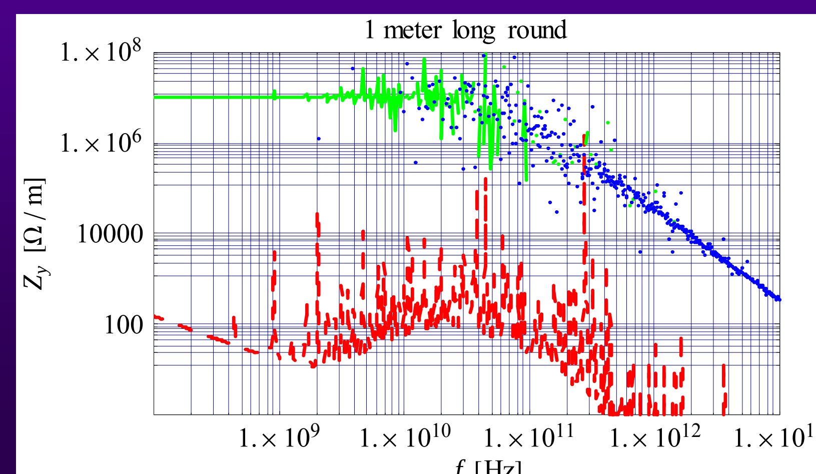
$\Longrightarrow$ **Zoom**



1 layer of thickness 10 cm and then PC

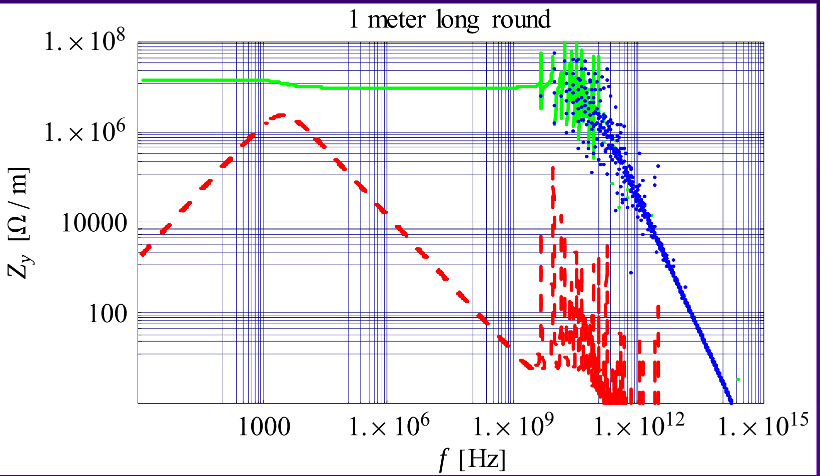


$\Longrightarrow$ **Zoom**

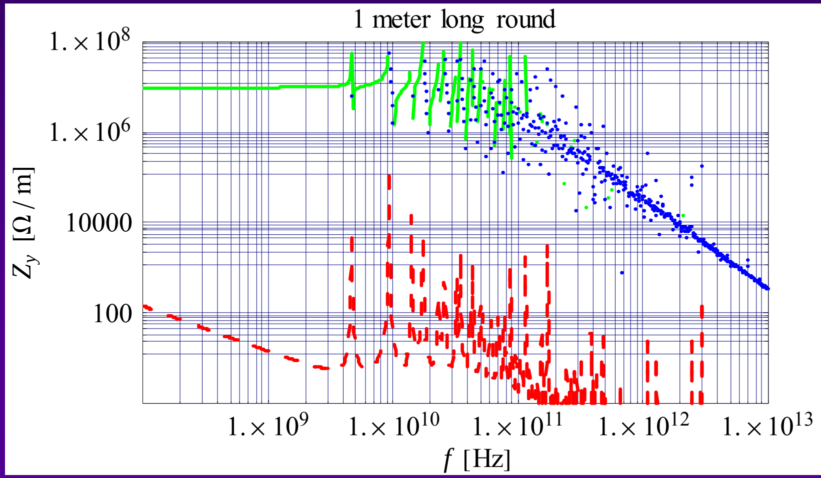


MORE DETAILED ANALYSIS OF THE THEORETICAL PREDICTIONS AT HIGH FREQUENCY (2/6)

1 layer of thickness 1 cm and then PC

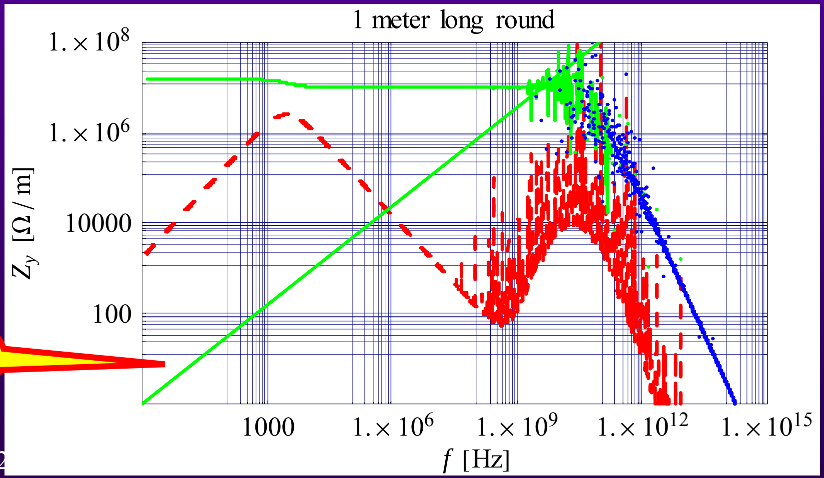


⟹ Zoom



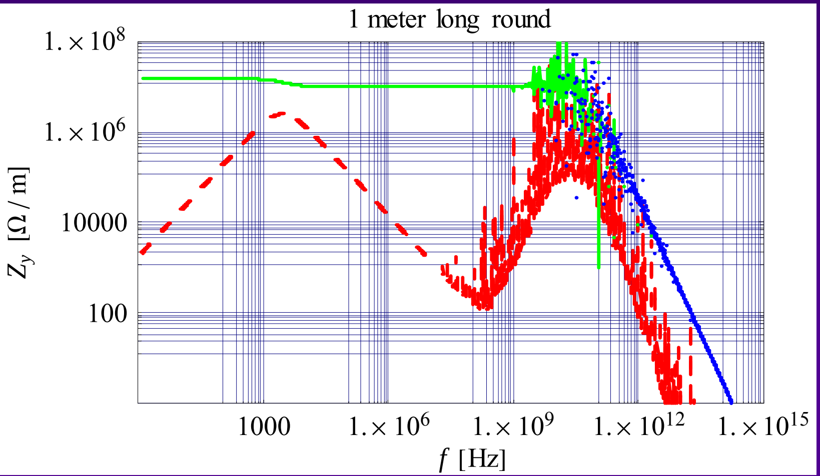
1 layer of thickness 10 m and then PC

Strange!

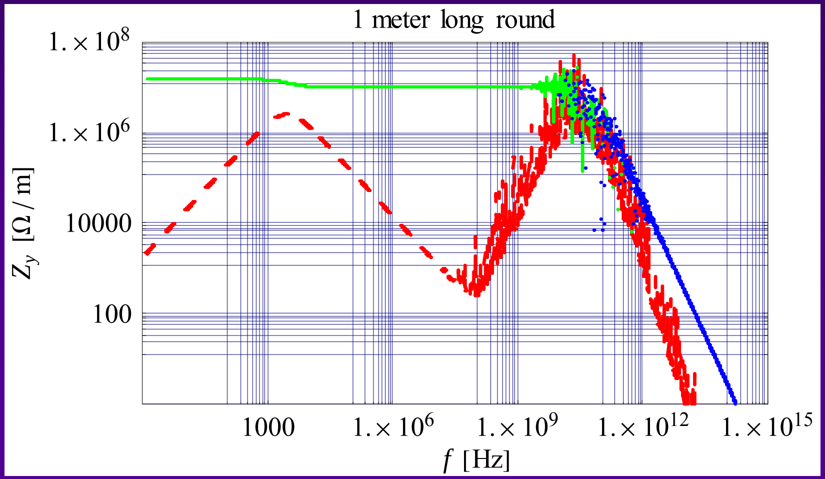


MORE DETAILED ANALYSIS OF THE THEORETICAL PREDICTIONS AT HIGH FREQUENCY (3/6)

