Resistive Wall in the CLIC Damping Rings: Different Regimes and Open Questions

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Resistive Wall in the CLIC Damping Rings

Objective: first estimation of the resistive wall impedance and wake fields due to the vacuum pipe in the CLIC Damping Rings

1. Principles of the formalism used

2. Impedance in the DRs: different regimes

3. Wake fields in the DRs

4. Open questions and conclusion

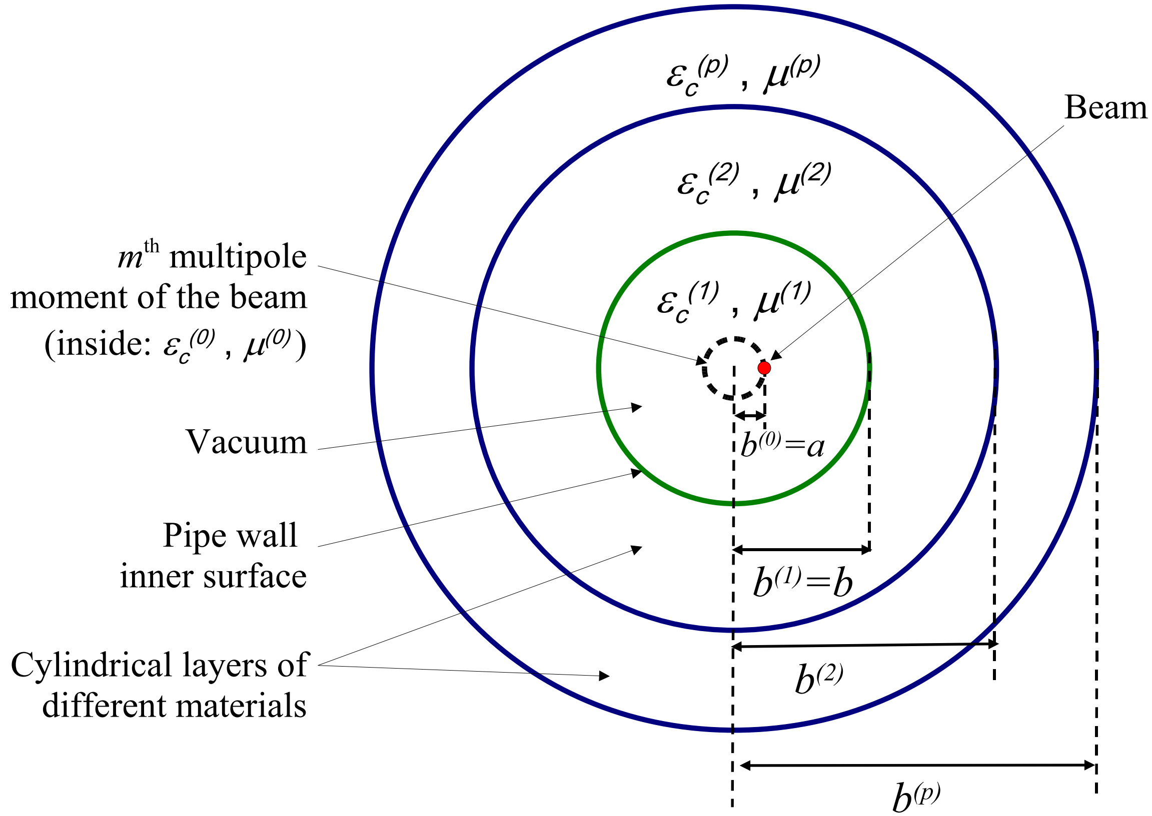
Principles of the formalism used

Analytical computation of the resistive wall impedance using Bruno Zotter's general formalism (Ref.: B. Zotter, CERN AB-2005-043). Ideas:

- Compute the electromagnetic (EM) fields in a chamber of circular shape and infinite length, where a macroparticle offset from the center travels at a given speed along the pipe axis.
- Multilayer pipe walls made of any number of linear materials (resistive, magnetic and/or dielectric) can be taken into account (Ref.: CERN BE-2009-039) .
- Compute the impedance felt by a test particle from those EM fields, taking only the linear terms with respect to test and source particles positions.
- Calculation is exact for a pipe of circular shape. For single-layer elliptic or flat chambers, we use Yokoya (or Laslett) factors that are approximations valid under certain conditions only.

EM fields calculation: geometry and sources

Pipe cross- section:



- Source (i.e. beam macroparticle) in time domain *(s*=longitudinal coordinate):

$$\rho(r,\theta,s;t) = \frac{Q}{a}\delta(r-a)\delta_p(\theta)\delta(s-vt)$$

and $\vec{J} = \rho v \vec{e}_s$

- Source in frequency domain:

$$\rho(r,\theta,s;\omega) = \frac{Q}{av}\delta(r-a)\delta_p(\theta)e^{-jks}$$

Principles of the analytical computation

- From the sources charge and current located at ($x_1 = a\cos\theta$, $y_1 = a\sin\theta$), we get the EM fields by solving analytically Maxwell's equations (boundaries taken into account with field matching) → get EM force $\vec{F}$
- Dipolar transverse impedance definition for a test particle of charge q located at (x_2 , y_2) (here horizontal):

$$Z_x^{dip}(\omega) = \frac{j}{Qqx_1} \int^L \mathrm{d}s\, F_x(x_2, y_2, s) e^{jks}$$

  in a resistive structure of length L.
- Note: we are considering the full impedance coming from the interaction of the beam with the pipe wall, i.e. resistive wall + indirect space charge (="Wall Impedance", cf. F. Roncarolo et al, PRST-AB 2009).

Obtaining the wake function

- We need to get the wake function (=integrated EM force in time domain for our delta function source, input of tracking codes such as Headtail):

$$W_x(z) = \frac{1}{2\pi} \mathrm{Im}\left(\int_{-\infty}^{\infty} e^{j\omega t} Z_x(\omega) \mathrm{d}\omega \right)$$

- Not possible analytically, and issues numerically since impedance spans a huge number of decades → standard discrete Fourier transform fails because the "frequency window" cannot be large enough (too many points).

