Dielectric Collimators for the CLIC Beam Delivery System?

First ideas from studies for the LHC collimators

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Many thanks for their help and advice to

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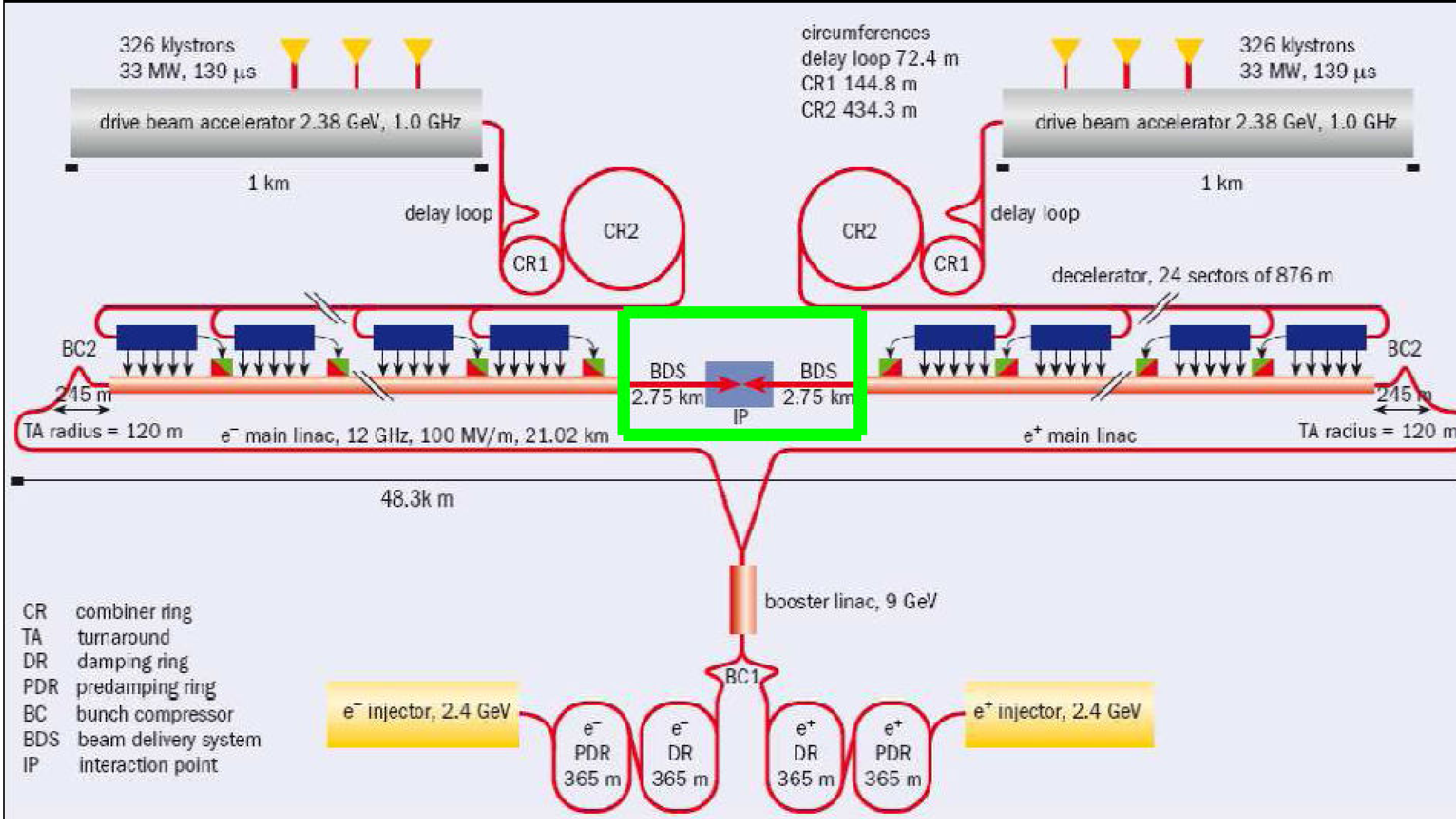
Agenda

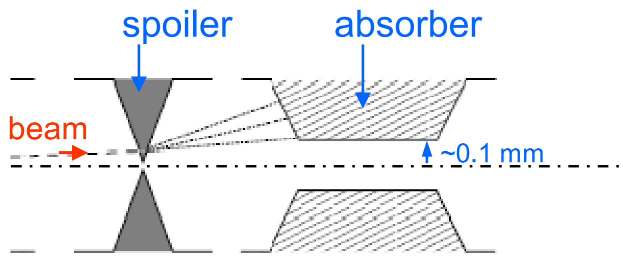
- Context
- Why consider dielectrics for LHC collimation?
  - Idea
  - Impedance code (ReWall)
  - Results and recommendations
- Coarse extrapolations to the case of the CLIC bunch as an introduction to future work
  - Analytical estimates
  - Electromagnetic simulations (CST Particle Studio)
- Perspectives

Beam Delivery System



Context: CLIC BDS collimation system

- BDS Collimation System needed for background reduction and machine protection



Courtesy: J. Resta Lopez

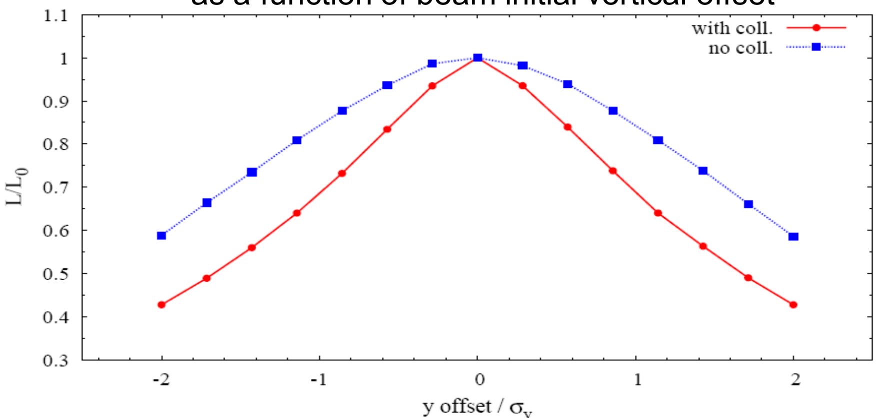
- However, collimators may generate strong wakefields and affect the beam quality

