Vacuum for Particle Accelerators Impedance tutorials:

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Programme

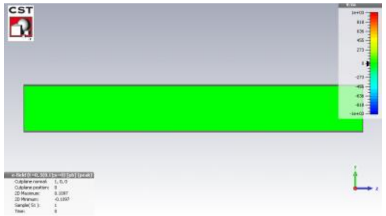
- Short recap on impedance
  - -> main key parameters:
    - - power loss and loss factor
    - - effective impedances and kick factor
    - - resonant modes
- Impact of material → ImpedanceWake2D
  (code developed at CERN by Nicolas Mounet et al)
- Impact of geometry → CST simulations
  (3D commercial code: www.cst.com)
- Main messages

Impedance?

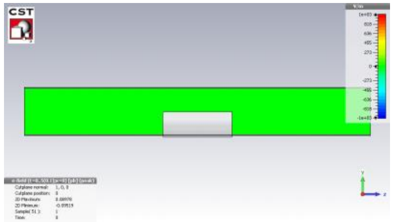
- When a beam of particles traverses a device which
  - is not smooth
  - or is not a perfect conductor,

  it will produce electromagnetic RF fields that will perturb the following particles
  → wakefields (in time domain) or impedance (in frequency domain).

- Example of wakefield perturbation caused by an obstacle in a beam pipe:



In a smooth beam pipe



In a beam pipe with a sharp obstacle → resonant RF mode

Impact of impedance?

1) Energy is lost by the beam
2) Resonant kicks to following particles

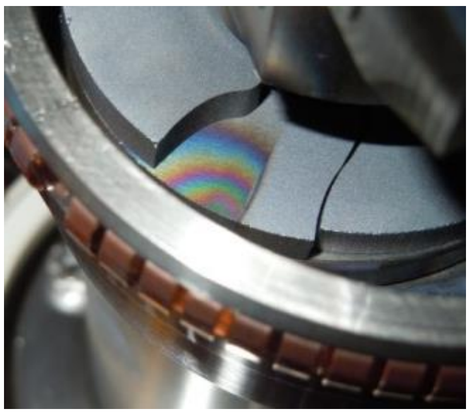
→ Are these impedance perturbations an issue?

Impact of impedance?

Impact of impedance?

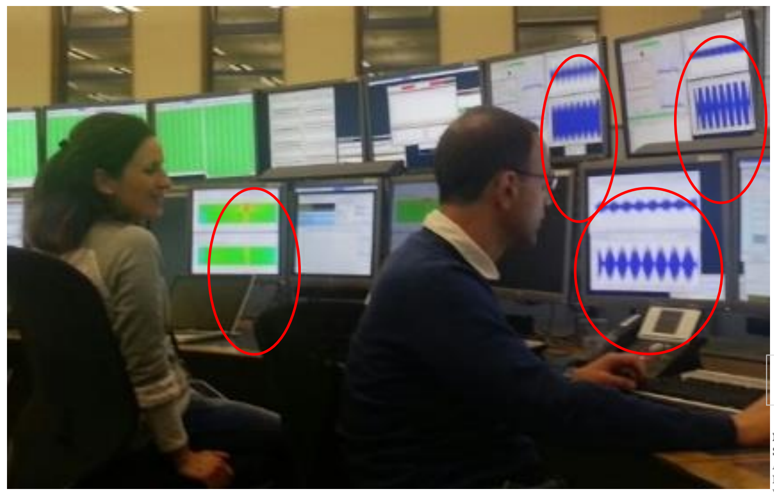
1) Energy is lost by the beam → dissipated in surrounding chambers → beam induced heating
2) Resonant kicks to following particles → instabilities → beam loss and blow-up

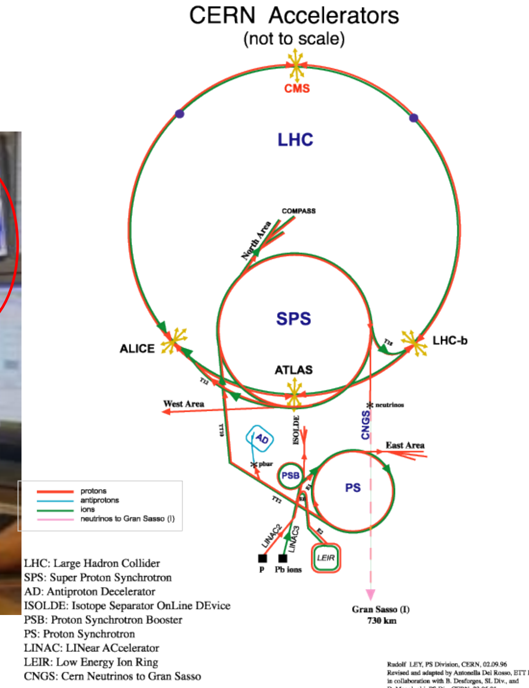
Damaged LHC equipment



Synchrotron Light monitor

Uncontrollable oscillating bunch motion





- More beam intensity → more perturbations → more damage and beam quality issues
- Impedance is a critical limit to increase the performance of most large accelerators
- Requires strict continuous follow-up and support

  → mandate of the impedance working group at CERN

Impedancewake2D

→ Solves Maxwell's equation in frequency domain for a multilayer vacuum chamber made of arbitrary materials
→ Ref: PhD thesis Nicolas Mounet (EPFL 2012)

and the corresponding integration coefficients for $\vec{G}$

$$\begin{aligned} Z_0 &= \frac{1}{\varepsilon_0 c} = \mu_0 c = \sqrt{\frac{\mu_0}{\varepsilon_0}}, \\ \vec{G} &= Z_0 \vec{H}, \\ C_{Ig}^{m\,(p)} &= Z_0 C_{Ih}^{m\,(p)}, \\ C_{Kg}^{m\,(p)} &= Z_0 C_{Kh}^{m\,(p)}, \end{aligned} \tag{1.64}$$

and letting

$$x^{p,p} = \nu^{(p)} b^{(p)} \qquad \text{and} \qquad x^{p+1,p} = \nu^{(p+1)} b^{(p)}, \tag{1.65}$$

the relation between the constants of adjacent layers can be written as

$$\begin{bmatrix} C_{Ie}^{m(p+1)} \\ C_{Ke}^{m\,(p+1)} \\ C_{Ig}^{m(p+1)} \\ C_{Kg}^{m\,(p+1)} \end{bmatrix} = M^{p+1,p} \cdot \begin{bmatrix} C_{Ie}^{m(p)} \\ C_{Ke}^{m\,(p)} \\ C_{Ig}^{m(p)} \\ C_{Kg}^{m\,(p)} \end{bmatrix} = \begin{bmatrix} P^{p+1,p} & Q^{p+1,p} \\ S^{p+1,p} & R^{p+1,p} \end{bmatrix} \cdot \begin{bmatrix} C_{Ie}^{m(p)} \\ C_{Ke}^{m\,(p)} \\ C_{Ig}^{m(p)} \\ C_{Kg}^{m\,(p)} \end{bmatrix}, \tag{1.66}$$

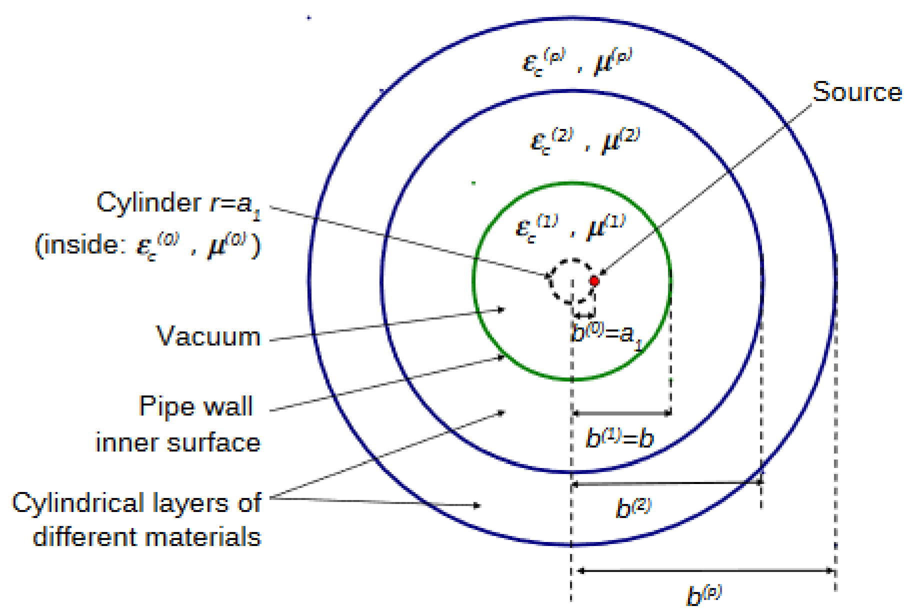
where $P^{p+1,p}$, $Q^{p+1,p}$, $R^{p+1,p}$ and $S^{p+1,p}$ are four 2×2 matrices given by

$$P^{p+1,p} = -\frac{\left(\nu^{(p+1)}\right)^2 b^{(p)}}{\varepsilon_1^{(p+1)}} \begin{bmatrix} \zeta_{IK}\left\{\frac{\varepsilon_1^{(p+1)}}{\nu^{(p+1)}}\kappa_p^{p+1} - \frac{\varepsilon_1^{(p)}}{\nu^{(p)}}\lambda_p^p\right\} & \zeta_{KK}\left\{\frac{\varepsilon_1^{(p+1)}}{\nu^{(p+1)}}\kappa_p^{p+1} - \frac{\varepsilon_1^{(p)}}{\nu^{(p)}}\kappa_p^p\right\} \\ \zeta_{II}\left\{-\frac{\varepsilon_1^{(p+1)}}{\nu^{(p+1)}}\lambda_p^{p+1} + \frac{\varepsilon_1^{(p)}}{\nu^{(p)}}\lambda_p^p\right\} & \zeta_{KI}\left\{-\frac{\varepsilon_1^{(p+1)}}{\nu^{(p+1)}}\lambda_p^{p+1} + \frac{\varepsilon_1^{(p)}}{\nu^{(p)}}\kappa_p^p\right\} \end{bmatrix}, \tag{1.67}$$

$$Q^{p+1,p} = -\left(\frac{\left(\nu^{(p+1)}\right)^2}{\left(\nu^{(p)}\right)^2} - 1\right)\frac{m}{\beta\varepsilon_1^{(p+1)}} \begin{bmatrix} -\zeta_{IK} & -\zeta_{KK} \\ \zeta_{II} & \zeta_{KI} \end{bmatrix}, \tag{1.68}$$

$$R^{p+1,p} = -\frac{\left(\nu^{(p+1)}\right)^2 b^{(p)}}{\mu_1^{(p+1)}} \begin{bmatrix} \zeta_{IK}\left\{\frac{\mu_1^{(p+1)}}{\nu^{(p+1)}}\kappa_p^{p+1} - \frac{\mu_1^{(p)}}{\nu^{(p)}}\lambda_p^p\right\} & \zeta_{KK}\left\{\frac{\mu_1^{(p+1)}}{\nu^{(p+1)}}\kappa_p^{p+1} - \frac{\mu_1^{(p)}}{\nu^{(p)}}\kappa_p^p\right\} \\ \zeta_{II}\left\{-\frac{\mu_1^{(p+1)}}{\nu^{(p+1)}}\lambda_p^{p+1} + \frac{\mu_1^{(p)}}{\nu^{(p)}}\lambda_p^p\right\} & \zeta_{KI}\left\{-\frac{\mu_1^{(p+1)}}{\nu^{(p+1)}}\lambda_p^{p+1} + \frac{\mu_1^{(p)}}{\nu^{(p)}}\kappa_p^p\right\} \end{bmatrix}, \tag{1.69}$$

$$S^{p+1,p} = \frac{\varepsilon_1^{(p+1)}}{\mu_1^{(p+1)}} Q^{p+1,p}, \tag{1.70}$$



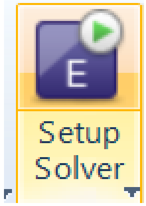
→ Field matching at all material boundaries
→ Quite a lot of maths with clever tricks to gain computing time, out of the scope of this tutorial
→ Outputs the impedance contributions as a function of frequency

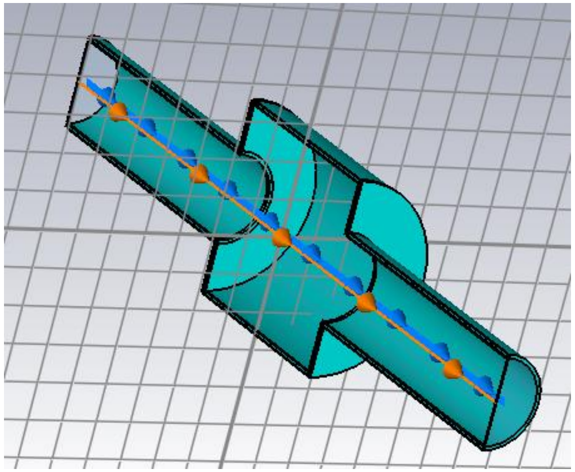
CST simulations

- 3D commercial code that allows:
  - Simulating a beam inside a device (wakefield solver)

    → time domain simulation
  - Finding resonant modes of a structure without beam (eigenmode solver)

    → frequency domain simulation



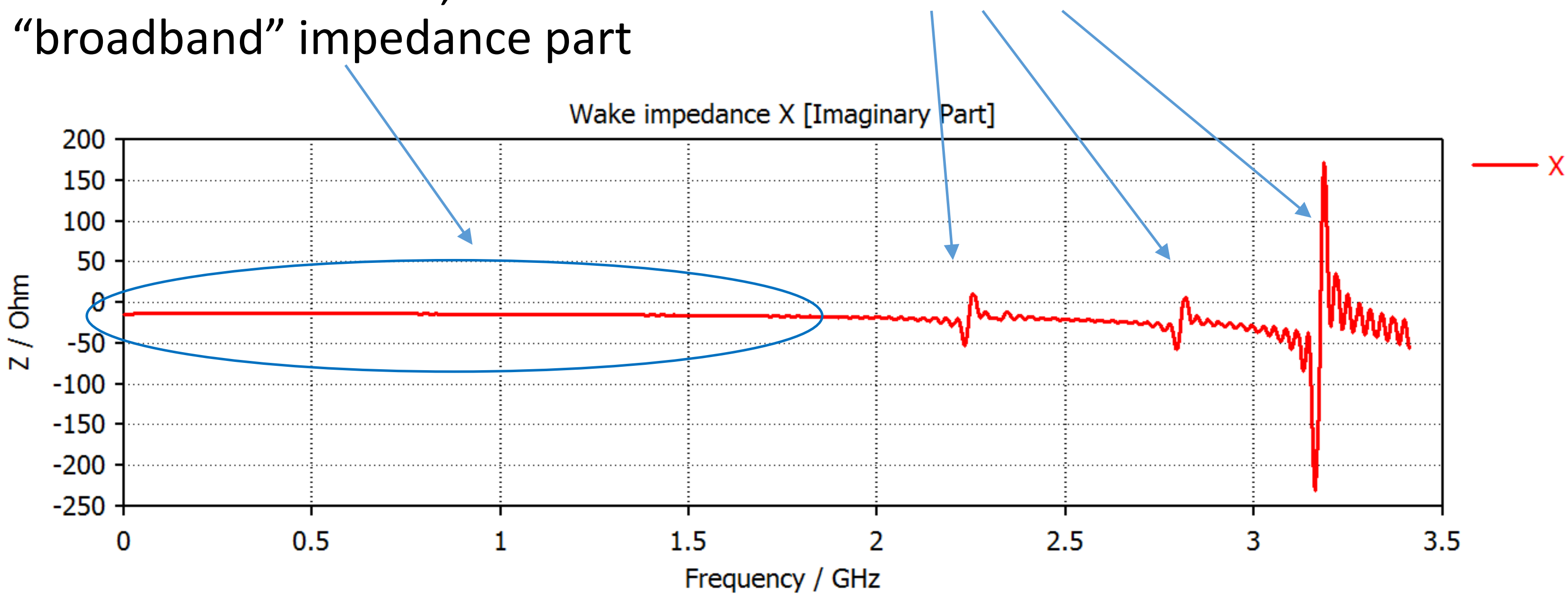


1st example: open and run the wakefield file 0_cavity_test.cst

Observe:
- the exciting bunch
- The resonant modes in the 2D/3D Results
- The resonant modes in the 1D Results wake impedance

Main impedance contributions to watch out for:

→For all contributions, need to check the resonant modes and the "broadband" impedance part

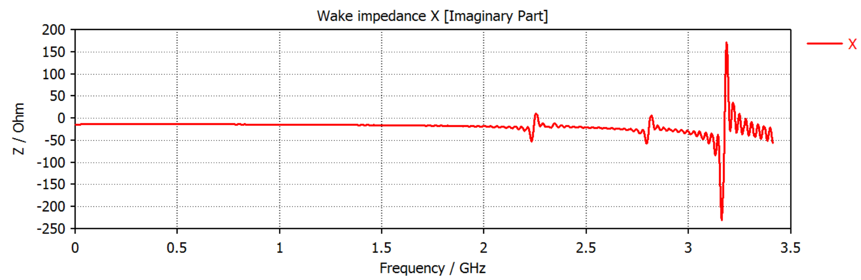


→First major message: impedance of a device is not a number, it is a complex function of frequency in all 3 planes

→ many contributions to check and optimize

Practical description of impedance (see Rainer Wanzenberg's talk)

- Discrete resonant modes:
  - Shunt impedance R
  - Quality factor Q
  - Resonant frequency f



- Integrated impedance: several conventions
  - Some use loss/kick factor to describe the impedance

    → advantage: direct link to energy loss and kick felt by a test particle
  - Some use effective impedances

    → advantage: contains both real and imaginary components for instability assessment with Sacherer's formalism

practical description: see Frank Zimmermann USPAS 2015

Effective impedance

$$\left(\frac{Z_0^{\parallel}}{n}\right)_{\text{eff}} \equiv \omega_0 \left(\frac{Z_0^{\parallel}}{\omega}\right)_{\text{eff}} = \omega_0 \frac{\int_{-\infty}^{\infty} \frac{Z_0^{\parallel}(\omega')}{\omega'} |\tilde{\rho}(\omega')|^2 d\omega'}{\int_{-\infty}^{\infty} |\tilde{\rho}(\omega')|^2 d\omega'}$$

$$(Z_1^{\perp})_{\text{eff}} = \frac{\beta_i}{\beta_{\text{ref}}} \frac{\int_{-\infty}^{\infty} Z_1^{\perp}(\omega') |\tilde{\rho}(\omega')|^2 d\omega'}{\int_{-\infty}^{\infty} |\tilde{\rho}(\omega')|^2 d\omega'}$$

Loss/kick factors

$$k_{\parallel} = \frac{1}{\pi} \int_0^{\infty} \text{Re}\left[Z_0^{\parallel}(\omega)\right] |\tilde{\rho}(\omega)|^2 \, d\omega$$

$$k_{\perp} = -\frac{1}{\pi} \int_0^{\infty} \text{Im}\left[Z_1^{\perp}(\omega)\right] |\tilde{\rho}(\omega)|^2 \, d\omega$$

→ Different conventions depending on the machine, the lab (or the group)
→ We will use effective impedances in this tutorial

Prewarning

Note: this is not a tutorial to get you impedance experts, but more to see how impedance experts deal with your inputs, needs and constraints.

→As little code writing as we could

→Many examples ready to run to see correlations and parameter dependence.

