Resistive-Wall Impedances of a Thin Coating on a Conductive Chamber*

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Introduction

- Non-Evaporable Getter (NEG) coating on vacuum chambers has been successfully used to achieve ultra high vacuum in many accelerators such as CERN LHC, ESRF, etc.
- A NEG coating is a TiZrV ternary alloy (such as 30% Titanium, 30% Zirconium and 40% Vanadium) and has a resistivity typically higher than that of the chamber material by a factor of $\sim$50.
- If a large amount of beam chamber is coated with NEG, it may increase the resistive-wall impedance of the machine significantly.
  - Mystery of impedance boost by NEG at Elettra (solved?)

Motivations of This Work

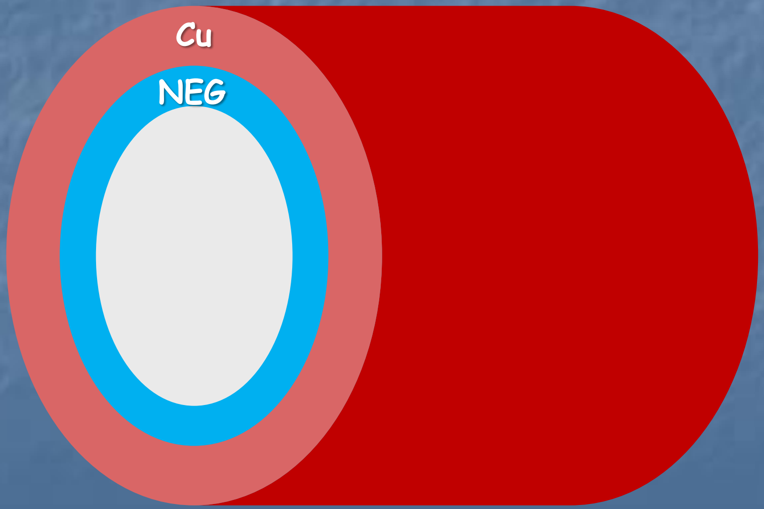
- I received an inquiry from SLS people if they can use ABCI for calculations of wake potentials of their NEG coated copper chamber for the SLS-II upgrade.
- Basically, it is a 2-D multi-layer problem, and it can be solved by the field matching technique.
  - This kind of problems have been extensively studied by CERN people, Fermi people, Hock (for ILC damping ring), etc.
  - We have worked on a similar, but 3-D problem before (so-called SCT theory).
  - SuperKEKB and cERL people may have similar concerns.
- We decided to make a new 2-D theory to study this issue so that we can make sure that all calculations are accurate and we know the scope of the theory precisely (i.e., too simple-minded).

Impedance Behavior at High Frequency

- Most of the previous works focus on the behavior of transverse impedance at low frequency (e.g., for LHC carbon collimators).
- In synchrotron light sources, the bunch length varies from less than 1 mm to a few cm, and their interest extends to behaviors of the both longitudinal and transverse impedances over a wide range of frequency, even beyond 100 GHz.
- In particular, the impedances at very high frequency have not been studied in details before.
- This study covers the impedances of a NEG coated copper chamber from very low frequency (~Hz) to very high frequency (~ 100THz).

2-D Theory and its Premise

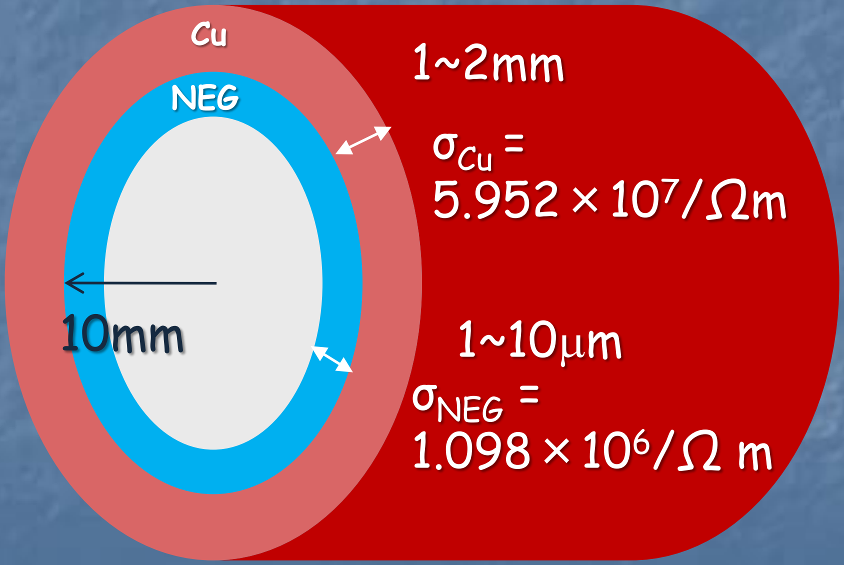
- I skip this part completely.
  - It is a 2D multilayer problem and can be solved by the field matching technique.
  - We assume for simplicity that all physical parameters such as the conductivity have no frequency dependence.
    - The relaxation time of the conductivity is set to zero.
- The configuration of consideration.



