Impedance of a ceramic break and its resonance structure

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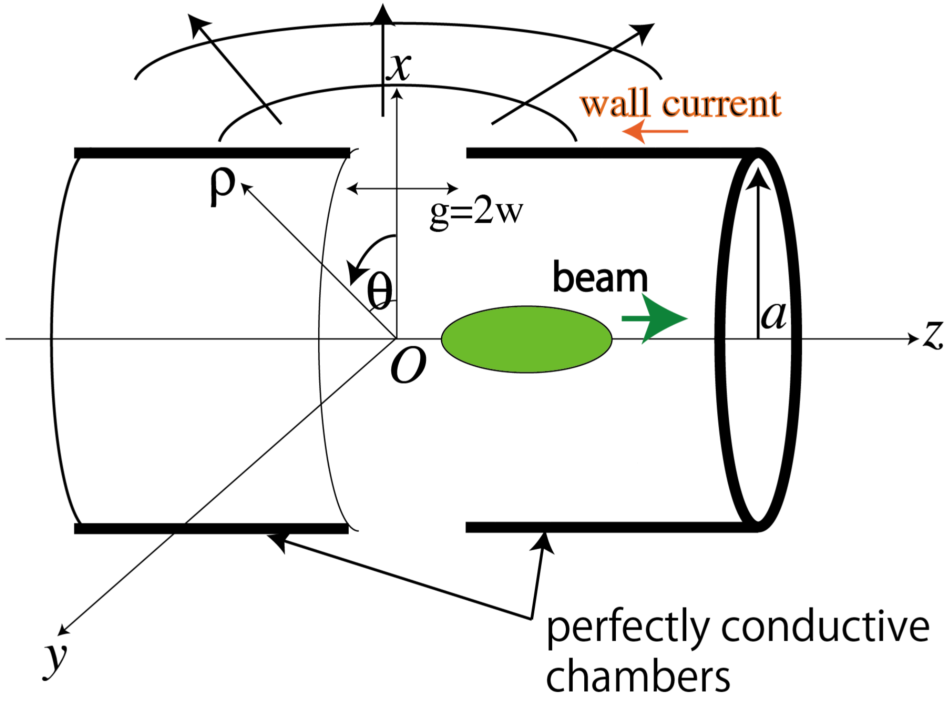
Outline

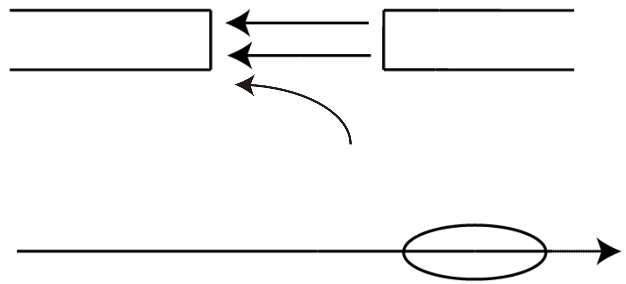
- *Characteristics of a gap impedance*
- *Characteristics of the ceramic break (without the TiN coating)*
- *Comparison between the impedance of the ceramic break with the TiN coating and that of the short resistive insert.*
- *Discussion about the impedance of the ceramic break surrounded by perfectly conductive chamber.*
- *Summary.*

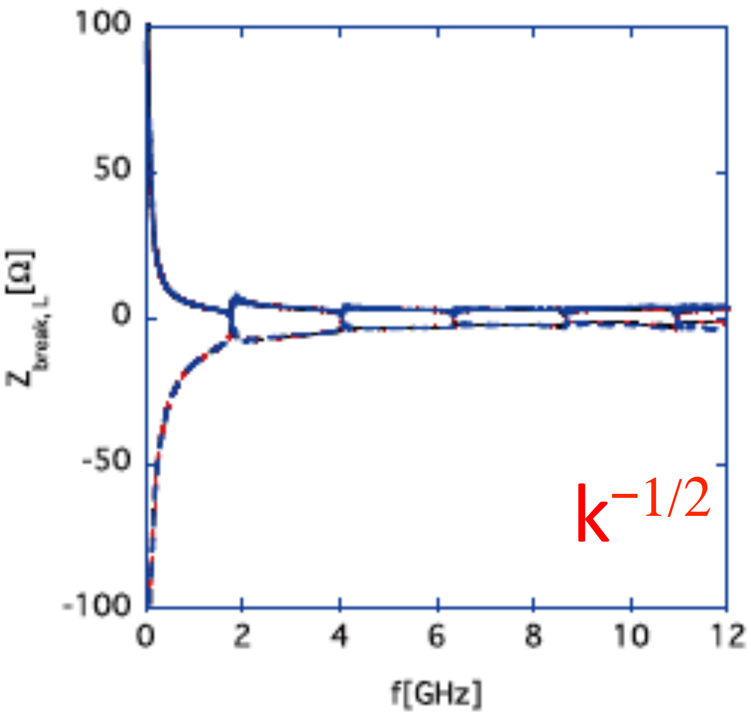
We have a theory of a gap impedance(PRST10,044403)