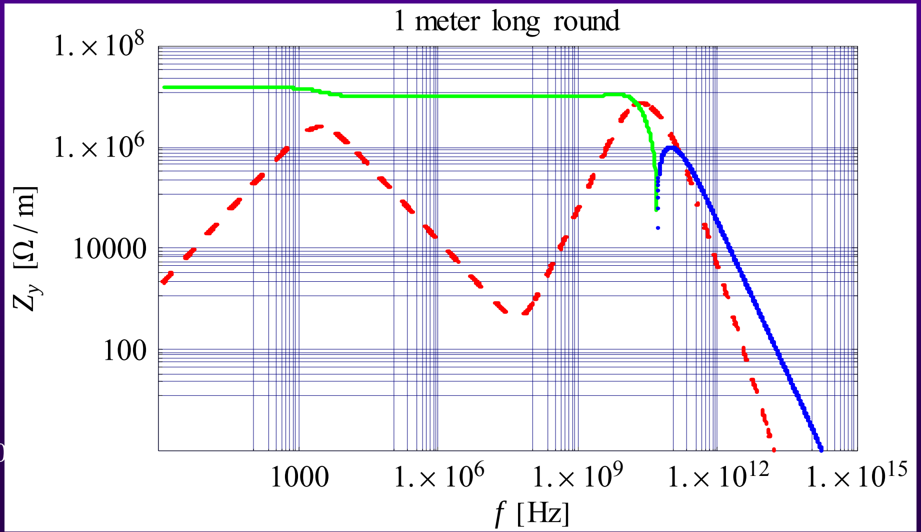
1 layer of thickness 100 m and then PC



1 layer of thickness 1000 m and then PC

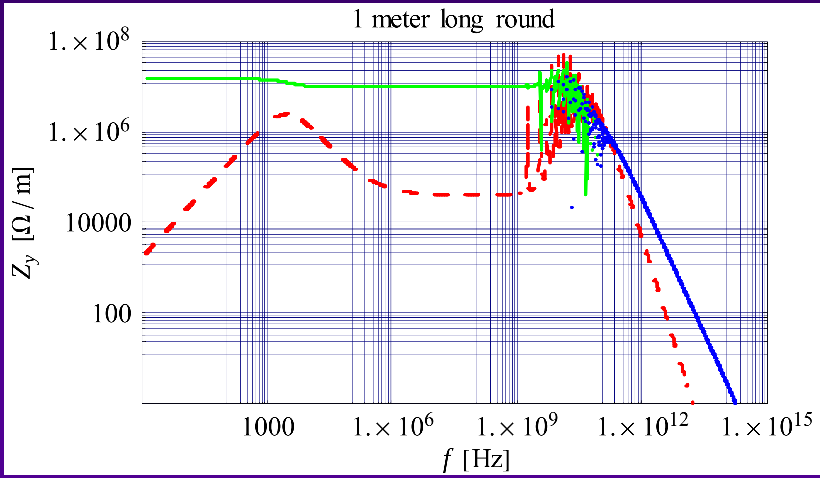


1 layer of thickness infinity



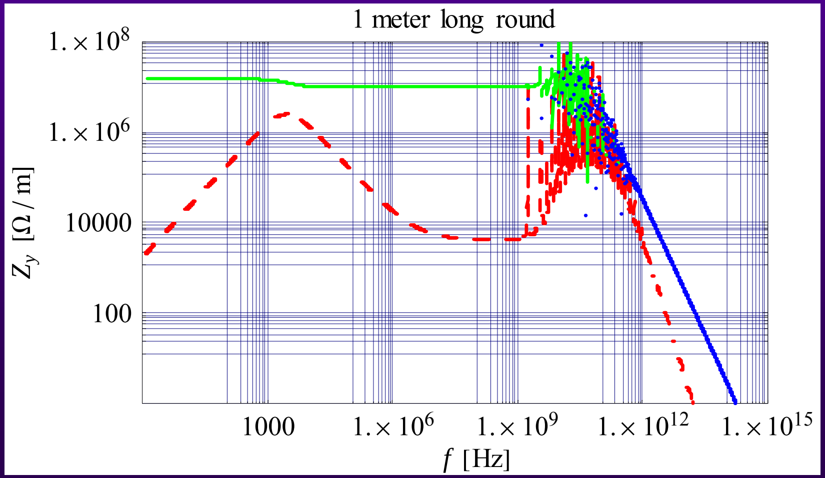
MORE DETAILED ANALYSIS OF THE THEORETICAL PREDICTIONS AT HIGH FREQUENCY (4/6)

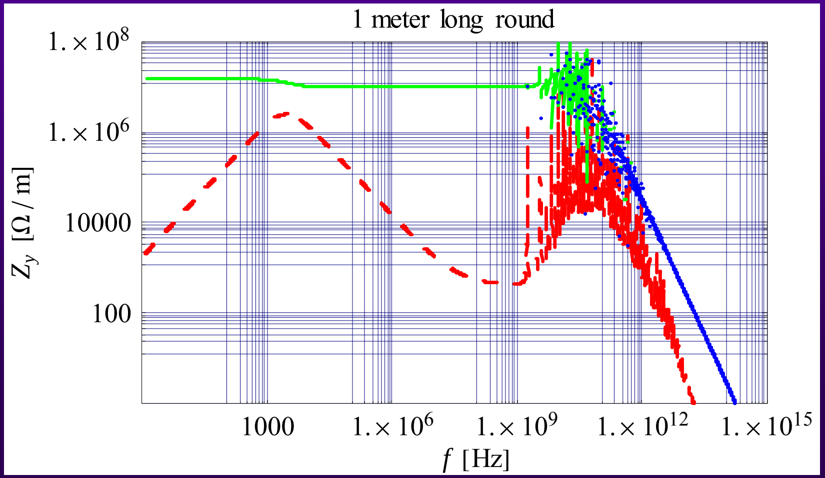
1 layer of thickness 2.5 cm and then Perfect Conductor + $\varepsilon_r = 5\times\left[1 - j\tan\left(0.01\right)\right]$



$\varepsilon_r = 5\times\left[1 - j\tan\left(0.001\right)\right]$

$\varepsilon_r = 5\times\left[1 - j\tan\left(0.0001\right)\right]$



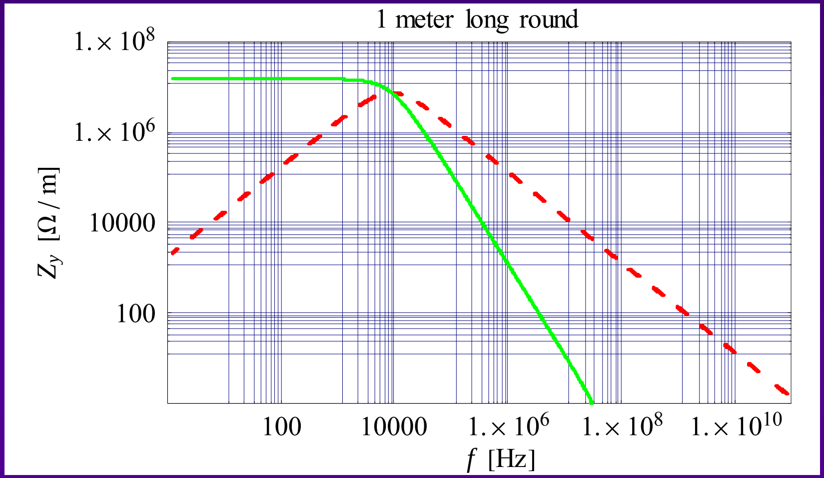


MORE DETAILED ANALYSIS OF THE THEORETICAL PREDICTIONS AT HIGH FREQUENCY (5/6)