→Try to get main messages through, the main ones:

Impedance is generally minimized when the surrounding beam pipe is:

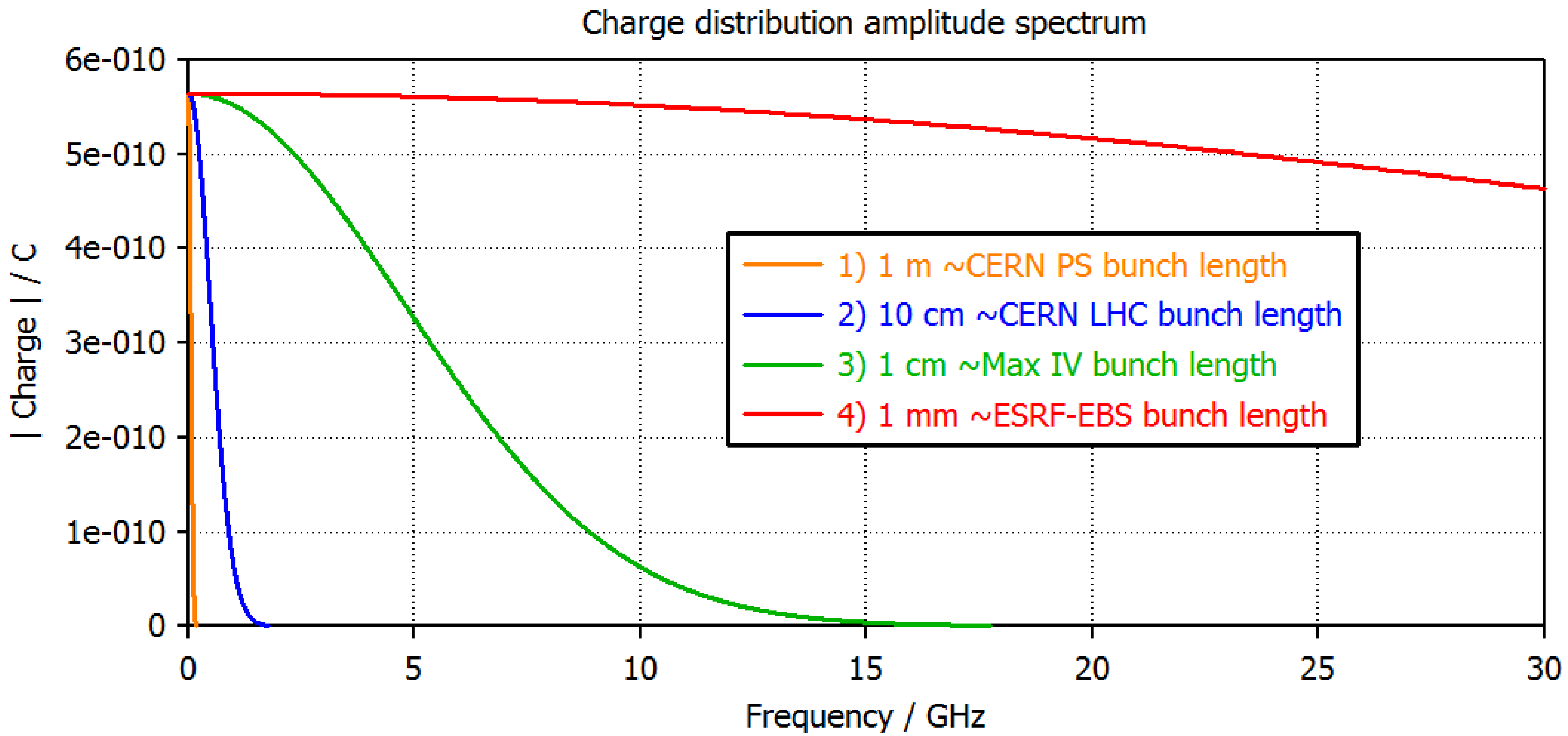
- far from the beam
- smooth
- as good conducting as possible in the frequency range of interest
- and cavities (large or small) are avoided or shielded

Prewarning: impact of bunch length

- Impedance can be strongly dependent on excitation frequency

→ change of bunch length directly affects the range of frequencies excited by the bunch

→ what is not causing trouble in one machine may be a very large issue in another machine



Smaller bunch length → larger frequency spectrum excited

Programme

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    - resonant modes

- Impact of material → ImpedanceWake2D
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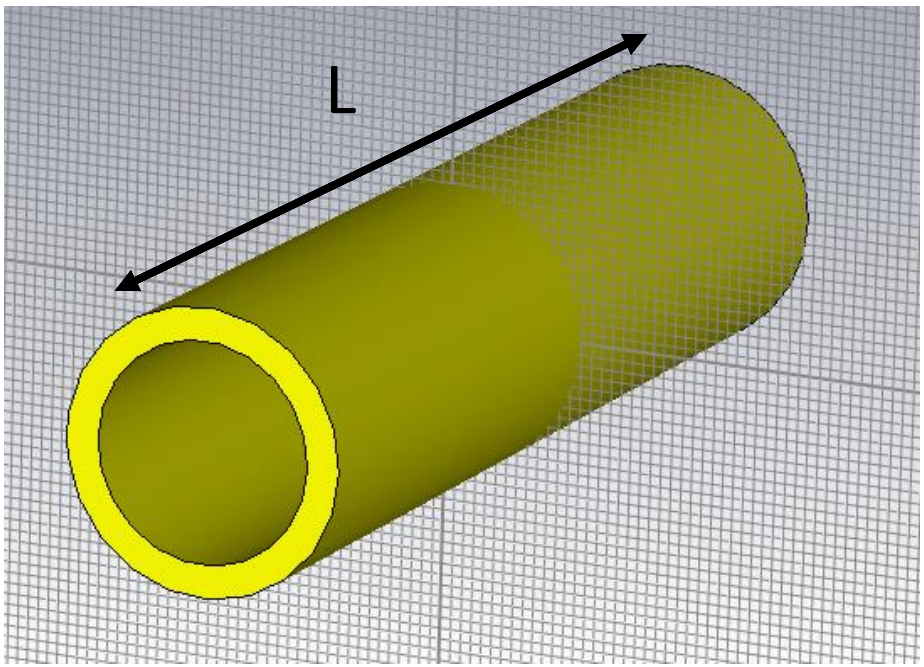
- Main messages

Impact of beam pipe

1) Length
2) Radius
3) Conductivity
4) Thickness
5) Bunch length
6) Coatings

Understanding the impact of material thickness:

Case of an 18 mm diameter pipe made of 1 mm thick copper, surrounded by vacuum



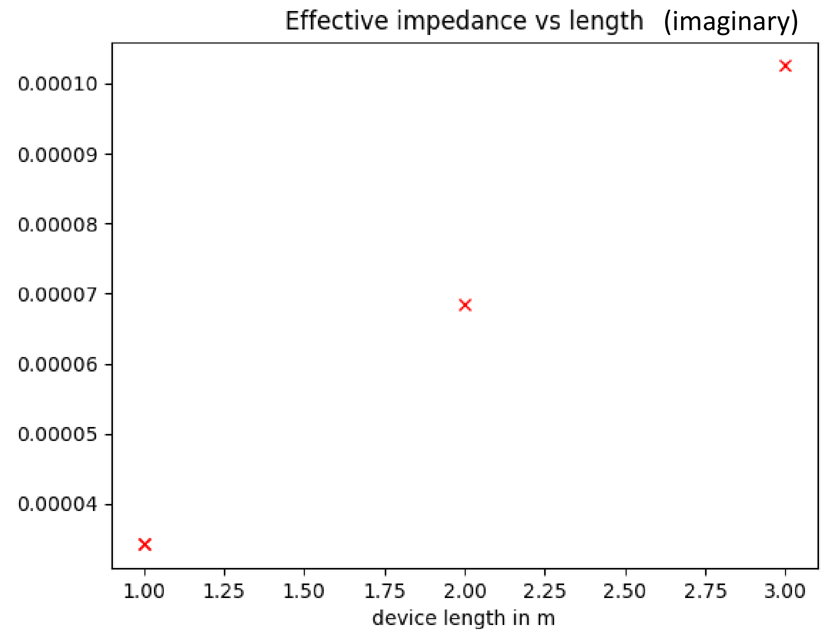
File: 0_CASvacuum_compare_length-final.ipynb

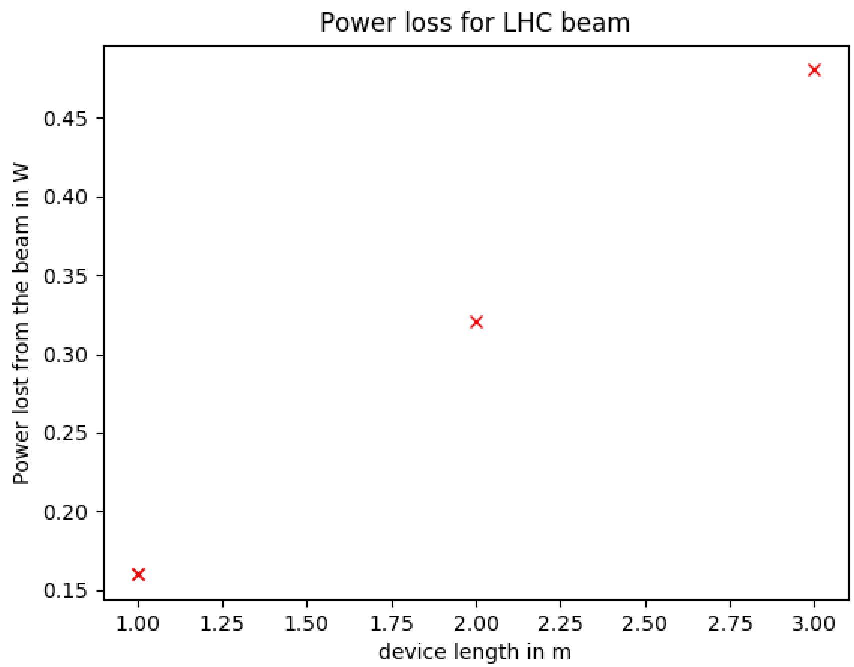
Question: how much length of such a copper pipe would be allowed in LHC assuming the current allowed limit is 0.2 MOhm/m at injection?

Impact of material length

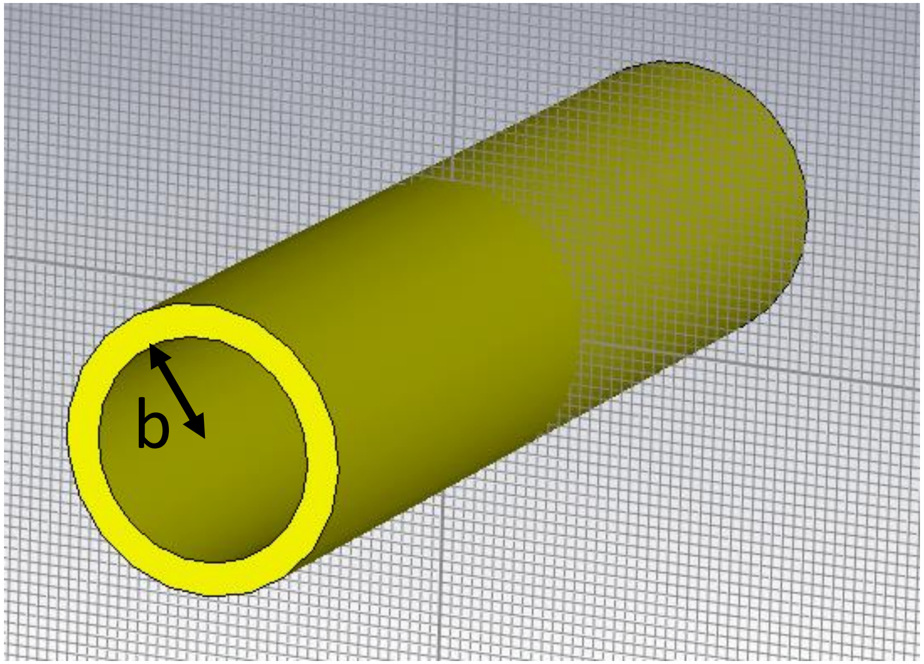
→Z_t^{eff} α L

→Ploss α L





Impact of beam pipe radius



File: 1_CASvacuum_compare_radius-final.ipynb

Question: what is the effective transverse impedance and power loss for 1 m of beam pipes with radius of

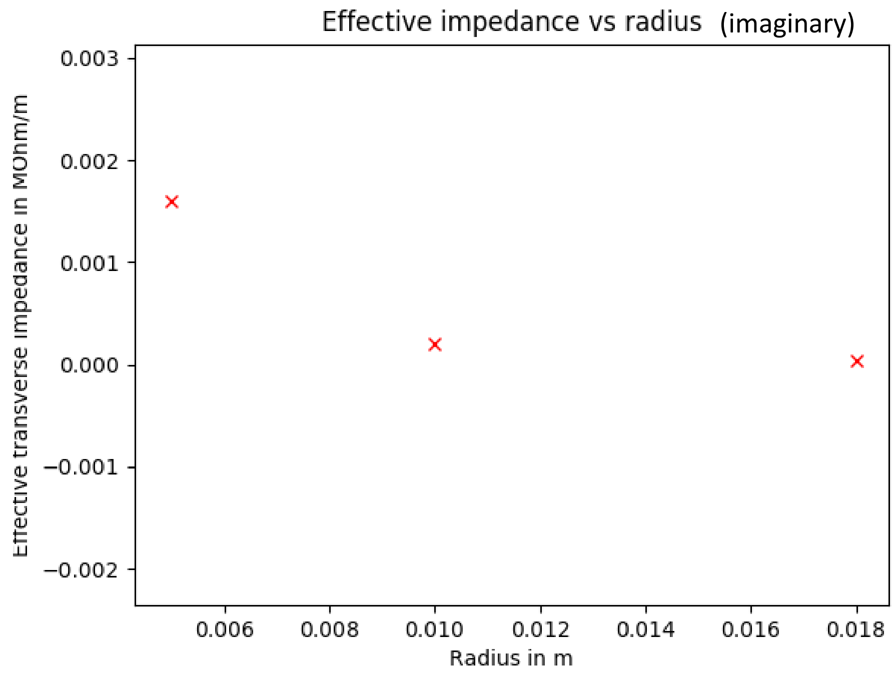
- 1 mm
- 5 mm
- 10 mm
- 30 mm

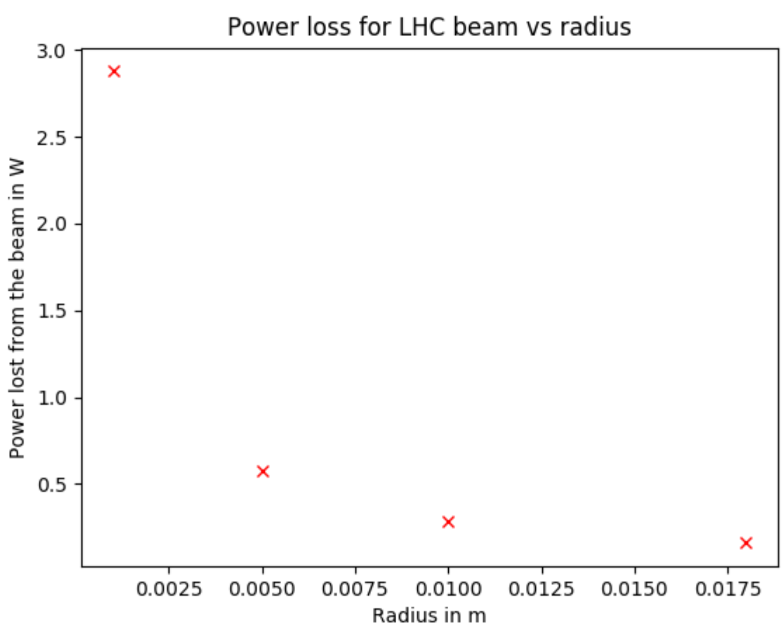
How do power loss and effective transverse impedance depend on radius?
How much length of LHC can you install if one assumes that the limit is 0.2 MOhm/m?

Impact of beam pipe radius

→ $Zt \propto L/b^3$

→ $Ploss \propto L/b$

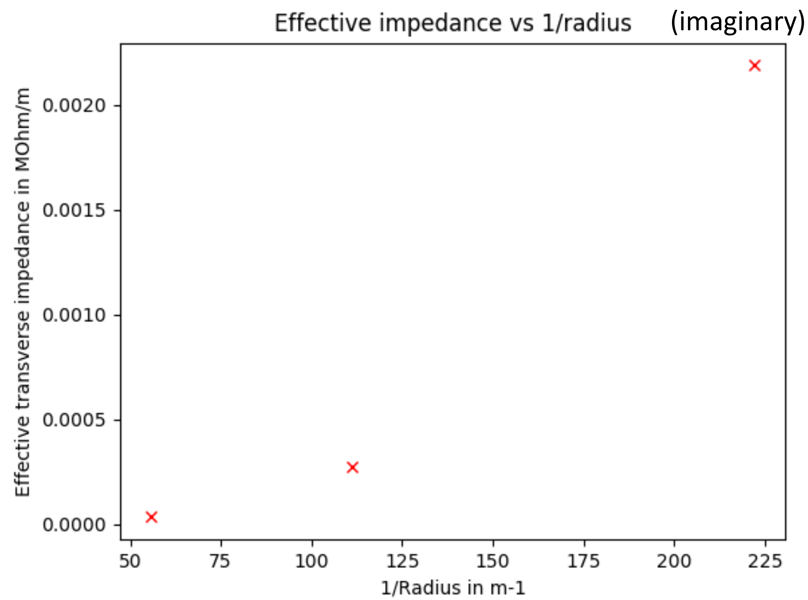


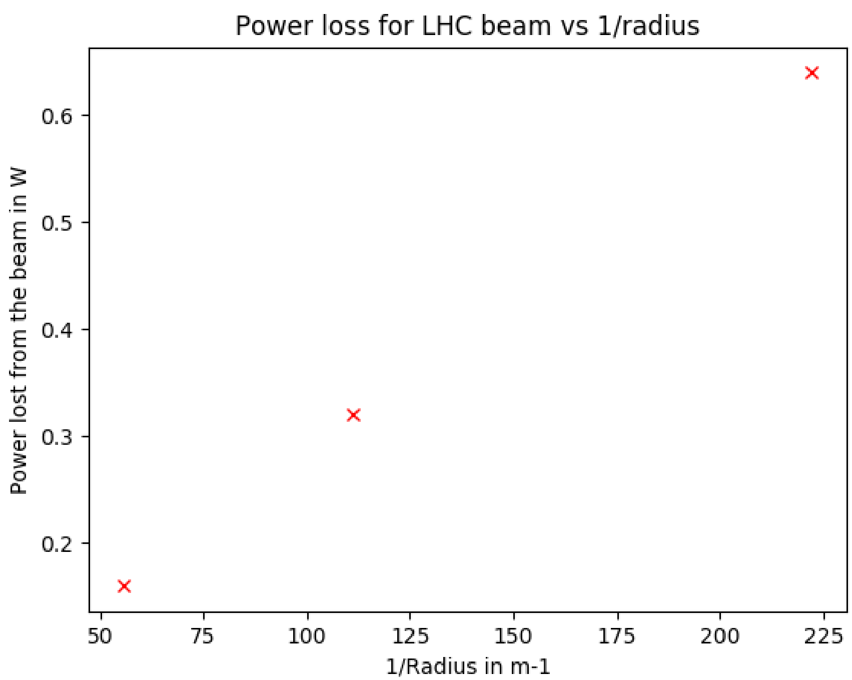


Impact of beam pipe radius

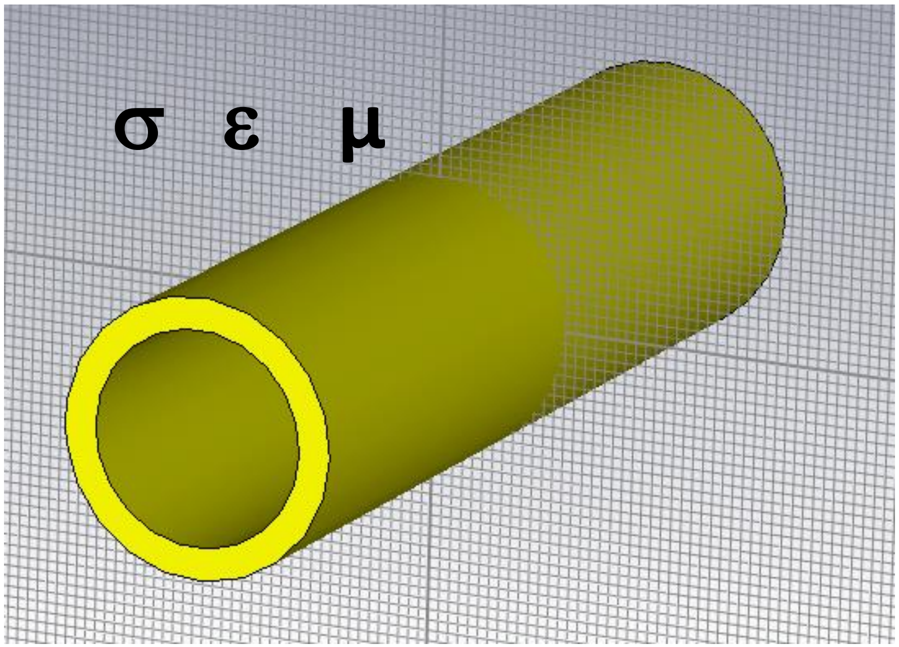
→ Zt α L/b^3

→ Ploss α L/b





Impact of material conductivity



File: 2_CASvacuum_compare_conductivity-final.ipynb

Question: what is the effective transverse impedance for 1 m of beam pipes with conductivity of

- 1e5 S/m (similar to graphite)
- 1e6 S/m (similar to stainless steel)
- 1e7 S/m
- 1e8 S/m (similar to copper)
- 1e10 S/m (similar to 20 K cold copper)

How much length of LHC can you install if one assumes that the limit is 0.2 MOhm/m?