  ⇒ Use a new accurate method (based on interpolation of Z_x and exact integration of the interpolating polynomials) to perform the Fourier integral, which enables to compute the wake at any point using a frequency window as large as we want

  (Ref: http://sps-impedance.web.cern.ch/sps-impedance/documents/FT.ppt)

- Finally: for each resistive wall element we need to weight its wake (and impedance) by the β function of the element over the mean β function of the ring (impedances have more impact where β is large).

CLIC Damping Rings Impedance: Parameters used (from Y. Papaphilippou)

Only two "elements" considered (for a first rough estimate):

- Vacuum pipe in wigglers:
  - Pipe of elliptic shape, with horizontal semi-axis (>16mm) much bigger than vertical semi-axis (=6.5 mm) → approximated by a flat chamber and use Yokoya factors (i.e. multiply the circular dipolar impedance by $\pi^2/12$ to get Z_y and $\pi^2/24$ to get Z_x).
  - Total length: 152m for 3TeV option, 4m for 500GeV option.
  - $\beta_x = 4.42$ m, $\beta_y = 4.40$ m (on average).

- Vacuum pipe in the rest of the machine:
  - Pipe of circular shape, with radius of 9 mm (estimate).
  - Total length: 341.05 m for 3TeV option, 489.05 m for 500GeV option.
  - $\beta_x = 4.14$ m, $\beta_y = 8.02$ m (on average).

CLIC Damping Rings Impedance: Parameters used (from Y. Papaphilippou)

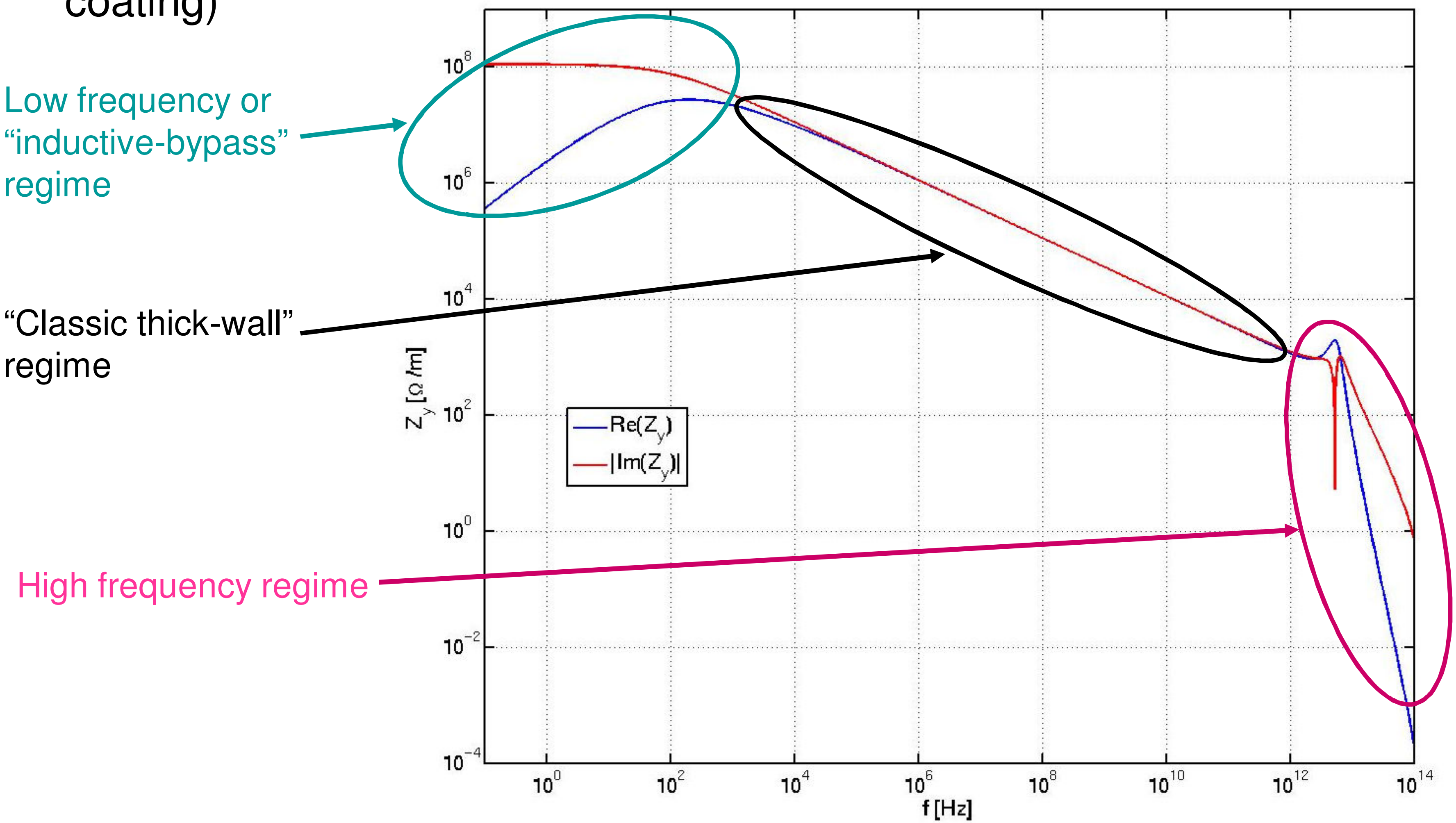
Other parameters:

- $p_0=2.86$ GeV/c, $<\beta_x>= 6.90$ m, $<\beta_y>= 4.23$ m for the whole ring.
- Pipe made of the same material all along the ring. We tried 4 options:
  - **Stainless Steel 304L,**
  - **Copper,**
  - **Copper with NEG coating (1μm, $\rho=10^6$ Ω.m),**
  - **Copper with amorphous carbon coating (1μm, $\rho=10^3$ Ω.m, with or without relaxation time $\tau=0.8$ ps).**

  The resistivities of the above coatings are only estimations obtained thanks to measurements (courtesy of S. Calatroni). The relaxation time introduced is that of graphite, so not realistic but only a mean to probe the influence of high frequency properties on the wake functions. High frequency properties remain quite unknown (cf. F. Caspers).
- Bunch longitudinal extension:
  - Bunch length (total) ≈ *6* mm,
  - Bunch spacing ≈ *0.15* m,
  - Length of bunch train ≈ *50* m.