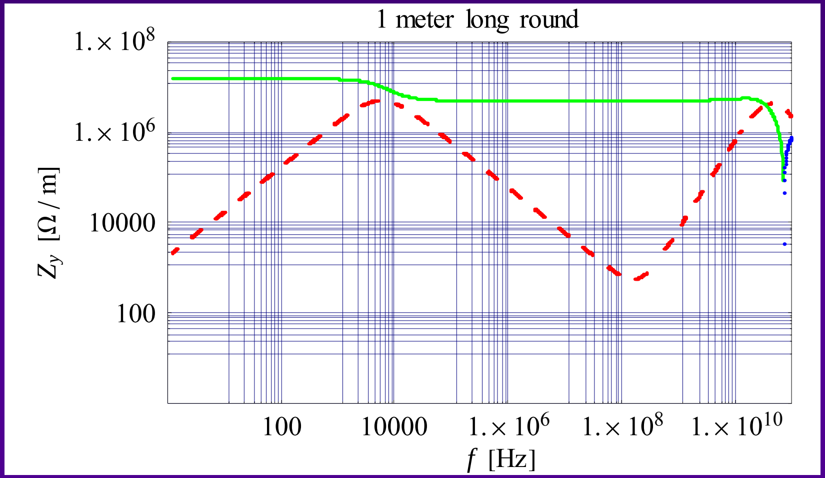
$\rho = 10^6\ \Omega\text{m}$

1 layer of thickness infinity

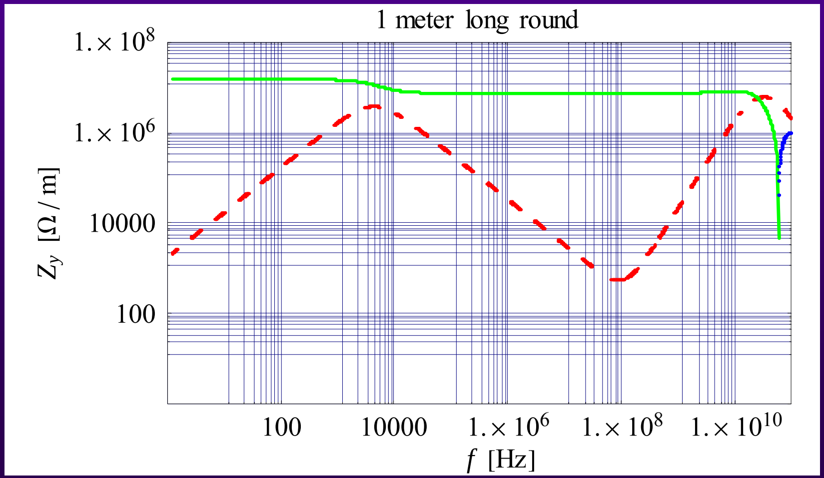
$\varepsilon_r = 1$



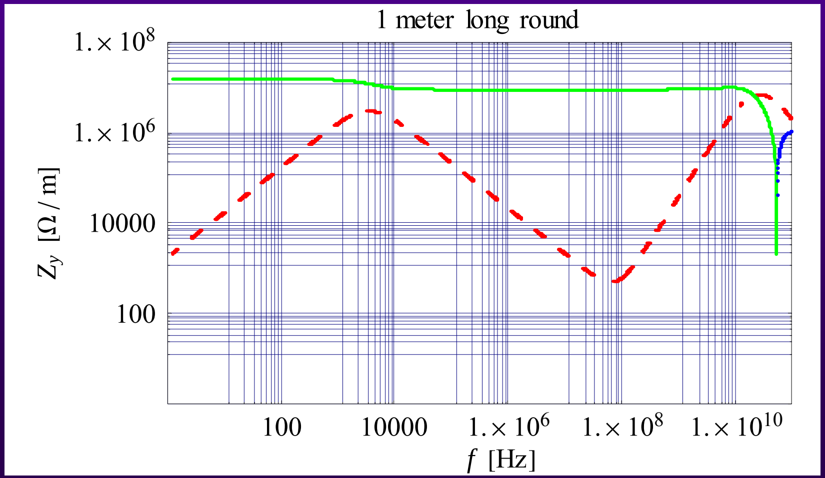
$\varepsilon_r = 2$



$\varepsilon_r = 3$



$\varepsilon_r = 4$

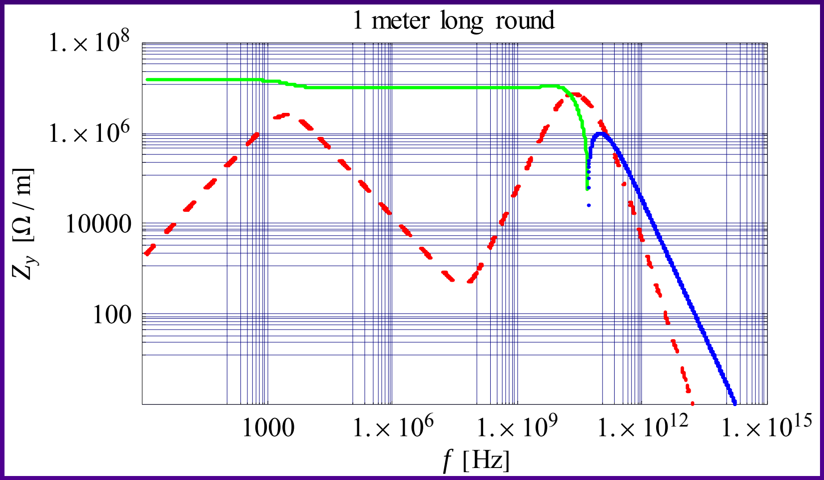


MORE DETAILED ANALYSIS OF THE THEORETICAL PREDICTIONS AT HIGH FREQUENCY (6/6)