Impact of material conductivity

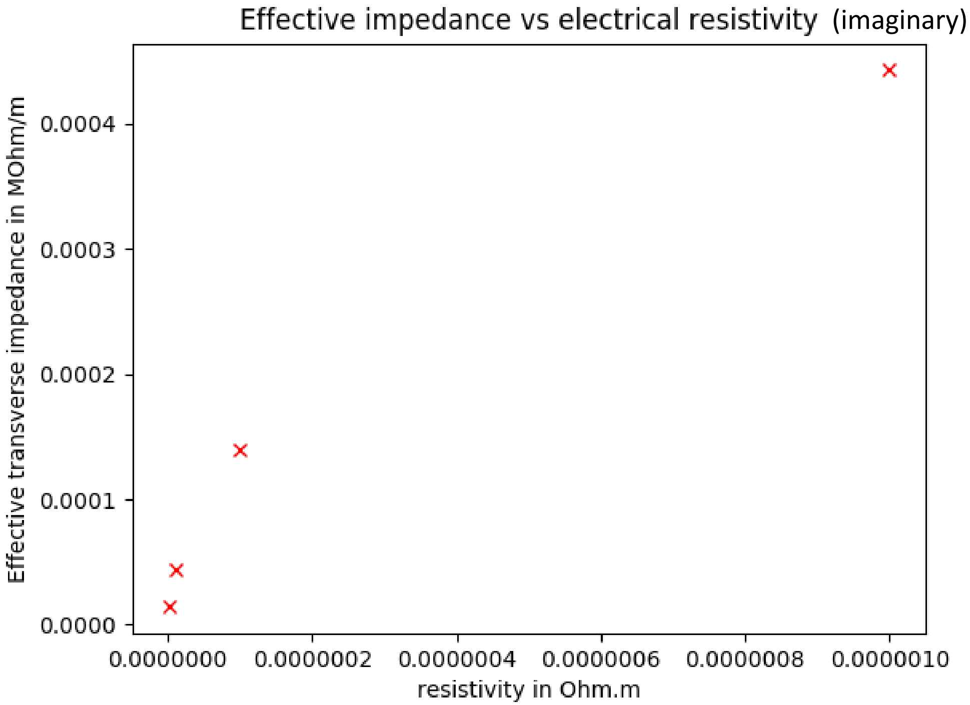
→ $Zt \quad \alpha \quad sqrt(rho)*L/b^3$

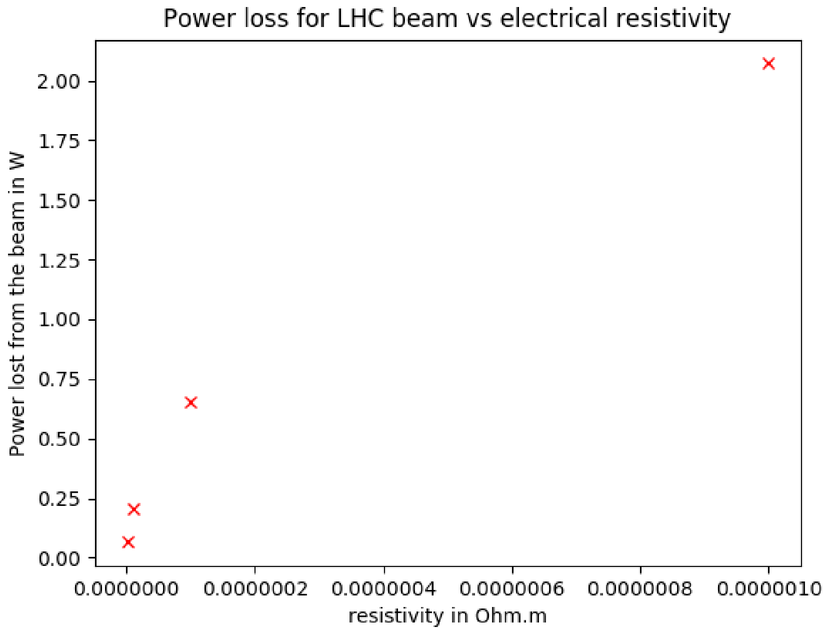
→ $P_{loss} \, \alpha \quad sqrt(rho)*L/b$

Impact of material conductivity

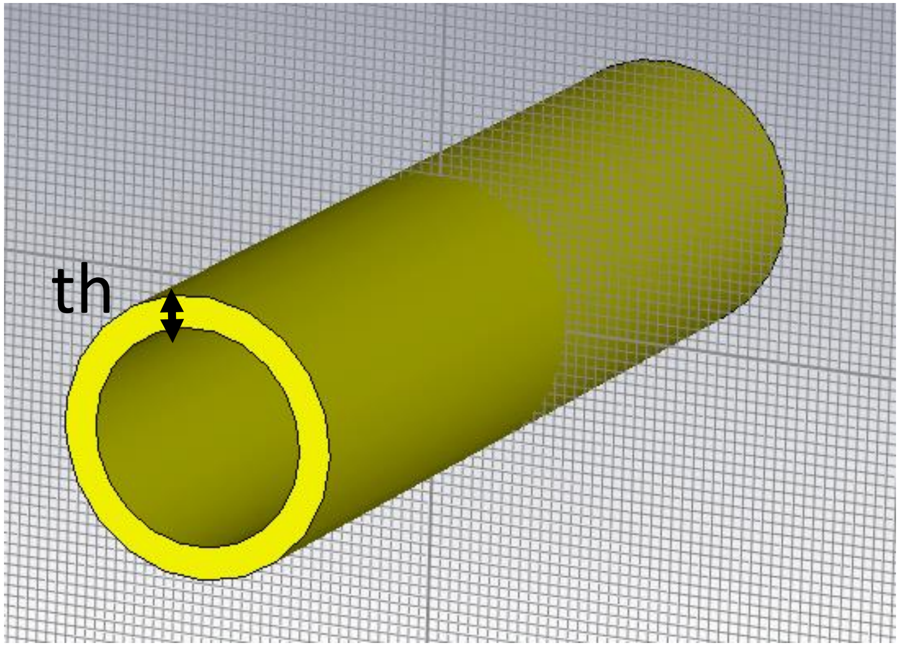
$\rightarrow Zt \;\; \alpha \;\; \text{sqrt(rho)*L/b}^3$

$\rightarrow P_{loss} \; \alpha \;\; \text{sqrt(rho)*L/b}$





Impact of material thickness



File: 3_CASvacuum_compare_thickness-final.ipynb

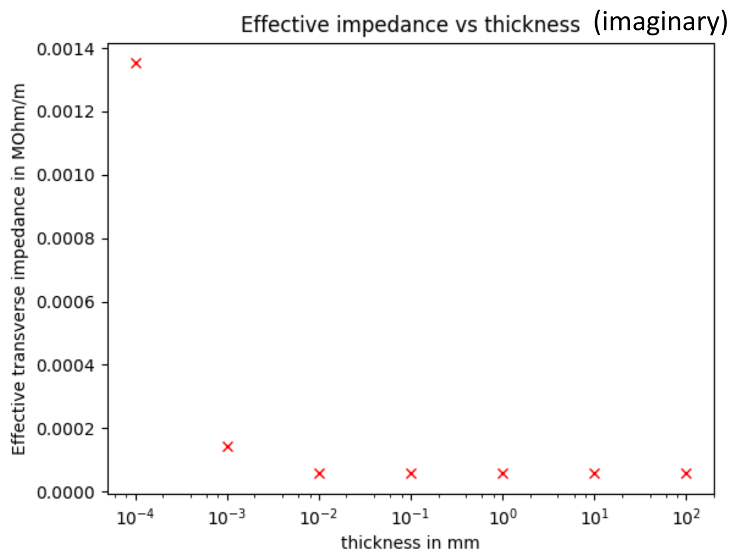
Question: what is the effective transverse impedance for 1 m of copper beam pipe with thickness of

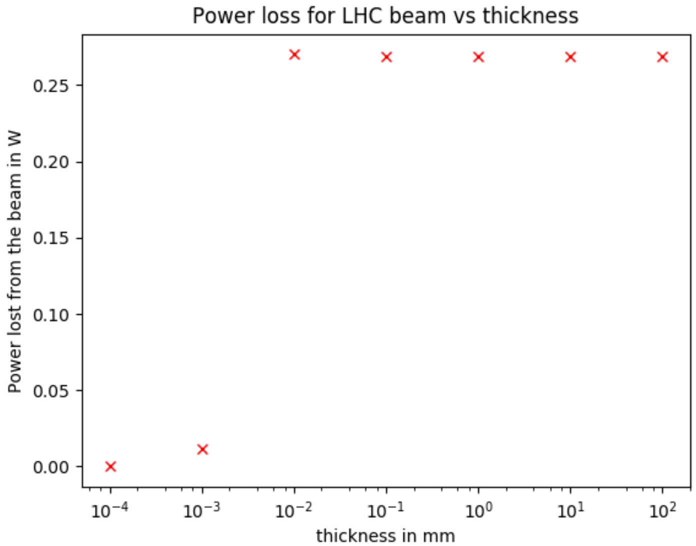
- 10 cm
- 1 cm
- 1 mm
- 0.1 mm
- 0.001 mm
- 0.0001 mm

Can we understand this behaviour?

Impact of beam pipe thickness

→Beyond a certain thickness related to the skin depth, changing the thickness does not have an impact on impedance



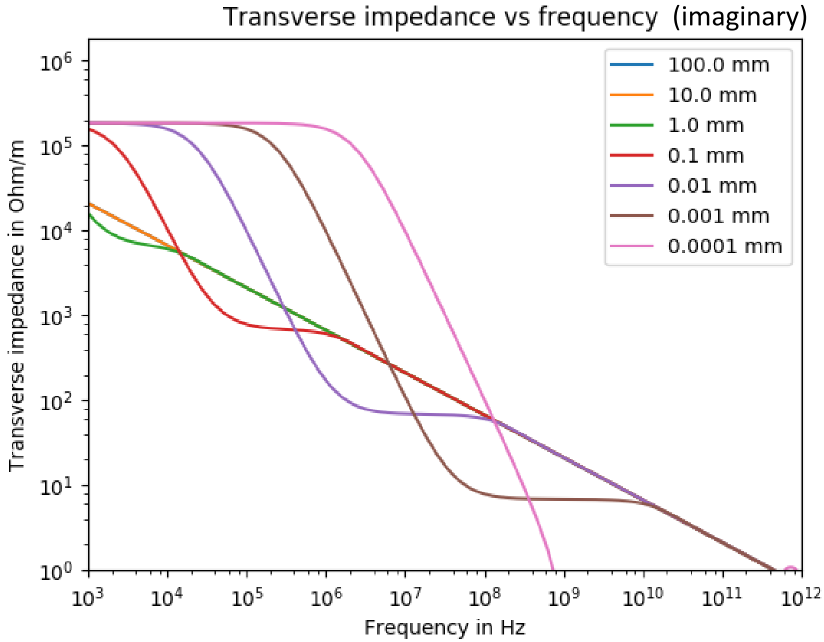


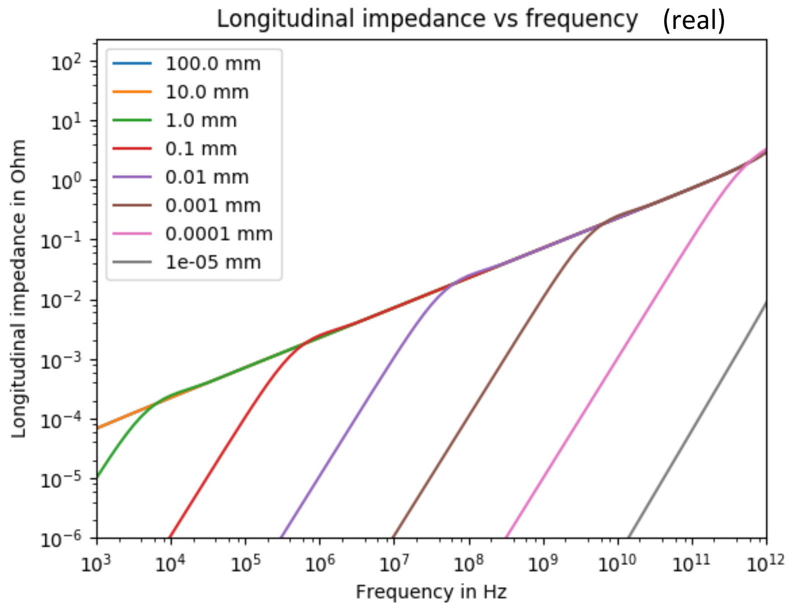
→ Skin depth is larger than the thickness
→ Fields escape → image currents have to stay closer to the beam → larger effective impedance

→ Skin depth is larger than the thickness
→ Fields escape → less power loss

→Not trivial, needs to compute solution every time

Impact of beam pipe thickness





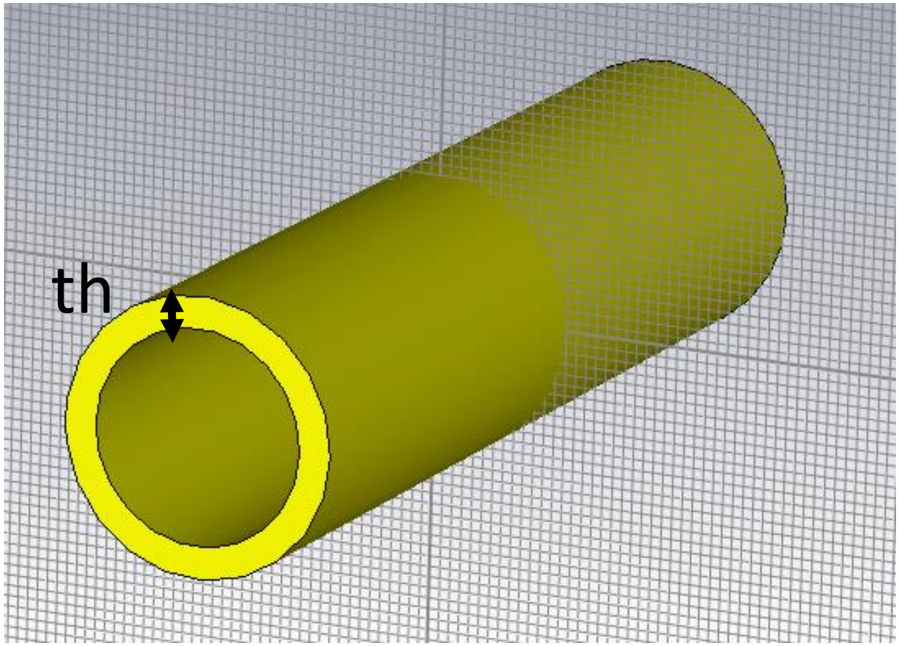
→ Change of sign of the difference with thick when thickness decreases

→ Always smaller when thickness decreases

→ Simple formula do not apply anymore

→ Strong impact of bunch length…

Impact of bunch length



File: 4_CASvacuum_compare_bunch_length-final.ipynb

Question: what is the effective transverse impedance for 1 m of copper beam pipe with thickness interacting with an rms bunch length of:

- 1 mm ESRF (0.012 ns)
- 1 cm MAX 4 (0.12 ns)
- 10 cm LHC (1.2 ns)
- 100 cm PS (12 ns)

Can we understand this behaviour?

Impact of bunch length

- The bunch length does not change the impedance itself, but changes the frequency range of interest.
- Beware: bunch length also comes in the computation of instabilities

Perturbation of transverse tune
Due to impedance

$$\Delta\omega_{m,q}^{x,y} = \left(|m| + 1 \right)^{-1} \frac{j\, e\, \beta\, I_b}{2\, m_0\, \gamma\, Q_{x0,y0}\, \Omega_0\, L} \left(Z_{x,y}^{eff} \right)_{m,q},$$

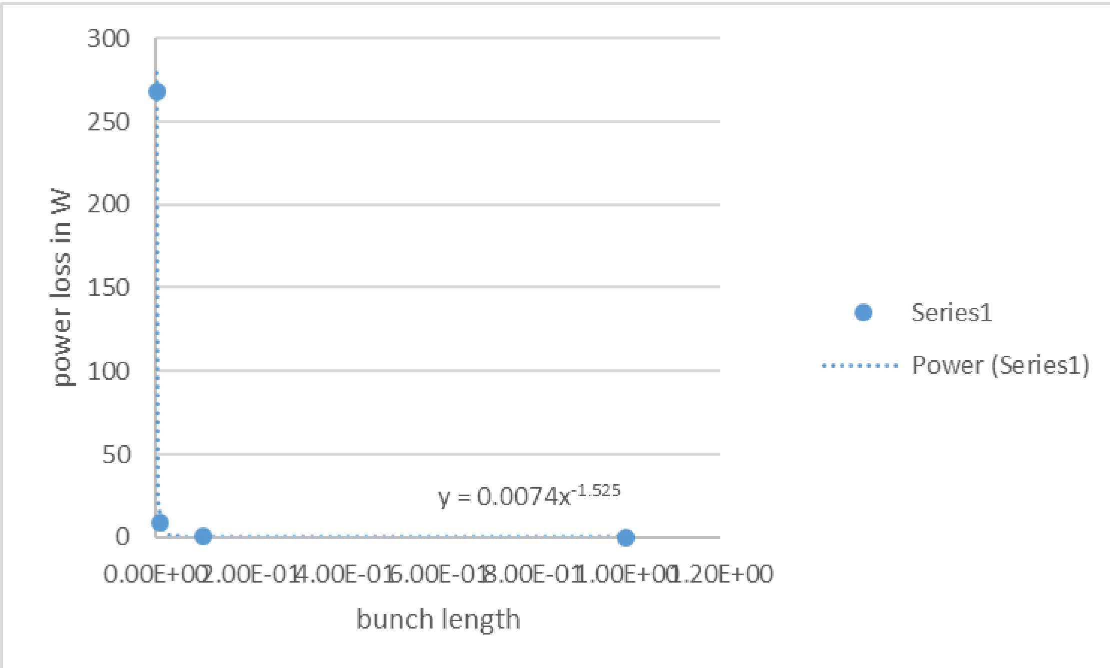
with

$$\left(Z_{x,y}^{eff} \right)_{m,q} = \frac{\sum_{k=-\infty}^{k=+\infty} Z_{x,y}\left(\omega_k^{x,y} \right) h_{m,q}\left(\omega_k^{x,y} - \omega_{\xi_{x,y}} \right)}{\sum_{k=-\infty}^{k=+\infty} h_{m,m}\left(\omega_k^{x,y} - \omega_{\xi_{x,y}} \right)},$$

→ In the end: beneficial impact of larger bunch length on instabilities
→ What works in one machine may not work in another!

Overview of Single-Beam Coherent Instabilities in Circular Accelerators", E. Métral, CARE workshop proceeding 2005 (pdf).

Impact of bunch length



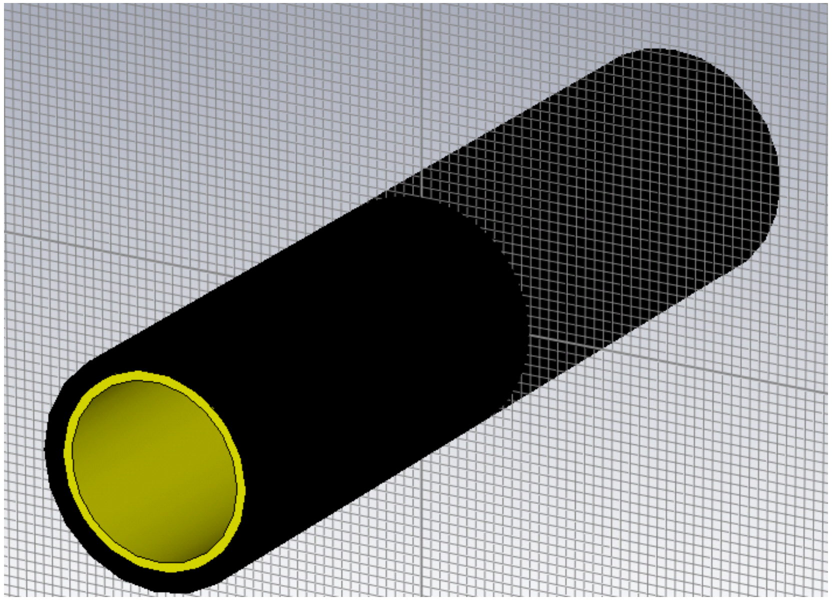
→ Ploss is proportional to sigma$^{-3/2}$

→ Machines with very small bunch length have more heating from resistive wall.