1st layer: very thin NEG coating
2nd layer: thin Cu chamber
3rd layer: air to infinity

Numerical Examples

- We use parameters similar to those of SLS-II upgrade.
- The conductivity of NEG is based on the measurement results by CERN for CLIC.



Cu

NEG

1~2mm

σ_{Cu} = $5.952 \times 10^7/\Omega\mathrm{m}$

10mm

1~10μm

σ_{NEG} = $1.098 \times 10^6/\Omega$ m

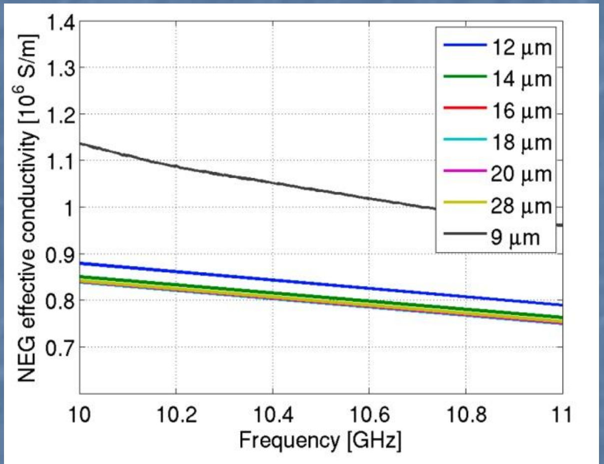
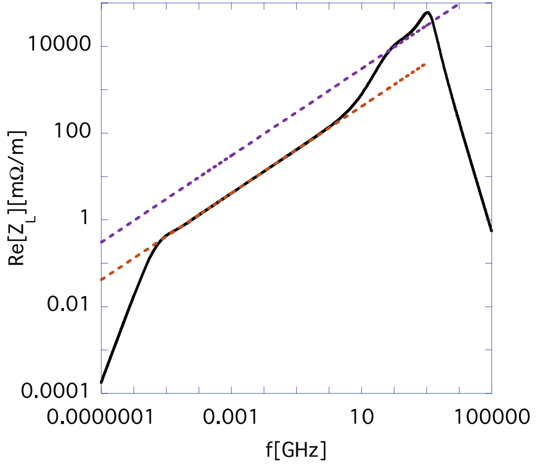


Figure 10: Effective conductivity of NEG.

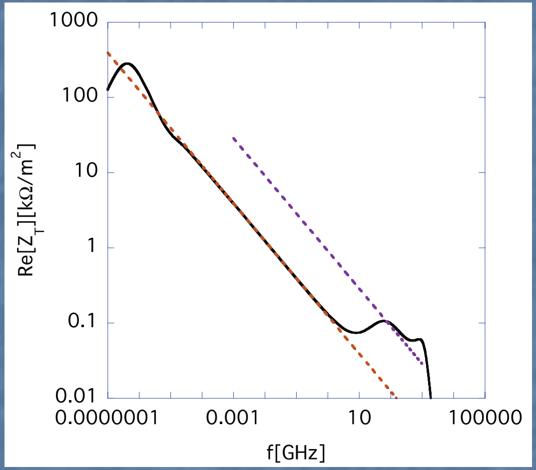
Measurement results for CLIC damping ring by E. Koukovini-Platia, G. Rumolo, C. Zannini, CERN (IPAC14, WEPME050)

Example

- Real parts of impedances for Cu thickness=1mm and NEG thickness=2μm



Longitudinal



Transverse

Brown lines: the impedance of the copper only chamber using the conventional formulae

$$\frac{Z_L}{n} = Z_0\beta\cdot\left(\frac{1-i}{2}\right)\frac{\delta_s}{b}\frac{g}{2\pi R}$$

Purple lines: the impedance of the NEG only chamber using the conventional formulae

$$Z_T = Z_0(1-i)\frac{g\delta_s}{2\pi b^3}$$

Observations at High Frequency

- The both longitudinal and transverse impedances slowly undergo transitions from the resistive-wall impedances of the copper only chamber to those of the NEG only chamber over 1-100 GHz frequency range.
- However, they start to deviate from the conventional impedance lines for the NEG only chamber at ~100GHz.
  - They go up first till ~1THz and then go down rapidly as a function of the frequency.
- The longitudinal impedance does not go up to infinity at the high frequency limit (indeed, it should not).
  - It has a peak at around 1THz and then goes down.