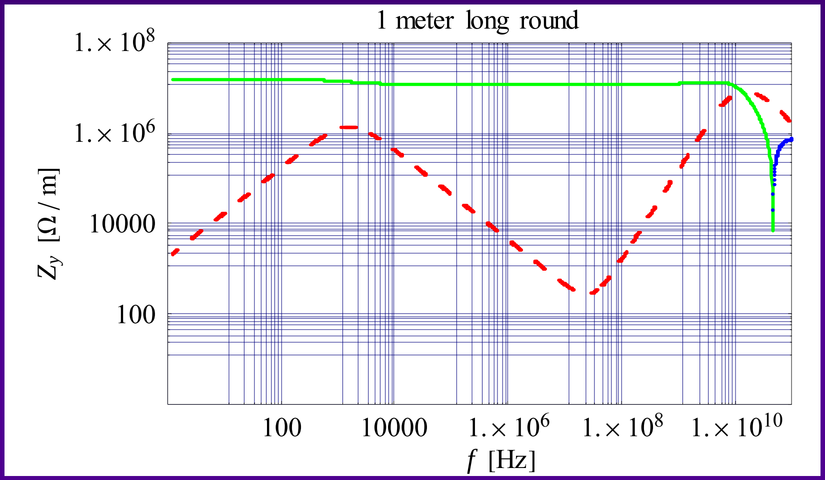
$\rho = 10^6\ \Omega\text{m}$

1 layer of thickness infinity

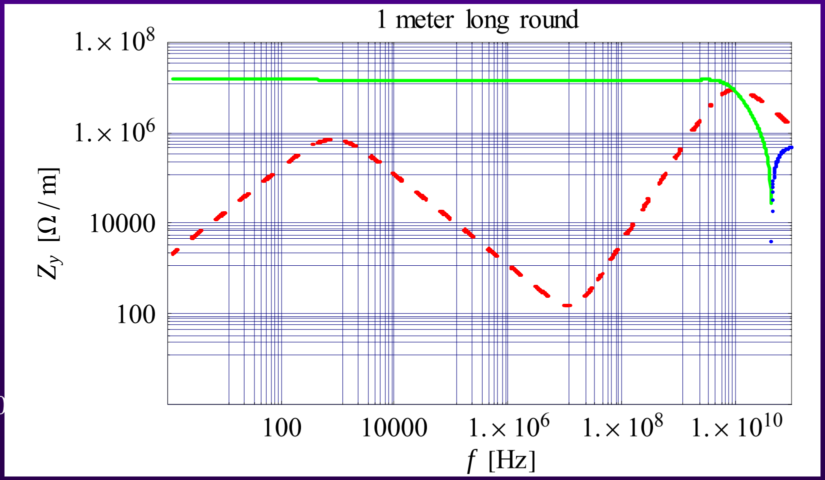
$\varepsilon_r = 5$



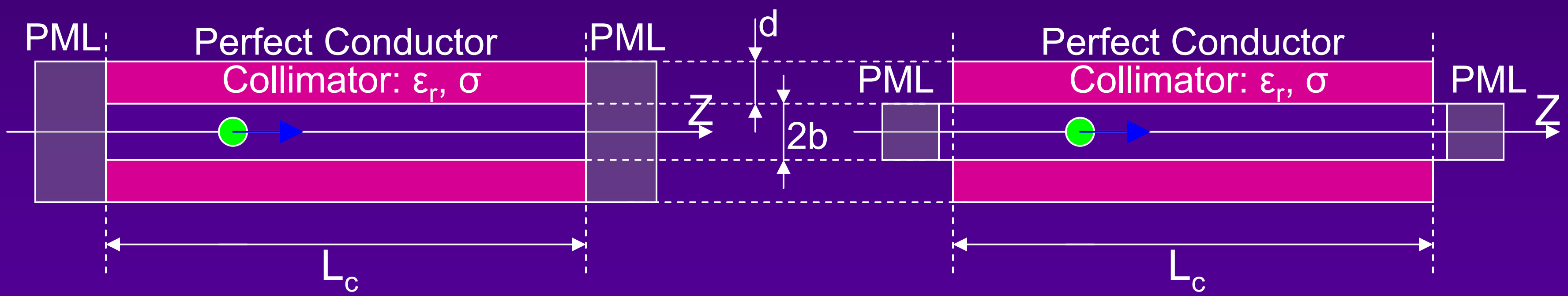
$\varepsilon_r = 10$



$\varepsilon_r = 20$

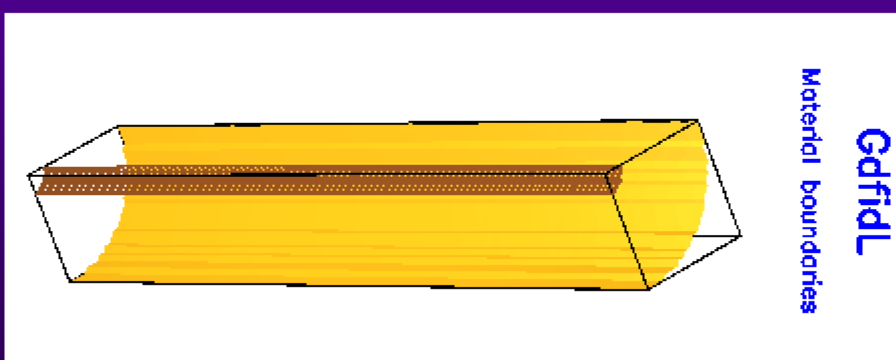


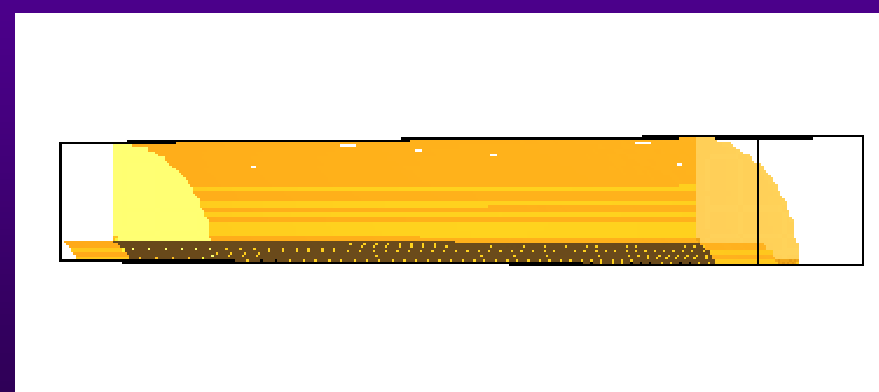
COMPARISON WITH HFSS AND GDFIDL SIMULATIONS