Open boundary

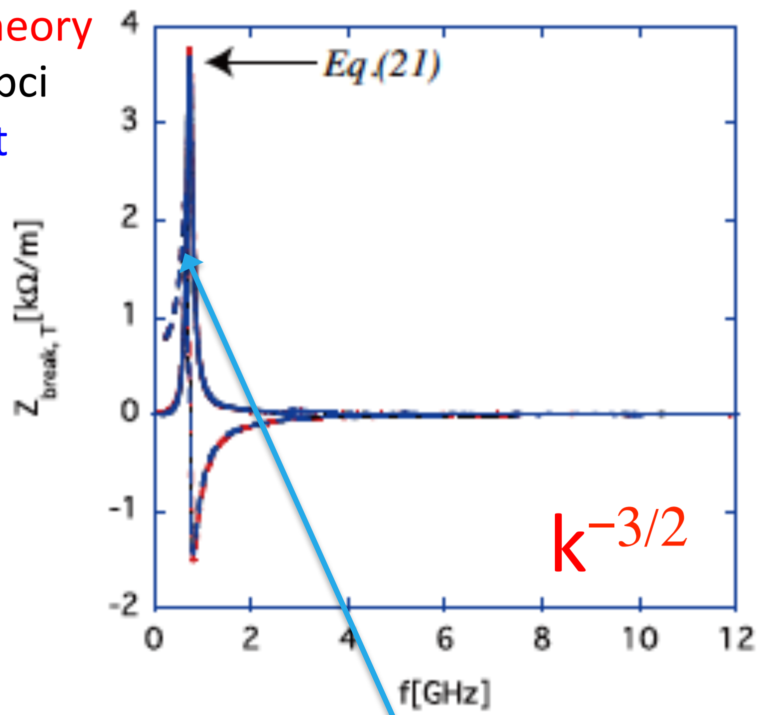
Radiation fields







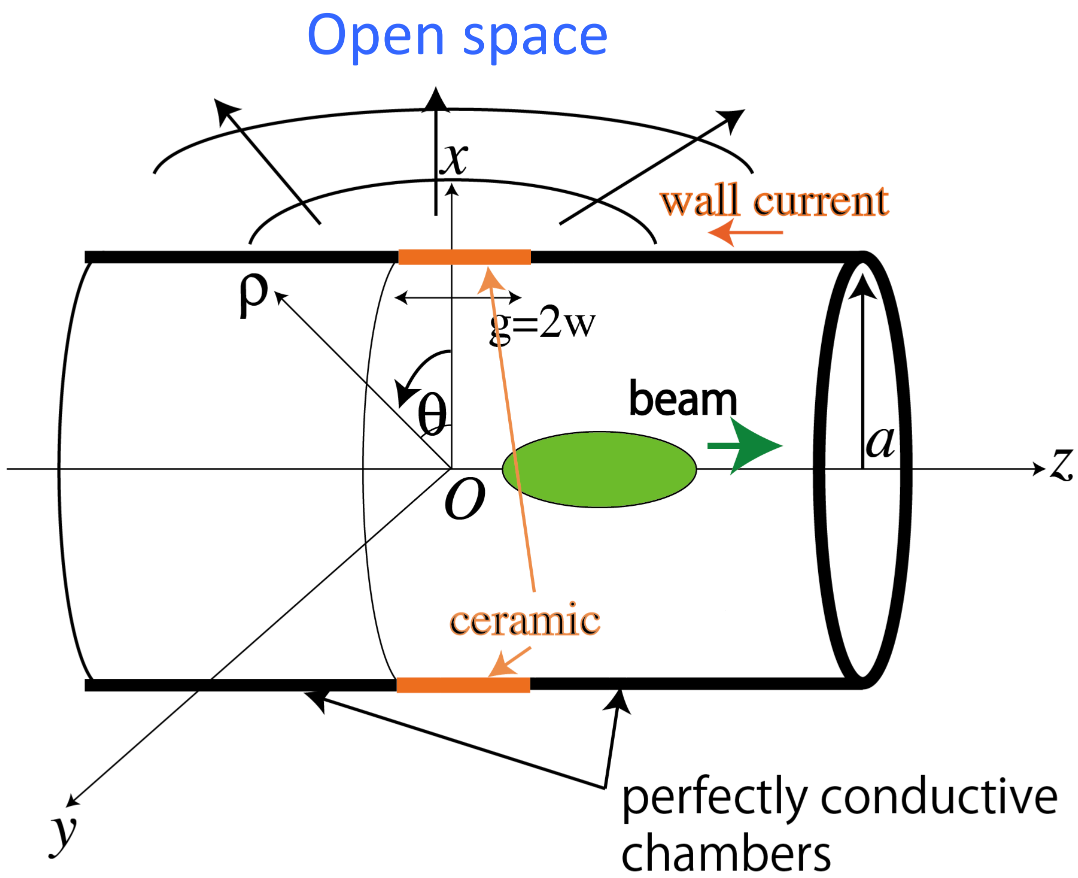
Red : theory
Black :abci
Blue :cst



The results are consistent with the diffraction theorem.

- The real part of the impedance goes to infinity at zero frequency.
- The dips correspond to the cutoff frequencies.
- The longitudinal impedance is capacitive because the gap works like capacitor.
- The transverse impedance resonates at the circumference of the beam pipe:2πa.

