Low Frequency Transverse Impedance Simulations of Collimators - Preliminary Results

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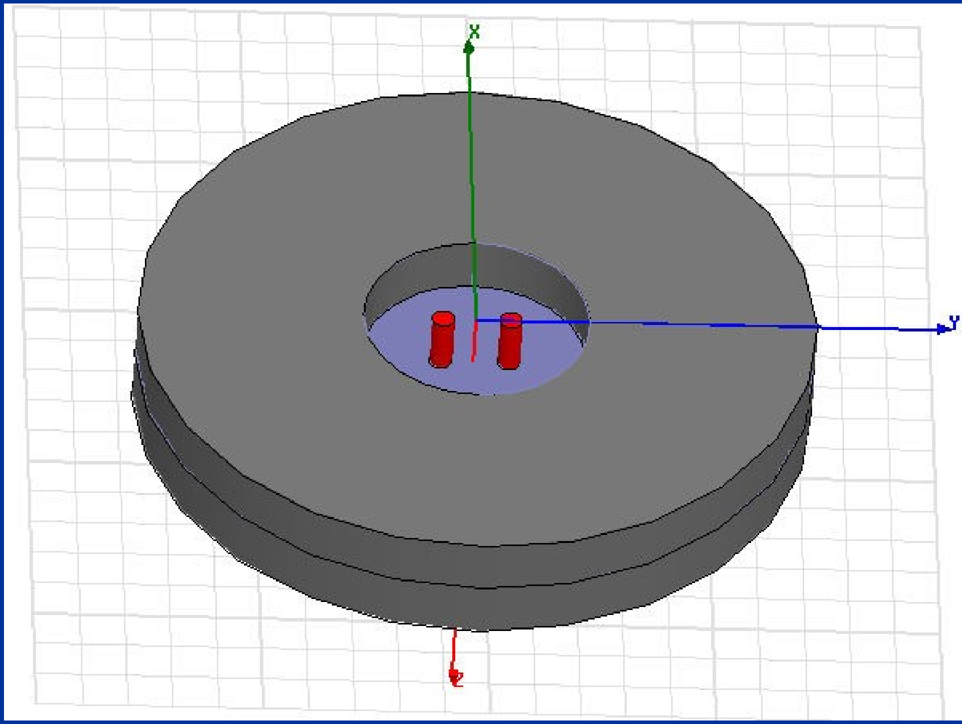
Introduction

- The low-frequency transverse impedance of the collimators constitutes a major part of the LHC impedance budget
- The case of graphite collimators in not easy to assess with measurements and theoretical models have been evolving considerably over the last years
- Conventional RF simulation tools face difficulties for frequency ranges below ~1 MHz, however there exist dedicated low frequency solvers, e.g. in CST EM Studio or Ansoft Maxwell. Currently we only have a license of the latter, which was therefore used. Typical applications of these tools are the design of AC transformers or the simulation of non-destructive testing devices using eddy currents

The Model 1

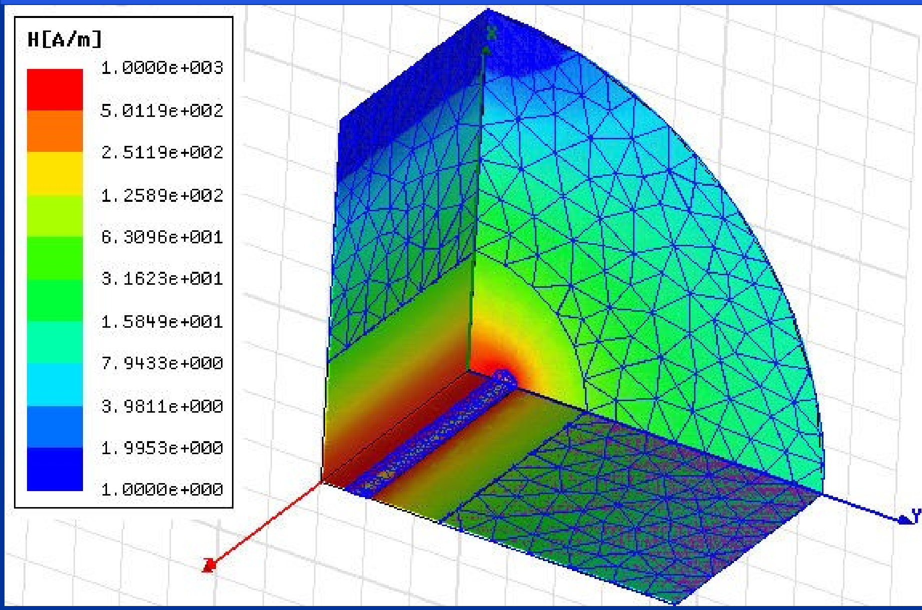
- First a simple graphite structure with rotational symmetry was used: 5 mm half gap
- A two-wire simulation was performed. On all outside boundaries of the structure the magnetic field was set to be purely tangential (perfect conductor). The excitation is done not with a waveguide port as in RF simulations but by defining an ideal current source for each conductor
- In order to get the appropriate field pattern the two wires were excited in phase opposition