  → luminosity limitation

- *CLIC collimation system review: optics issues and wakefield effects*, J. Resta Lopez, 15/01/2009

- *Tracking with Collimator Wake-Fields through the CLIC BDS*, A.Latina, G.Rumolo, D.Schulte, 19/05/2006

Simulated loss of CLIC luminosity as a function of beam initial vertical offset



Courtesy: J. Resta Lopez

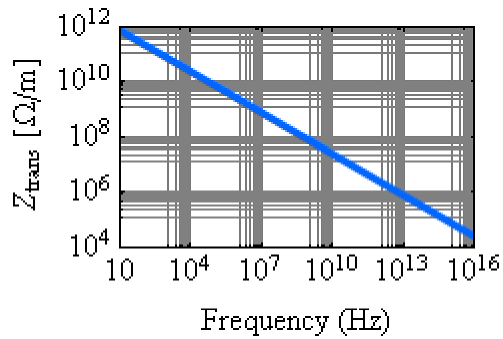
→ Need to minimize the BDS collimation wakefield

Context: Recent ideas for LHC collimation

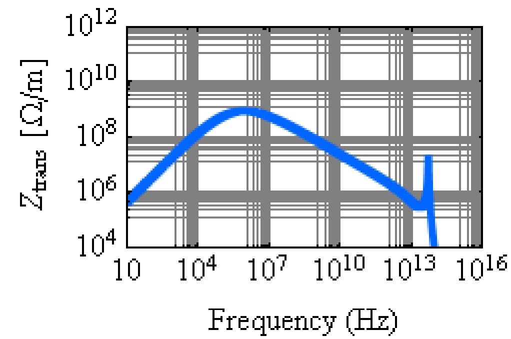
- Concern for the high impedance of the collimators, especially at low frequencies

Example:
Real part of impedance of a cylindrical collimator (infinitely thick copper layer) (aperture radius = 0.1 mm, length 60 cm)

Classical thick wall theory



"New" formalisms (Zotter/Metral, Burov/Lebedev)



- However, impedance does not increase steadily at low frequencies

  Comparison between Laboratory Measurements, Simulations and Analytical Predictions of the Transverse Wall Impedance at Low Frequencies, F. Roncarolo et al, EPAC'08 and submitted to PRST/AB .

- As a consequence, materials with low conductivities could also be considered

  → In particular, dielectric materials offer a wide range of electrical, mechanical and thermal properties.

  → may be an opportunity to find an optimized solution for the phase II collimation system

Question : would it be a good idea to also consider dielectric materials for the CLIC BDS collimation system?

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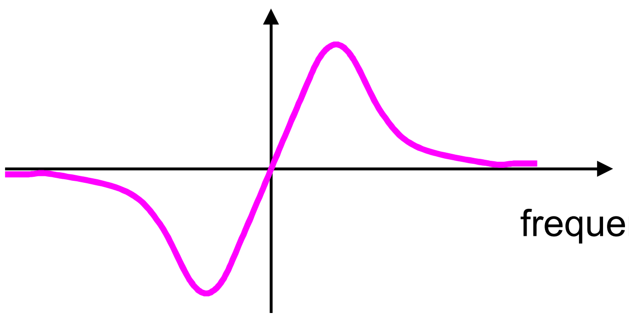
Why consider dielectrics for LHC collimation?
→ idea

- For circular accelerators, the impact of the transverse impedance $Z_{trans}(\omega)$ on the beam behaviour depends on the bunch power spectrum $h(\omega)$:

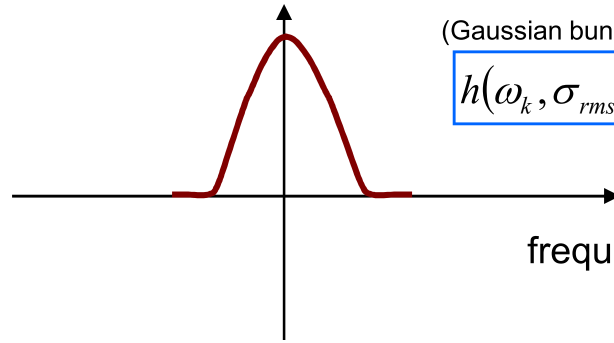
Real impedance $Re(Z_{trans})$



Bunch power spectrum h

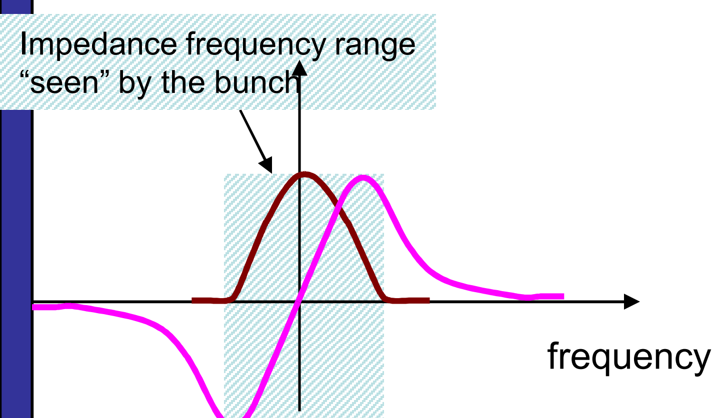
(Gaussian bunch of rms length σ_{rms})