Resistive Wall Impedance: Different Regimes

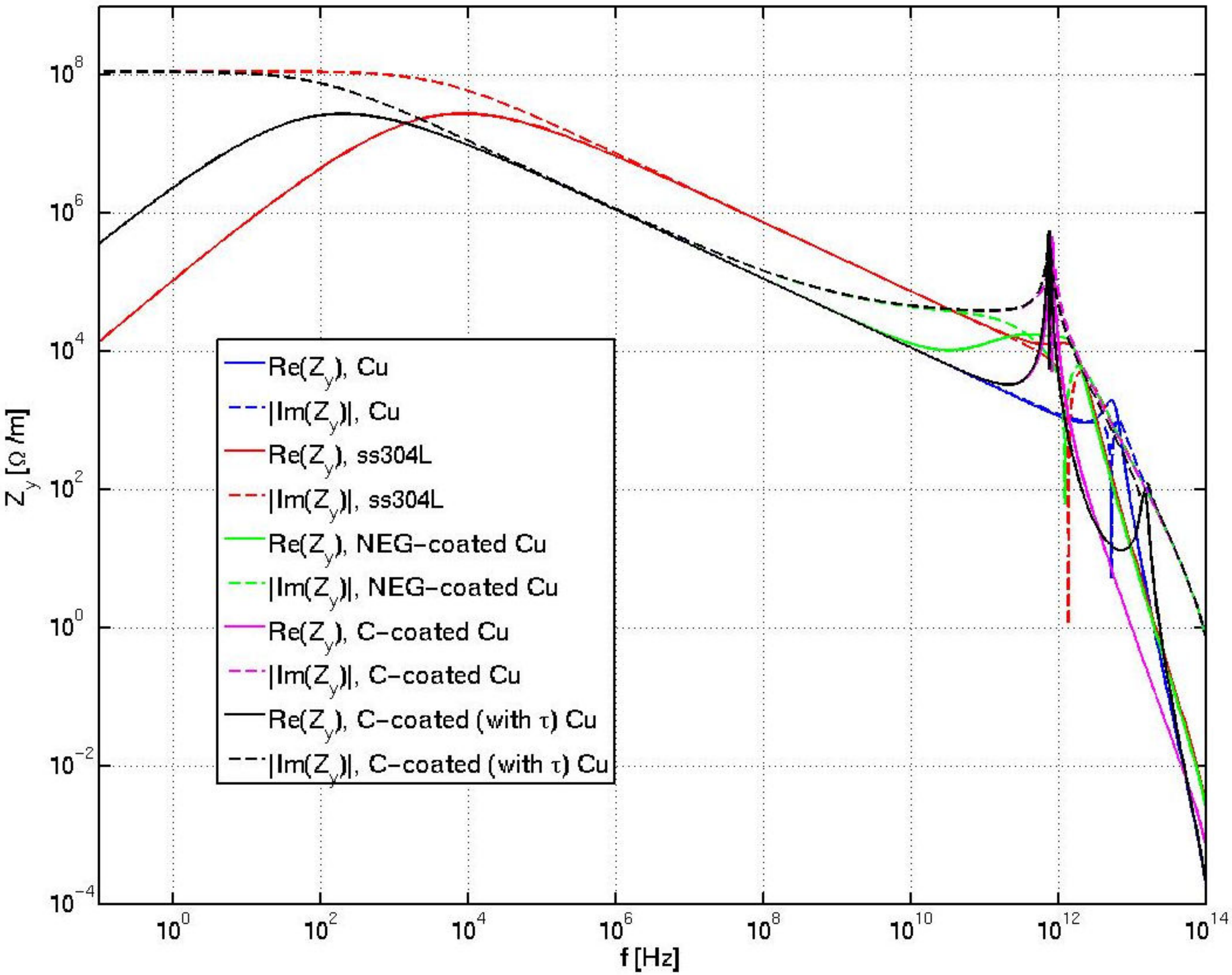
- Vertical impedance in the wigglers (3 TeV option, pipe in copper without coating)



Note: all the impedances and wakes presented have been multiplied by the beta functions of the elements over the mean beta, and, when needed, the Yokoya factors.