Observations at Low Frequency

- At very low frequency, the both longitudinal and transverse impedance go down to zero in proportion to the frequency.
  - This behavior has been extensively studied by many works.
  - There, the skin depth exceeds the thickness of the copper chamber and thus wake fields leak out to the outside air, leaving only a small amount of the image current running on the copper chamber.

Ampere-Maxwell Equation

- The mathematical reasons of those behaviors of the impedances at high frequency are simple.
- Ampere-Maxwell equation:
  - $\epsilon_0 \frac{\partial \vec{E}}{\partial t} + \vec{j} = \nabla \times \vec{H}$

Induction term

Electric current term

- Assuming that electromagnetic fields have time dependence of $e^{j\omega t}$, it can be written inside a conductive material as
  - $(j\epsilon_0 \omega + \sigma)\vec{E} = \nabla \times \vec{H}$

Conductivity

Three Frequency Regions

- $\epsilon_0 \omega \ll \sigma$ (below ~100GHz)
  - The usual (simplified) formula of the skin depth and the conventional formulae are valid in this frequency range.

$$\delta = \sqrt{\frac{2}{\omega \sigma \mu_0}}$$

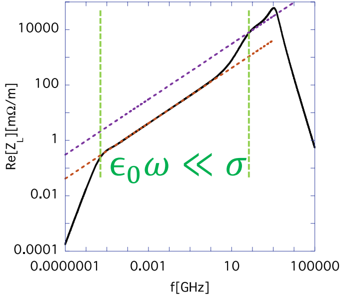
Surface impedance

$$Z_S \equiv R_S + jX_S = \sqrt{\frac{j\omega\mu_0\mu_r}{\sigma + j\omega\varepsilon_o}} \cong \sqrt{\frac{j\omega\mu_0\mu_r}{\sigma}} \quad \text{with} \quad \omega < 10^{15}\ \text{rad/s}$$

$$\gamma_S \equiv \alpha_S + j\beta_S = \frac{j\omega\mu_0\mu_r}{Z_S} = \sqrt{j\omega\mu_o\mu_r\sigma} \quad \text{and} \quad \delta_S = \frac{1}{\Re\{\gamma_S\}} = \frac{1}{\alpha_S}$$

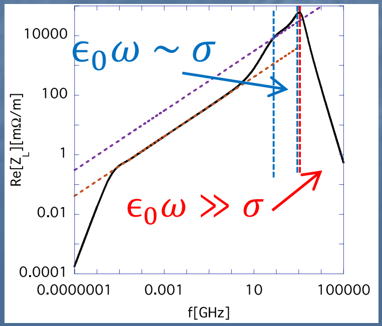
Attenuation constant

  - The magnetic fields vary in space due to the electric current.
  - The time changes in the magnetic fields induce spatial changes in the electric fields through the Faraday's law.
  - Through these processes, the electro-magnetic fields attenuate inside the conductive material.



At High Frequency

- $\epsilon_0 \omega \sim \sigma$ (between ~100GHz and ~1THz)
  - In this frequency region, the induction term $\epsilon_0 \partial \vec{E} / \partial t$ becomes comparable with the current density term $\vec{j}$.
  - The usual formula of the skin depth is no longer valid and thus the impedances deviate from the conventional formulae.
- $\epsilon_0 \omega \gg \sigma$ (above 1THz)
  - In this very high frequency region, the induction term dominates the current density term, and the conductivity contributes little to the Maxwell equations.
  - As the result, the conductive material behaves almost like vacuum.
  - The electromagnetic fields can now freely propagate away from the chamber and thus the longitudinal impedance diminishes.