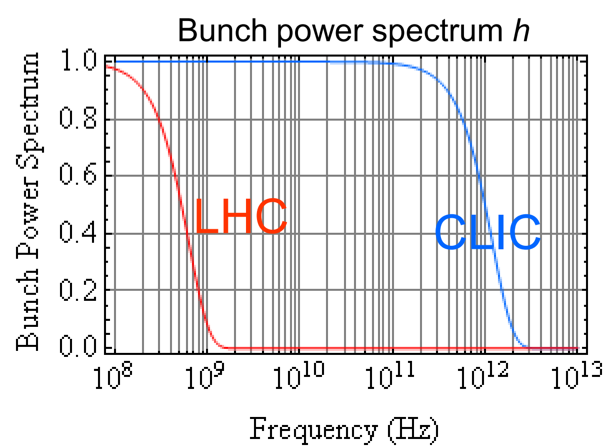
$$h(\omega_k, \sigma_{rms}) = e^{-(\omega\sigma_{rms})^2}$$



$$Z_{eff}(\sigma_{rms}) = \frac{\sum_{k=-\infty}^{+\infty} Z_{trans}(\omega_k) h(\omega_k, \sigma_{rms})}{\sum_{k=-\infty}^{+\infty} h(\omega_k, \sigma_{rms})}$$

(simplified formula for the sake of understanding
see Sacherer's formula for a more complete description
including chromaticity and bunched beam modes)





Frequency range of impedance "seen" by the bunch:

LHC → 1 GHz
CLIC→ a few THz

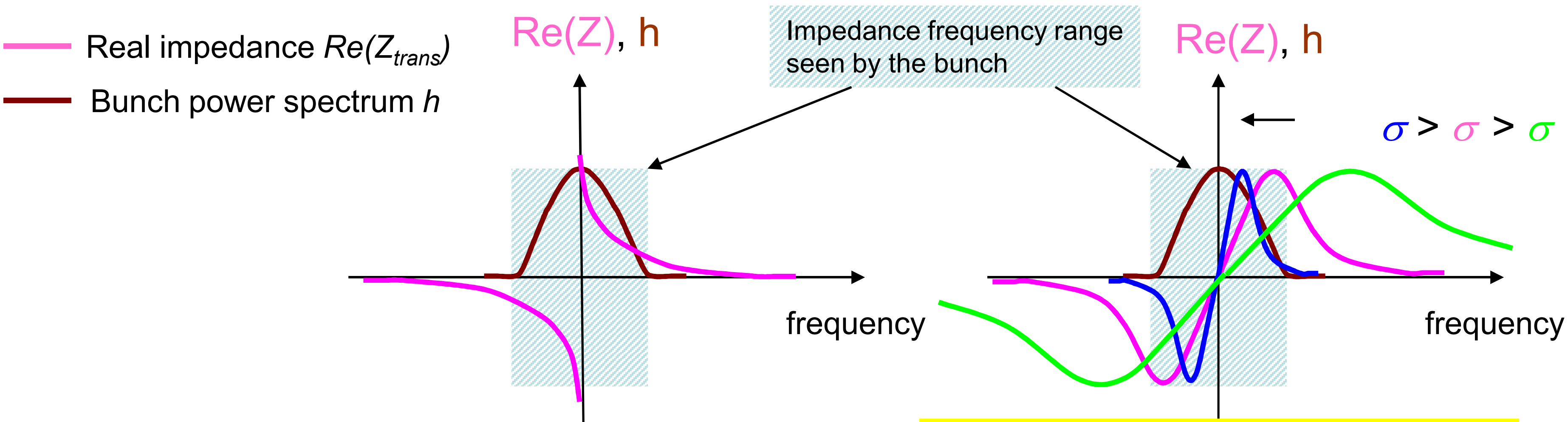
Why consider dielectrics for LHC collimation?
→ idea

- Classical impedance theory
  → primary concern for LHC collimators was the high impedance at low frequency (10 kHz) and the resulting coupled bunch instabilities.

- "New" theories, the impedance is no longer monotonous.
  → higher conductivity shifts the peak to lower frequencies

Classical "thick wall" impedance theory

"New" formalisms (Zotter/Metral, Burov/Lebedev)



In this case, the diverging impedance at low frequency is more critical

In this case, it really depends on the frequency and bandwidth of the impedance peak

Idea: can we shift the impedance peak outside of the LHC bunch spectrum? And reduce the impedance that interacts with the beam

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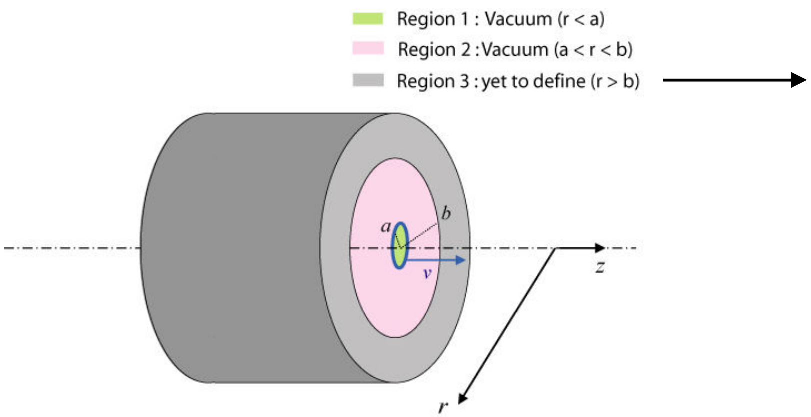
Why consider dielectrics for LHC collimation?