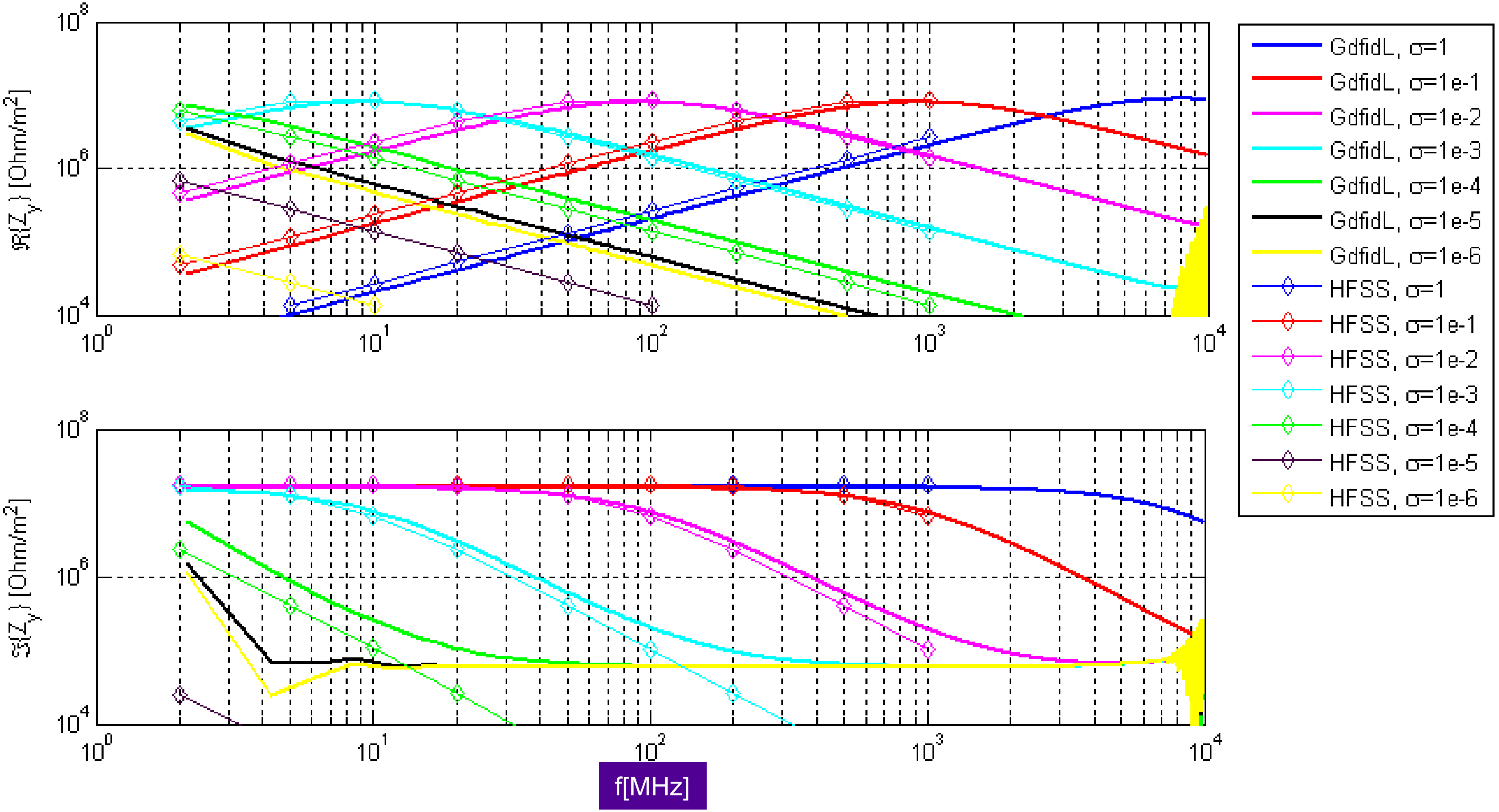
Setup 1: PML b.c.
infinitely long setup

Setup 2: Short Circuit b.c.
finite length setup



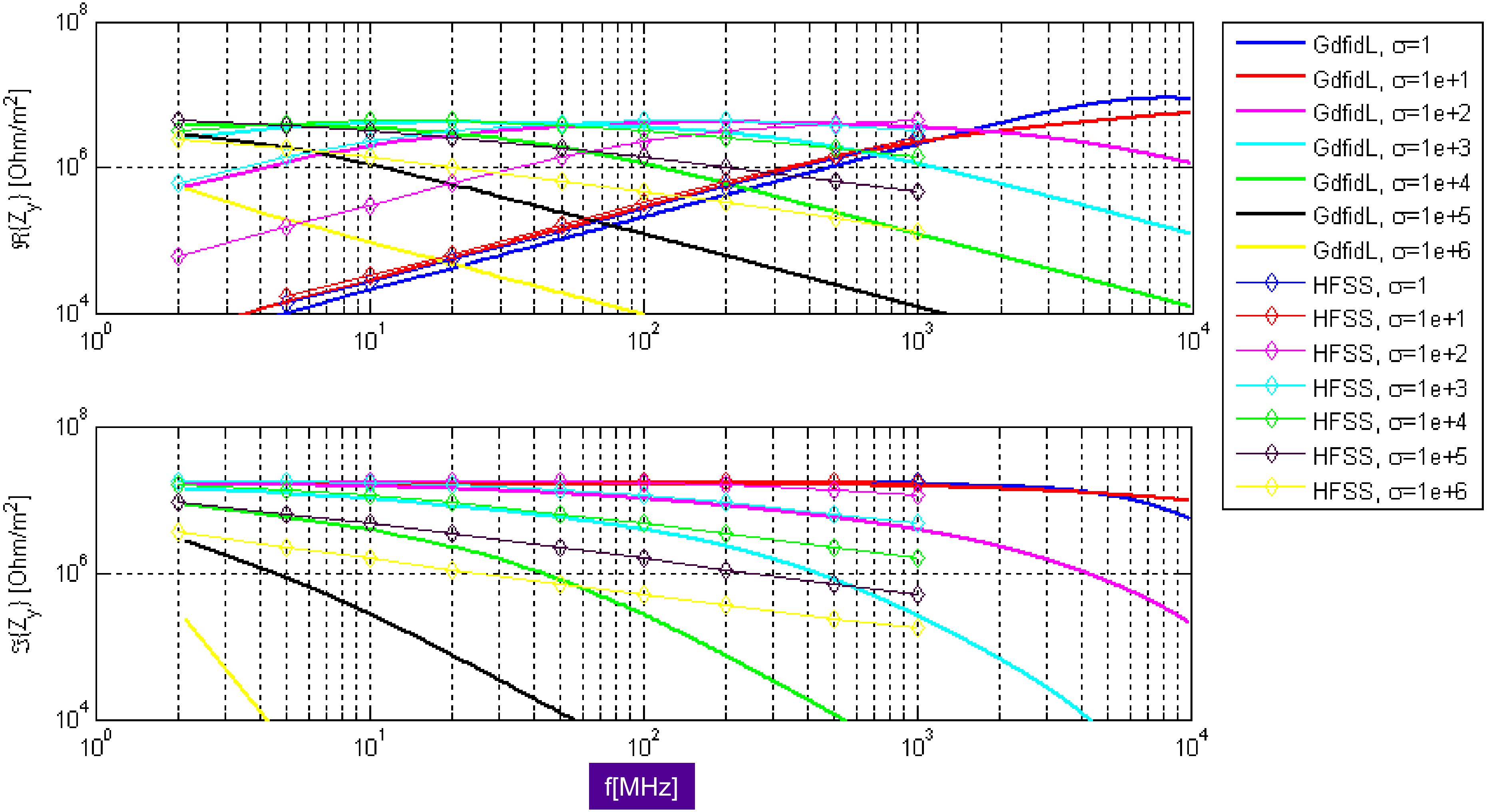


Variation of σ = 1 - 10^{-6}, ε_r = 1 , L_c= 1m, d = 10 mm



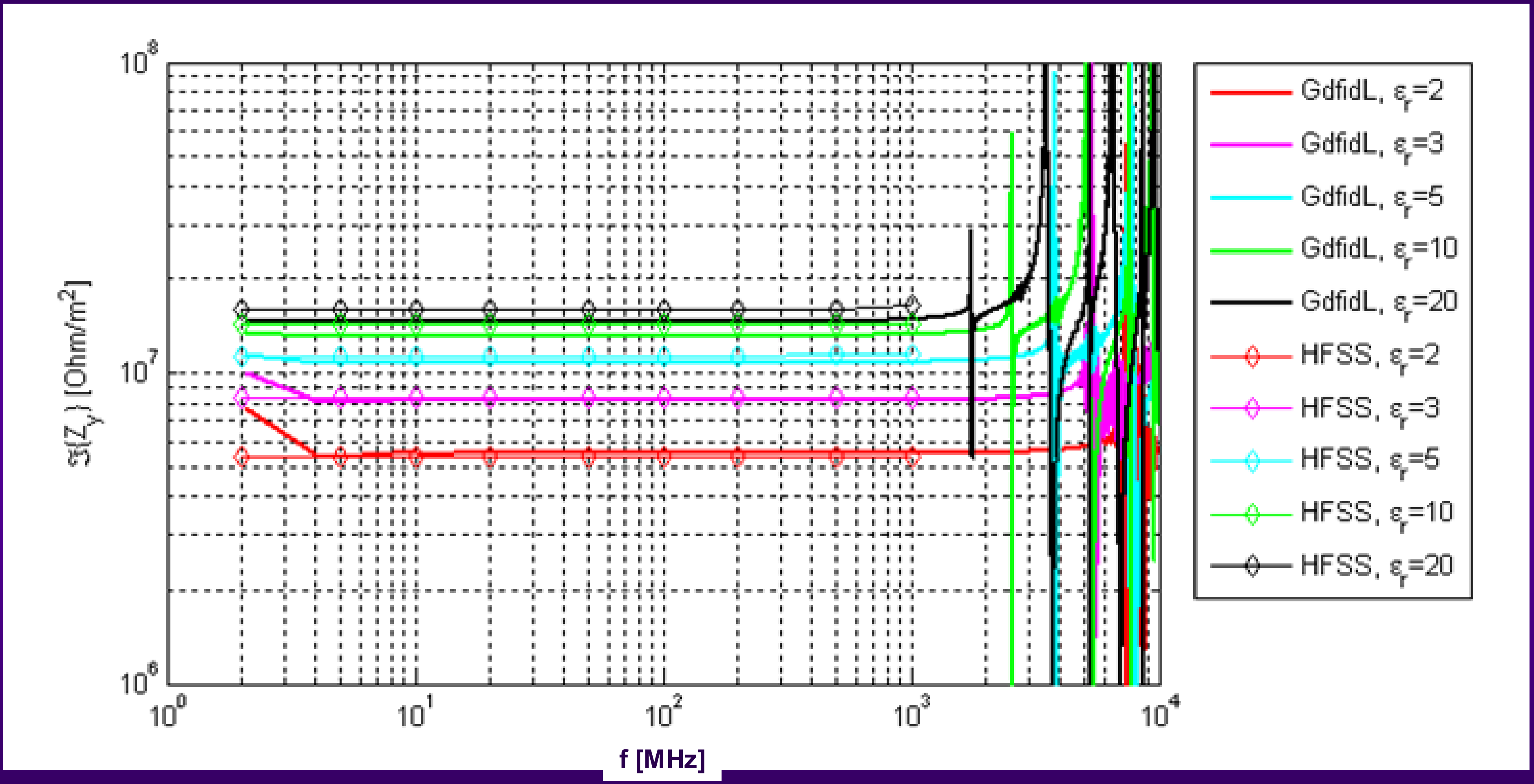
⟹ **Very good agreement between HFSS and GdfidL**