A ceramic break

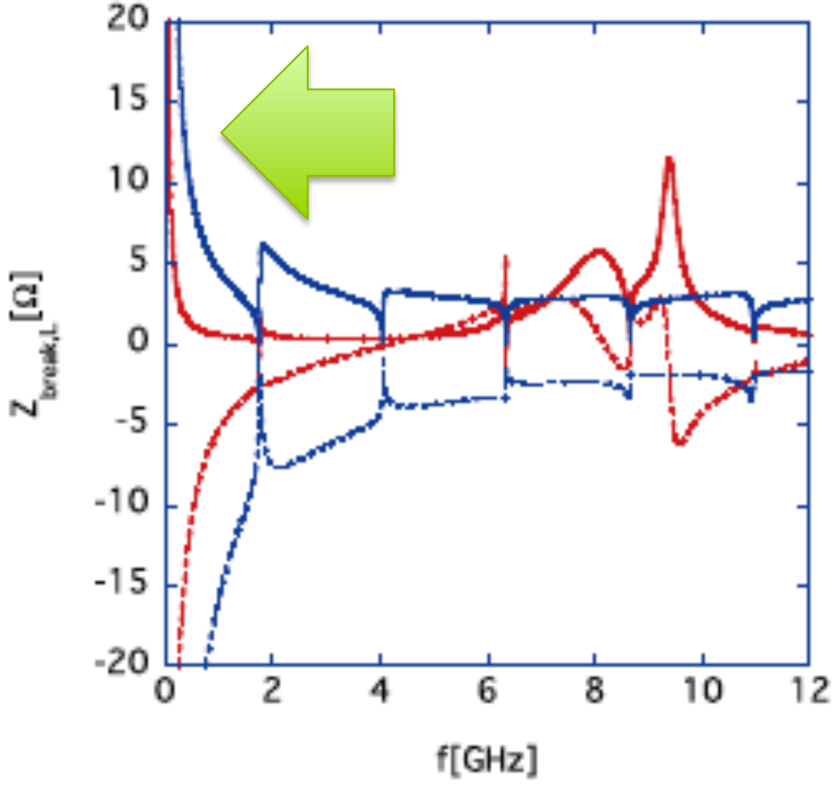


- The vacuum gap is filled with the ceramic.
- Dielectric constant ε of vacuum and that of ceramic is different.
- Velocity of light becomes slower by the factor of 1/√ε.

  =>wavelength contraction occurs.

Comparison between the impedance of vacuum gap and that of ceramic break

Longitudinal impedance



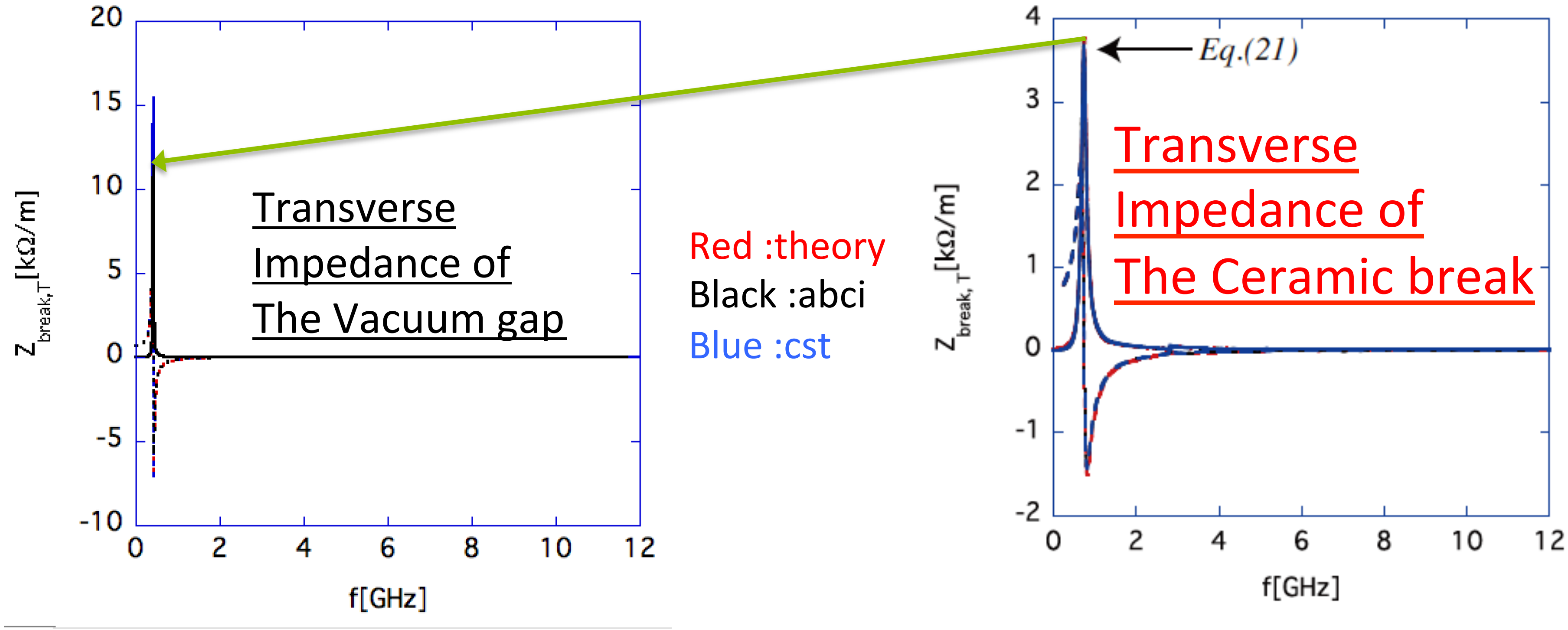
The loss factors
the ceramic break:
22.34 mV/pC

the vacuum gap:
73.44 mV/pC

Blue :gap
Red: ceramic break
(Relative Dielectric Constant :ε=11.)

- The wavelength contraction effect reduce the impedance of the ceramic more rapidly.
- Consequently, the loss factor of the ceramic break is a few times smaller than that of the vacuum gap.
  => The ceramic is beneficial to suppress the energy loss of the beam.