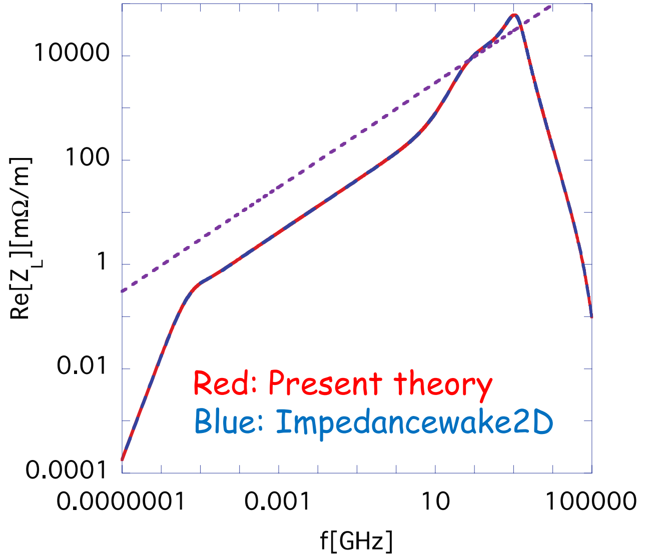


In Reality

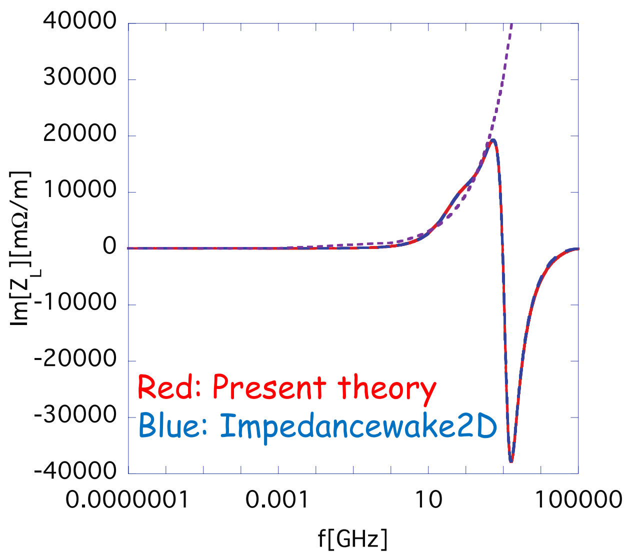
- Here, we assume that all physical parameters such as the conductivity have no frequency dependence.
- In reality, however, a conductive material may have much more complicated physical properties at very high frequency or on a tiny size scale.
  - For example, the conductivity has usually the relaxation time.
  - For more accurate calculations, the physical properties at high frequency have to be known by some means, in particular, those of a coating material.
    - This may not be a trivial task in reality.
- Thus, actual behaviors at high frequency may be very different from those of the present simple model.
- Interesting to point out that the concept of the skin depth fails at both very low and high frequencies.

Accuracy Check

- Comparisons with Impedancewake2D
  - Same set of SLS-II parameters as the previous figures.
  - The γ-dependence is restored in the present theory for comparisons ($\gamma = 7460.52$).