Variation of $\sigma = 1 - 10^6$, $\varepsilon_r = 1$, $L_c = 1m$, $d = 10mm$

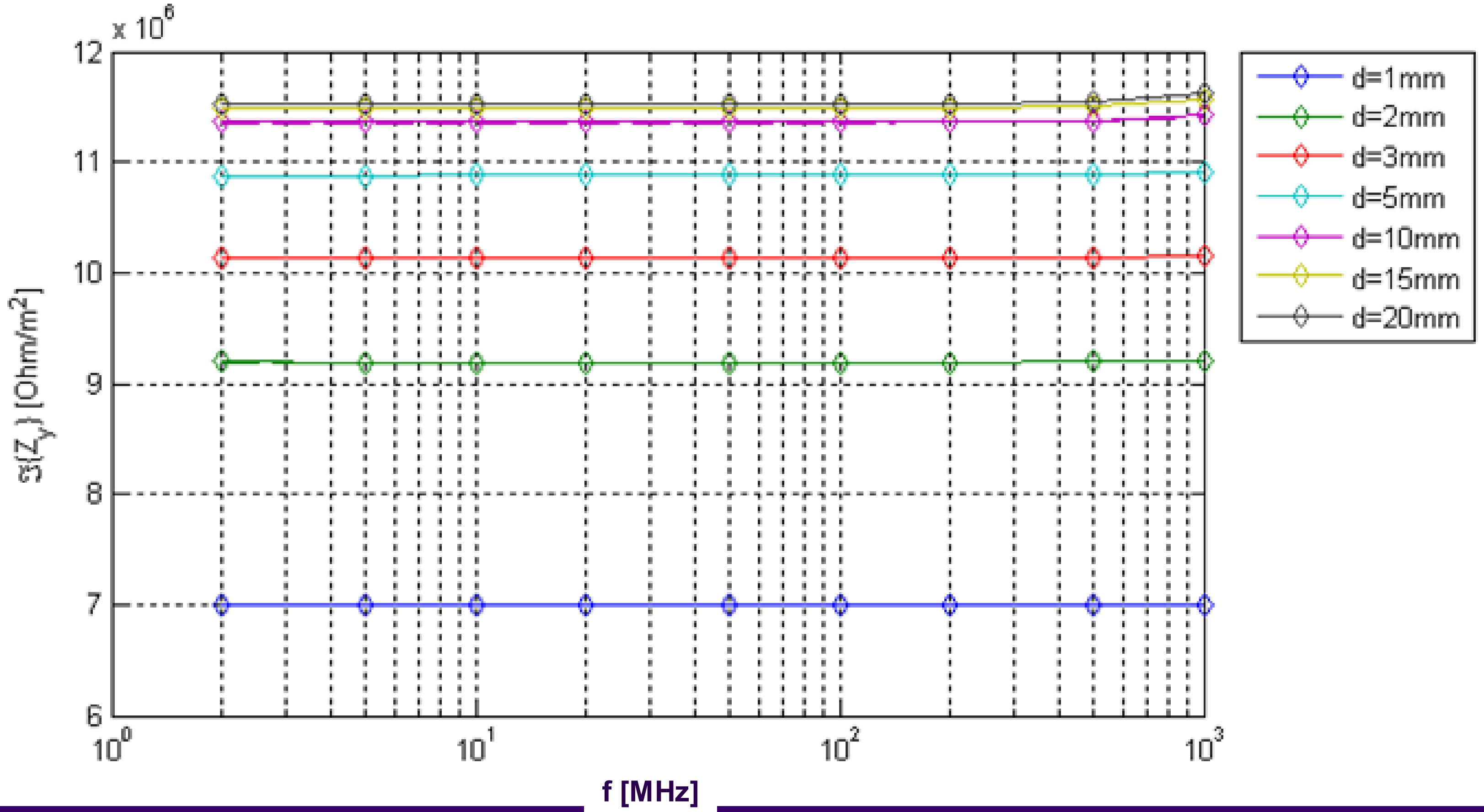


⟹ **No agreement between HFSS and GdfidL for σ > 10. GdfidL mesh is too bad ?**

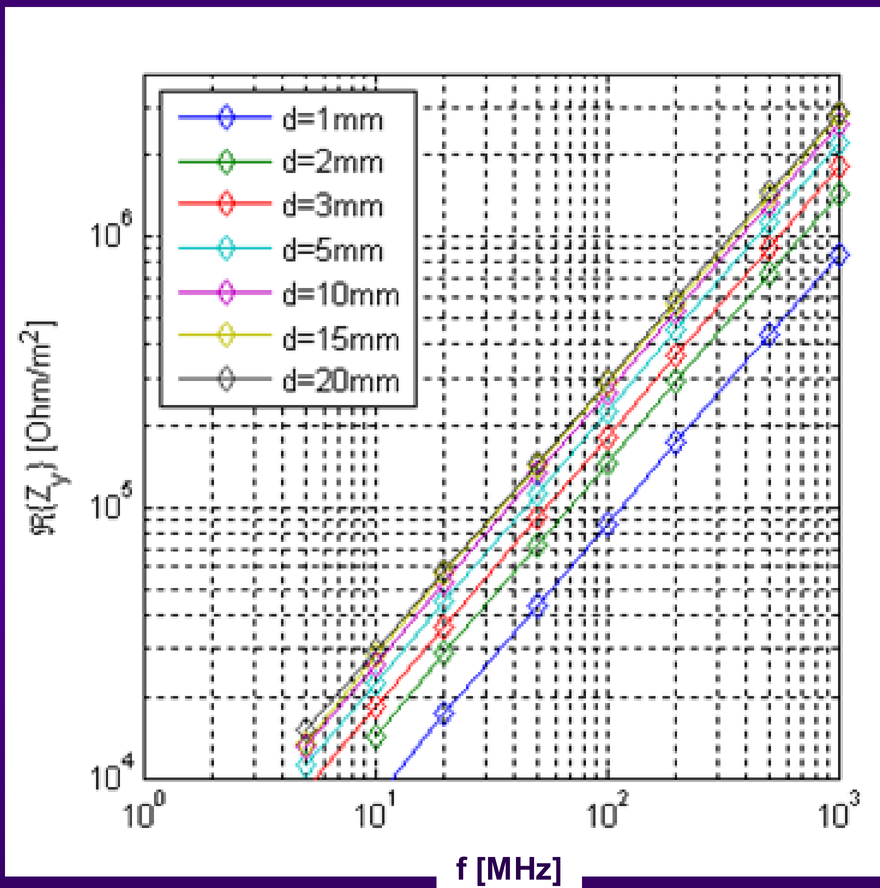
Variation of ε_r = 2-20, σ = 0, d = 10mm

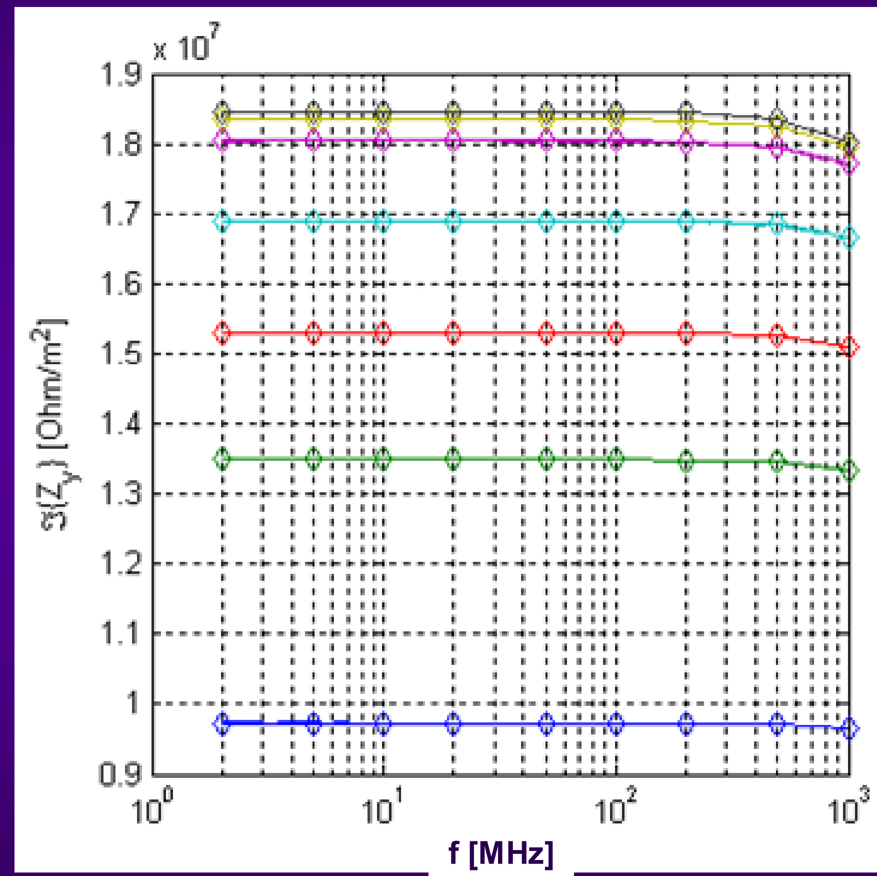


Variation of d = 1-20mm, σ = 0, ε_r = 5. HFSS setup

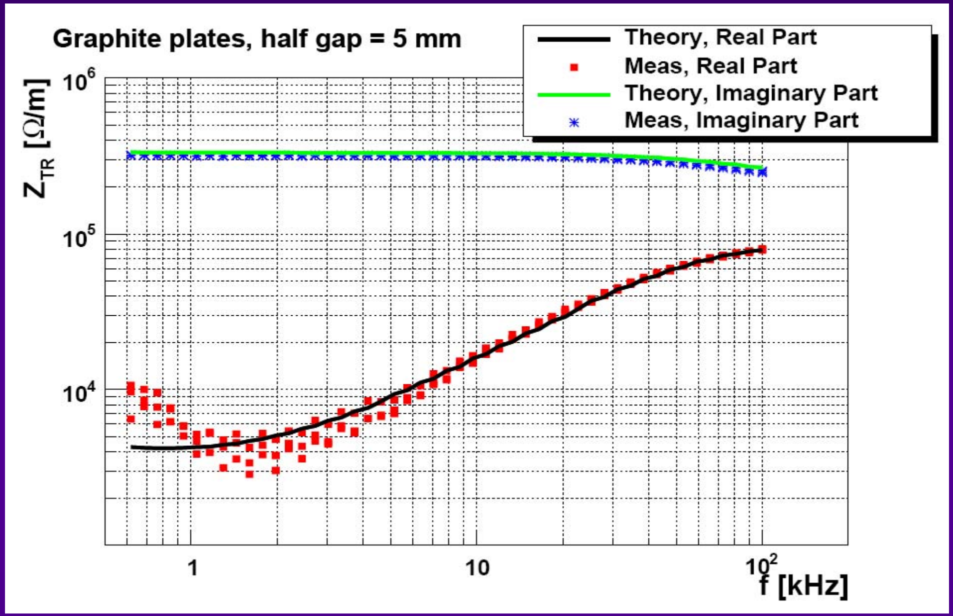


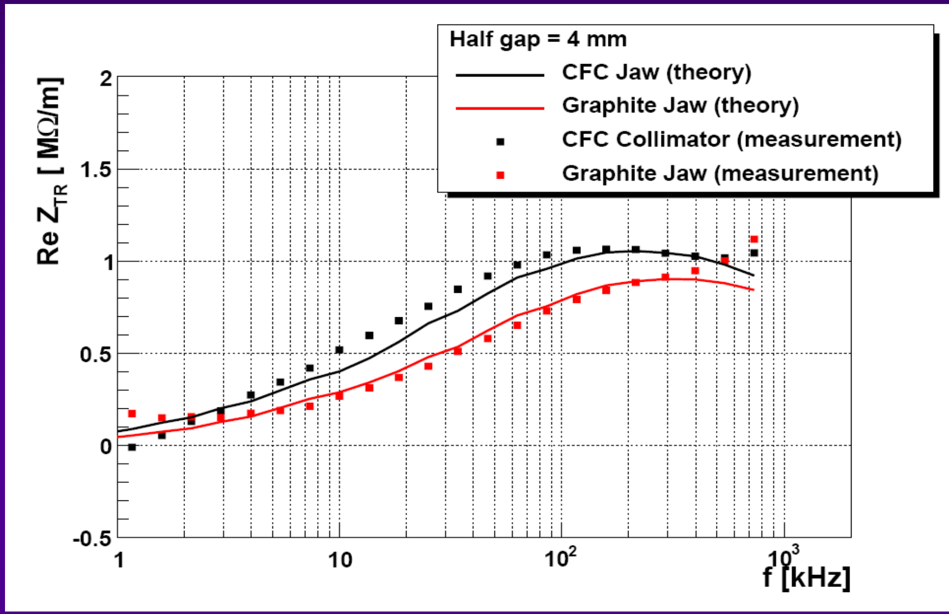
Variation of d = 1-20mm, σ = 1, ε_r = 1. HFSS setup