Resistive Wall Impedance: Various options for the pipe

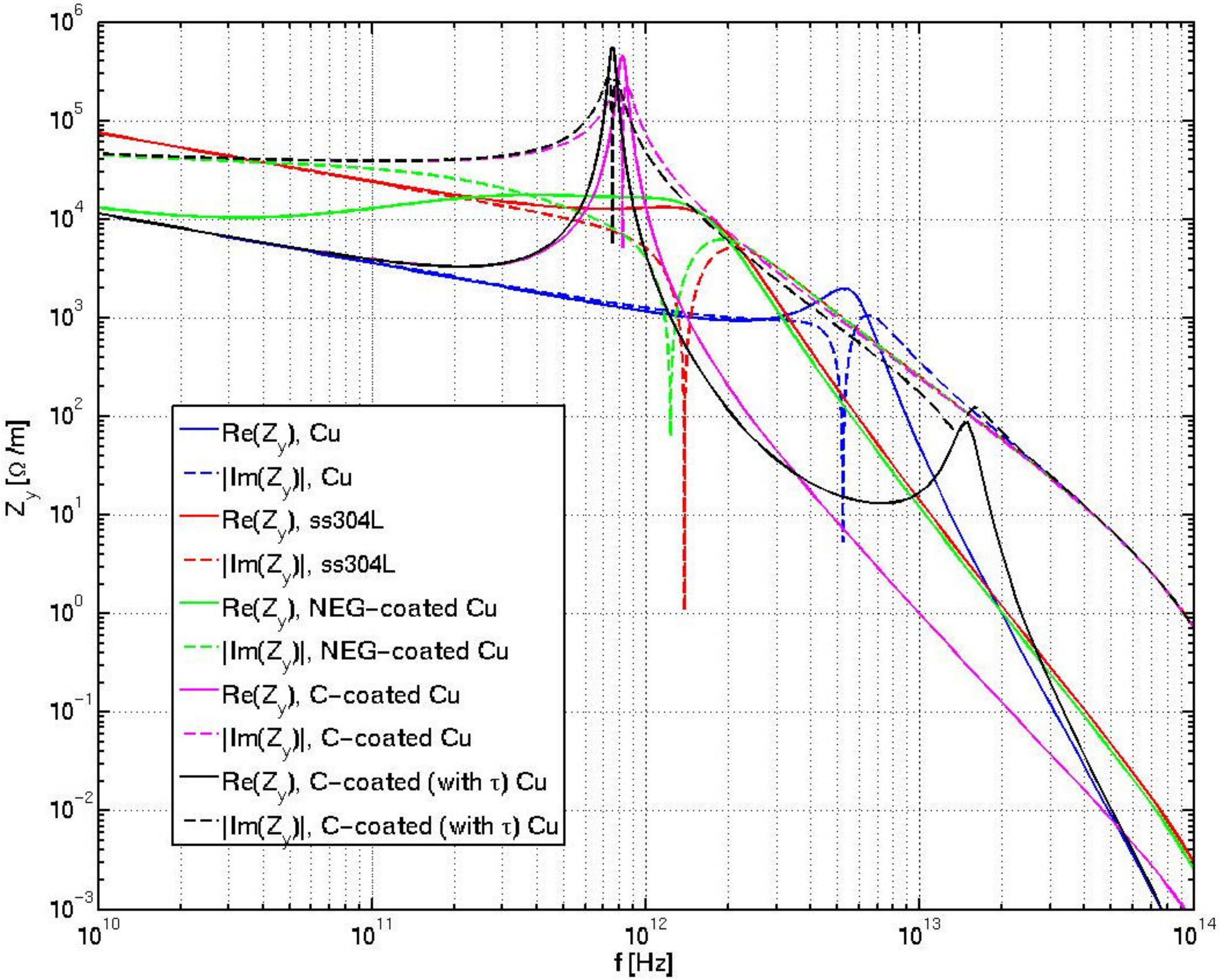
- Vertical impedance in the wigglers (3 TeV option) for different materials



$\Rightarrow$ Coating is "transparent" up to ~*10* GHz

Resistive Wall Impedance: Various options for the pipe

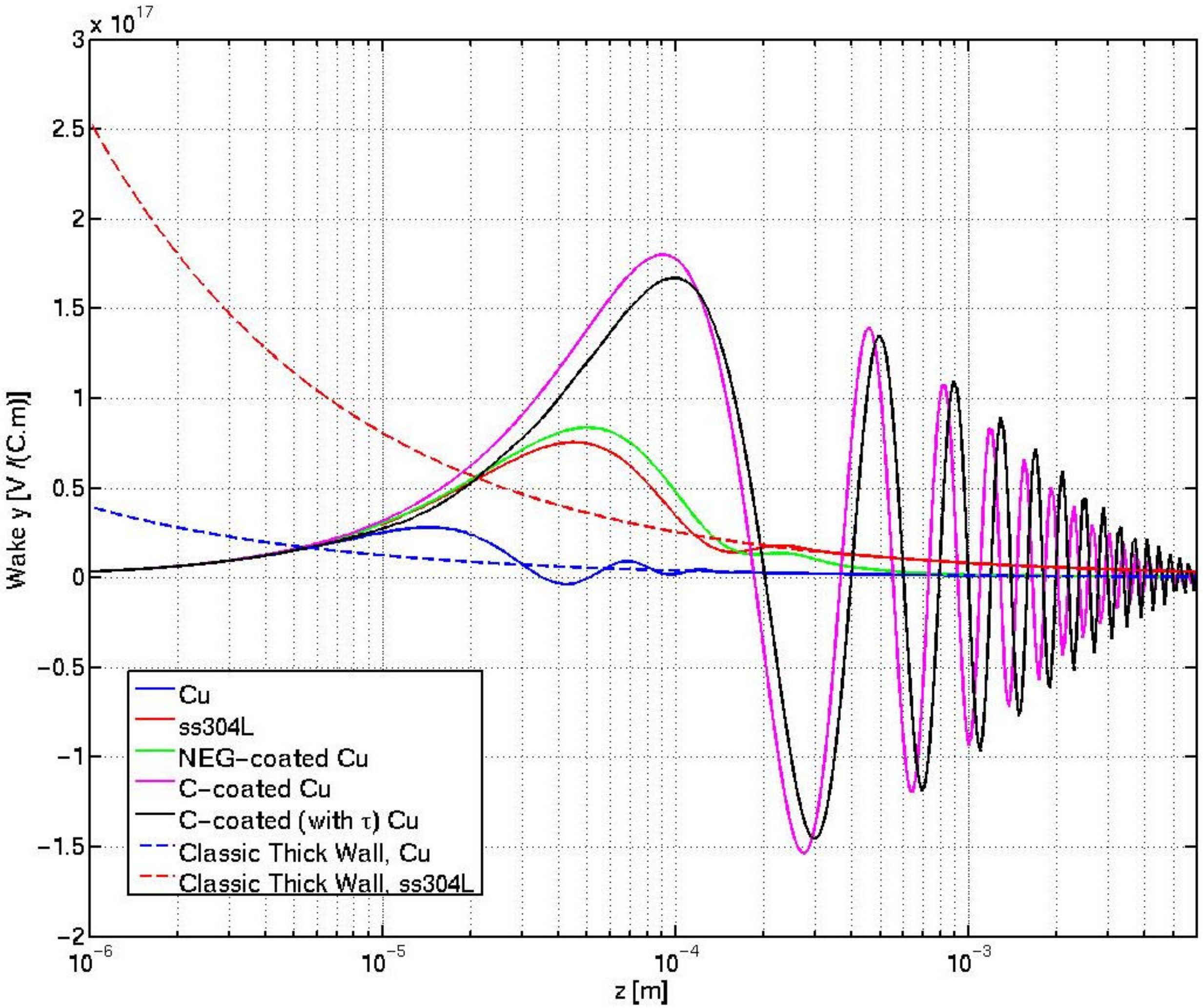
- Vertical impedance in the wigglers (3 TeV option) for different materials: zoom at high frequency



⇒ Above *10* GHz the impact of coating is quite significant.