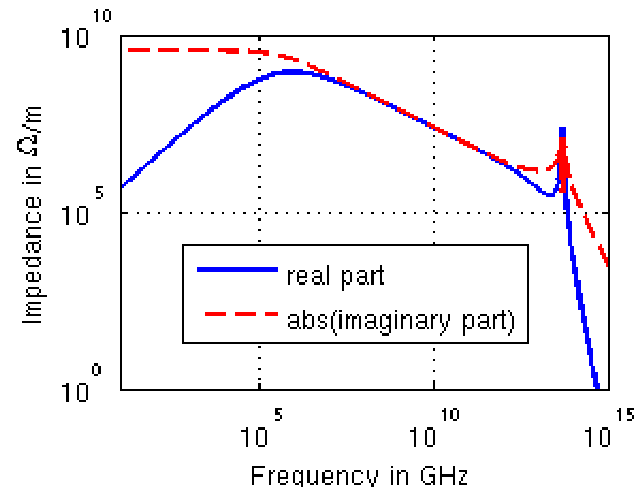
→ impedance model (ReWall)

- We wrote an analytical code which is able to compute the beam coupling impedance of a cylindrical structure composed of various layers of different materials (no restriction on the material parameters).



copper
graphite
ceramic

Example of impedance result



- This impedance code solves Maxwell equations and uses field matching at al all material boundaries to find the total longitudinal and transverse impedance of the structure (Zotter/Metral formalism).

- Impedance of a round collimator can be calculated, and analytical coefficients (Yokoya/Laslett) are applied to obtain the impedance of a flat collimator.

- This code makes no approximation, is numerically very demanding, and the number of layers can not be too high if no simplification is to be made.

- The wakes can be computed from the impedance via DFT (not a trivial step).

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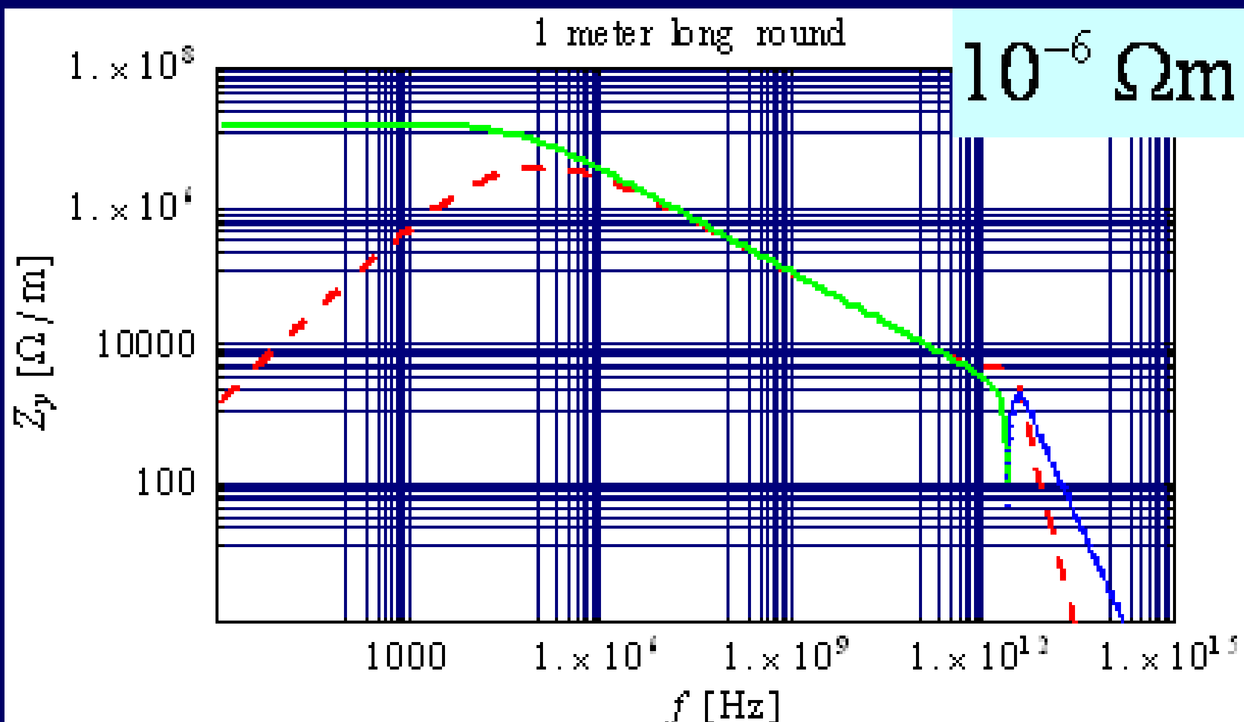
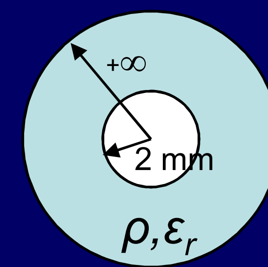
STUDIES ONGOING FOR A CERAMIC COLLIMATOR (1/10)

ANALYTICAL PREDICTIONS

⑨ Scan in resistivity ρ from 10^{-6} to 10^{20} Ωm and $\varepsilon_r = 5$

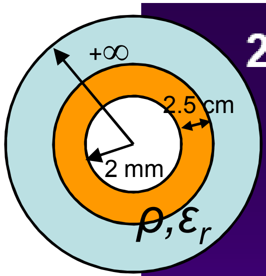




$$f_{\text{1st peak}} \propto \rho$$

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

Higher resistivity leads to → real part peak shifts to very high frequencies (for LHC…)
→ increase of the imaginary part at high frequencies