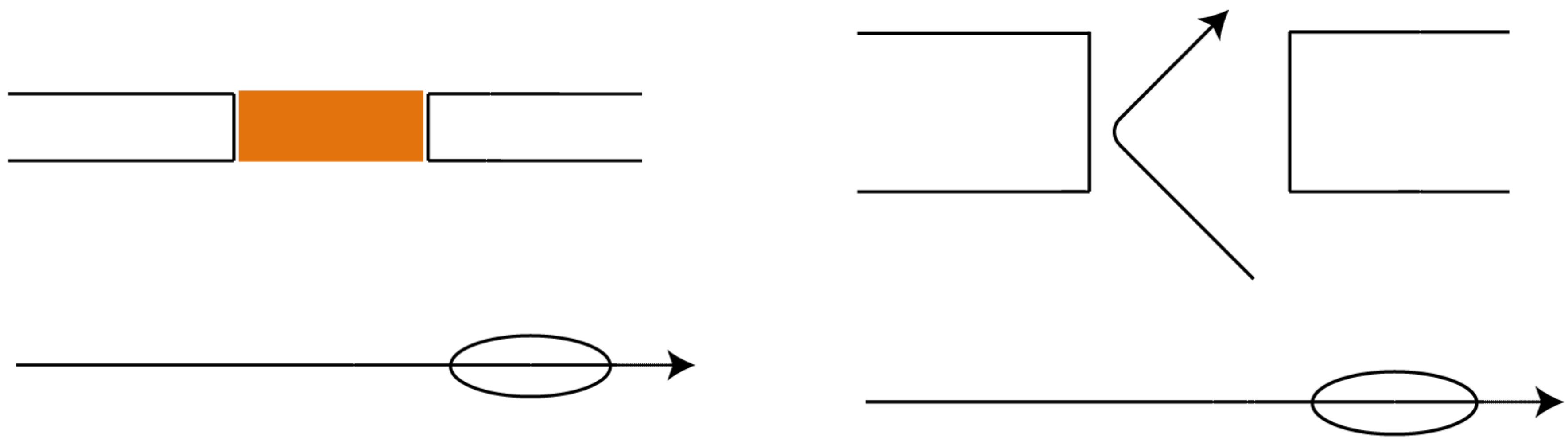
Transverse impedance



- The resonance, which already appears in the vacuum gap case, is lowered by the wave contraction effect in the ceramic.

$$f \sim \frac{c}{2\pi a}\sqrt{\frac{a^2 + 1.5(a_2^2 - a^2)}{a^2 + 1.5\epsilon'(a_2^2 - a^2)}}.$$

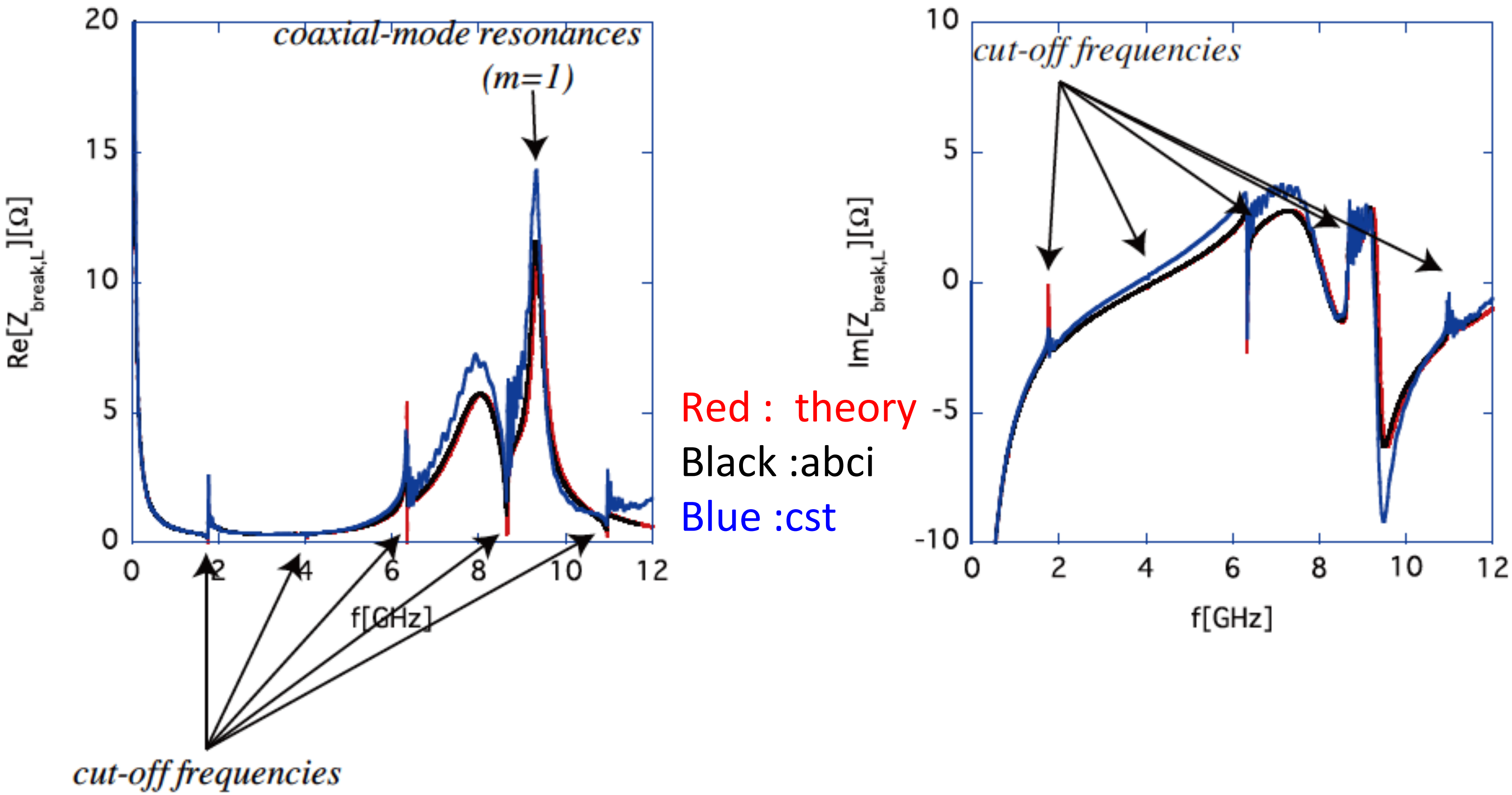
- The wavelength contract effect effectively broaden the space of the ceramic.