Resistive Wall Wake: Single bunch

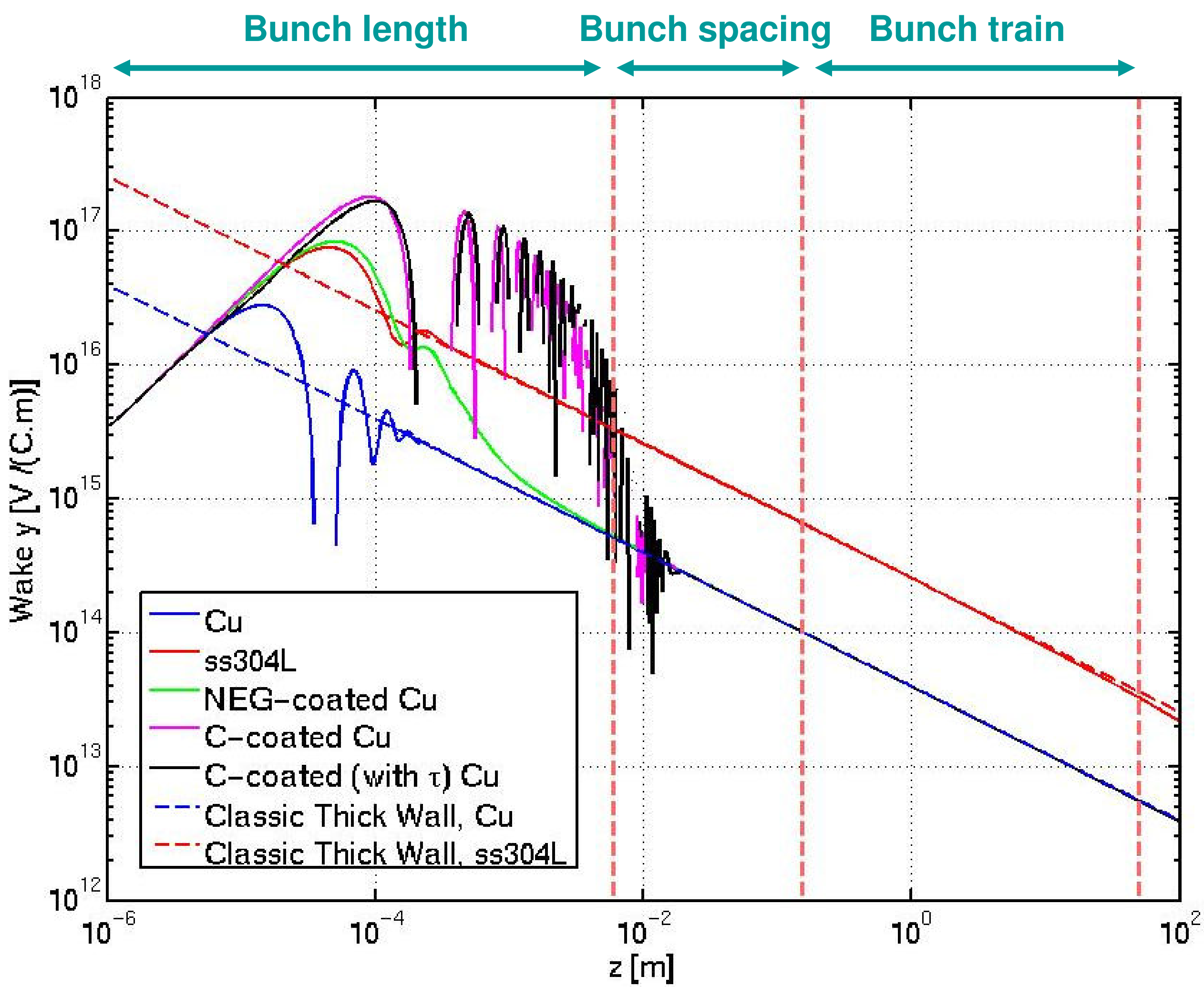
- Vertical wake function over the bunch length (6mm) in the wigglers (3TeV option), for different materials, and comparison with classic formula:



⇒ Important impact of the coating or the pipe material for the wake in the bunch. Classic thick wall formula cannot be applied.

Resistive Wall Wake : Multi-bunch

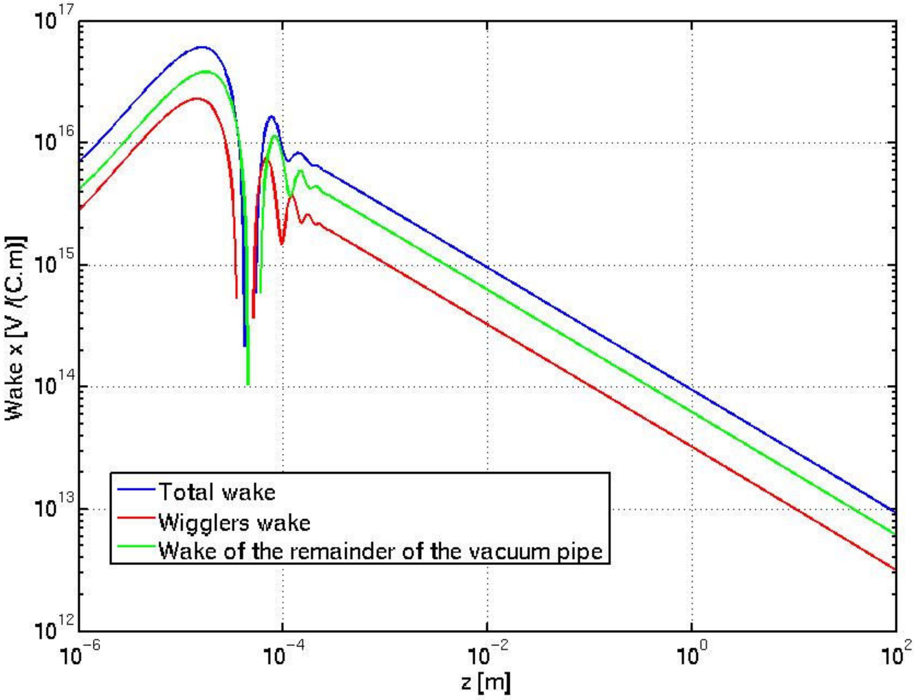
- Vertical wake function over the bunch train (~*50*m) in the wigglers (3 TeV option), for different materials, and comparison with classic formula:

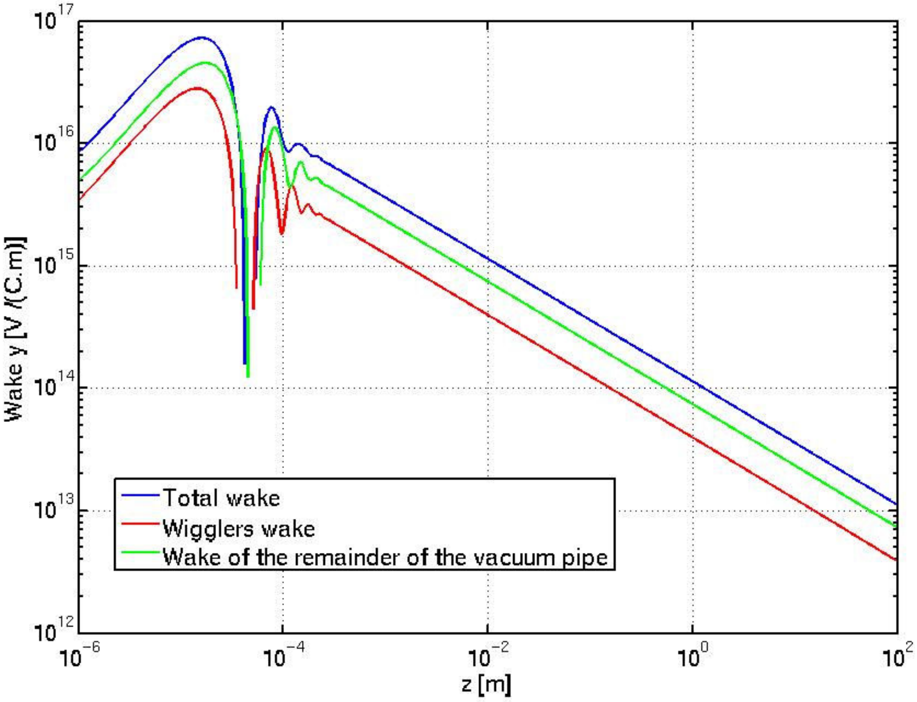


$\Rightarrow$ For the wake all along the bunch train and apart from the 1st bunch, the coating is "transparent", only the conductivity of the pipe matters. Classic formula can be applied.

Resistive Wall Wake: Summing the contributions – 3TeV option

- Horizontal and vertical wake function from the wigglers pipe, from the remainder of the vacuum pipe, and sum of the two contributions (copper without coating):