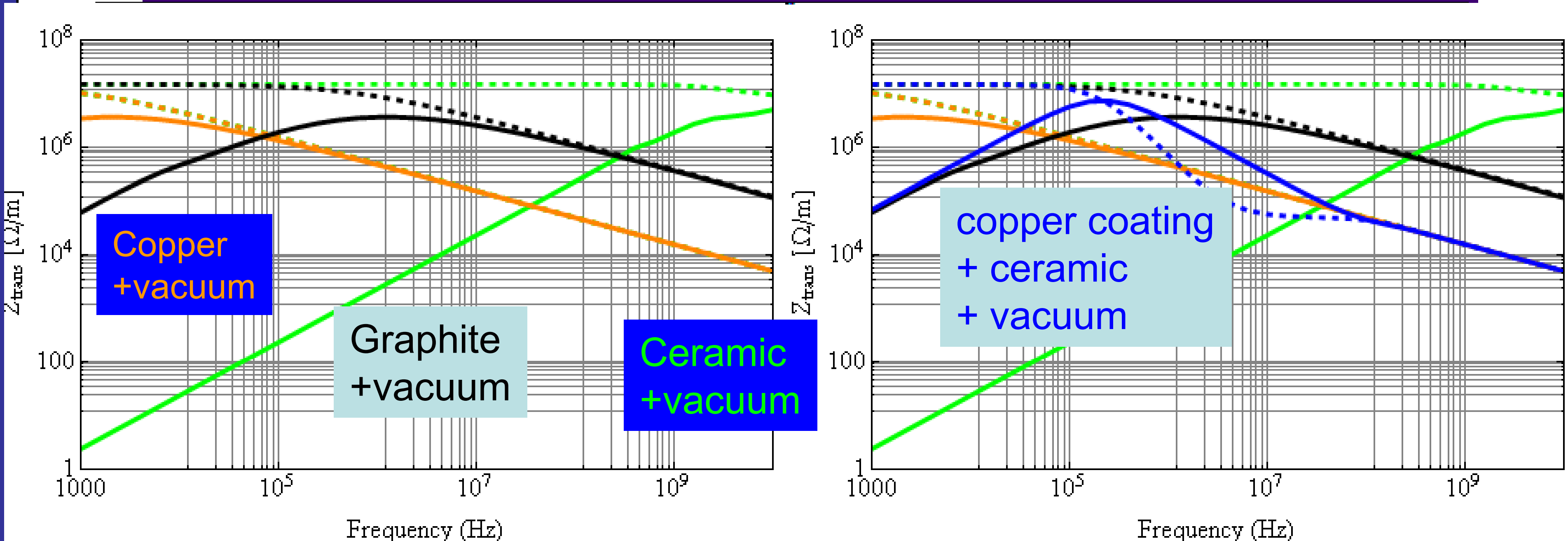
2nd ROUTE: SECONDARY COLLIMATORS MADE OF CERAMICS?

ceramic $\varepsilon_r = 5$ $\rho = 1\ \Omega\text{m}$

$L = 1\ \text{m}$

$b = 2\ \text{mm}$

TRANSVERSE IMPEDANCE



Real part → full
Imaginary part → dashed

- 2.5 cm ceramic + vacuum
- 2.5 cm graphite + vacuum
- 2.5 cm copper + vacuum
- 10 µm copper coating + 2.5 cm ceramic + vacuum

Elias Métral, Conceptual Design Review LHC Phase II Collimation, CERN, 02-03/04/2009

→ dielectric alone leads to higher real and imaginary impedance above 10 MHz → not good
→ however copper coated ceramic may be tuned to lead to lower impedance, depending on the ceramic and the beam parameters

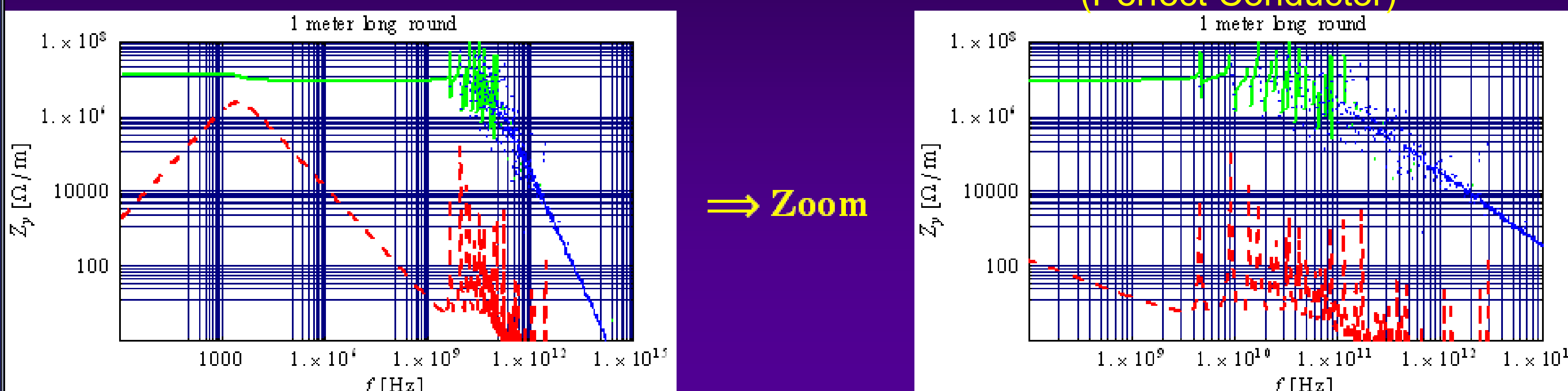
Why consider dielectrics for LHC collimation?

- In addition, another issue also comes up with dielectrics:

If a perfect conductor is placed behind the dielectric (instead of vacuum),
→ many resonances appear due to constructive interference in the dielectric
(multiple reflections at metal/dielectric and dielectric/air interfaces)

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

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



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A copper coating would also prevent these resonances from happening

And for CLIC?

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Impedance of the CLIC BDS collimator

- 2 contributors:
  - Geometric impedance (taper)
  - Resistive impedance (collimator is very close to the beam)

    → What are their relative weight?

- The resistive part can be estimated by our analytical code

- Time domain electromagnetic simulations can help calculating wake fields for the geometric part (ABCI, CST, GdfidL, Xwake…)

- 2 challenges:
  1) What is our material??? Conductivity, permittivity and their frequency dependence?