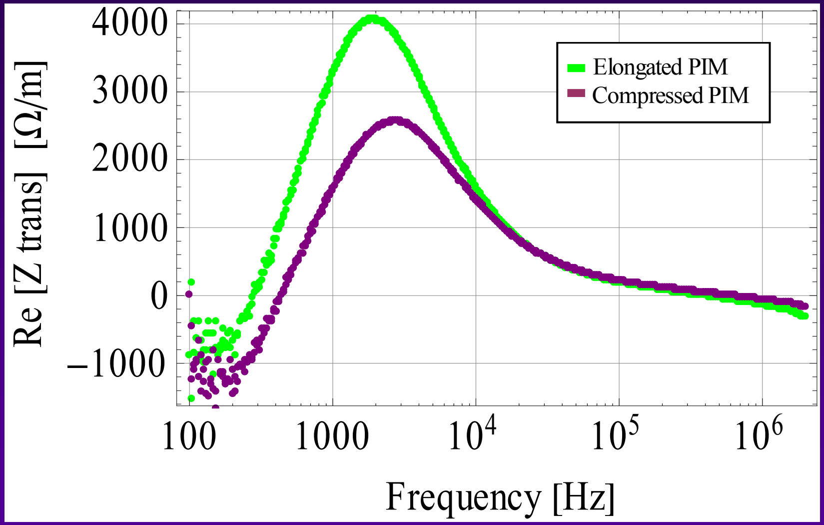
EPAC08 PAPER BY FEDERICO et al. ⟹ LHC COLLIMATOR

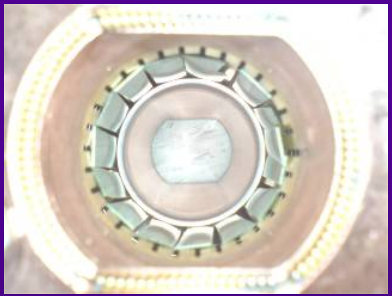


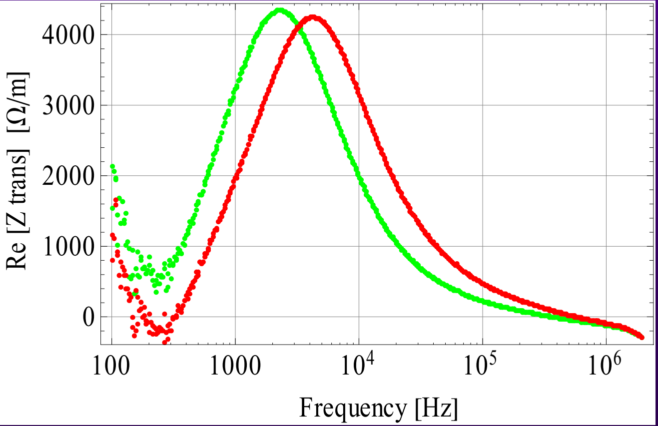


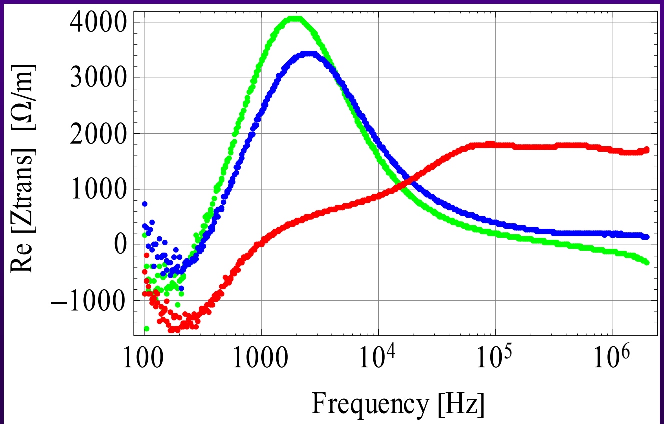
⟹ Good agreement between theory, measurements (and simulations)

EPAC08 PAPER BY BENOIT et al. ⟹ LHC PIMS







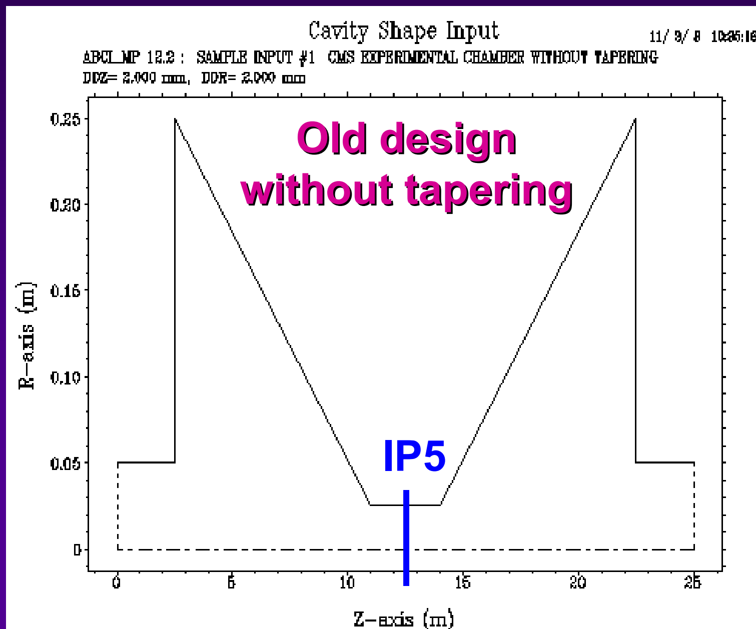


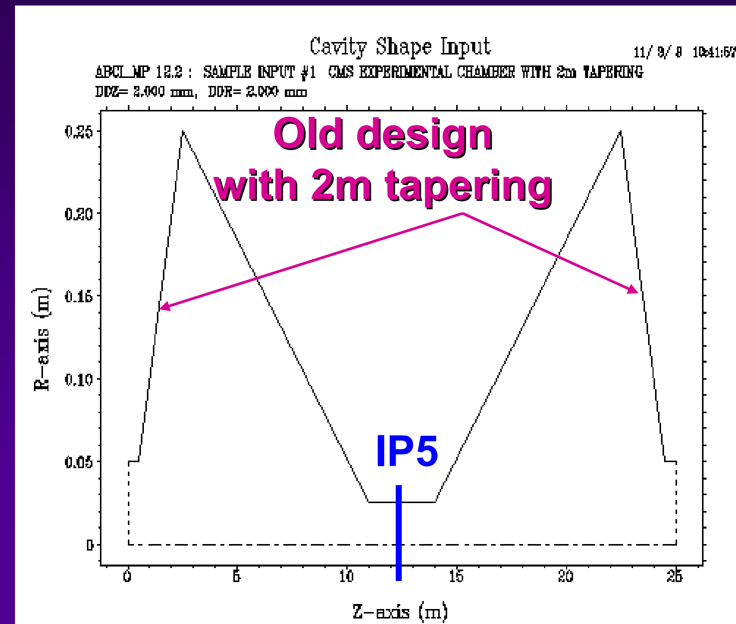
CMS EXPERIMENTAL CHAMBER (1/4)

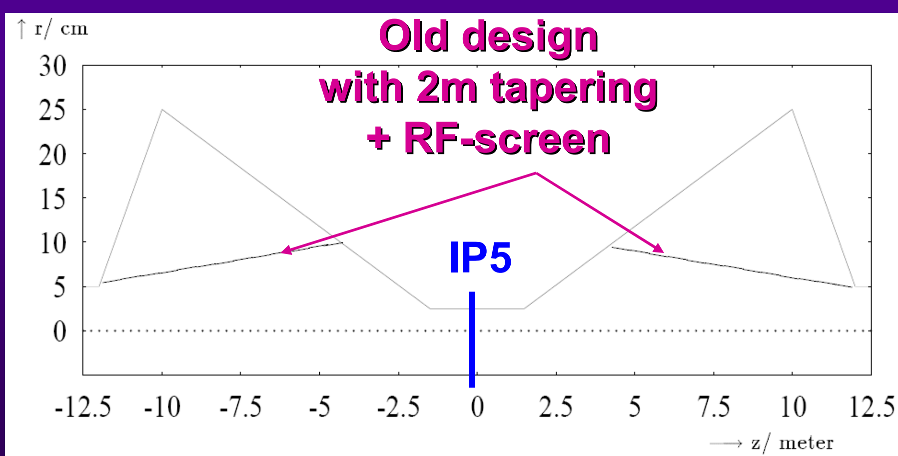
LHC Project Notes 14-36-63 (1995-96)