The Model 2

- To speed up simulations only the upper right quarter of the structure was modeled, with appropriate boundary conditions to make sure that we get the desired field symmetry
- The maximum mesh size in the graphite was 2 mm, which corresponds to one skin depth at 1 MHz => upper limit of frequency range for graphite; for Cu with the same meshing one can go to about 10 to 100 kHz
- The magnetic field is that of a dipole; it is concentrated in the plane of the two wires => related to horizontal transverse impedance

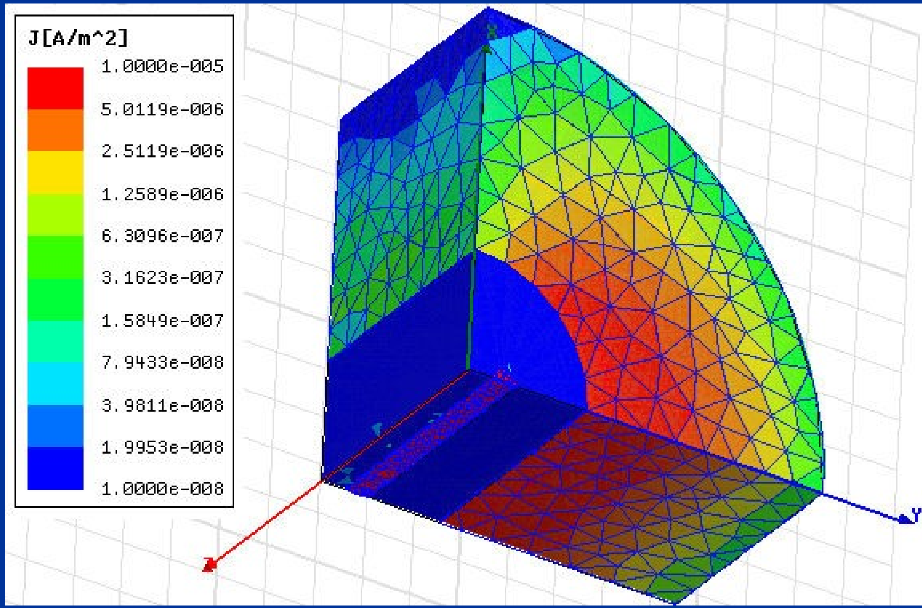
H field, logarithmic color code



Evaluation

- The code solves Maxwell's Equations directly without theoretical approximations as it seems.
- Once one knows the resulting current density the Ohmic losses can be calculated, which are proportional to the transverse impedance
- In more detail: from the local current density and the resistivity the local Ohmic losses are calculated and integrated over the structure. Then the transmission S_{21} is calculated, which gives the via the log formula an impedance, from which for a given wire spacing the transverse impedance is obtained