     → Need for precise description.

  2) Micrometer bunch in a meter long structure… numerically challenging

     → GdfidL moving mesh or 2D code?

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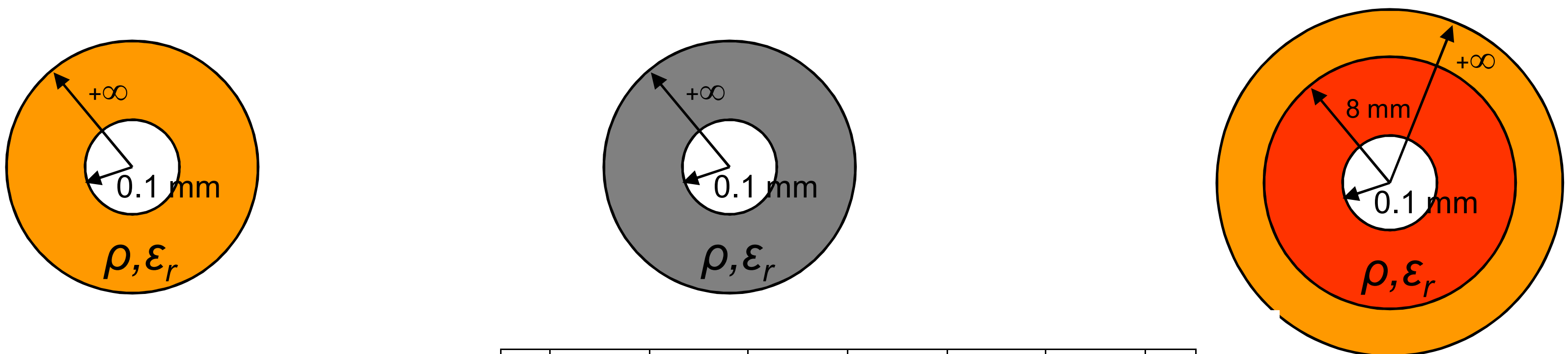
Analytical estimates: Resistive wall impedance

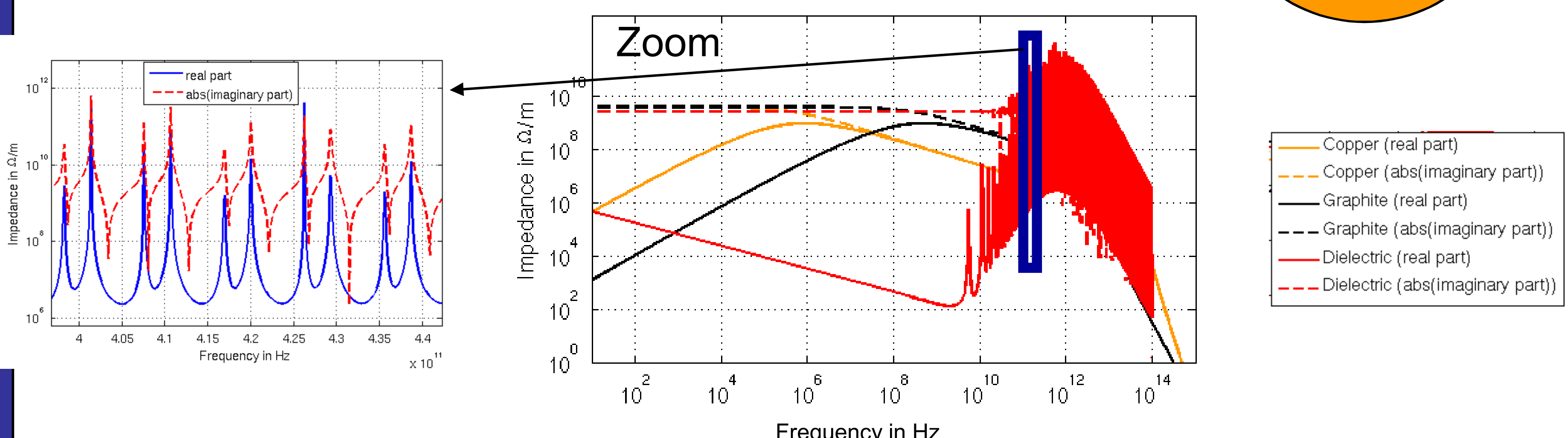
- CLIC BDS collimator:
  - Length 60 cm, inner radius 0.1 mm, γ = 3 10^6

Copper
resistivity ρ = 1.7 10^{-8} Ω.m
relaxation time τ =2.7 10^{-14} s)

Graphite
resistivity ρ = 1 10^{-5} Ω.m
relaxation time τ =8 10^{-13} s)

Dielectric + copper
dielectric resistivity ρ = 10^{12} Ω.m
Dielectric permittivity ε_r = 5



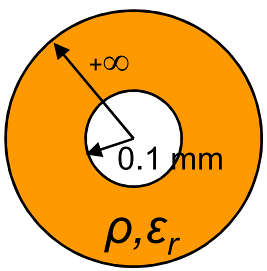


Now let’s take the DFT to obtain the wake!