- Trapped modes are generated in the ceramic and thus they increases the impedance.
- We call them coaxial modes.
- The positive integer m (coaxial mode) denotes the number of half wavelength in the ceramic.

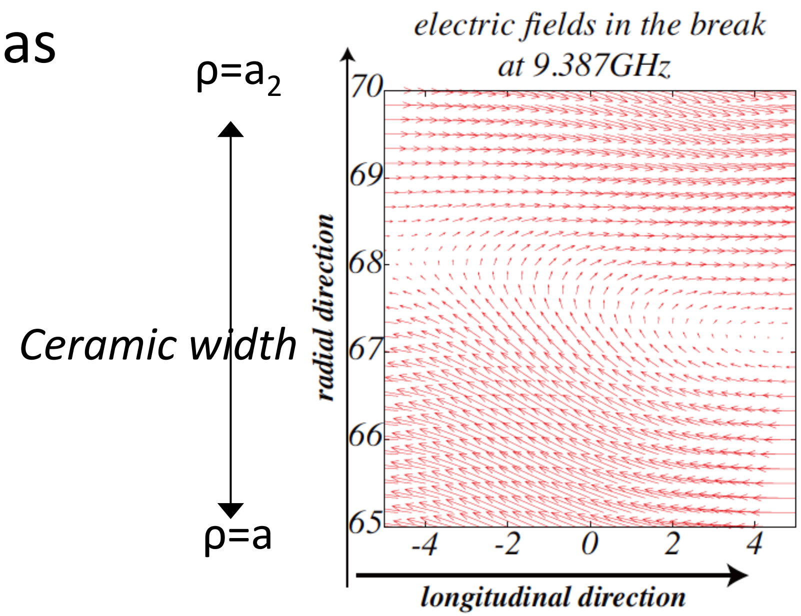
Numerical comparison between the theoretical and simulation results

Longitudinal impedance of the ceramic break



- All the calculation results (the theory, ABCI and CST) reveal the resonance structures and show good agreements between them, in particular, between the theory and ABCI.
- CST tends to provide higher impedances, notably at resonance frequencies, than the others.

◆ One of the coaxial modes has a resonance at 9.387GHz.



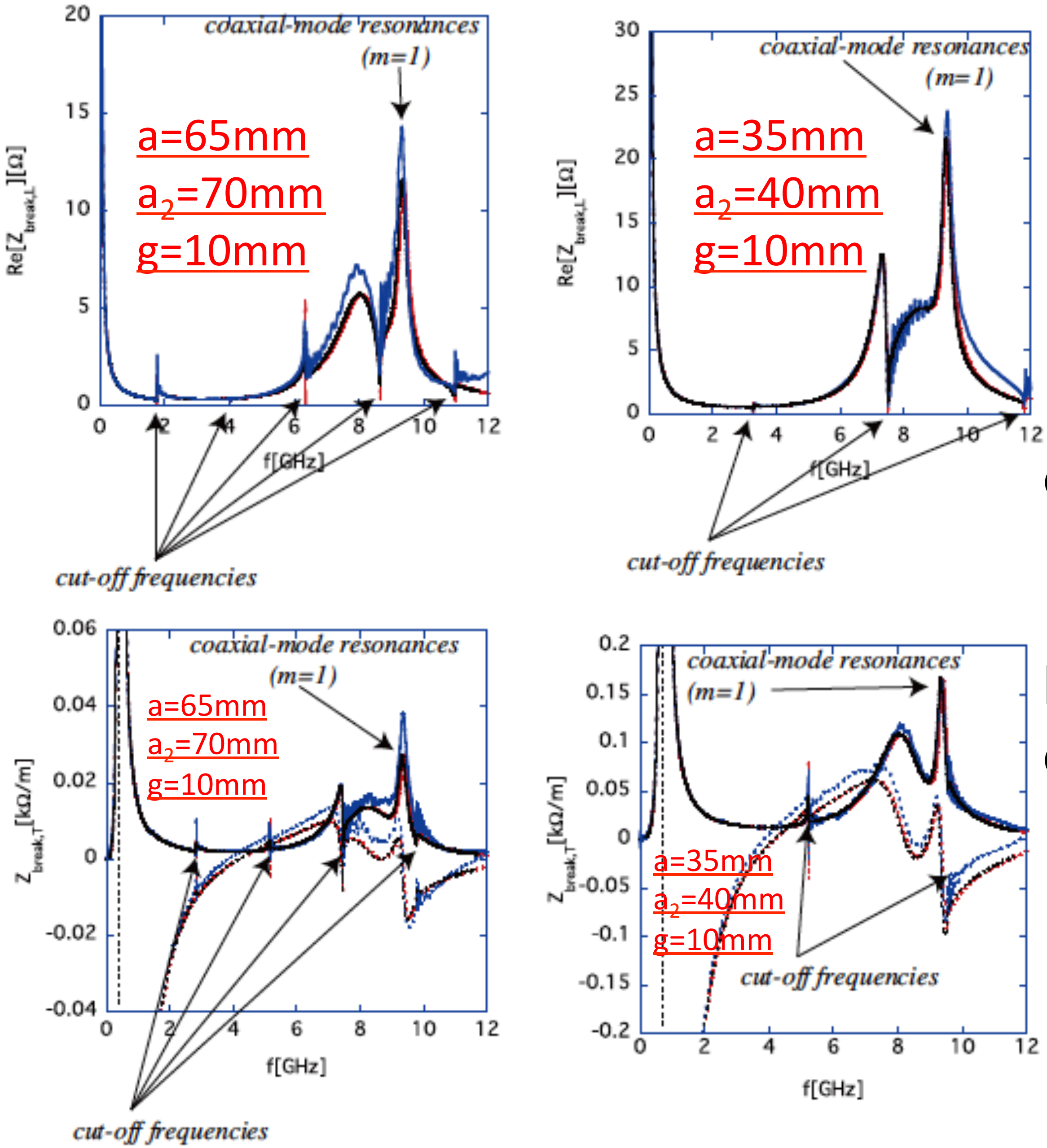
◆ The electric fields are almost parallel to the longitudinal direction at $\rho = a$ and $\rho = a_2$.