Current density, logarithmic color code

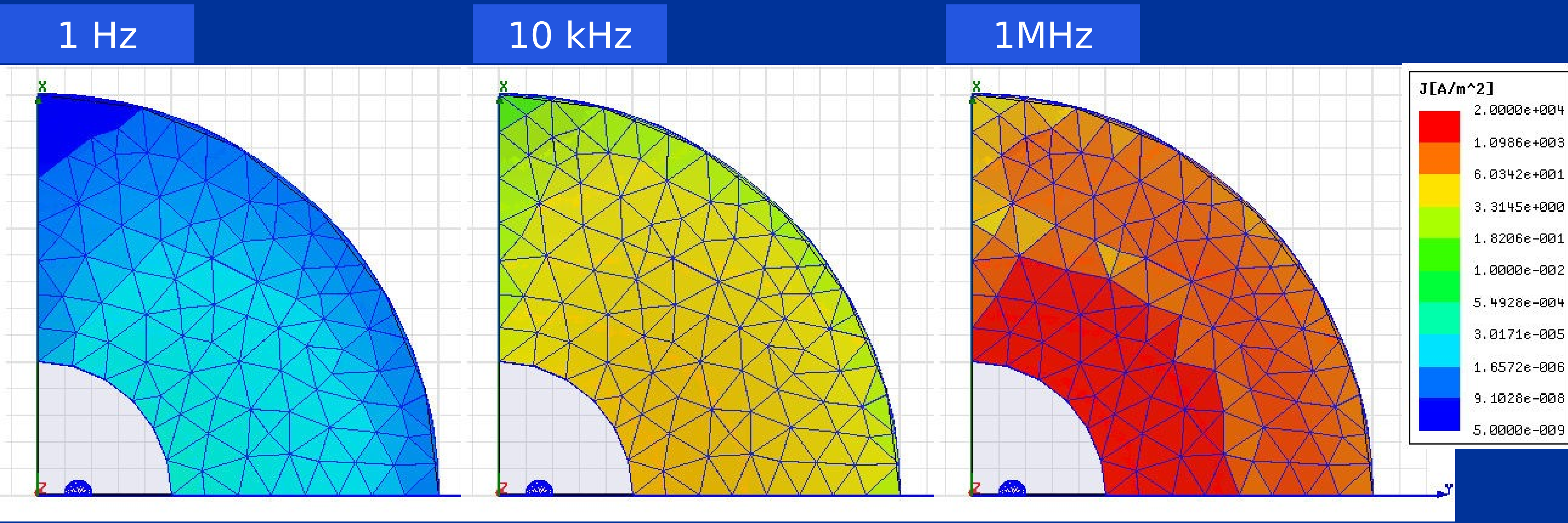


The Physics Picture

- At DC all the current is flowing in the surrounding perfect conductor => the impedance is zero.
- Going from DC to low frequencies currents are induced in the less well conducting regions close to the beam due to Faraday's law rot E = -dB/dt, E ~ f, I ~ f => losses and thus impedance ~ f^2. For the calculation of the transverse impedance one has to divide by f => ZTR ~ f for low frequencies
- At very high frequencies all the currents are flowing on a very thin layer on the inner conductor surface. The impedance increases with frequency with sqrt(f) due to the skin effect => ZTR ~ 1/sqrt(f) for high frequencies.
- Thus somewhere between low and high frequencies ZTR must have a maximum; this maximum appears when the skin depth is about equal to the conductor thickness

Currents

- The situation of the currents leaving the surrounding perfect conductor and getting drawn to the beam at higher frequencies is illustrated below. Please note the log scale.
- At 10 kHz the graphite layer is roughly one skin depth thick; at 1 MHz the currents are concentrated in the innermost layers due to the skin effect. Not very clear here due to the scale...