Impact of beam screen

1) Length
2) Radius
3) Conductivity
4) Thickness
5) Bunch length
6) Coating
    - Copper on stainless steel (good on bad conductor)
    - NEG on copper (bad on good conductor)

Case of copper coating on graphite



File:

5_CASvacuum_compare_CuSScoating-final.ipynb

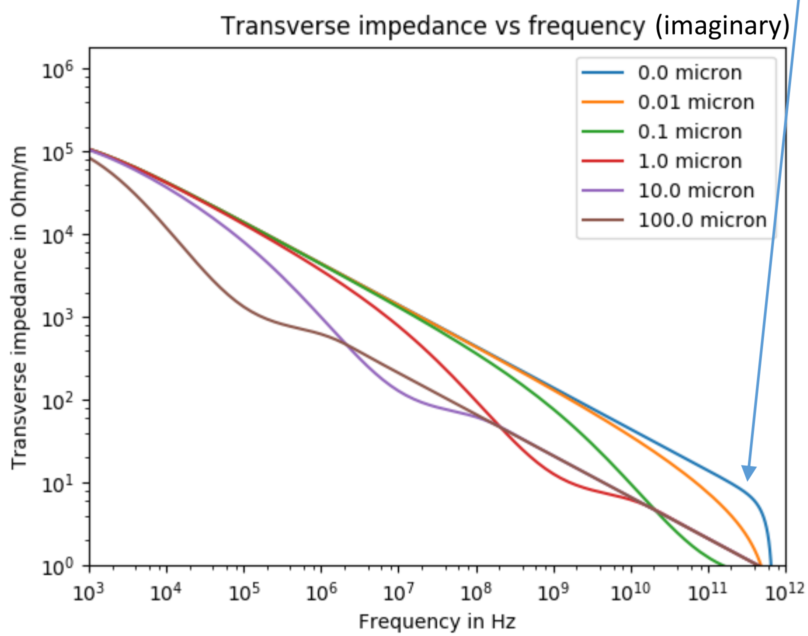
Question: what is the effective transverse impedance for 1 m of stainless steel beam pipe with a copper coating of thickness:

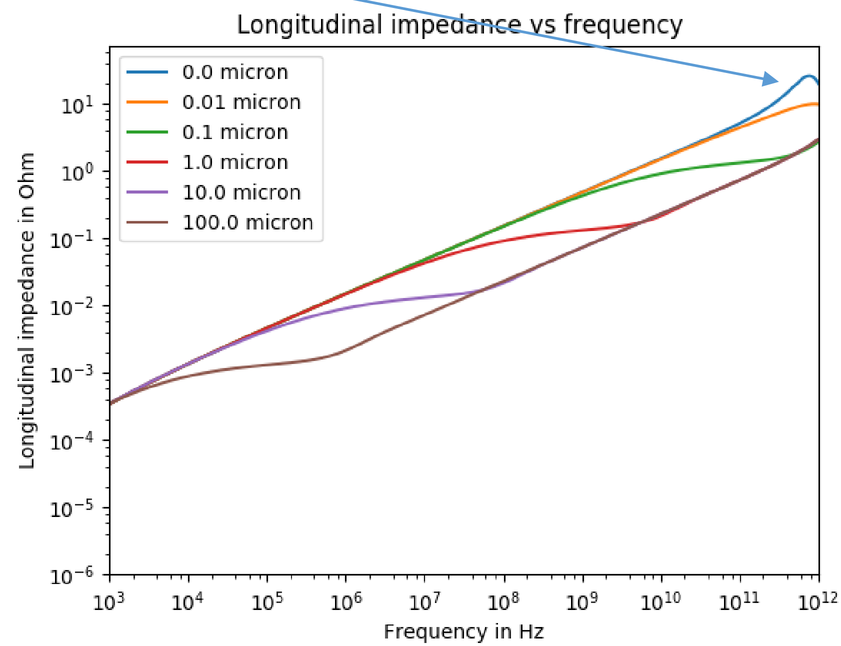
- 10 nm
- 100 nm
- 1 micron
- 10 micron
- 100 micron

Can we understand this behaviour? How much copper coating thickness is needed to recover the copper case?

Copper coating on stainless steel

Bare stainless steel



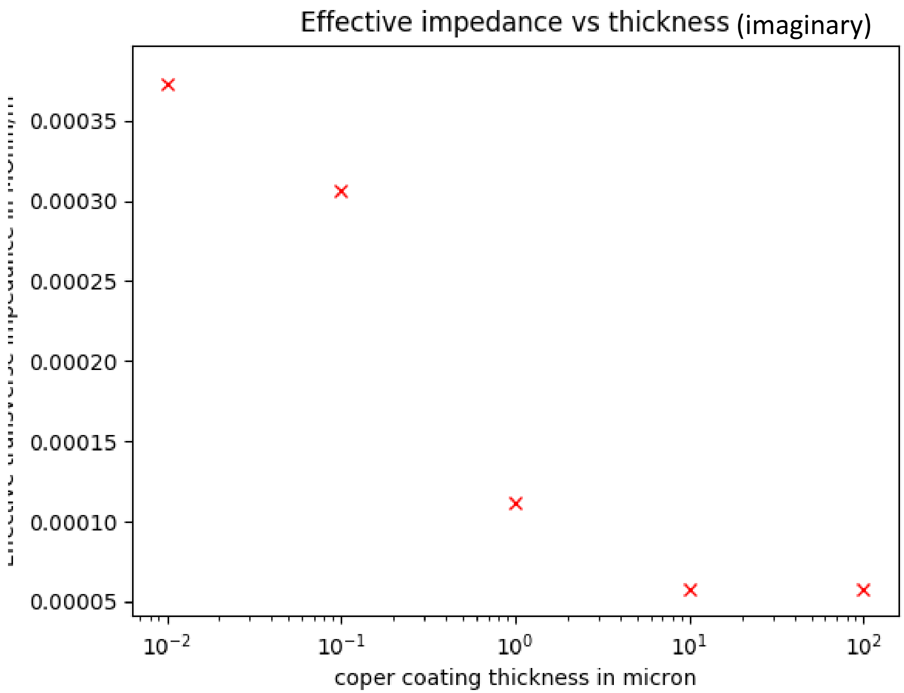


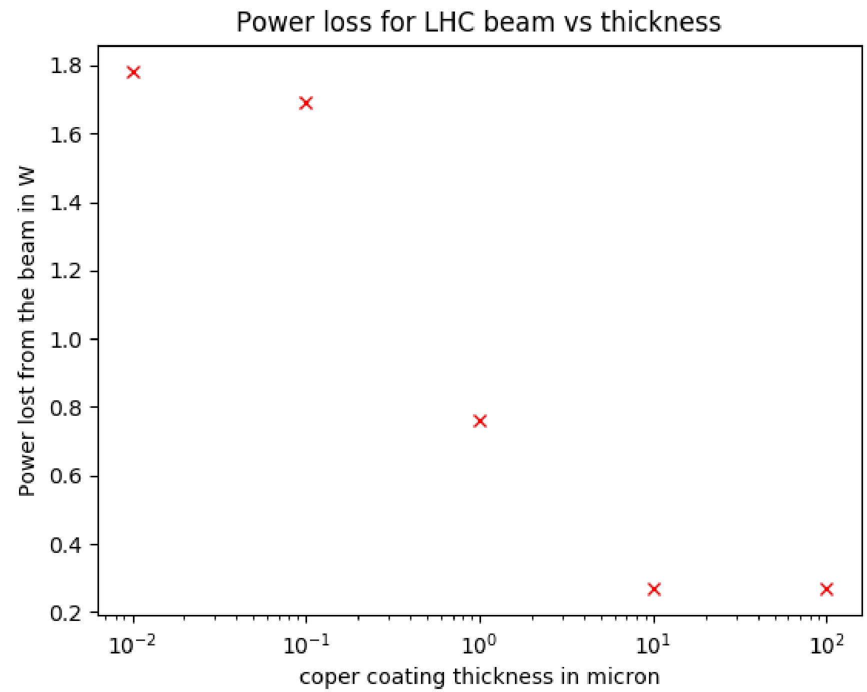
→ When skin depth is larger than the coating thickness, fields penetrate inside the stainless steel

→ Transition between "copper alone" line and "stainless steel" line depends on coating thickness

→ Very important to tune this transition with the bunch length to integrate over frequencies over which mainly copper matters, and not what is behind

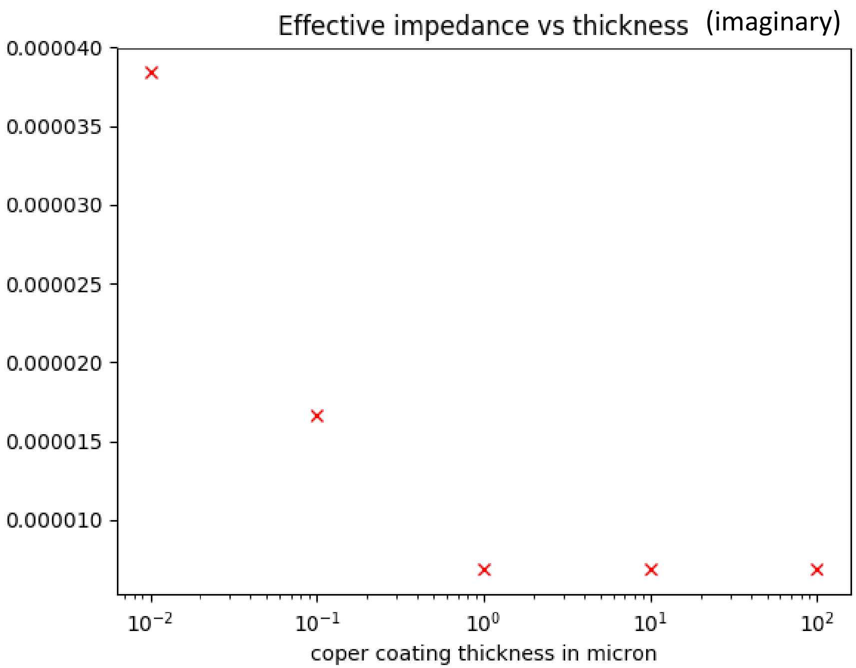
Copper coating on stainless steel

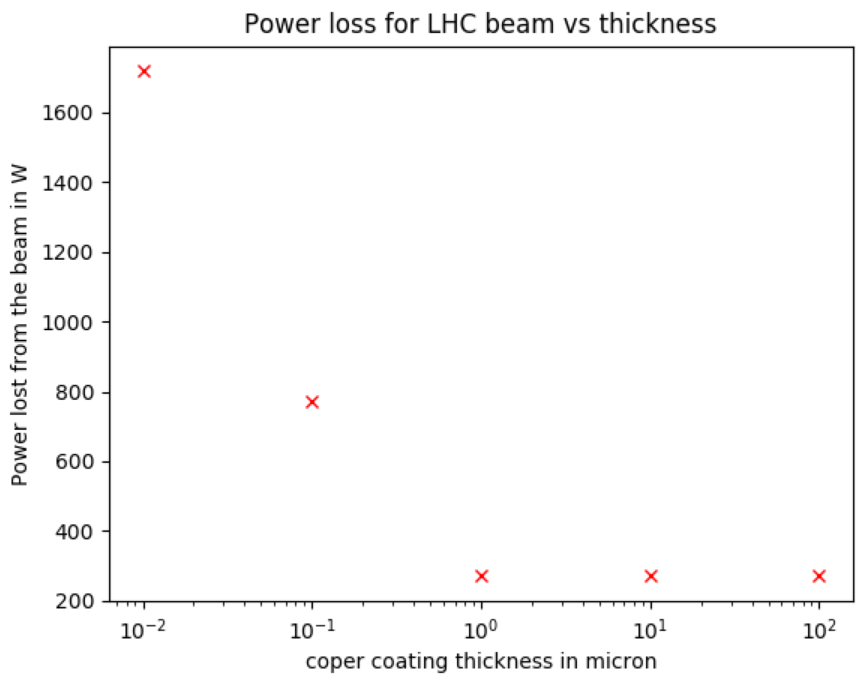




→10 microns of copper coating are enough to mimic a bulk copper for the LHC type beam (~10 cm bunch length)

Copper coating on stainless steel for ~1 mm bunch length





→ Integrate to higher frequencies for which the skin depth is smaller

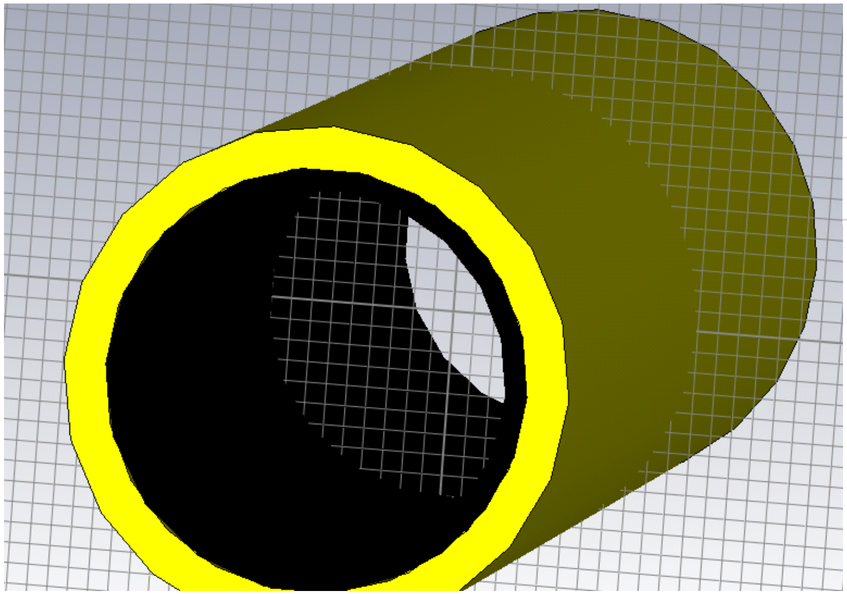
→ 1 microns of copper coating are enough to mimic a bulk copper for the LHC type beam (~10 cm bunch length)

→ Large factors can be gained! Coatings are very important to push performance!

Impact of beam pipe

1) Length
2) Radius
3) Conductivity
4) Thickness
5) Bunch length
6) Coating
   - Copper on stainless steel (good on bad conductor)
   - NEG, carbon and TiN on copper (bad on good conductor)

Case of NEG coating on copper



6_CASvacuum_compare_NEGcoating-final.ipynb

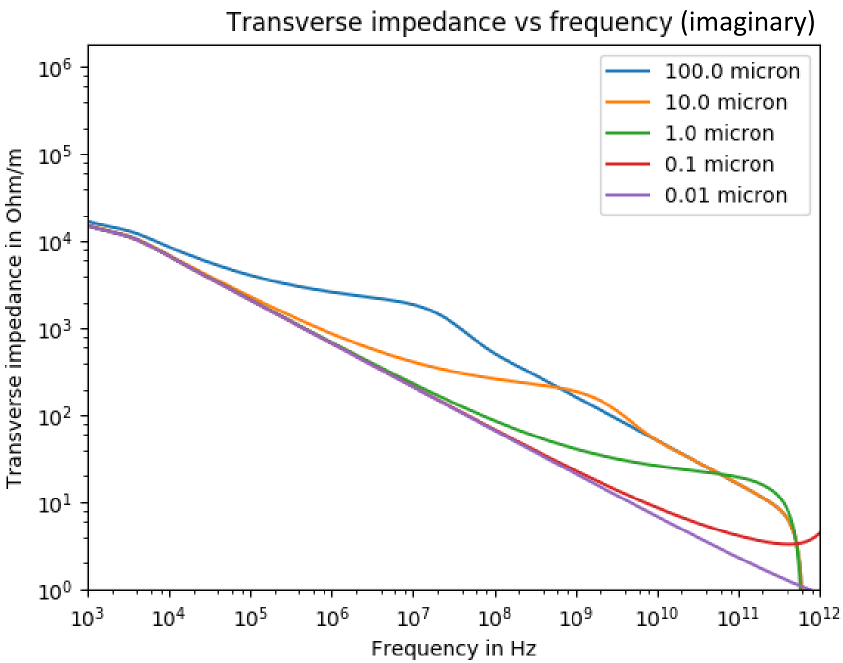
NEG: conductivity =1e6

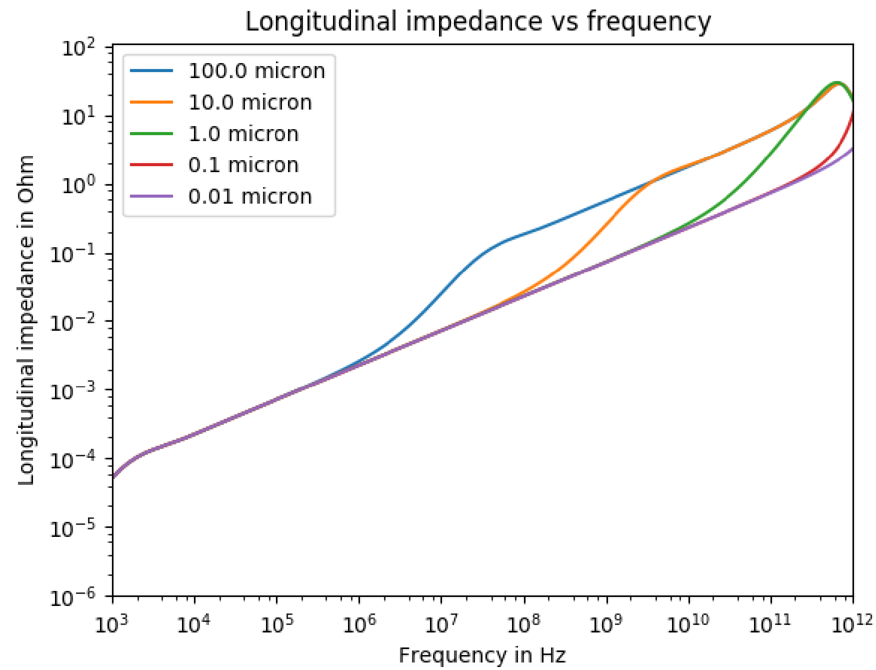
Question: what is the effective transverse impedance for 1 m of stainless steel beam pipe with a copper coating of thickness:

- 100 nm
- 1 micron
- 10 micron
- 100 micron

Can we understand this behaviour? How much NEG coating thickness is needed to minimize the impact of the NEG?

Case of NEG coating on copper

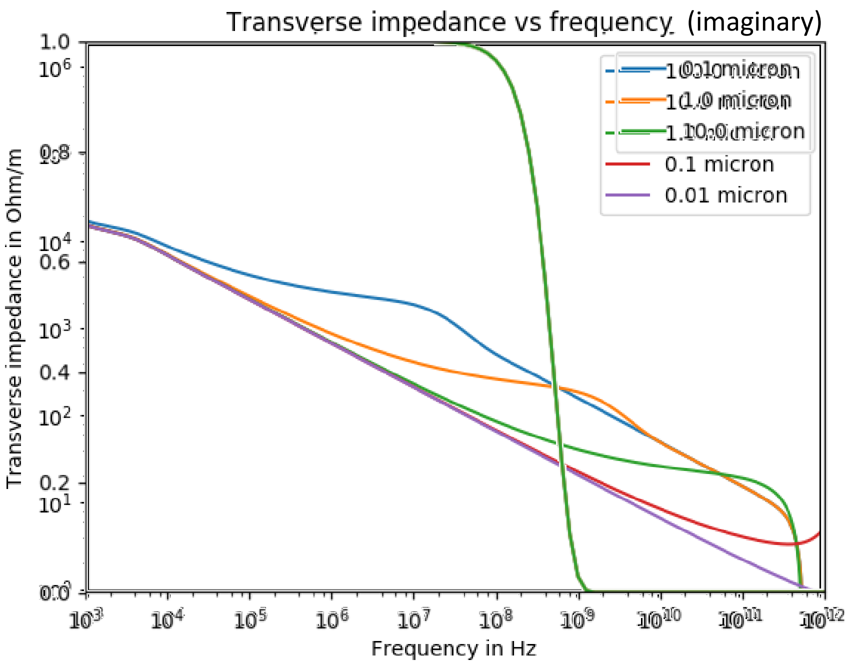


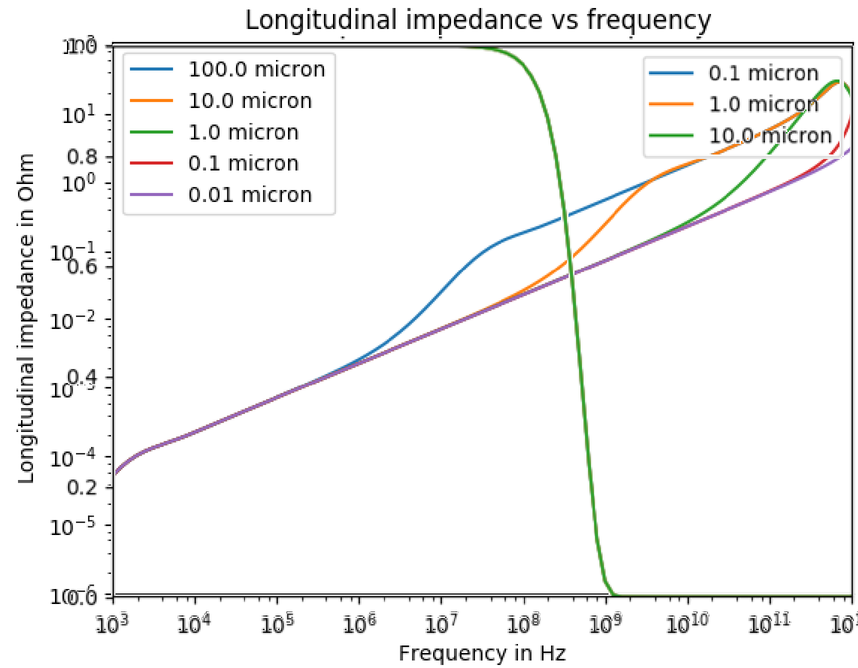


→ Same as before: slow transition from Copper alone to NEG alone

→ Impact of decrease of bunch length?