◆ The fields behave like antenna both on the inner and outer surface of the ceramic.

◆ The fields can propagate away both inside and outside of the chamber.

=> The impedance has sharp peaks at their frequencies.

Except the coaxial mode resonance, cavity-mode resonance exists.

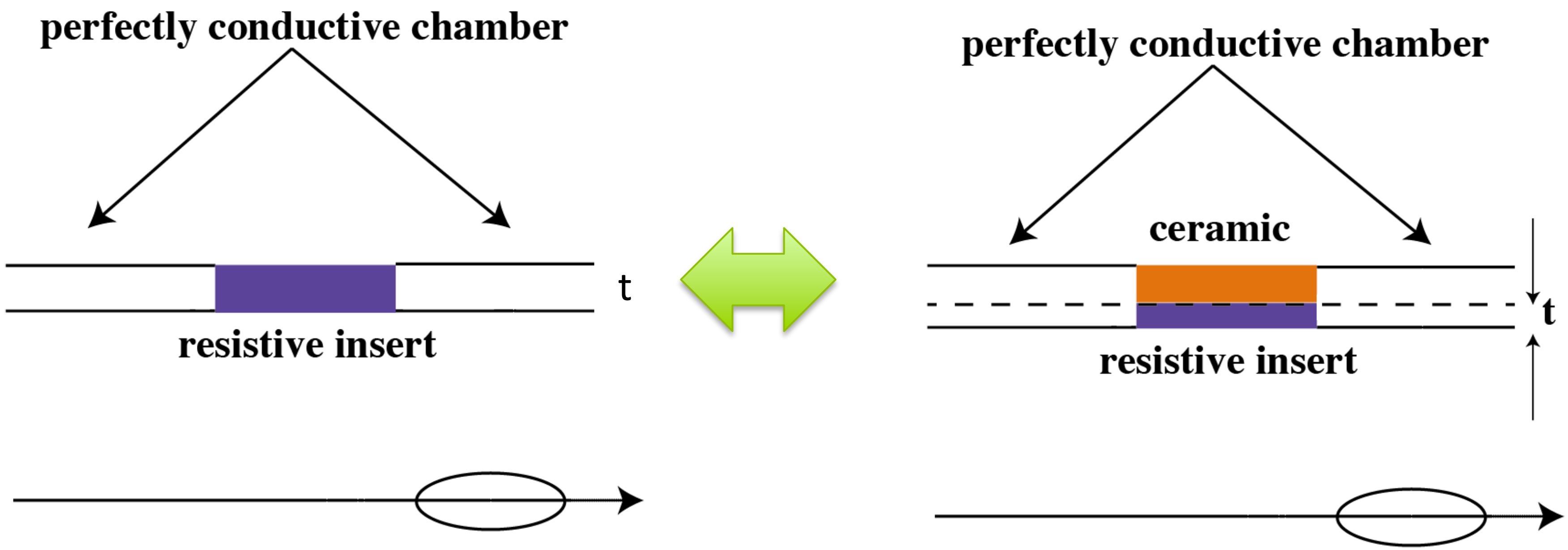


- The cut-off frequencies of the two chamber cases are quite different.
- The resonance behavior are drastically changed between them.

Impedances of ceramic breaks coated with TiN

- Our theory can be applied to the ceramic, which is coated with TiN with the conductivity σ_{TiN}(=5.88* 10^6 S/m) and the thickness t.

- We have already had a theory of a short resistive insert(PRST12,094401).