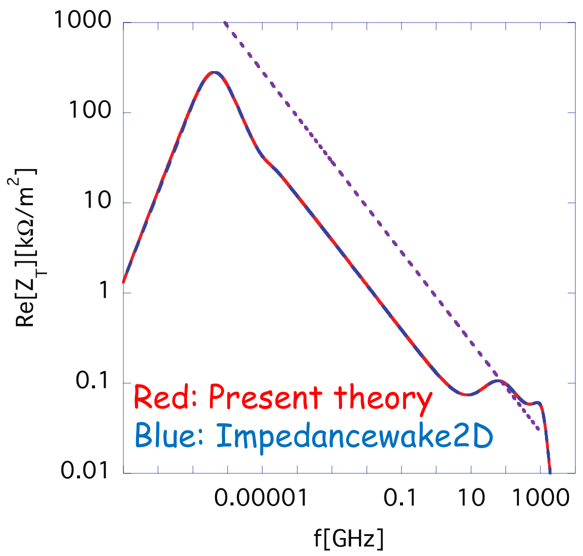


Real part of longitudinal impedance

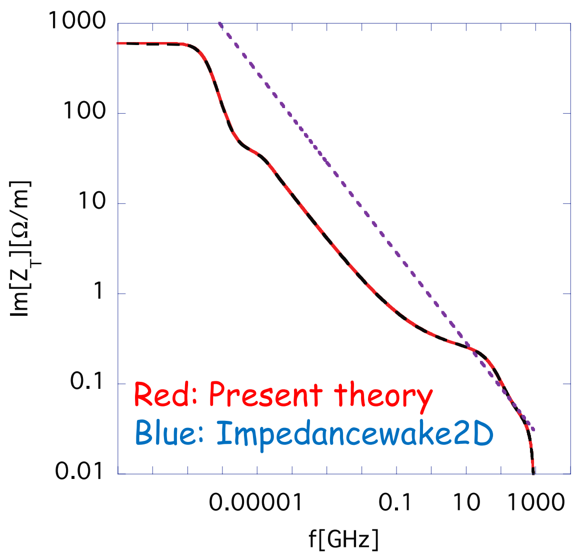


Imaginary part of longitudinal impedance

Transverse Impedance



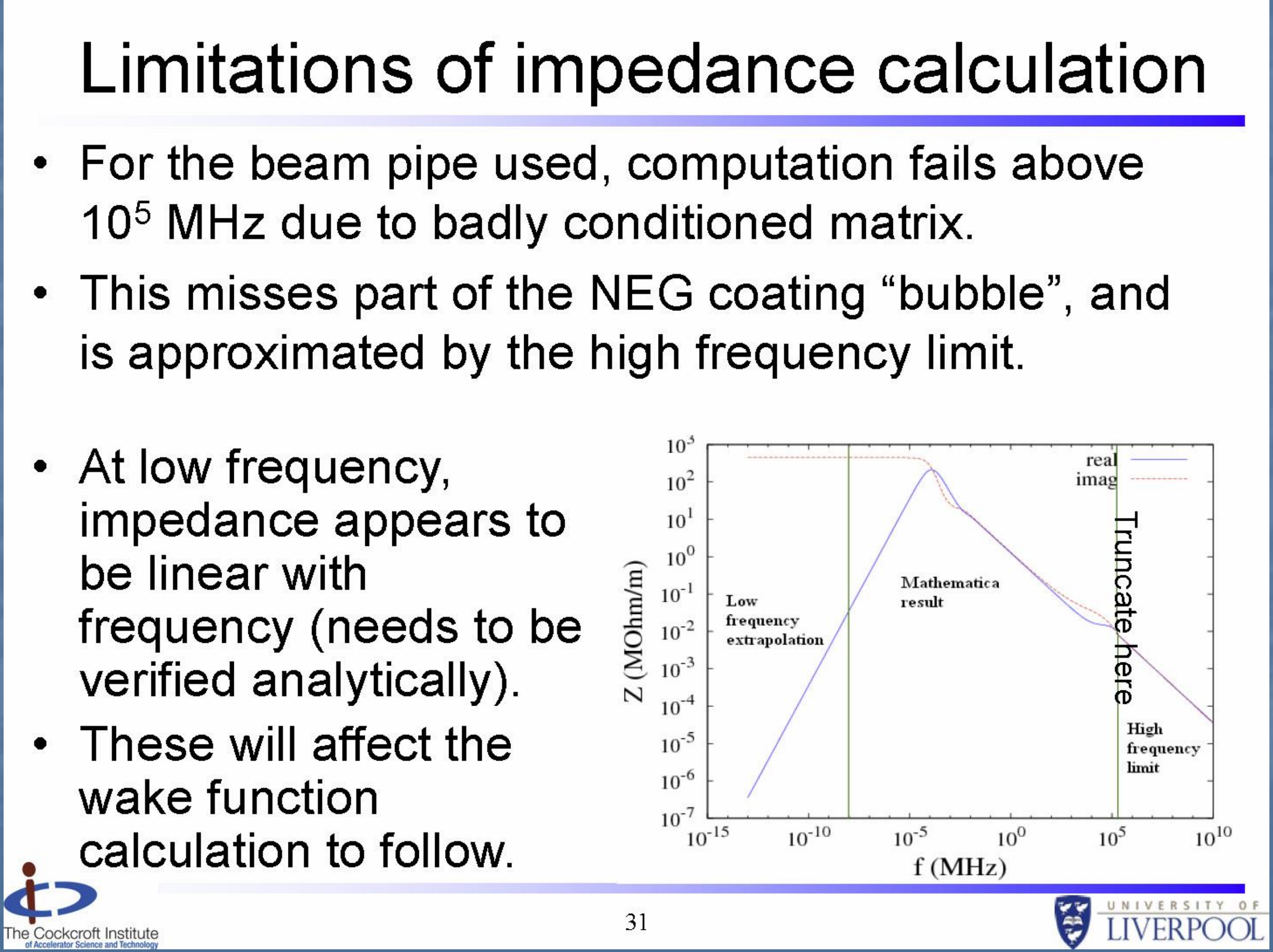
Real part of transverse impedance



Imaginary part of transverse impedance

Excellent agreements!
Good for Impedancewake2D!

Hock's Result is Different at High Frequency: Sometimes, Assuming Misleads You.