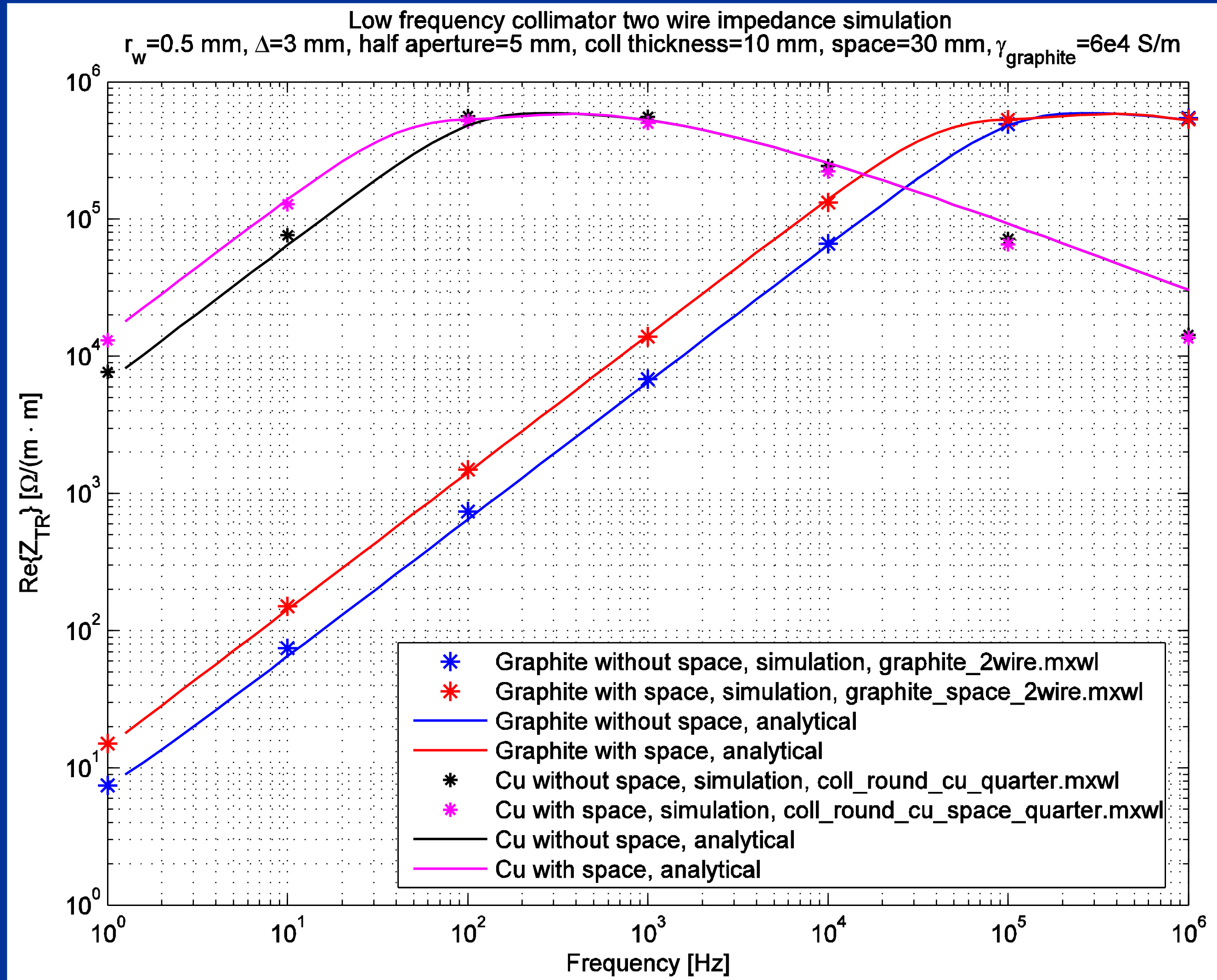


Considered Structures

- Three geometries were considered
  - Rotationally symmetric structure for direct comparison with Burov-Lebedev formula
  - Two plates, as used in the collimator bench measurements
  - A simplified collimator cross-section
- Behind the structure there was either directly a perfect conductor or some space (30 to 220 mm) and a perfect conductor
- The conductor materials graphite (conductivity 6e4 S/m) and copper (conductivity 6e7 S/m) were used
- To limit the memory requirements 5 to 10 mm thick slices were modeled