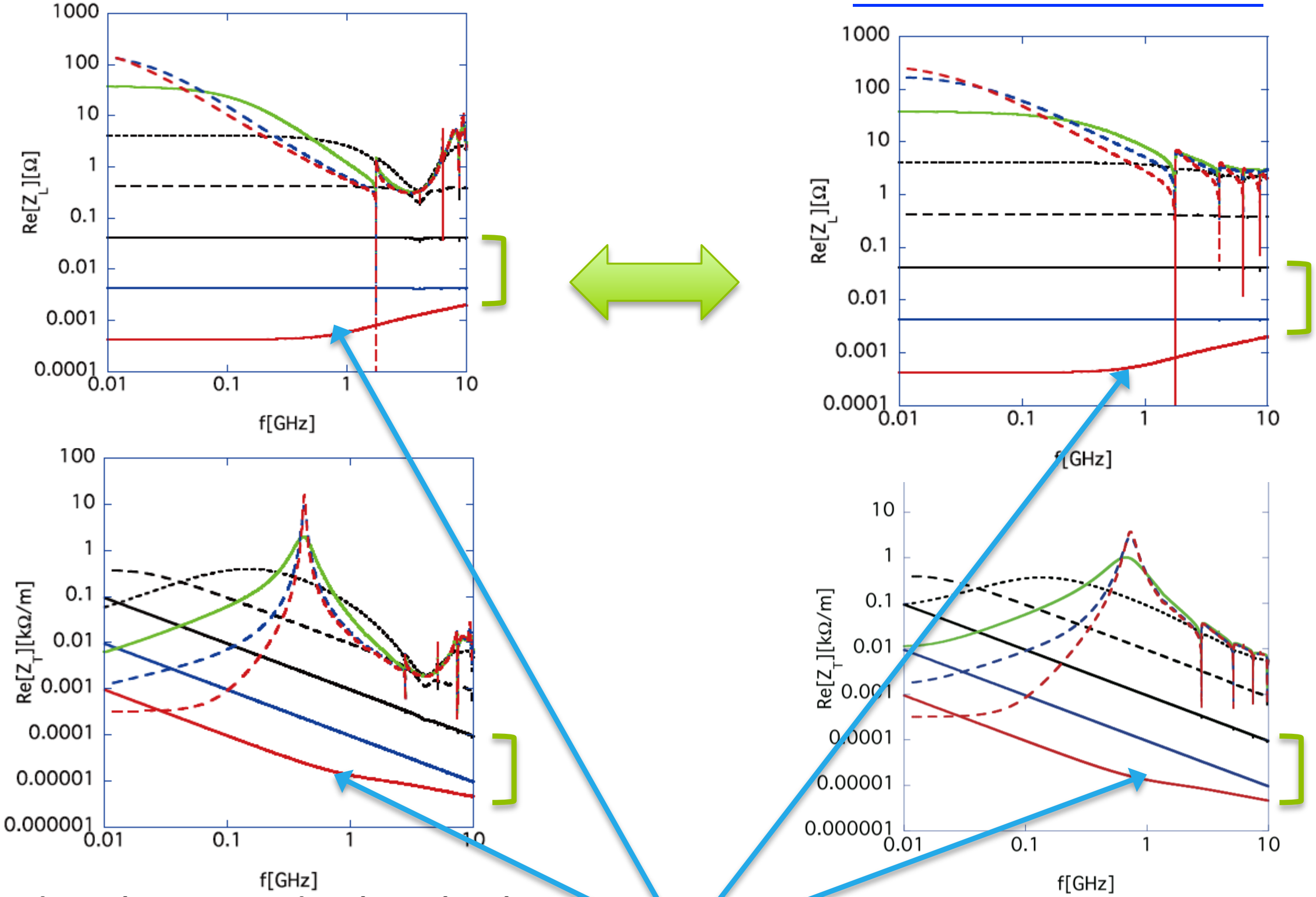


Comparison between the longitudinal impedance of the ceramic break with the TiN coating and that of the short insert.

Ceramic Break with the TiN coating

Resistive Short insert

t=0m(dash)
t=10pm(dash)
t=100pm
t=1nm(dot)
t=10nm(dash)
t=100nm
t=1um
t=10um



- When the skin depth exceeds the thickness t, the impedance becomes wall current dominant, and is proportional to 1/t.
- The impedance does not depend on whether the ceramic exists or not.
- This is because the wall current tries to flow the TiN coating and shields the electro-magnetic effect from the world outside the TiN.

◆ At low frequency (kβ √ε' a   << 1), the longitudinal impedance is approximated as,

$$Z_{cerTiN,L} \simeq \frac{\frac{4a_2 I_1^2(\bar{k}\sigma)}{\sigma^2\bar{k}^2 a I_0^2(\bar{k}a)}\left(\frac{\sin kw}{kw}\right)^2}{\frac{jk\beta a_2(\langle J(z)\rangle+\langle Y(z)\rangle)}{Z_0}-\frac{j\pi a_2\kappa_{TiN}\tanh\kappa_{TiN}t}{wk\beta Z_0}+\frac{j\omega\epsilon'\pi a_2(a_2-a)}{cZ_0 w}}$$

Resistive wall term

Radiation term

the capacitive part made by the ceramic

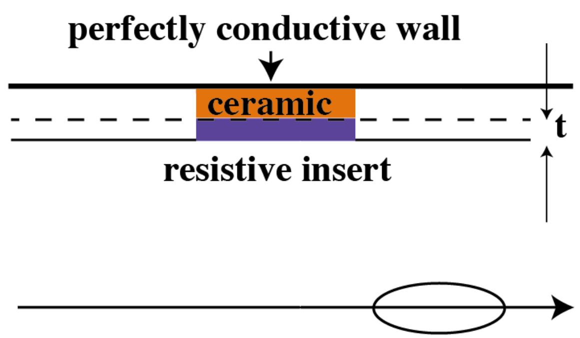
- The impedance of the ceramic break is approximately obtained by adding three impedances(radiation, resistive, capacitor) in   parallel.

In the case of the ceramic is surrounded by the perfectly conductive chamber.