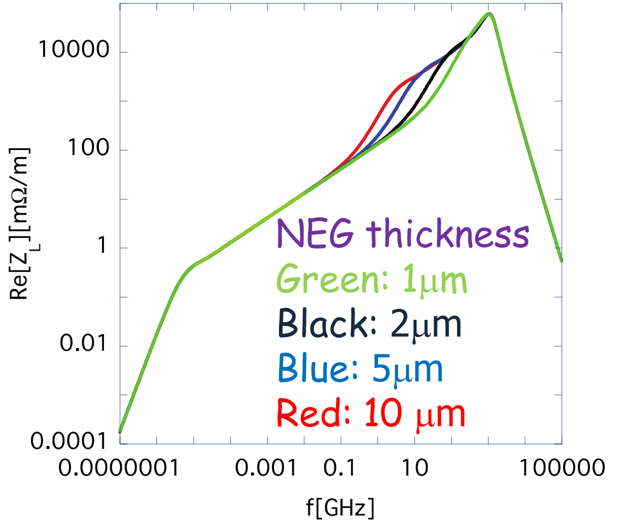
Limitations of impedance calculation

- For the beam pipe used, computation fails above 10^5 MHz due to badly conditioned matrix.
- This misses part of the NEG coating "bubble", and is approximated by the high frequency limit.

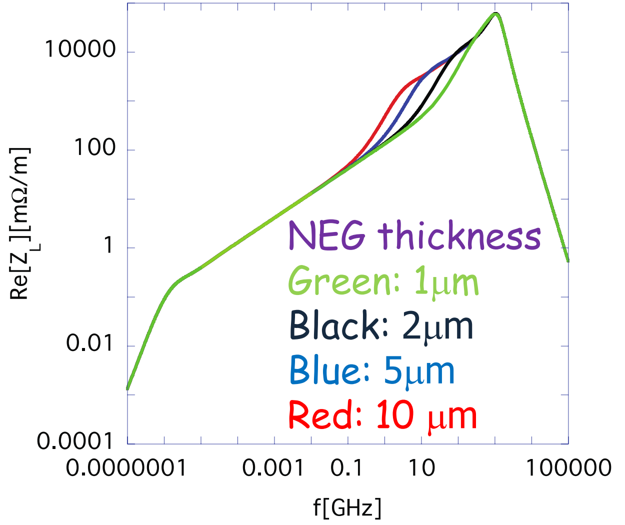
- At low frequency, impedance appears to be linear with frequency (needs to be verified analytically).
- These will affect the wake function calculation to follow.

Effects of the Thickness of the Copper Chamber and the NEG Coating

- Real part of longitudinal impedance



Cu thickness=1mm



Cu thickness=2mm

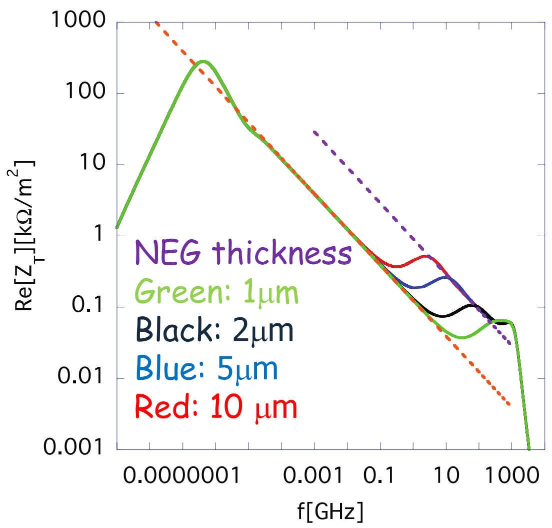
- Only difference between the two figures appears at lower than a few kHz where the wake fields leak out of the copper chamber to the outside air.

Effects of NEG Thickness

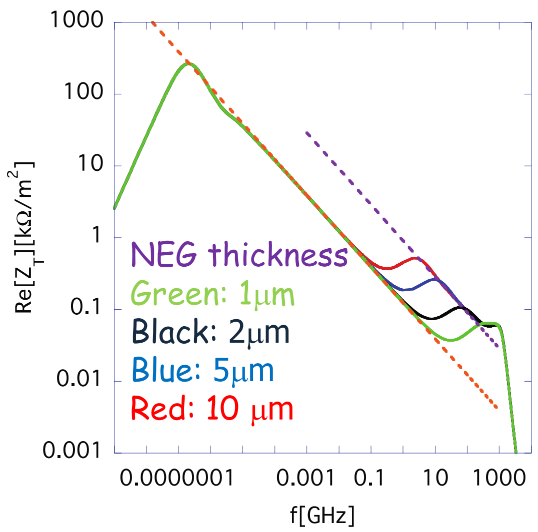
- At high frequency region where the skin depth is much smaller than the NEG thickness, all lines converge to the same result.
- The frequencies where the skin depth becomes comparable to the thickness of the NEG coating are
  - 230 GHz for 1 μm,
  - 57.6 GHz for 2μm,
  - 9.2 GHz for 5μm
  - 2.3 GHz for 10 μm
- The transitions of impedances from the copper only case to the NEG only case are almost completed at around those frequencies.