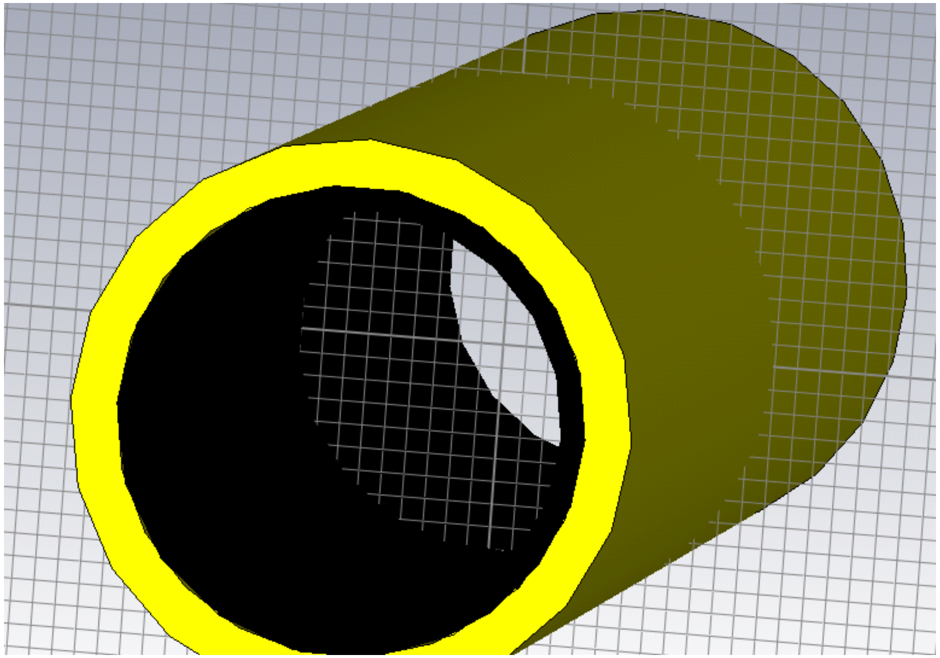
Case of NEG coating on copper





→ Same as before: slow transition from Copper alone to NEG alone
→ Impact of decrease of bunch length?

Case of carbon and TiN coating on copper



Try with carbon coating and TiN:
conductivity =1e4 S/m and 5e6 S/m

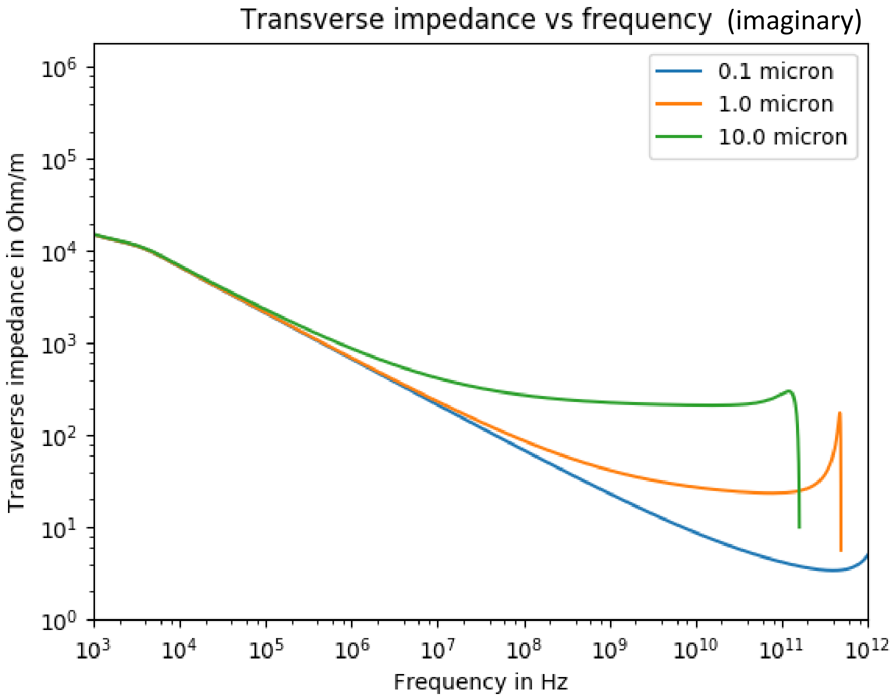
- 6_CASvacuum_compare_Carboncoating-final.ipynb
- 6_CASvacuum_compare_NEGcoating-final.ipynb
- 6_CASvacuum_compare_TiNcoating-final.ipynb

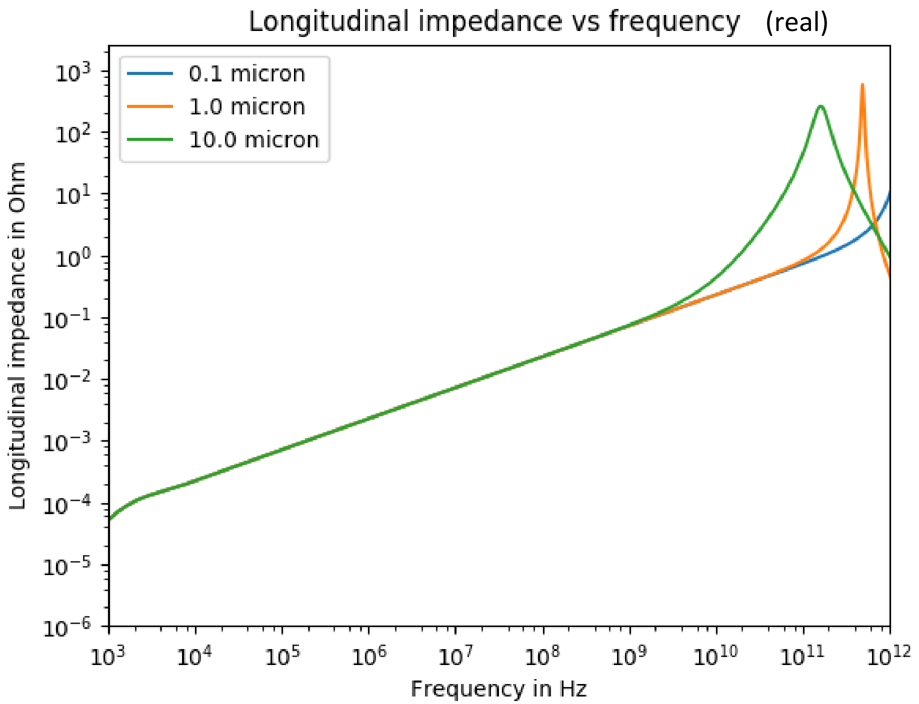
Question: what is the effective transverse impedance for 1 m of copper beam pipe with a carbon/TiN coating of thickness:

- 100 nm
- 1 micron
- 10 micron

Conclusion?

Carbon coating on copper

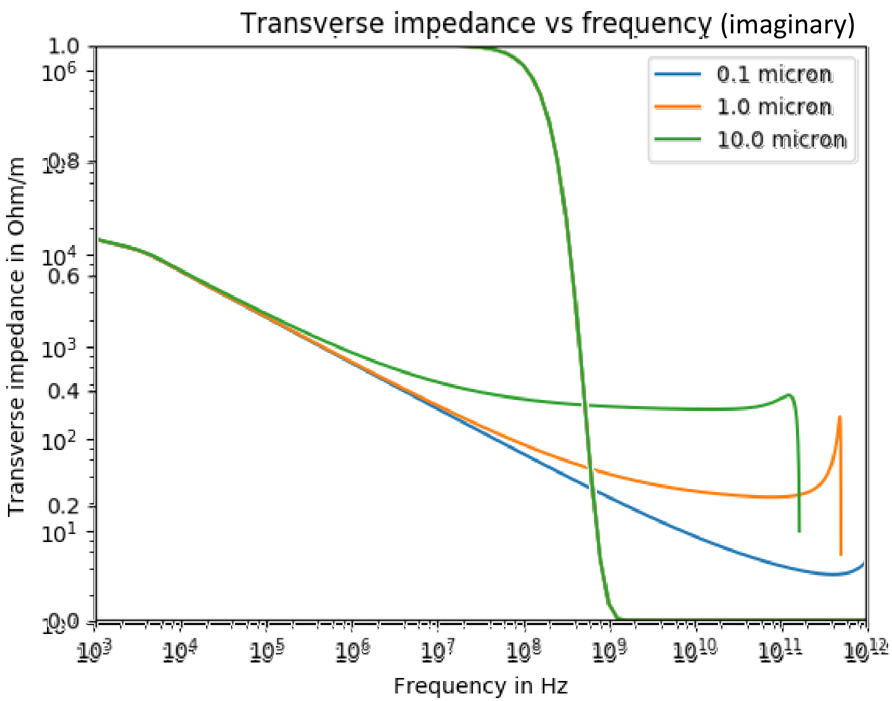


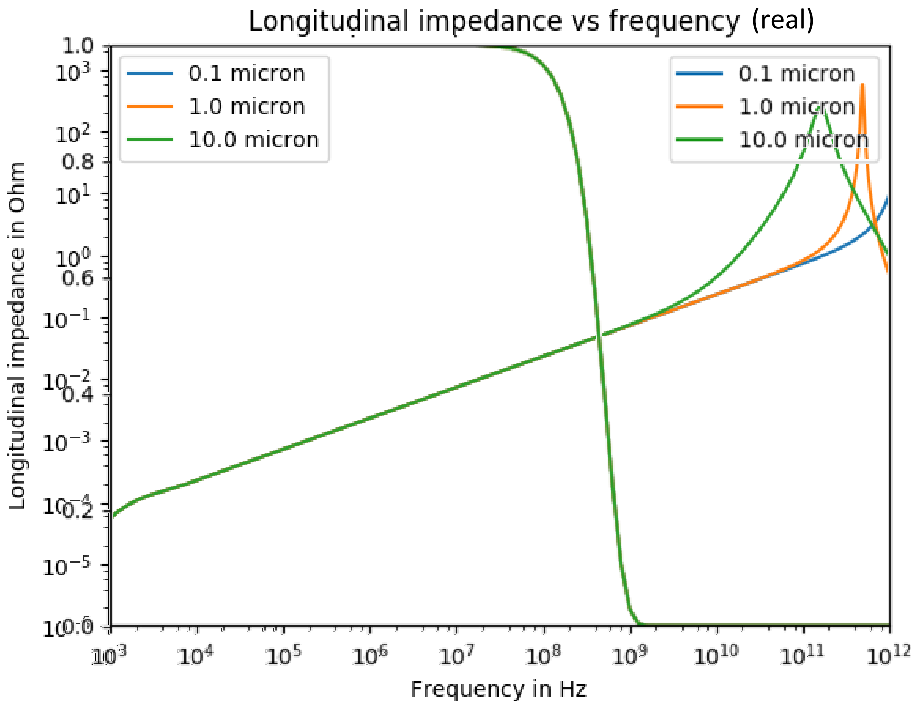


→ Large impact on effective imaginary impedance

→ Small impact on real impedance → almost no power loss

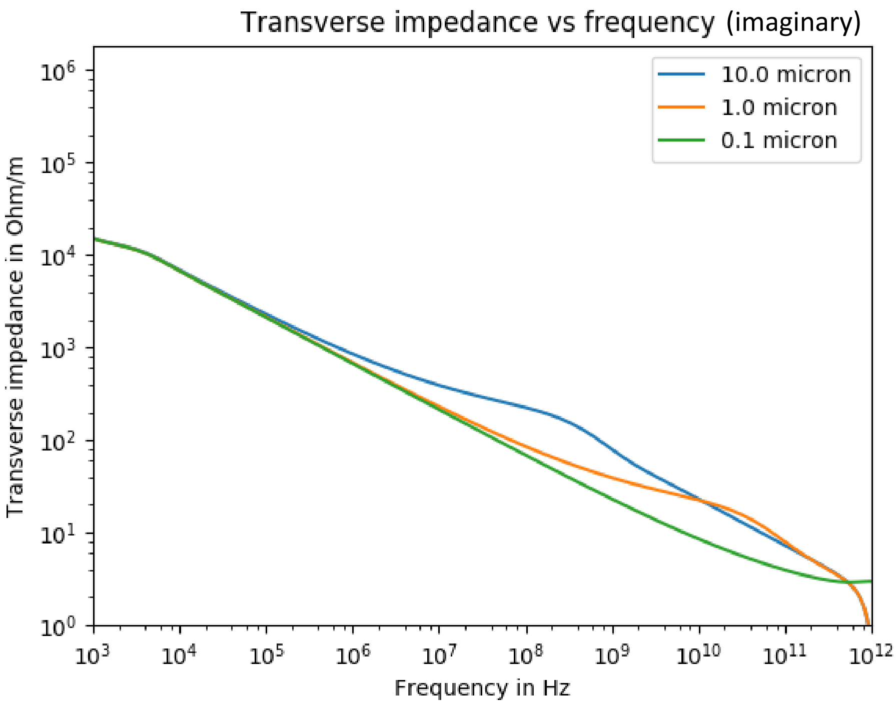
Carbon coating on copper

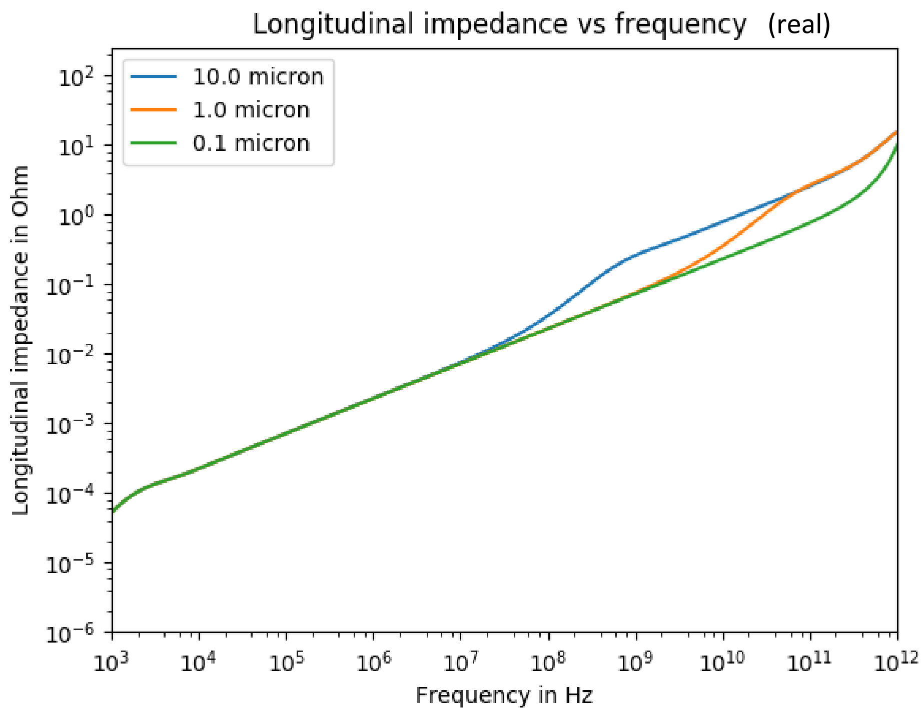




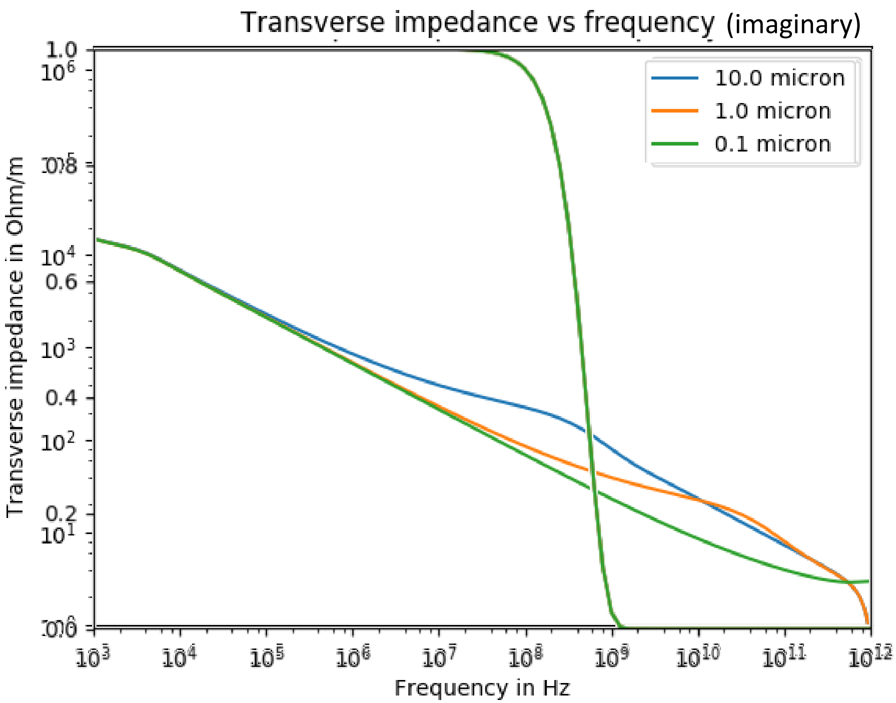
→ Large impact on effective imaginary impedance as the fields are dephased by the thin layer
→ Small impact on real impedance → almost no power loss in the coating
→ How does this change with decreasing bunch length?

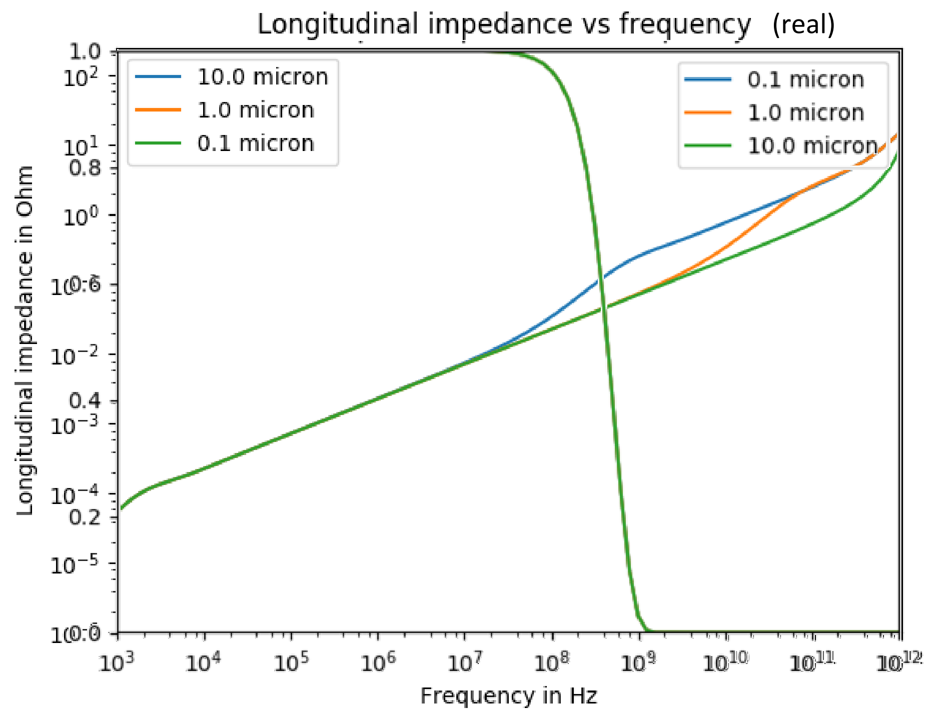
TiN coating on copper





TiN coating on copper

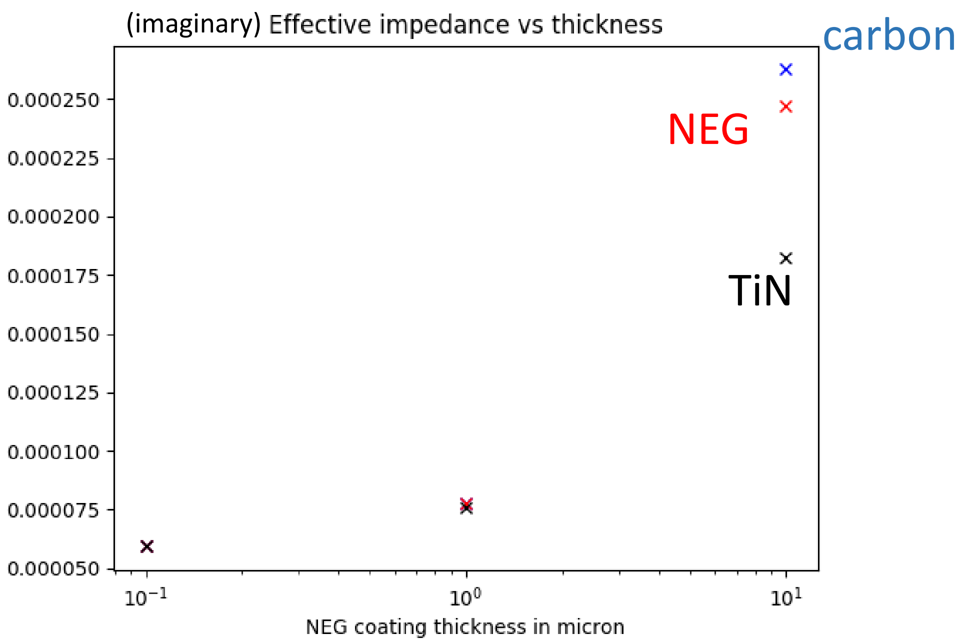


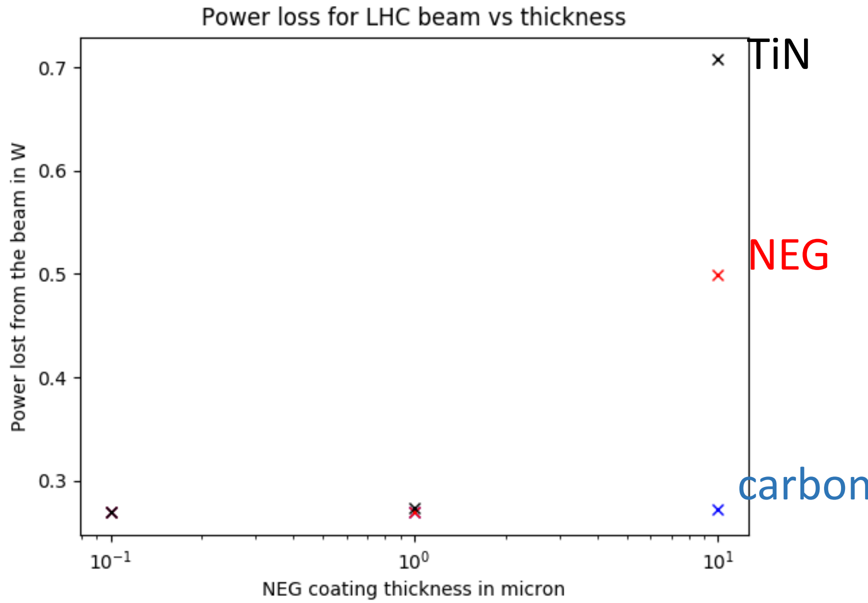


→ also impact on effective imaginary impedance

→ larger impact on real impedance as more currents are contained in the TiN layer for the same frequency

Case of carbon and TiN coating on copper





Important conclusion:

- If coating thickness is low enough, limited impact and **independent of conductivity**
- **Better conductivity is not always better**
- **Very strong impact of bunch length**

Just for fun…

- Replace copper by dielectric (high resistivity 4e12 Ohm.m and epsilon’=5).