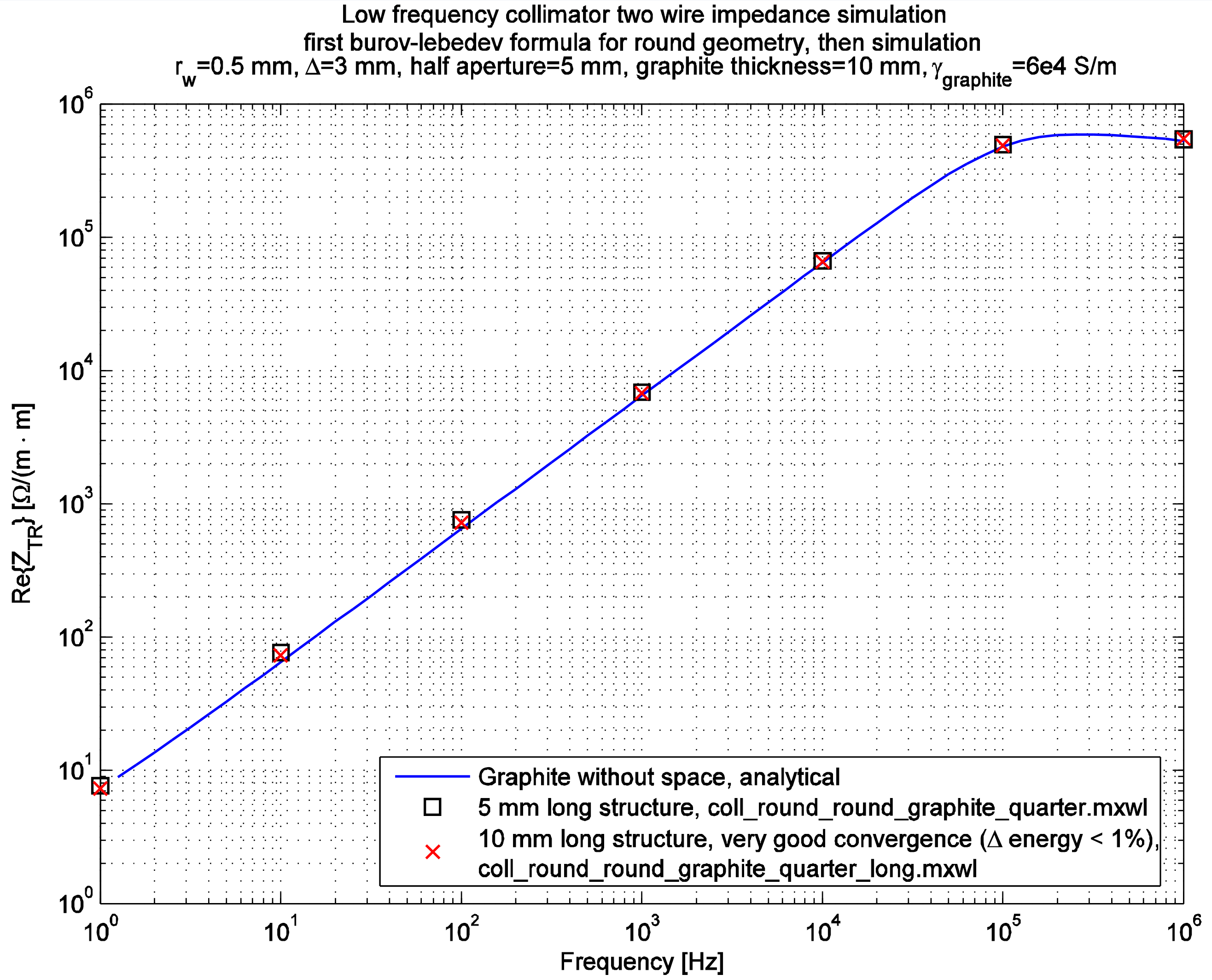
Results – Comparison to Burov-Lebedev

- Very good agreement between simulation and the Burov-Lebedev theory for various structures with rotational symmetry
- At 100 kHz and above the results for Cu become doubtful due to insufficient meshing in the copper