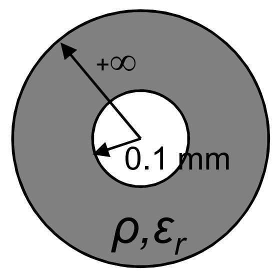
Analytical estimates: Resistive wall wake

- CLIC BDS collimator:
  - Length 60 cm, inner radius 0.1 mm, γ = 3 10^6

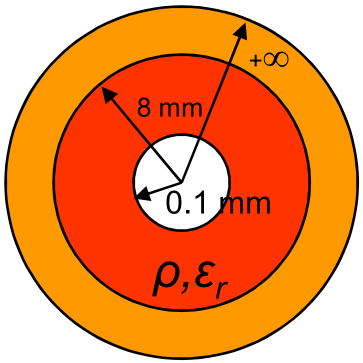
Copper
resistivity ρ = 1.7 10^{-8} Ω.m
relaxation time τ =2.7 10^{-14} s)

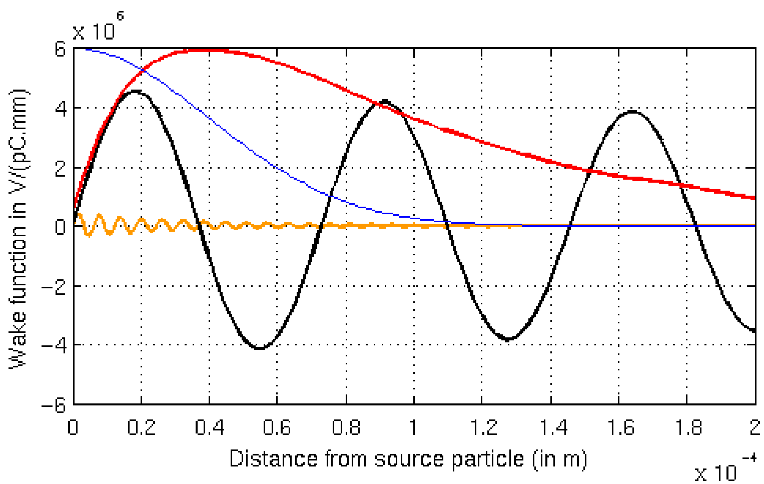


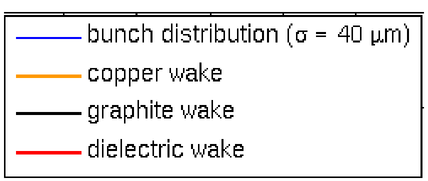
Graphite
resistivity ρ = 1 10^{-5} Ω.m
relaxation time τ =8 10^{-13} s)



Dielectric + copper
dielectric resistivity ρ = 10^{12} Ω.m
Dielectric permittivity ε_r = 5







→This dielectric example is worse than copper
→Graphite is probably not a good idea
→High frequency properties are essential!!!

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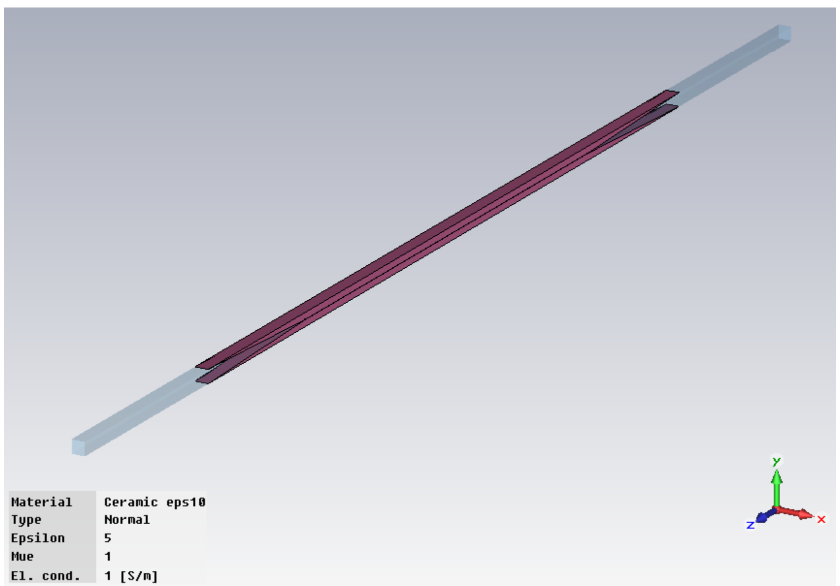
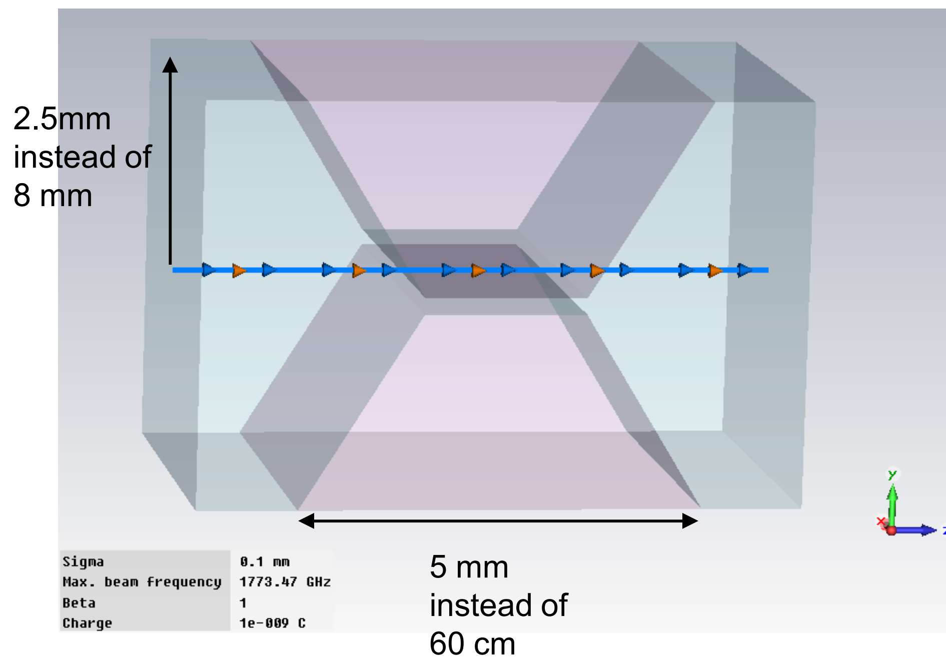
Disclaimer