Try your own beam and vacuum chamber parameters

- Who wins for power loss?

Materials: what have we learnt?

Assignment #1

Find out a trade-off for power loss, longitudinal impedance, transverse impedance and SEY of the current design of the FCC-ee beam screen:

- Carbon coating
- NEG coating
- Laser treatment
- TiN coating
- No coating
- Other ideas?
- High temperature superconductor

• Substrate:

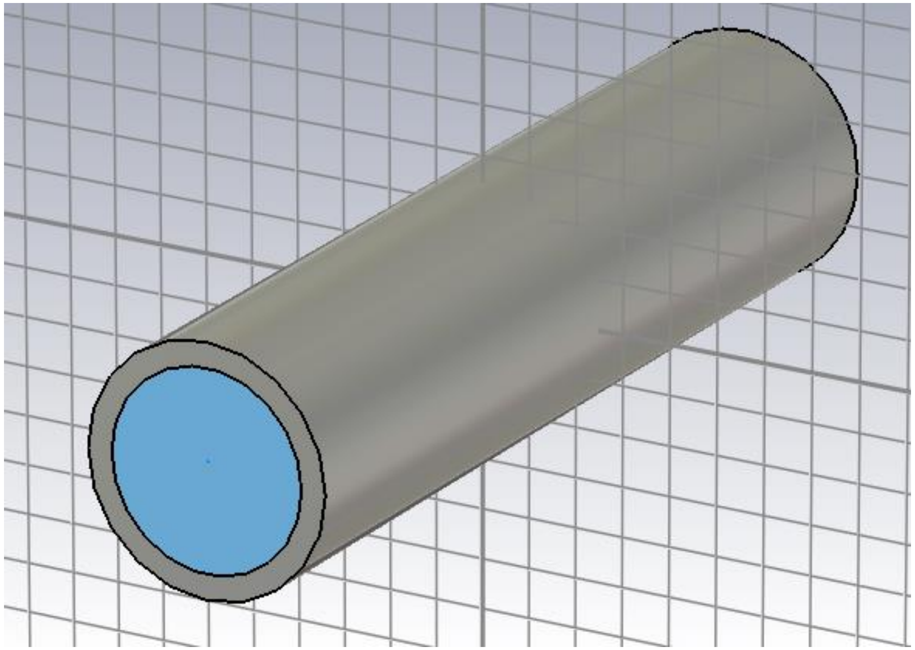
- Stainless steel
- Copper
- Other ideas

References: R. Kersevan FCC week 2017 Berlin
https://indico.cern.ch/event/556692/contributions/2487640/attachments/1468449/2271161/FCC-Berlin-HS.pptx
E. Belli et al, FCC week 2017 Berlin
https://indico.cern.ch/event/556692/contributions/2590409/attachments/1468391/2271528/FCCWeek2017_Belli_CollectiveEffectsFCCee.pptx

Simulations

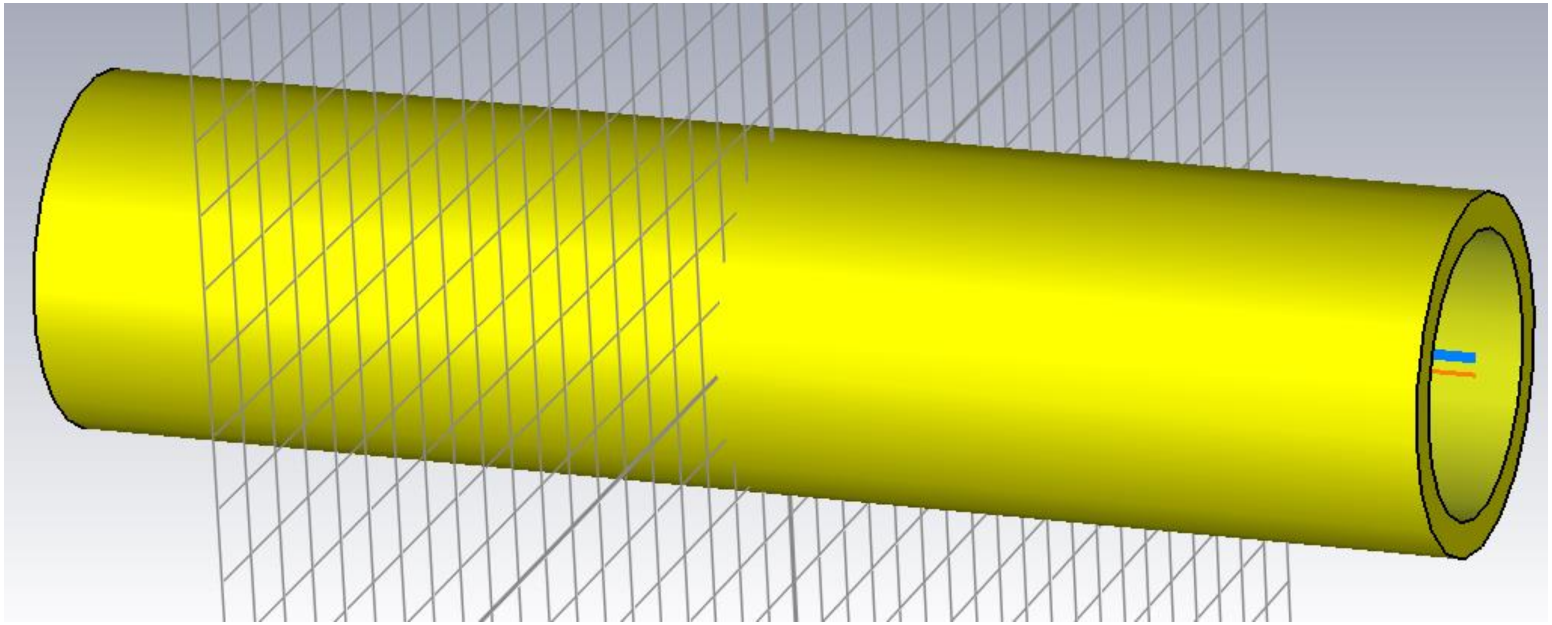
- tubes
- Bellows
  - Impact of number of convolutions
  - Impact of convolution depth
  - Impact of pipe radius
- Cavities
  - Impact of radius and length
  - Tapers
  - Shielding with fingers
  - Funnelling?

Perfect conducting tube:
file: 1_PECtube.cst



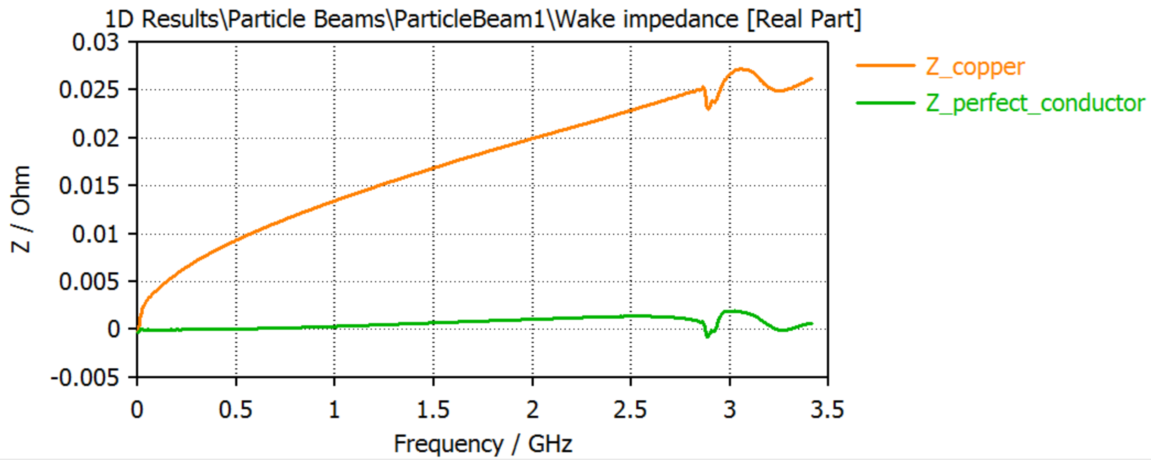
- Question: what impedance do we expect?
- How do you interpret what you see?
- Look at the 3D fields to see the beam fields and the wakefields

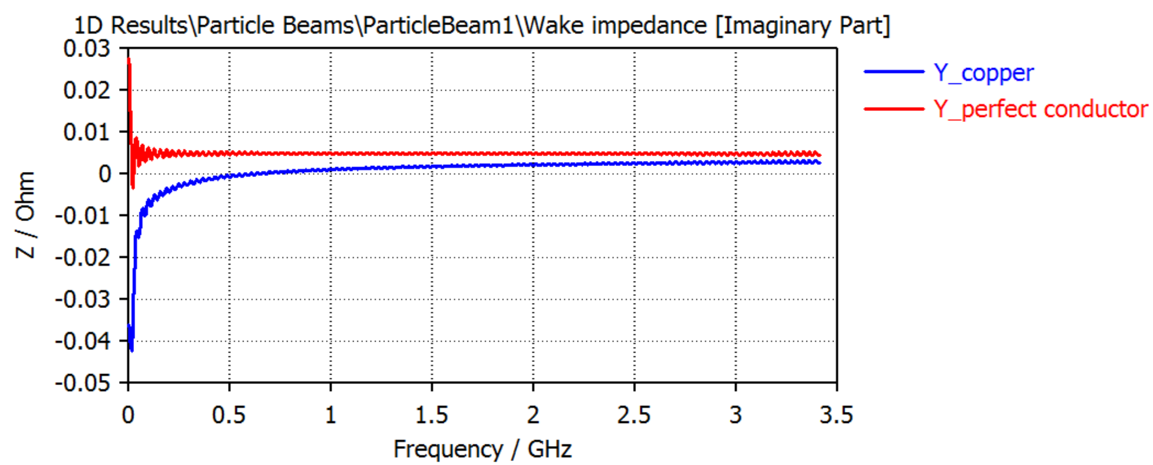
Copper conducting tube:
file: 2_coppertube.cst



- Question: what is the difference?
- do we recover what we computed with the analytical tool?

Comparing perfect conducting tubes

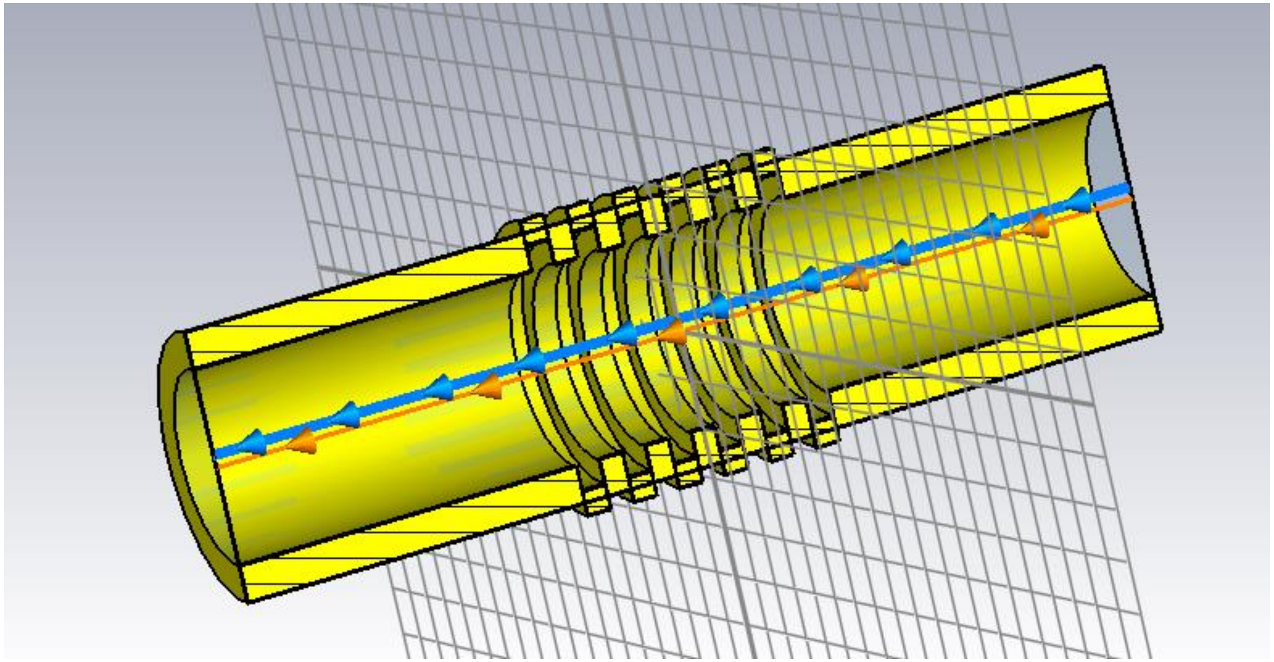




→ conclusion: beware of numerical noise!

→ When impedance is already well optimized, relative error bar increases

Bellow:
file 3_bellow_PEC.cst

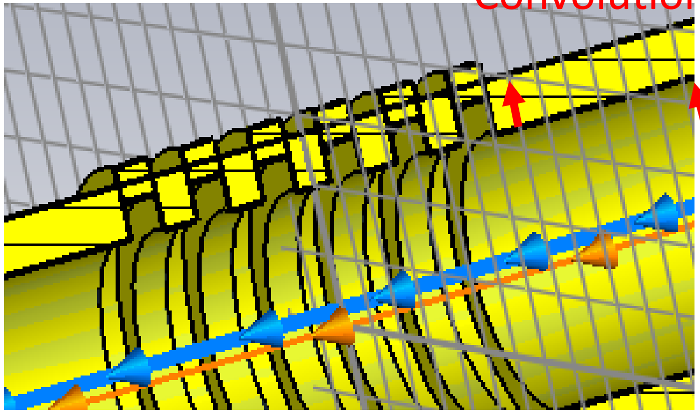


Number of convolutions can be varied (in pair) with ***n_conv***.
Here ***n_conv***=3.
Convolution depth and length can be varied with ***conv-depth*** and ***conv_length.***
The pipe radius can be changed with ***inner_radius***

- Question: what are the major differences with the pipe without convolutions in the impedance spectra?
- Can you find the dependence of the impedance properties (low frequency contributions and mode frequencies) with the convolution depth, convolution length, pipe radius and number of convolutions?

Formula for bellows

Theory: K. Ng
http://lss.fnal.gov/archive/fn/FN-0449.pdf



Longitudinal effective impedance

$$\frac{Z_\parallel}{n} = j\frac{Z_0\beta\ell}{2\pi R}\ln\frac{b+\Delta}{b}$$

Proportional to l*Δ/b if Δ<<b

Transverse effective impedance

$$Z_\perp = j\frac{Z_0\ell}{2\pi}\left[\frac{1}{b^2}-\frac{1}{(b+\Delta)^2}\right].$$

Proportional to l*Δ/b^3 if Δ<<b

→ Linear impact of convolution depth and overall bellow length
→ Strong impact of the radius

Bellows contributions

Let's assume:

- n_conv=3
- inner_radius= 20 mm
- conv_length=8 mm
- conv_depth=8 mm

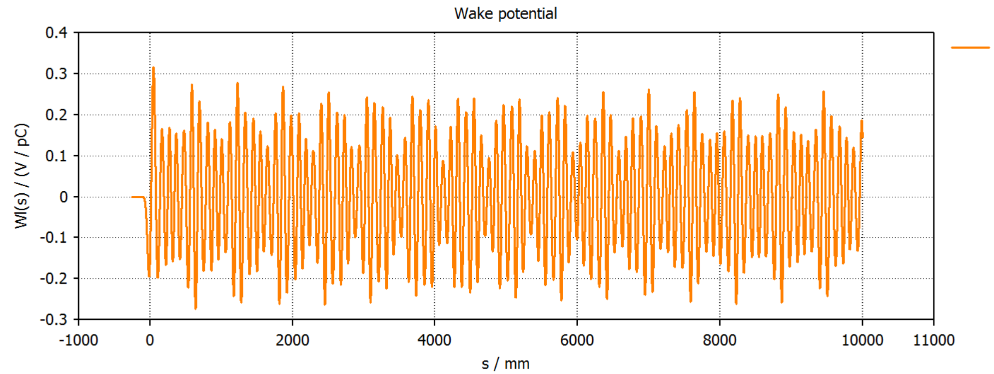
How many such bellows could we install in LHC if the full LHC budget at injection was allocated to bellows (2 MOhm/m in the transverse plane and Z/n=0.1 Ohm in the longitudinal plane)?

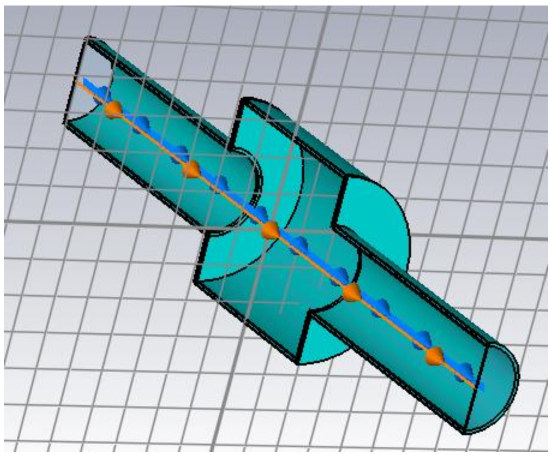
To how much length of 20 K cold copper beam pipe does 1 bellow correspond to for the transverse plane?

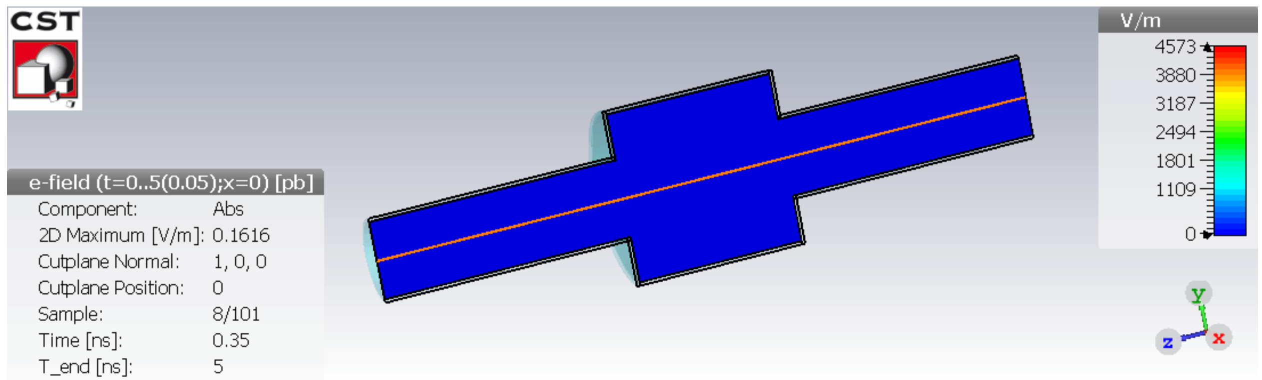
→ conclusion: please avoid bellows whenever possible or shield them!