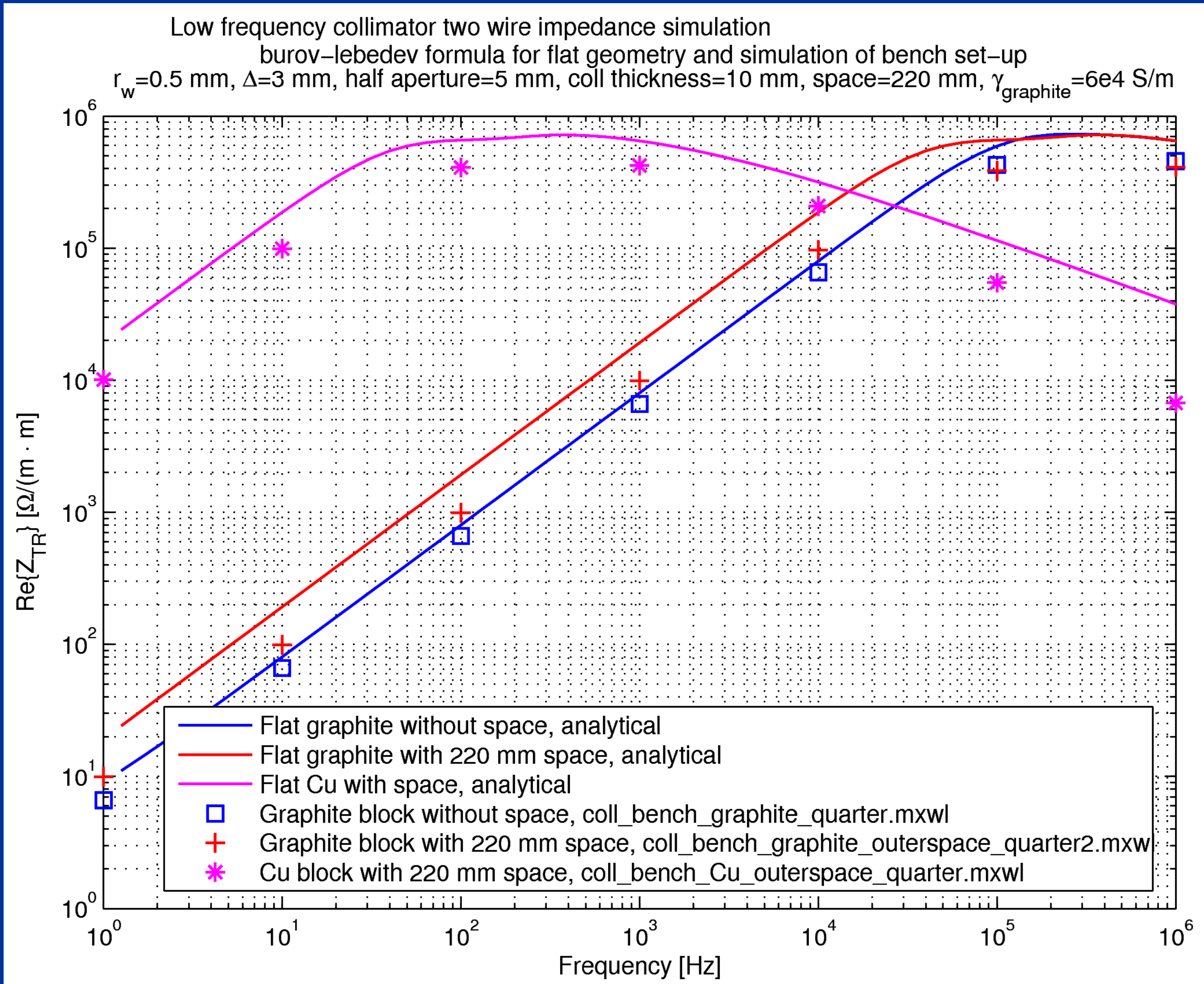
Results – larger structure length

- Doubling the length from 5 to 10 mm did not noticeably affect the results
- Good convergence was made sure of in the latter case (energy error < 1 %)