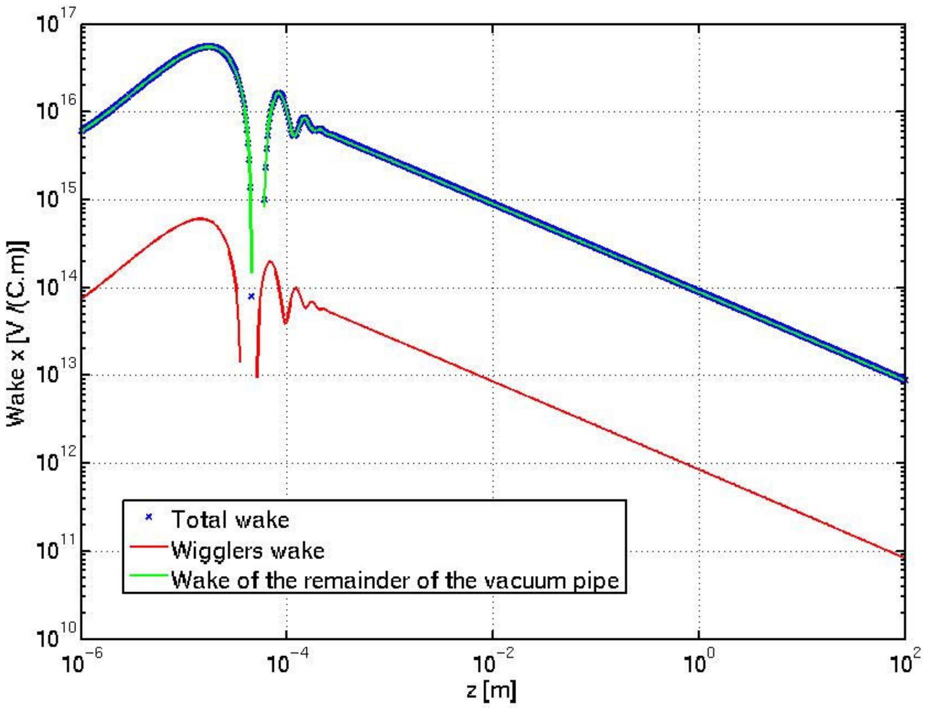


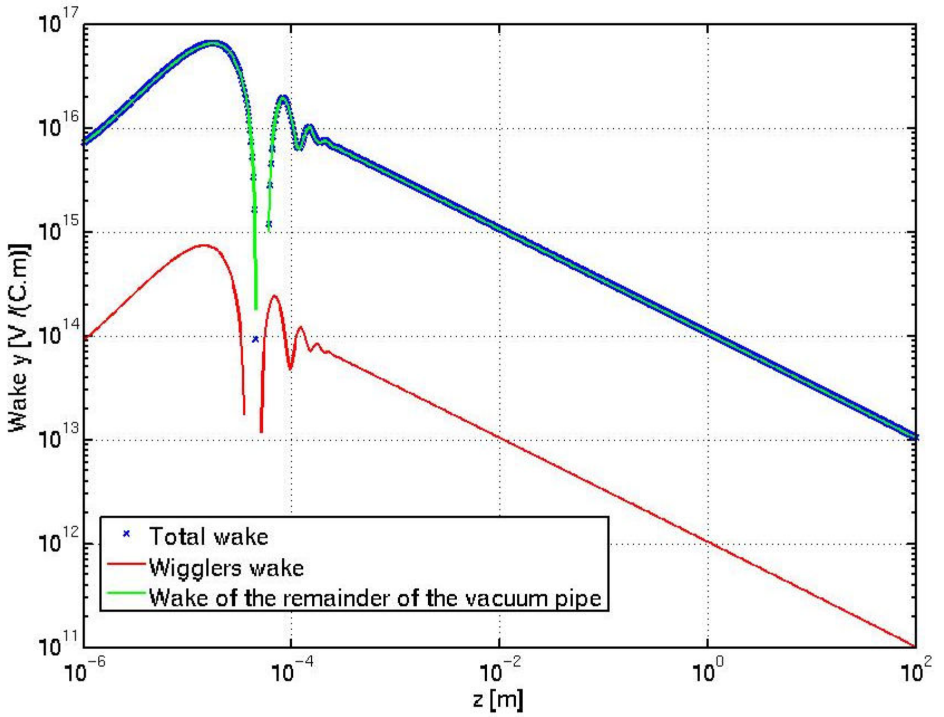


⇒ The main contribution is from the vacuum pipe outside the wigglers.

Resistive Wall Wake: Summing the contributions – 500GeV option

- Horizontal and vertical wake function from the wigglers pipe, from the remainder of the vacuum pipe, and sum of the two contributions (copper without coating):



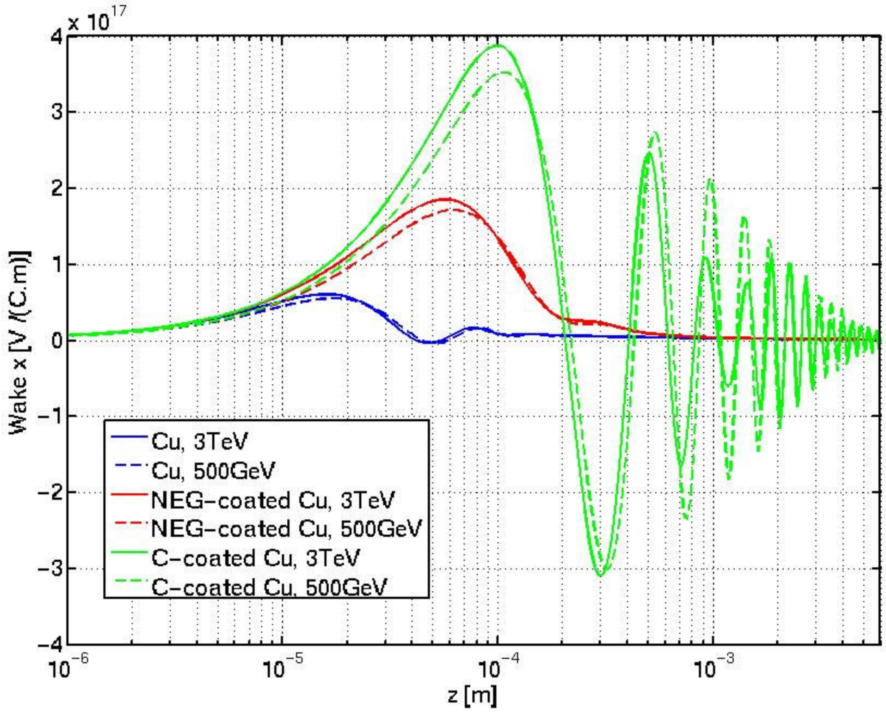


⇒ The wigglers contribution is negligible.

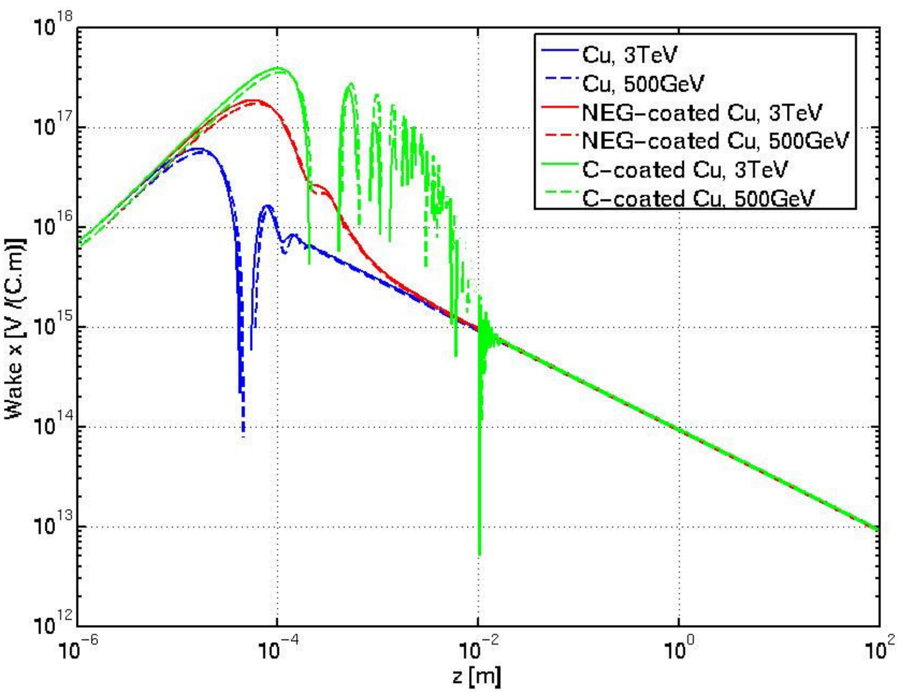
Resistive Wall Total Wake

- Horizontal total wake function of the vacuum pipe for different configurations (500GeV and 3TeV options):