- The following simulations are just first attempts on a much smaller collimator structure.
- Very small rms bunch length (~0.1 ps) compared to collimator size (1m*16mm*16mm)
  → very small mesh size required in a very large volume
  → not achievable with CST Particle Studio (Could be achieved with GdfidL with a moving mesh focused on obtaining the short range wake)

CLIC BDS Collimator plan

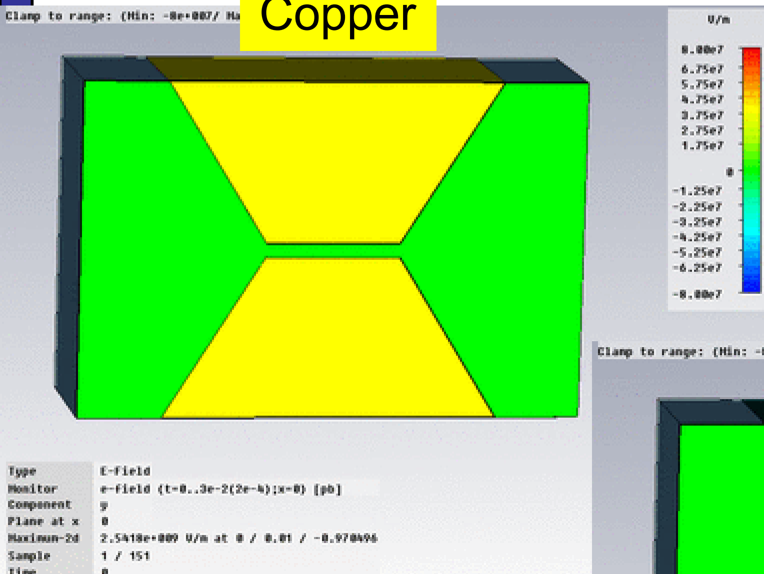


Simulated geometry



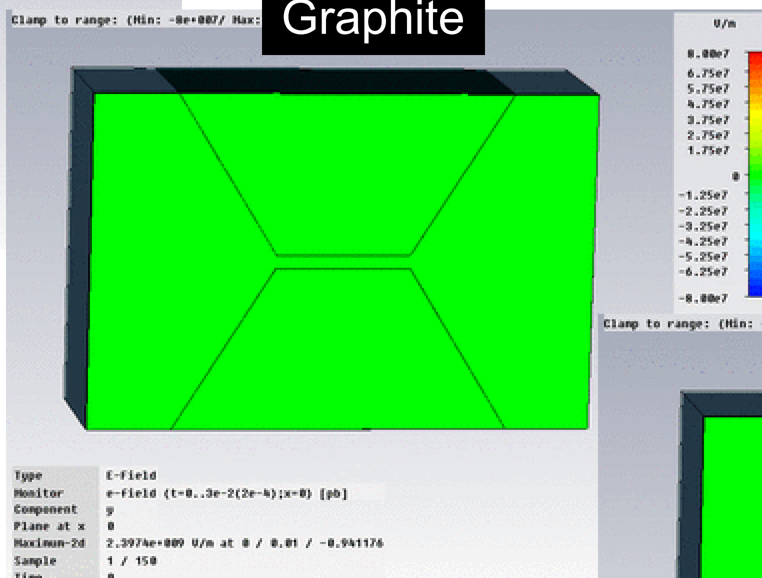
Vertical Electric field simulated by particle studio

Copper



No relaxation time

Graphite



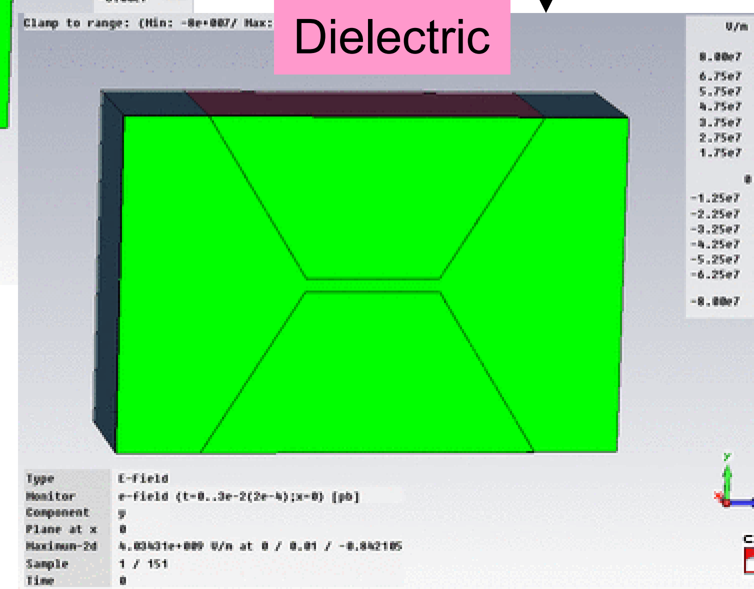
No relaxation time

Angle of the shock wave agrees with cerenkov effect

$$\sin(\vartheta) = \frac{1}{\beta n} = \frac{1}{\sqrt{\varepsilon_r}}$$

ε_r=5
ρ=1 Ωm

Dielectric



→ Less reflections with a dielectric taper?

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Conclusions

- The reasons that lead us to consider dielectrics as low impedance materials for LHC collimations may not be relevant for CLIC.
- However, fine tuning of the material properties is still possible to try and minimize the wakes
- With the examples studied, it seems the geometric impedance of the taper could be smaller for a dielectric than for copper (to be checked with GdfidL), but the resistive wall impedance will be larger.
- These wakes could be input into PLACET (or Headtail?) for more precise beam dynamics simulations.
- Both time domain simulations and analytical computations are demanding for CLIC BDS collimator parameters. An idea would be to use a 2D code such as ABCI, Mafia or Xwake to gain in simplicity.
- High frequency specifications and measurement of the materials seem to be essential.

Many thanks for your attention!