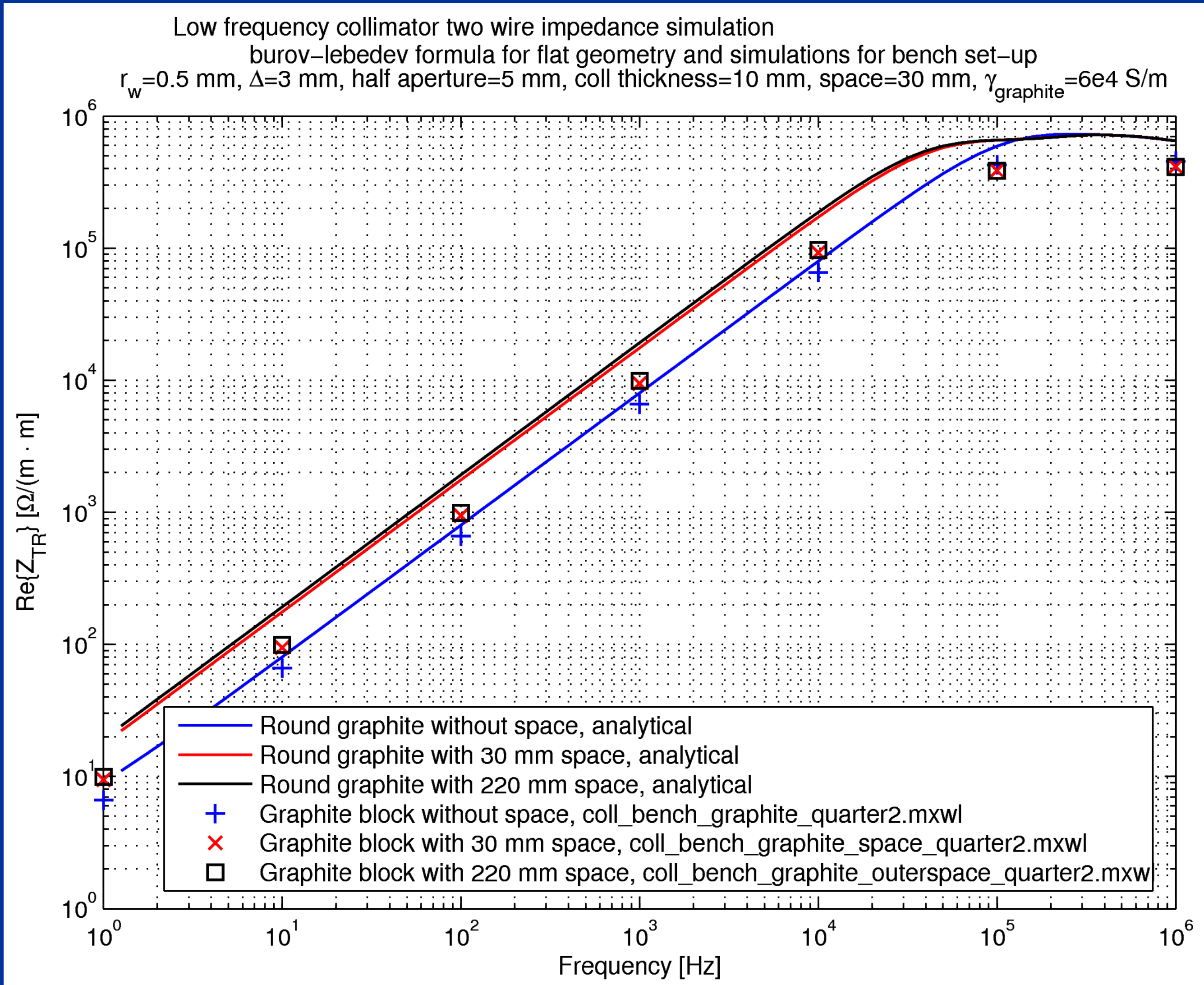
Results – bench geometry 1

- Comparison between the ZTR expected for the bench measurements and Burov-Lebedev formula for a flat geometry (correction factor $\pi^2/8$ with respect to round geometry)



Results – bench geometry 2

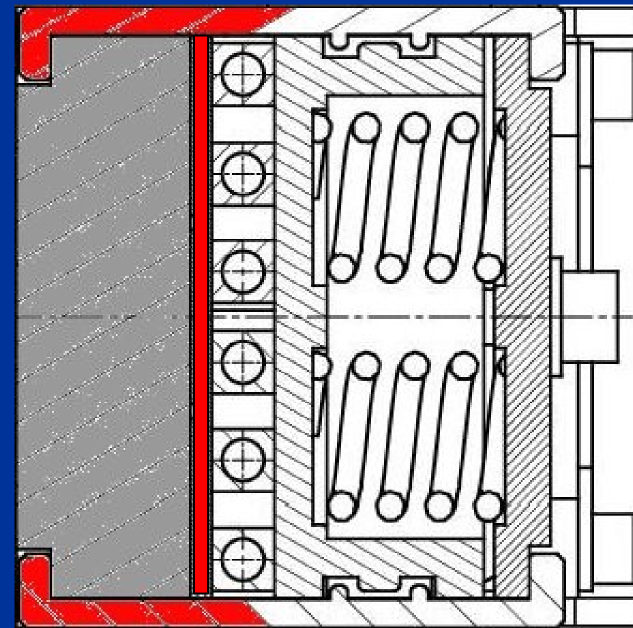
- The simulation as well as the analytical formula show an increase in ZTR when space is added between the graphite and the perfect conductor on the outside boundary. Going from a spacing of 30 to 220 mm does not have a large impact on ZTR