Transverse Impedance

- Real part of transverse impedance



Cu thickness=1mm

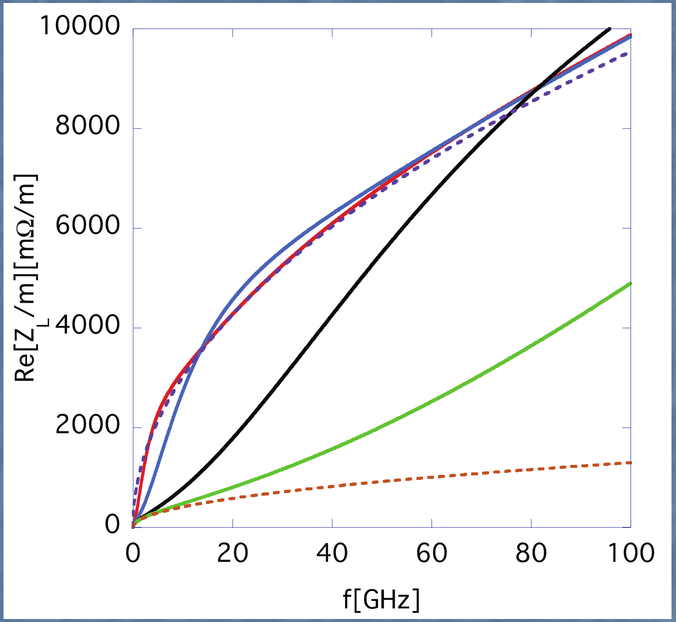


Cu thickness=2mm

- The slow transitions from the resistive-wall impedances of the copper only chamber to those of the NEG only chamber can be observed over 0.1-100 GHz range.

Closer Look on Linear Scale up to 100 GHz

- Real part of longitudinal

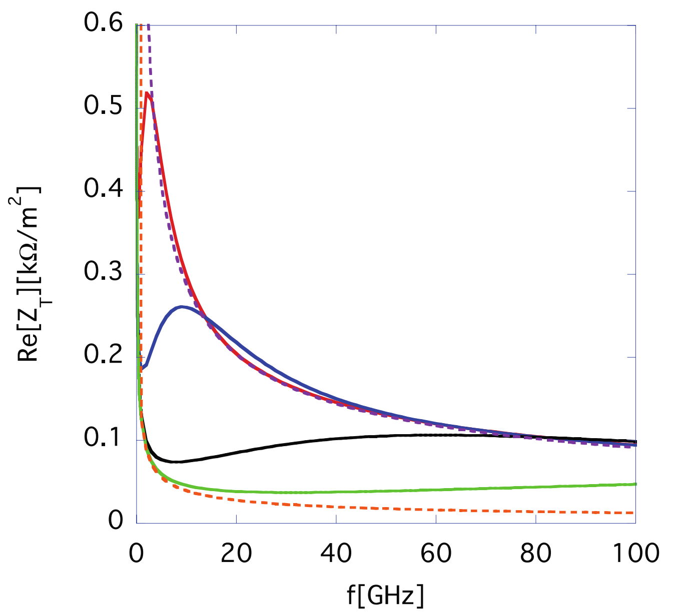


NEG thickness
Green: 1μm
Black: 2μm
Blue: 5μm
Red: 10 μm

- The real part of the longitudinal impedance increases almost linearly to the frequency when the thickness of NEG coating is small (a few μm).
- The impedance shape almost saturates at around 5μm as a function of the NEG thickness.

Transverse Impedance

- Real part of transverse



NEG thickness
Green: 1μm
Black: 2μm
Blue: 5μm
Red: 10 μm

- It varies widely as a function of the thickness of the NEG coating.
- Above around 20 GHz, the transverse impedance looks saturated as a function of the NEG thickness.
- But below that frequency, the transverse impedance increases significantly for a thicker NEG coating.