- It seems that the present results look contradict to some previous studies related to ceramic chambers(Tsutui *et al*, Biancacci *et al(PRST17,021001)*).
- *where the real part of longitudinal impedance goes to zero at zero frequency*

$$Z_L \simeq \frac{wZ_0}{\pi\beta a(Z_0 t\sigma_{TiN} - \frac{j\epsilon'}{(\epsilon'\beta^2-1)ka\log\frac{a_2}{a}})}.$$

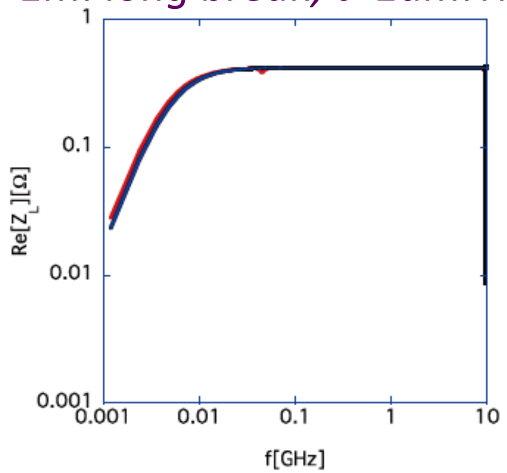
(e.g. Tsutsui's approximate results)



- However, in their studies,
  - the (finite) element (or ceramic chamber) is surrounded by perfectly conductive walls.

- To simulate this case, the boundary conditions is modified in the present theory.

g=1m: long break, t=1um:TiN thickness



Red: our results(complete results)
Black: obtained by using rigorous 2D model.
Blue: Tsutui's approximate results.

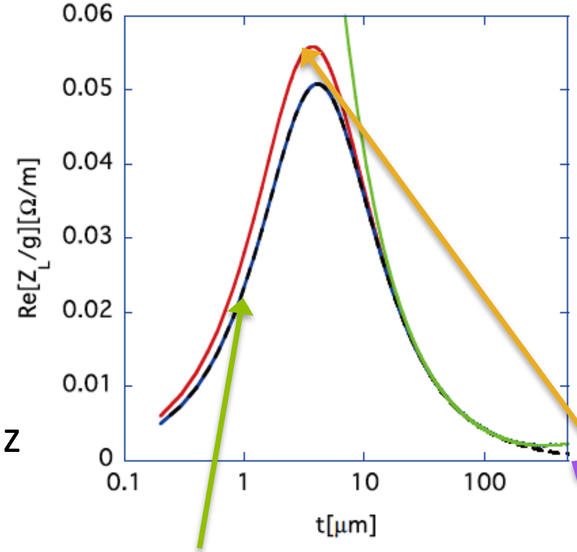
This results reveals that the perfectly conductive boundary condition makes the impedance go to zero at zero frequency.

- Another recent study (Mounet &Metral IPAC 2010) shows that *the impedances of an infinitely long* and axisymmetric beam pipe *goes to zero at zero frequency*.
- In the case, the perfectly conductive chamber does not appear explicitly.
- However, the chamber exists implicitly at far infinity.
- Moreover, the field does not longitudinally modulate at zero frequency.

=> That is why *the impedance* of an infinitely long and axisymmetric beam pipe *goes to zero at zero frequency*,
even when the beam pipe is not directly surrounded by the perfectly conductive chamber.

TiN-Thickness dependence of Longitudinal impedance for 10mm long *where the ceramic is surrounded by perfectly conductive walls.*

@1.2MHz



Green: Not surrounded by PEC

Red: complete solution

Blue: an infinitely long and axisymmetric beam pipe

Dashed black: Tsutsui's approximate solution

$$Z_L \simeq \frac{wZ_0}{\pi\beta a(Z_0 t\sigma_{TiN} - \frac{j\epsilon'}{(\epsilon'\beta^2-1)ka\log\frac{a_2}{a}})}.$$

- In the thin TiN coating region, the rigorous solution for the infinitely long ceramic (the blue line) agrees well with its approximate solution (the dashed black line).
- However, they start to deviate at the thick TiN region (because the approximation is only valid when the skin depth is larger than the thickness t).
- The complete solution (the red line) shows larger impedance values in the range where the TiN coating is smaller than 10 um, since it includes the contributions of the fields trapped inside the ceramic sandwiched by the perfectly conductive chambers on both sides.
- In this case (a=65mm,a_2=70mm,g=10mm), it is observed that the longitudinal impedance is maximum at a given TiN thickness (several um in the present example),
- This means that the design of such inserts could profit from this theory to find a coating thickness that would minimize the impedance of the insert.

Summary

- A new theory is developed to describe longitudinal and transverse impedances of ceramic breaks.
- The theoretical and numerical simulation results calculated by ABCI and CST Studio are all in good agreement for the ceramic break without the TiN coating.
  - Particularly, the agreements between the theoretical and ABCI's results are excellent.
- The impedance of the ceramic break has new resonance structures, because the dielectric constant of ceramic effectively broadens the space in the ceramic and creates the trapped mode there.

- The theory can be also applied to the calculation of the impedance of ceramic break coated with thin TiN.
- For the TiN thickness (~a few ten nm), the wall current shields the electro-magnetic effect from the world outside the TiN.
  - Consequently, the impedance does not depend on whether the ceramic exists or not.

- When the ceramic with finite length is surrounded by conductive walls,
  - The perfectly conductive boundary condition makes the impedance go to zero when the frequency approaches to zero.
  - The longitudinal impedance takes the maximum at a certain thickness.
  - Below this thickness, thinner coating is preferable from the impedance point of view.