Cavity:

file: 5_cavite_wake.cst



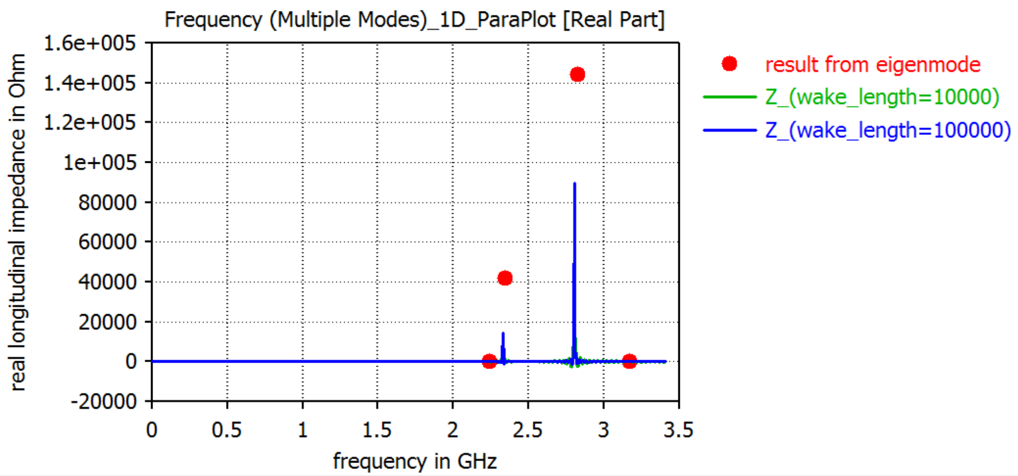


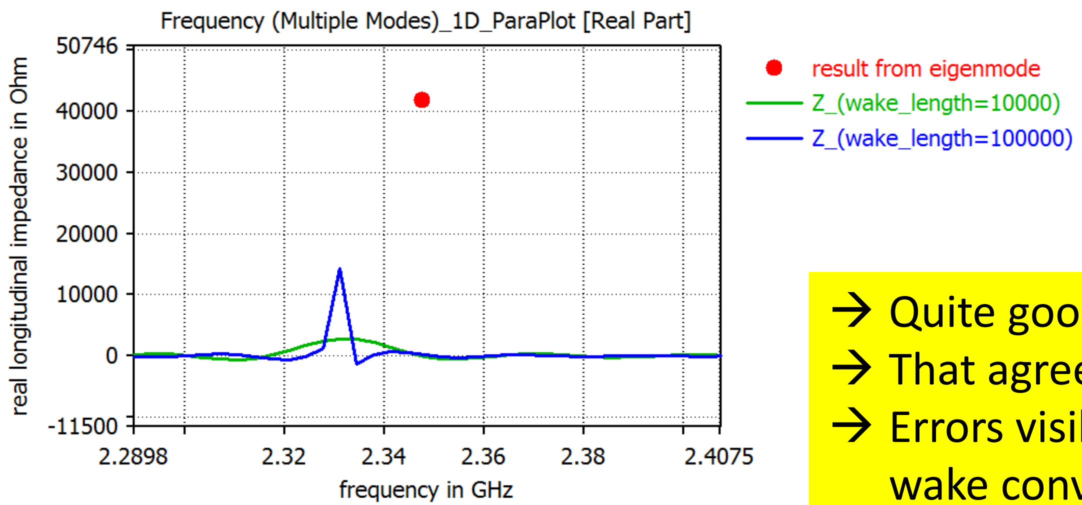


→ Resonant modes resonate for ever in the structure if the structure is a good conductor
→ Eigenmode simulations are better suited to quantify resonant modes

Cavity with eigenmode solver

file 5_cavite.cst

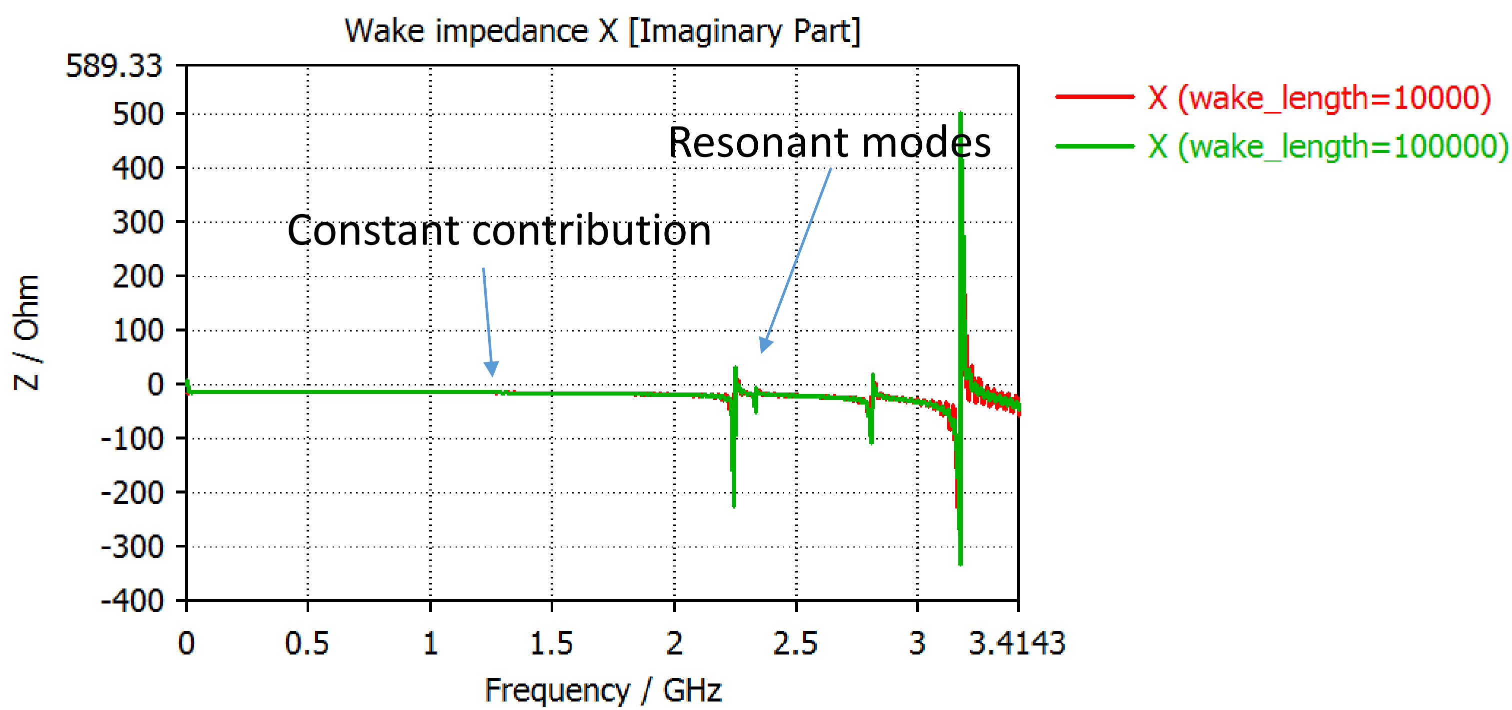




- → Quite good agreement between solvers
- → That agreement is necessary to trust the results
- → Errors visible on frequency (~20 MHz) and wake convergence

Cavity impedance: what should be watched?

- Low frequency contribution in particular before the first main resonant modes (impact proportional to the sum of R/Q of all modes)
- Resonant modes themselves (impact proportional to R)



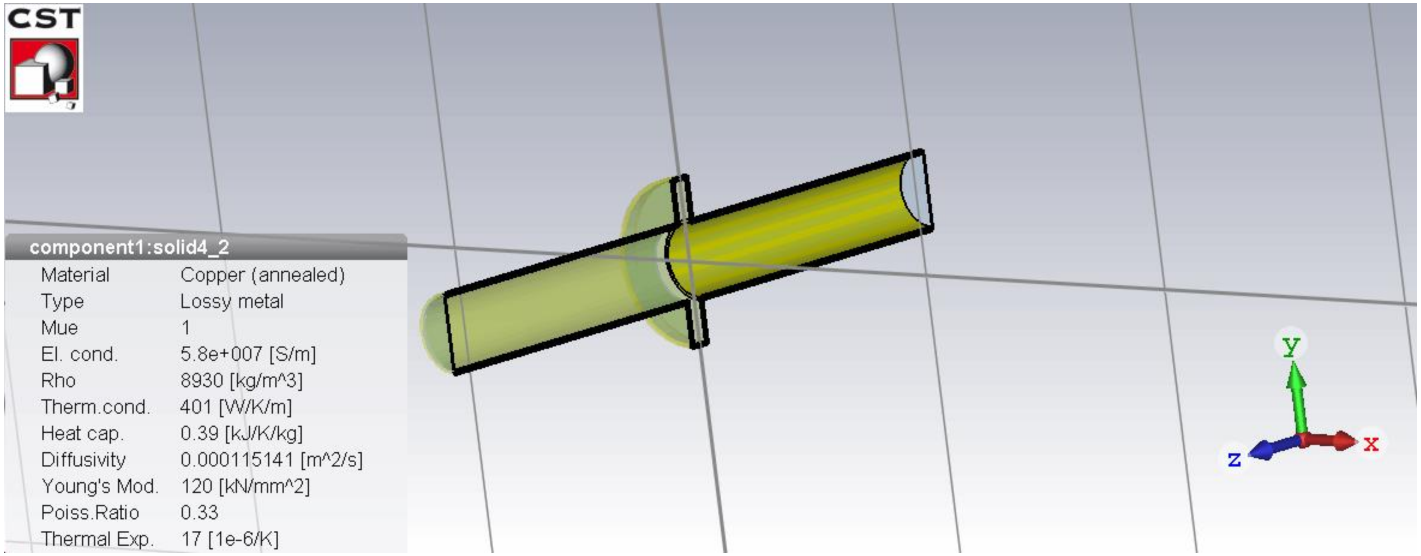
→ True for longitudinal and transverse impedance contributions
→ How can we reduce these contributions?

Mitigating cavity modes?

- Changing the shape
- Changing the material
- Using taperings
- Shielding the cavity with RF fingers

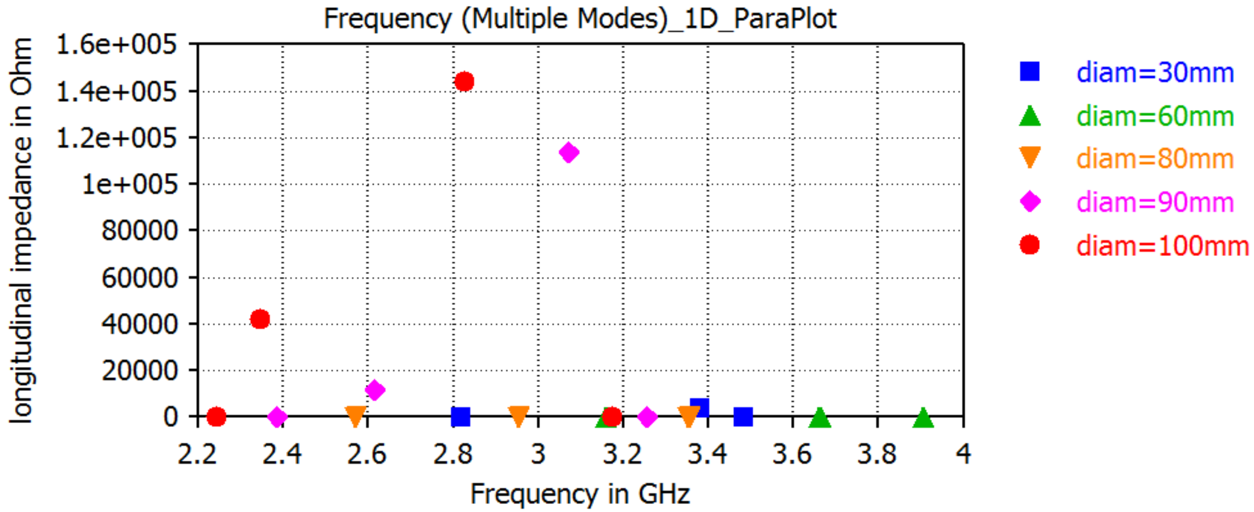
Mitigating cavity modes: changing dimensions

- Simulate changes of radius and length of the cavity
- File: 5_cavity_dimensions.cst



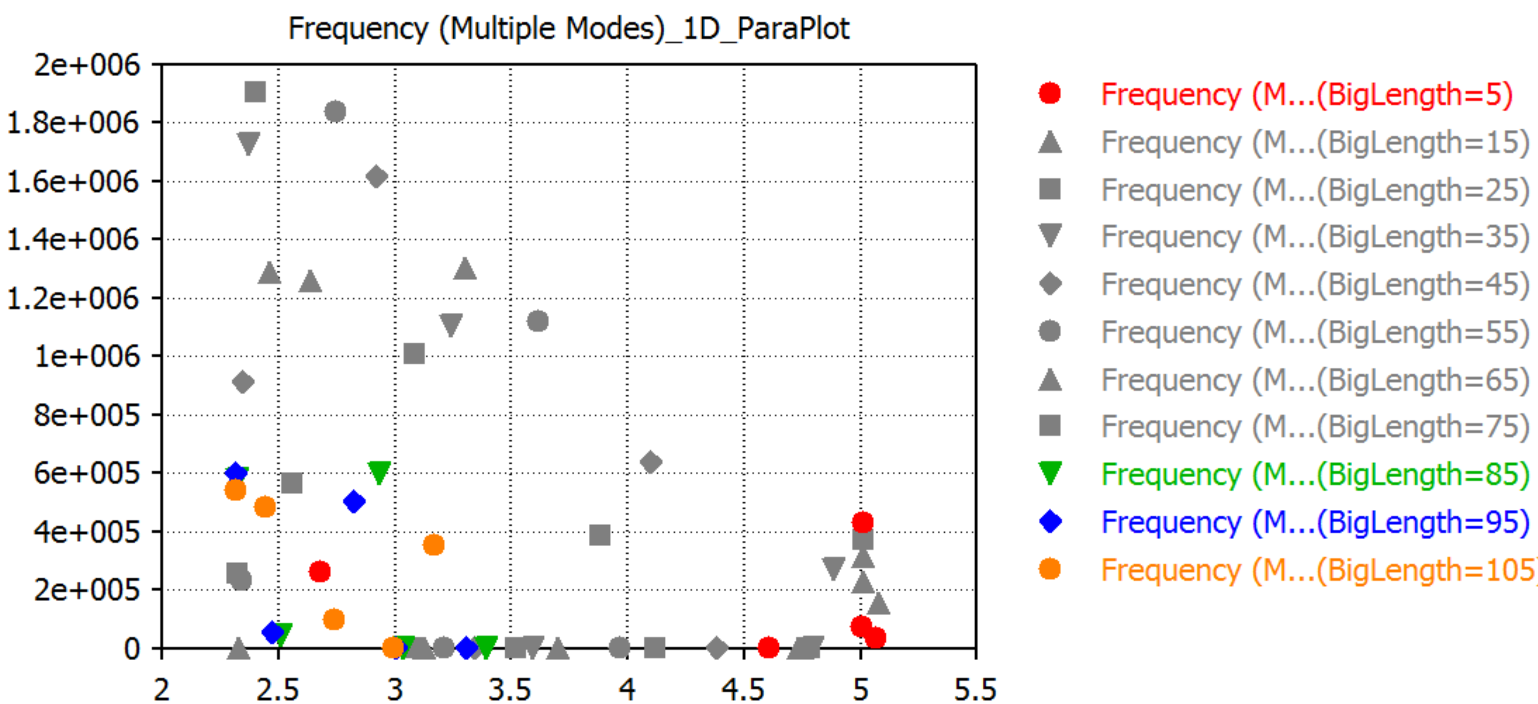
Outcome (1)

- Q factors more or less constant
- Reducing the diameter clearly helps with reducing the shunt impedance R



Outcome (2)

- Changing the length: the cavity should be very short or very long, but avoid the order of magnitude of the radius.



Mitigating cavity modes?

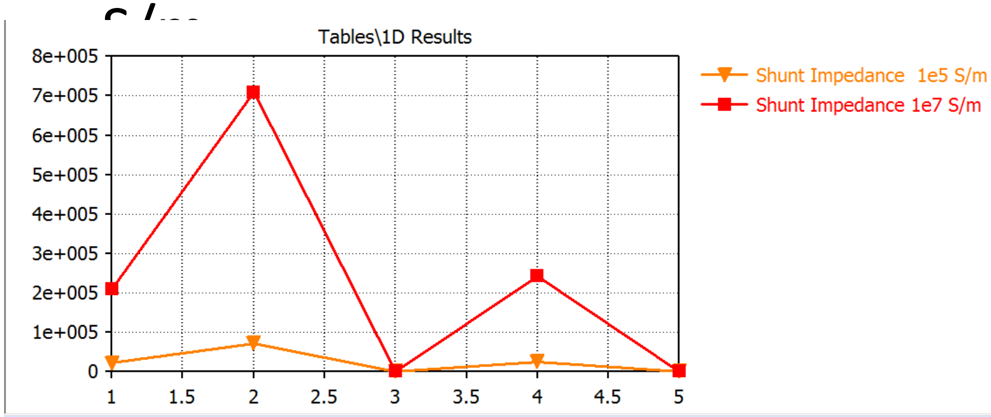
- Changing the shape
- Changing the material
- Using taperings
- Shielding the cavity with RF fingers

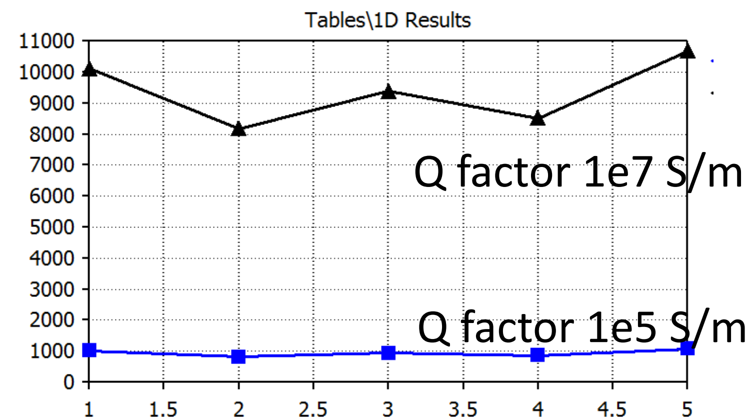
Mitigating cavity modes: changing materials

File: 5_cavity_material.cst

[note the parameter sweep does not work].