Observations

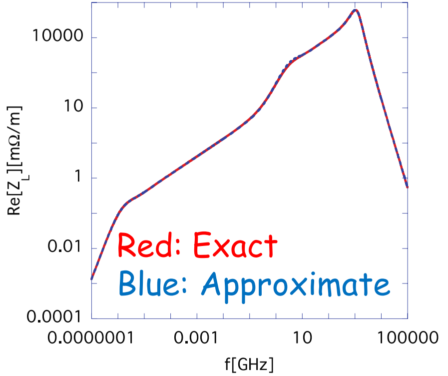
- The effect of the NEG coating may be unnoticeable when
  - The NEG coating is very thin (such as 1μm)
  - The bunch is long (such as 1cm) so that the impedance behavior matters only at relatively low frequency, say up to 20 GHz.
- Otherwise, the choice of the NEG thickness may have a great impact on the impedance budget of a machine.
- In the middle frequency region from a few kHz till 10 MHz, the wake fields see mostly the copper chamber so that the transverse impedance has a little dependence on the thickness of the NEG coating.

HOM Heating

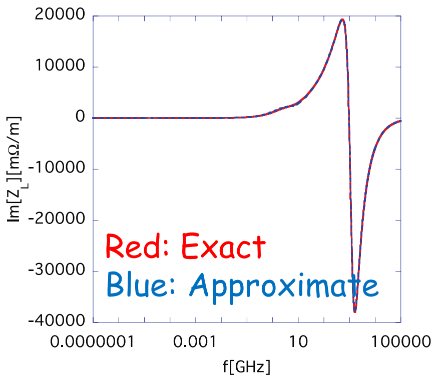
- When the bunch length is 3mm, the loss factor per unit length is
  - 0.0122 V/(pC m) for the NEG coating thickness =1μm
  - 0.0741 V/(pC m) for the NEG coating thickness = 10 μm.
- Let us assume a SLS-II like ring
  - Circumference=288 m
  - Total beam current = 400 mA
  - Single bunch current of 1 mA
- The power deposition on the chamber per unit length is about 30 W/m for the NEG thickness of 10μm.
- It may not be significant power deposition that requires a special cooling system for the copper chamber.

Simpler Approximate Formulae

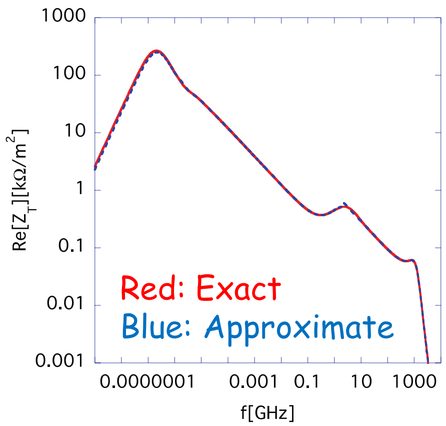
- We have also derived simpler approximate formulae for the both longitudinal and transverse impedances for quick and easy calculations.



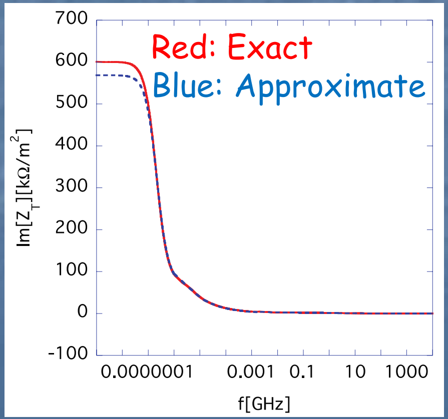
Real part of longitudinal impedance



Imaginary part of longitudinal impedance



Real part of transverse impedance



Imaginary part of transverse impedance

Slight difference at low frequency below 100Hz

Conclusions

- The both longitudinal and the transverse impedances are in the middle of the transit states between the copper only chamber and the NEG only chamber in the frequency range of 0.1-100 GHz in terms of the conventional resistive-wall impedance formulae.
- In this frequency range, the longitudinal impedance seems to be saturated at around 5 μm as a function of the thickness of the NEG coating.
- But the transverse impedance still has large dependence on the thickness of the NEG coating.
- At very high frequency over ~100 GHz, the impedances deviate from the conventional impedance lines for the NEG only chamber.

Cont.

- At the SuperKEKB, they have considered to use the NEG coating on chambers in the interaction region to achieve high vacuum there (they gave it up, though).
- They think that the NEG thickness needs to be at least several μm for effective pumping and for a long lifetime.
- In this regard, the choice of the NEG thickness may have a great impact on the impedance budget of a machine.
- The present theory and findings will provide a good guidance for design of vacuum chambers with a thin coating and a tool to accurately estimate their resistive-wall impedances.