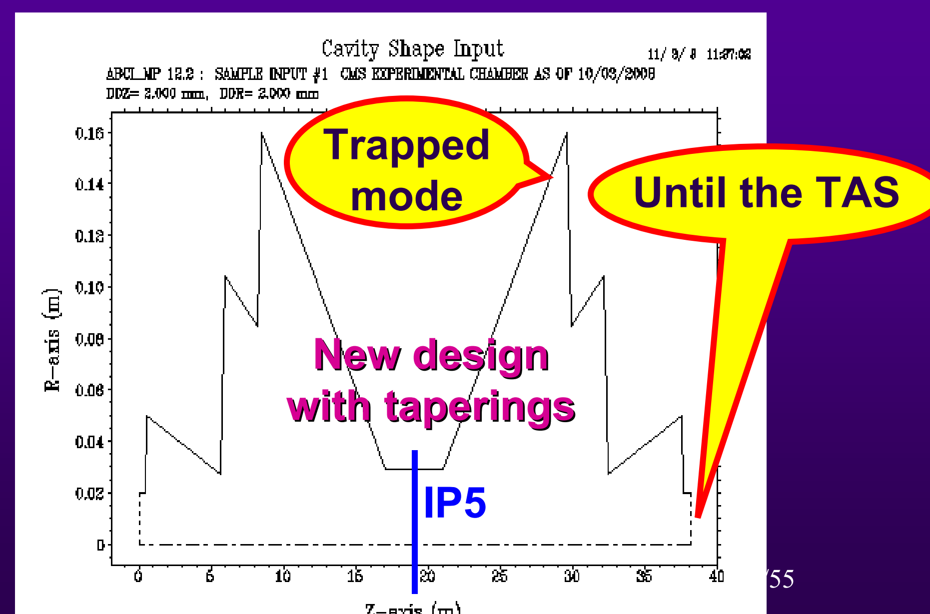
- Old design (1995) without tapering
- Suggestion by O. Bruning in 1995 to introduce a tapering length of 2 m on both sides to reduce the total (incoherent) power loss by ~ 2 orders of magnitude (⟹ OK). However, coherent loss from high-Q HOMs still a concern (as high as 2 kW if bunch frequency is resonance with one of trapped mode frequencies) ⟹ Additional RF-screen proposed to reduce the coherent losses to values as low as 40 W
- New drawings given to me by Wolfram Zeuner (PH/CMM) on 10/03/2008 ⟹ No RF-screen…

CMS EXPERIMENTAL CHAMBER (2/4)









CMS EXPERIMENTAL CHAMBER (3/4)

$M = 2808$ $N_b = 1.15 \times 10^{11}$ p/b $f_{rev} = 11.245$ kHz

	Loss factor [V/pC]	Incoh. power loss [W]
Old design without tapering	- 0.09	- 962
Old design with 2m tapering	- 0.00067	- 7
New design with taperings	- 0.0013	- 14

CMS EXPERIMENTAL CHAMBER (4/4)

- **The coherent loss from HOMs should (ideally) be re-evaluated for the new design**

- **After several discussions and scaling it was concluded that it is not too harmful**

- **This will/should be checked by Rainer when he comes to CERN during Summer**

COLLABORATION WITH RAINER WANZENBERG FROM DESY

- **He came one week from April 21 to April 24 2008**
  - **Learnt how to use GdFidL (thanks Alexej for all the explanations)**
  - **He can now run GdFidL in // from DESY**

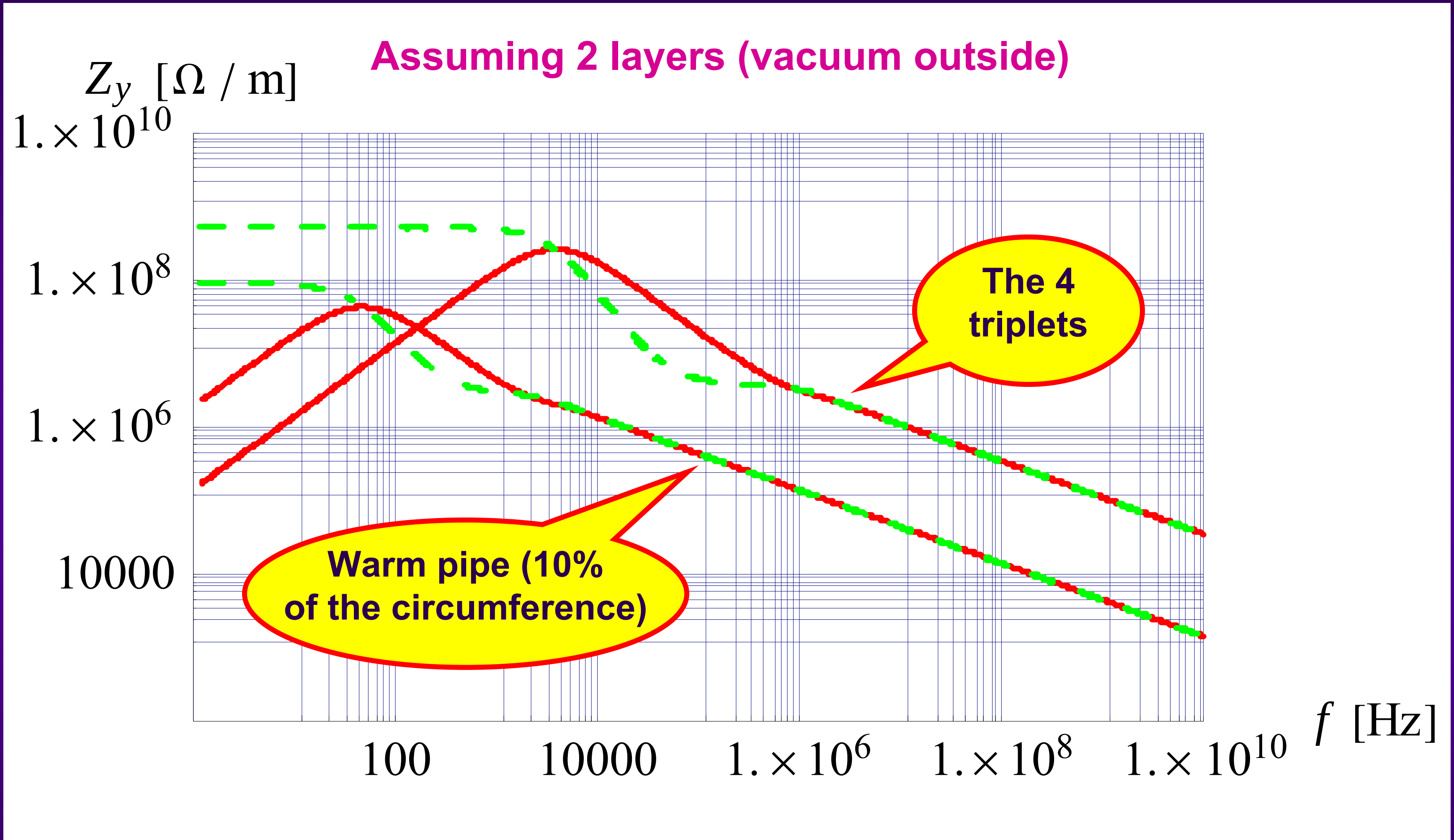
- **He will come back for 1 month from August 6 to September 6**

  $\Longrightarrow$ **He will help use with ZBASE**

QUESTION FROM STEPHANE AND RANKO (1/3)

- **There is some work on the 4 triplets ($\Longrightarrow$ 4 × 40 m = 160 m) with a beam screen diameter of 110 mm in SS**
- **Is it better or worse than the warm pipe of the LHC (which is 10% of the 27 km)?**
  - **Beta function = 12 km (it is the average one, i.e. ~ 70 m, for the warm pipe)**
  - **SS thickness = 0.6 mm (it is 2 mm of Cu for the warm pipe)**
- **Reminder:**
  - $\rho_{SS} = 10^{-6}$ **Ωm and** $\rho_{Cu} = 1.5 \times 10^{-8}$ **Ωm at room temperature**
  - $\rho_{Cu,cold} = 5.5 \times 10^{-10}$ **Ωm (i.e. it decreases by a factor ~ 30)**
  - $\rho_{SS,cold} = 5 \times 10^{-7}$ **Ωm (i.e. it decreases by a factor ~ 2 only)**

QUESTION FROM STEPHANE AND RANKO (2/3)



Skin depth (SS, 8 kHz) = 4 mm

Skin depth (Cu, 8 kHz) = 0.7 mm

QUESTION FROM STEPHANE AND RANKO (3/3)