Change the conductivity of the material from 1e6 S/m to 1e7 S/m

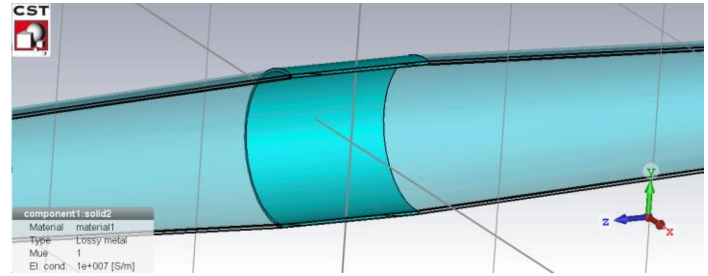


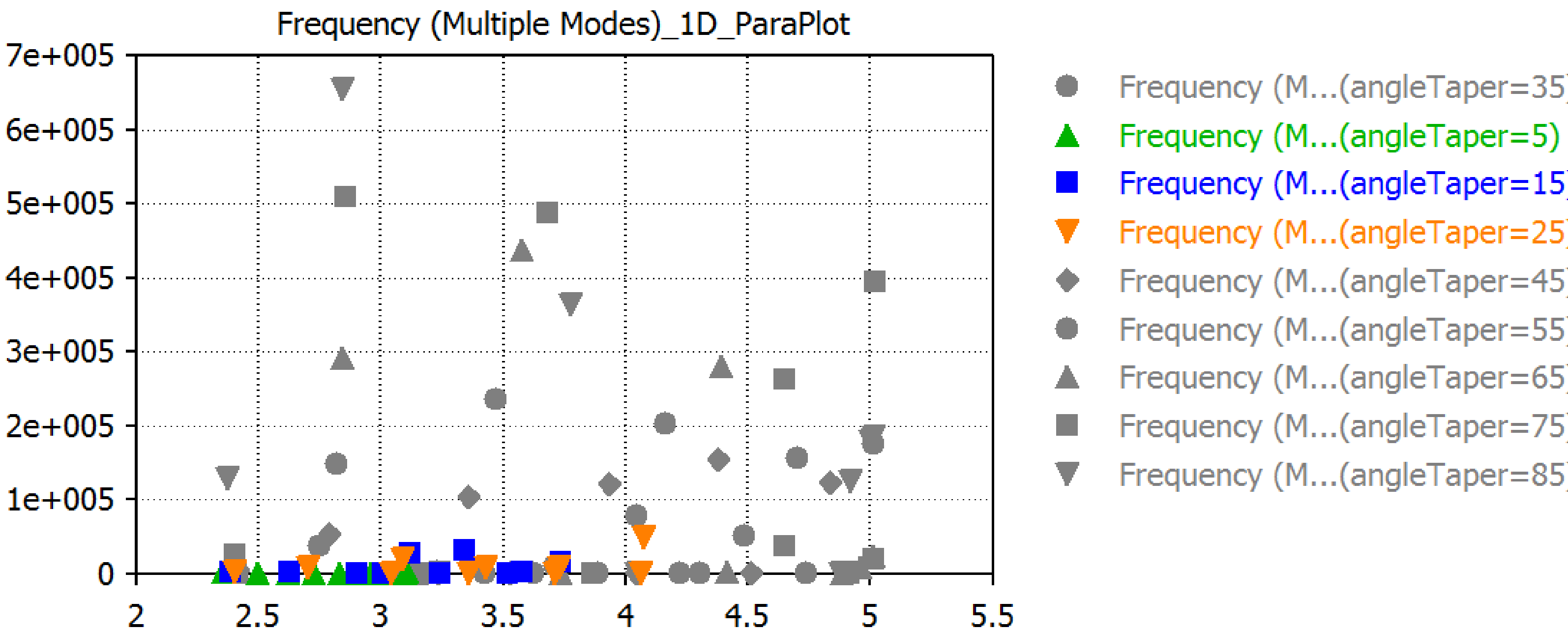


→ Q factors and shunt impedances R scale both with sqrt(sigma)
→ R/Q depends little on the material, but R can be reduced by increasing material losses
→ If losses are deliberately generated by decreasing Q and R, the lossy material should be able to sustain the remaining power loss

Mitigating modes: adding tapers

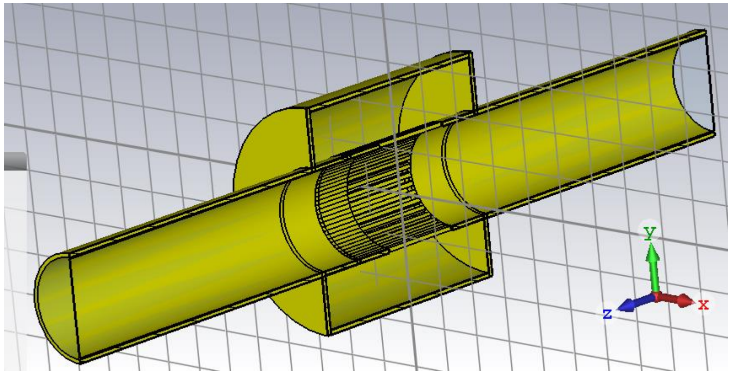
File: 5_cavity_taper.cst



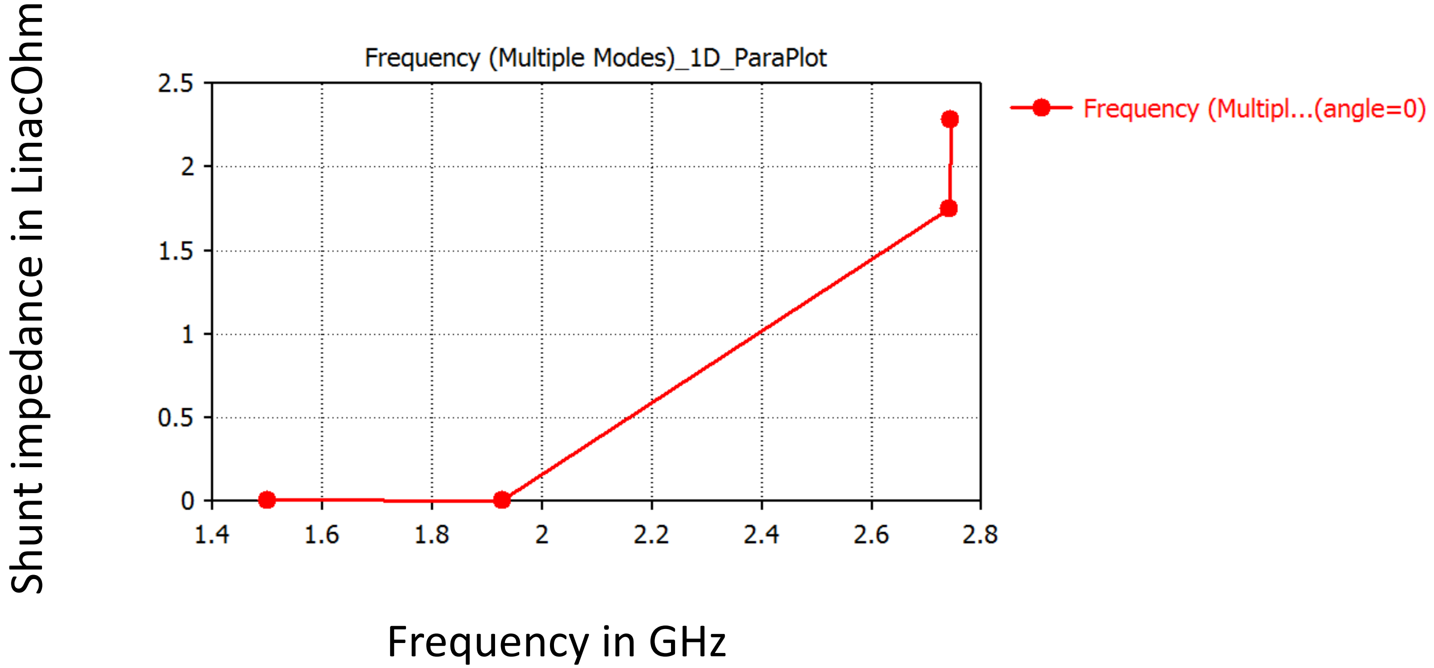


→ Tapers help but do not suppress the modes

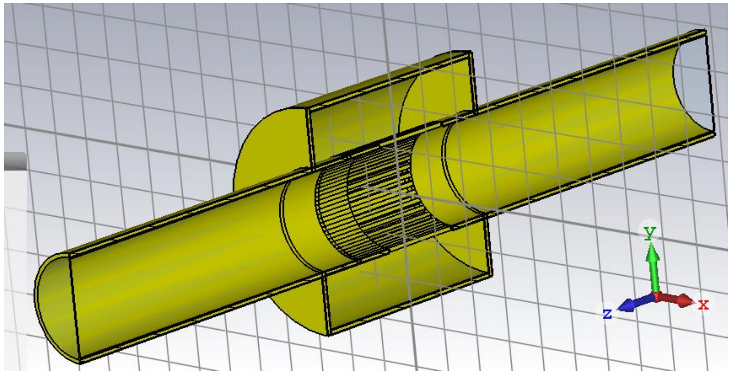
Mitigating modes: shielding with RF fingers



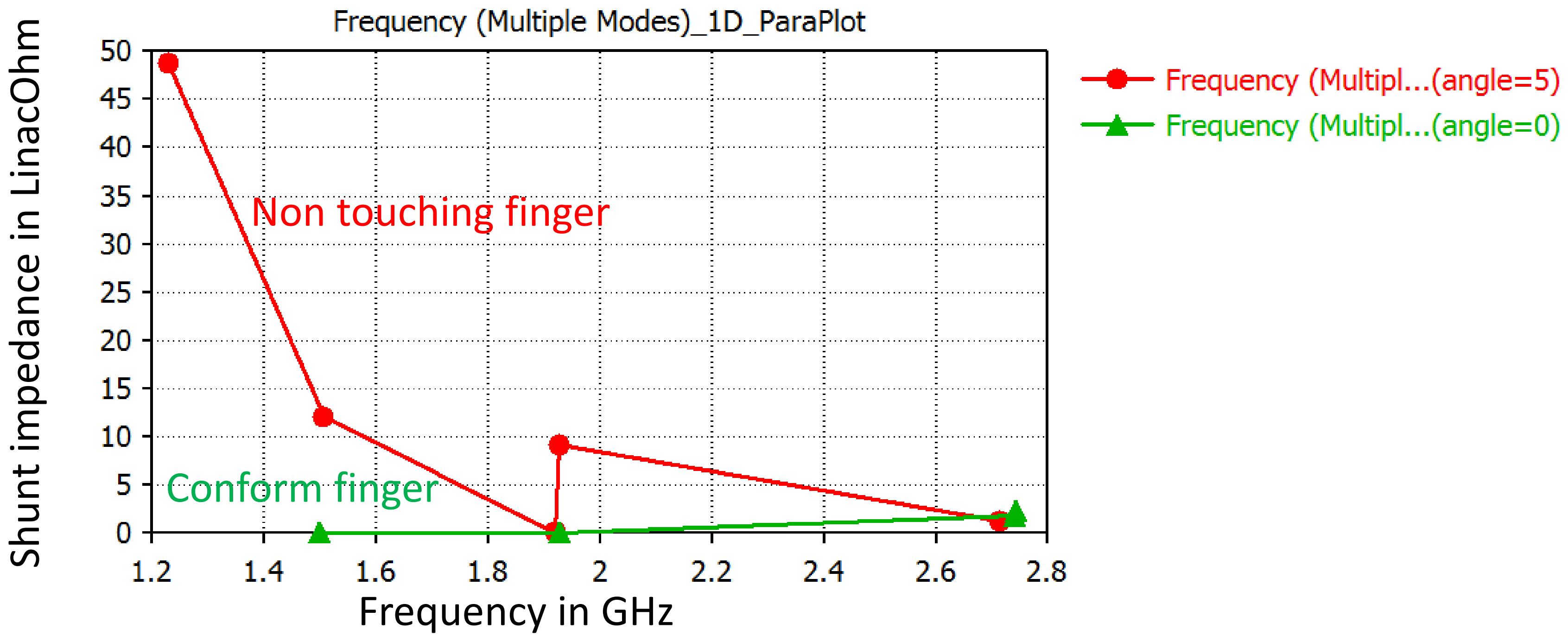
File: 5_cavity_PIMS.cst



Mitigating modes: shielding with RF fingers

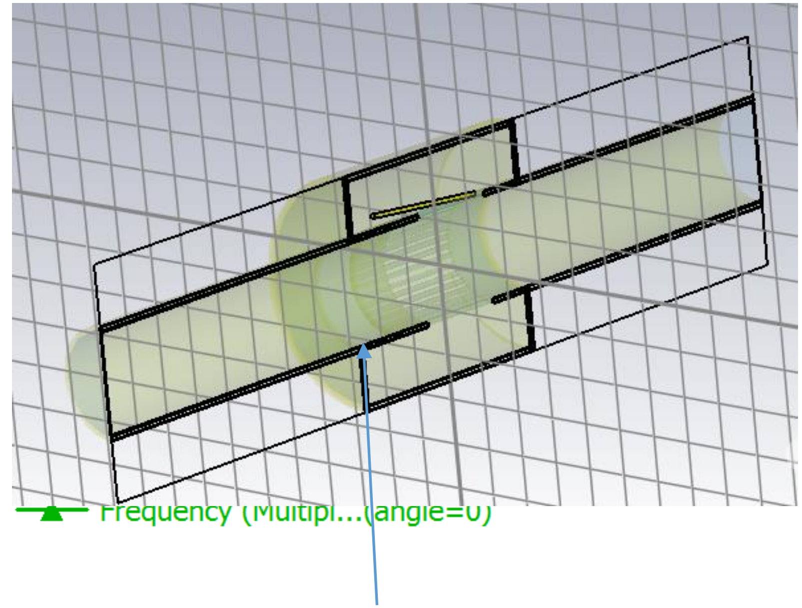


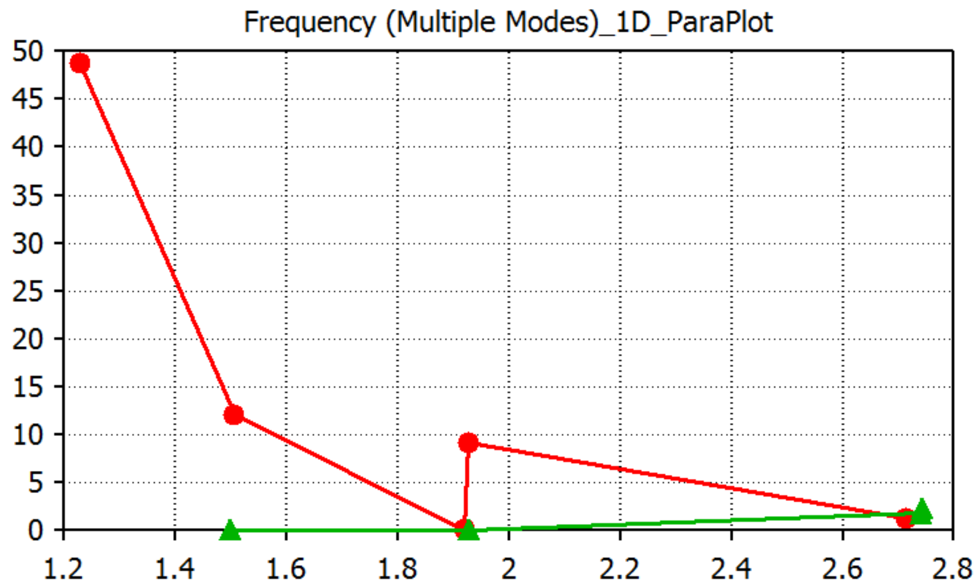
5_cavity_taper



Mitigating modes: shielding with RF fingers

→ In case of non conformities: finger not touching

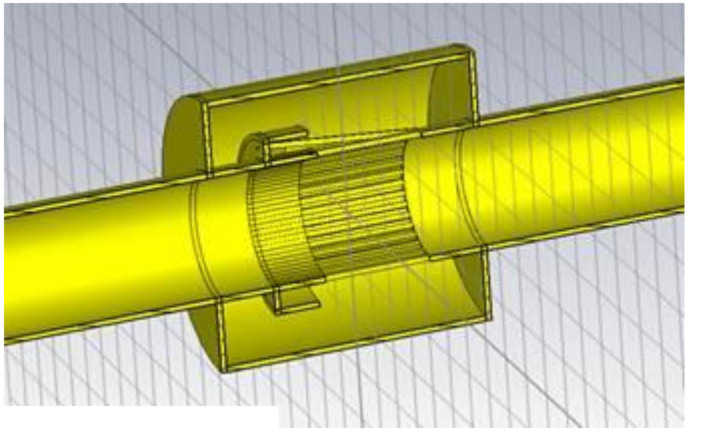


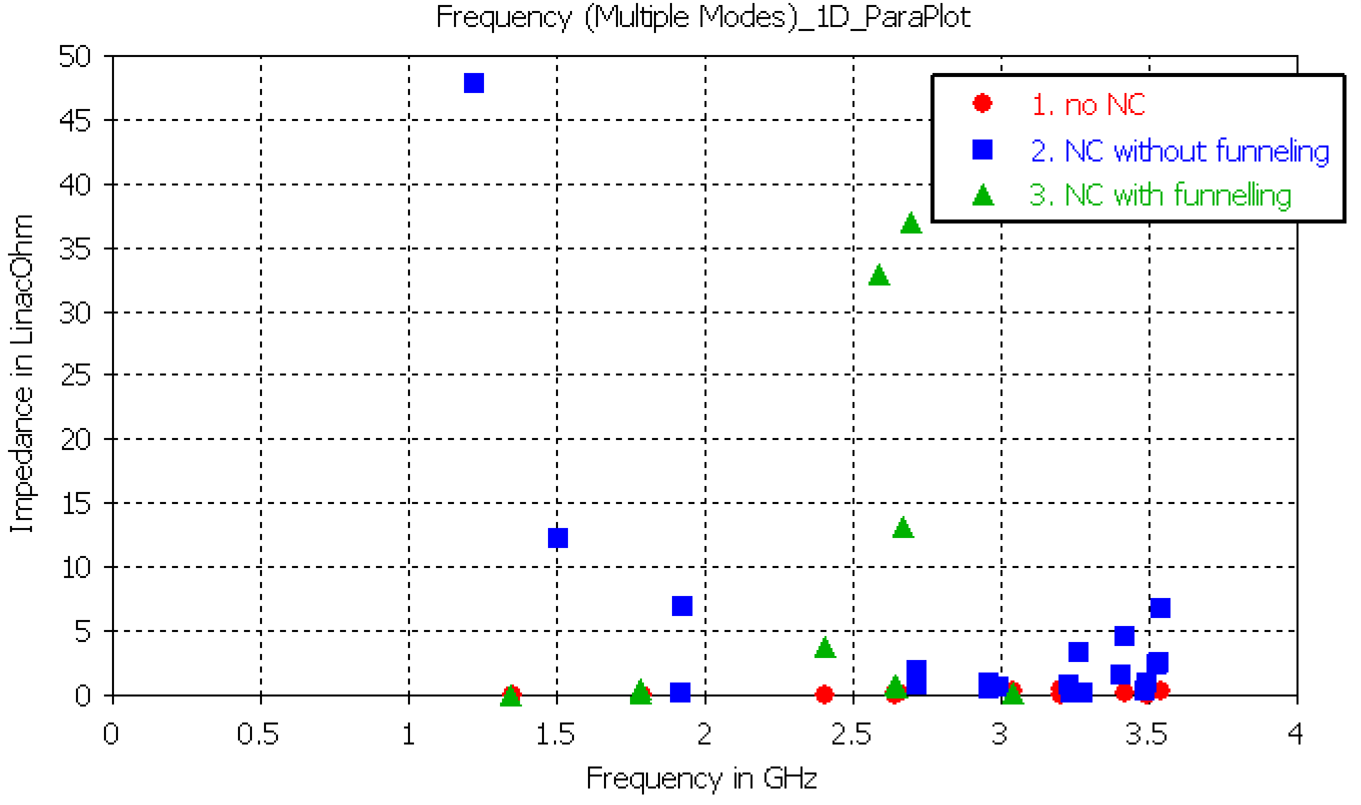


Could be much worse than the situation without fingers!

Recommendation: use funneling

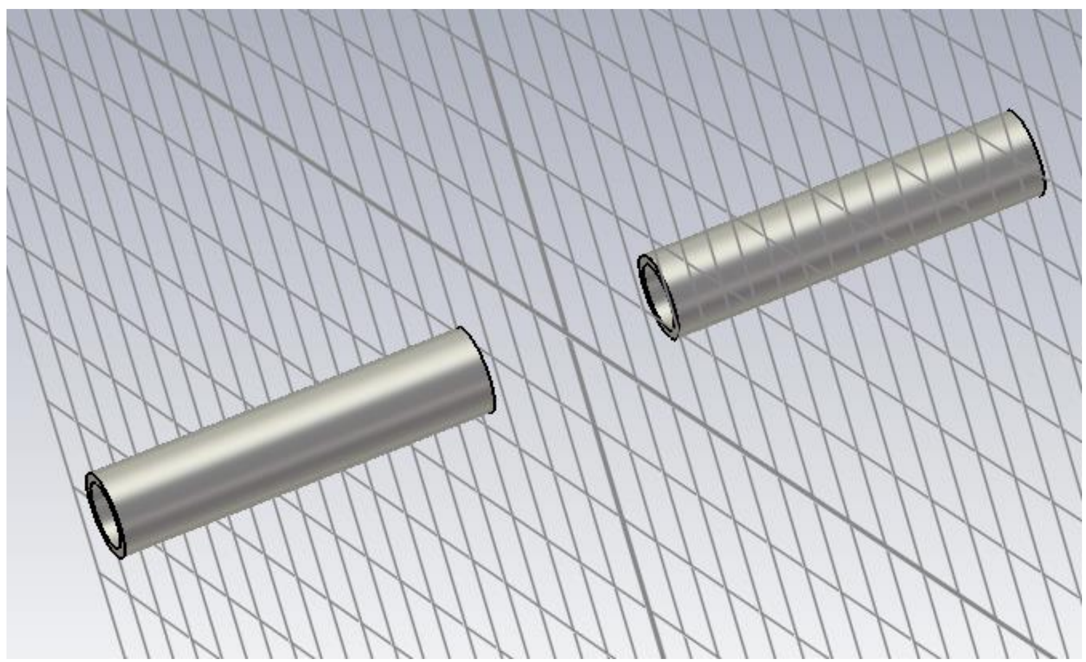
5_cavitePIMSmissingfingersandfunneling





Assigment #2

- Consider two sets of 2 vacuum tubes that need to be connected by a bellow (diameter of 7 mm and 18 mm).
- Find for each case a suitable tradeoff between mechanical and impedance constraints



Summary

- The impact of the in-vacuum elements on the beam strongly depends on bunch length

- To reduce resistive wall impedance
  - higher conductivity ($Z \sim \sqrt{\sigma}$)
  - higher radius ($Z \sim 1/b$ or $1/b^3$)
  - lower length ($Z \sim L$)
  - use coating with good conductor
  - Thickness of bad conducting material on good conducting material has a much stronger impact on impedance than the conductivity of the coating

- Bellows:
  - no power loss if perfect conducting and no resonance excited
  - Z linear with number of convolution and convolution depth
  - Z linear with $1/b$ or $1/b^3$ if convolution is much smaller than radius b

- Cavities:
  - higher cavity radius → lower frequency
  - Cavity length should avoid the order of magnitude of the radius if possible
  - Tapering helps reducing the impedance
  - Shielding with fingers or beam screen is very efficient, but beware of non conformities
  - Use funneling for fingers

Final remarks

If you held until the end, you are welcome in the impedance team!

Confusion with electrical impedance?

- Ohm's law:

  $U= Z.I$ Power loss: $P=Z.I^2$

- Longitudinal beam coupling impedance

  $\Delta Q_{long} \alpha Z_{long} .I_{beam}$ Power loss: $P \alpha Z_{long} .I_{beam}{}^2$

- Transverse beam coupling impedance

  $\Delta Q_{trans} \alpha Z_{trans} .I_{beam}$