Along one bunch



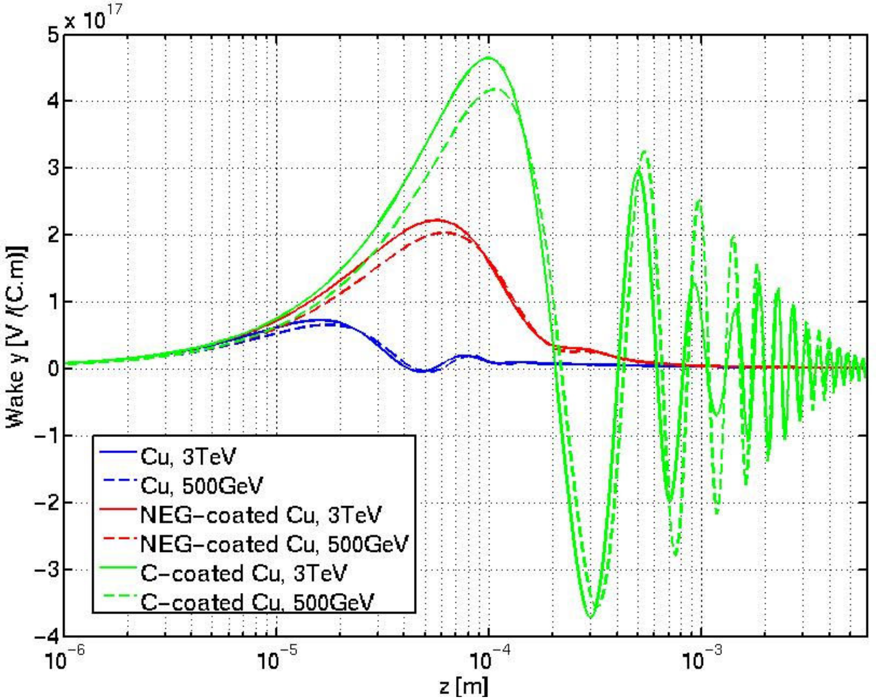
Along the bunch train



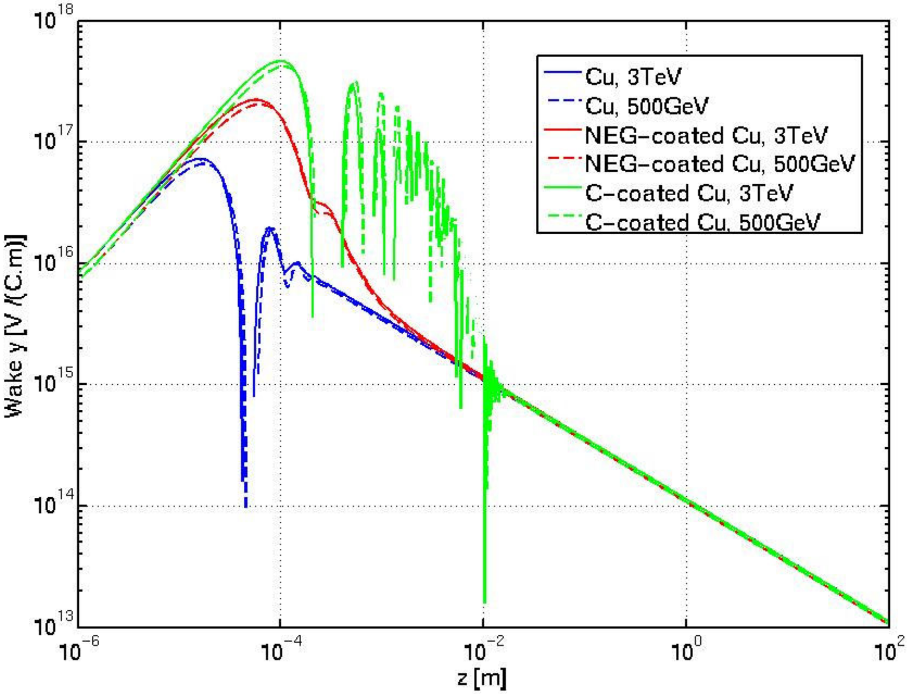
Resistive Wall Total Wake

- Vertical total wake function of the vacuum pipe for different configurations (500GeV and 3TeV options):

Along one bunch



Along the bunch train



- The single bunch wake is strongly affected by the coating, but not the wake along the bunch train, as already seen for the wigglers only.
- 500GeV and 3TeV configurations have very similar wakes.

Resistive Wall Impedance and Wakes in DRs: Open Questions

Questionable assumptions of our analytical approach:

- Geometry (aperture) of the vacuum pipe is a very simple estimation.
- No curvature in the particle trajectory→ we neglect the synchrotron radiation part of the EM fields.
- Validity of the Yokoya factors (elliptic or flat chamber) has been proven only for conductors in the usual classic thick wall regime, not at high frequency.
- Anomalous skin effect (Ohm's law breaks down at high frequency): important above 25 GHz for Cu at 273 K (Ref: F. Zimmermann & K. Oide, PRST-AB 2004).
- High frequency properties of materials (especially coatings) require measurements and models (surface roughness, AC conductivity, more generally AC permittivity, etc.).

Conclusions

- According to our analytical approach (still a rough estimate):
  - ➢ The vacuum pipe outside the wigglers is the main contributor to the resistive wall transverse wake, compared to the contribution of the narrower pipe in the wigglers. For the 500 GeV lattice, the latter is even negligible.
  - ➢ Along the bunch train (→ coupled-bunch effects), classic thick wall formula for the impedance is valid, and the coating (a-C or NEG) is transparent.
  - ➢ In one bunch (→ single-bunch effects, transverse mode coupling instability), coating has a drastic effect and usual classic thick wall formula don't apply. High frequency effects are dominant (up to THz).
  - ➢ 500GeV and 3TeV options exhibit very similar wake functions.
- Many issues remain to be addressed to give reliable impedance and wake estimations, especially concerning the high frequency properties of the walls.