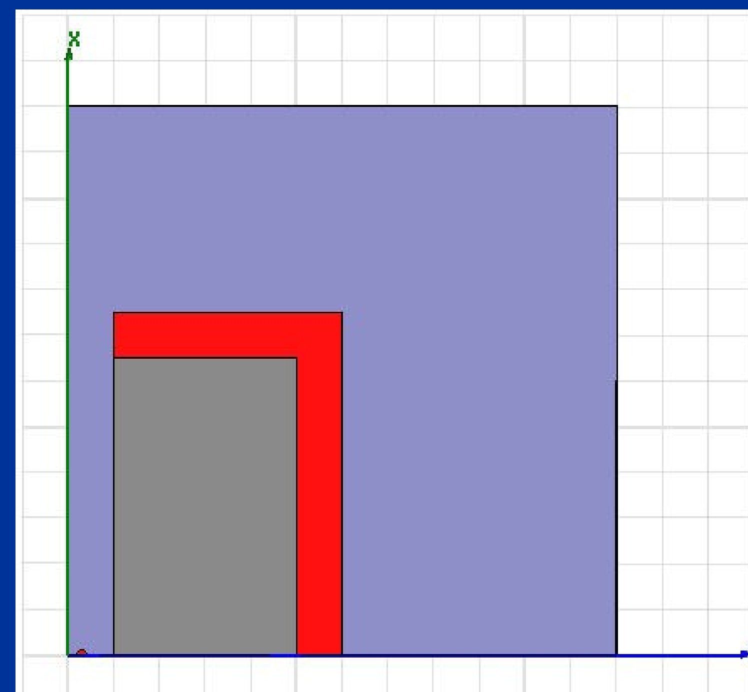
Collimator cross-section

- For the simulation of the graphite collimators a quickly simplified geometry was used: The metallic support structure was modeled as a U-shaped channel structure. Graphite in grey, copper in red.
-

beam



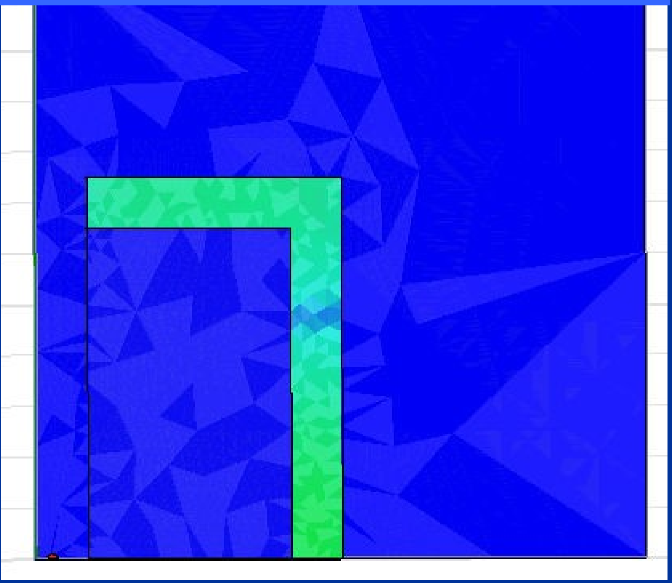
beam



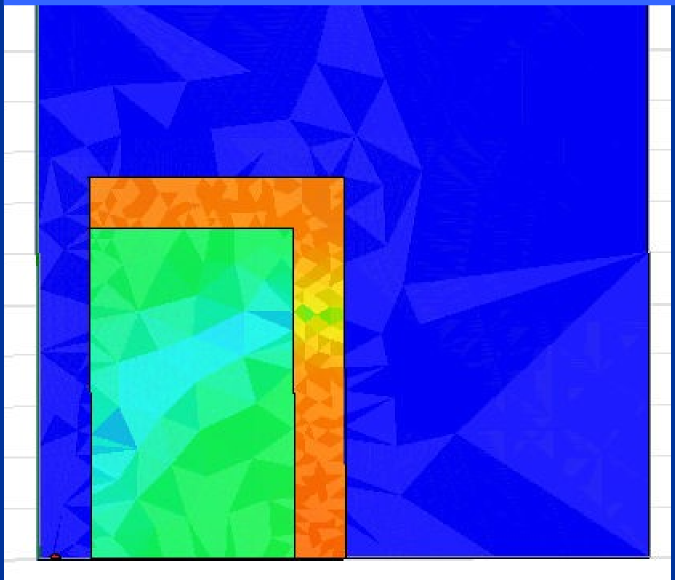
Collimator - Currents

- In collimator there are three regimes:
  - Low frequencies: skin depth large both in Cu and graphite, most of the current in the copper due to its smaller resistivity
  - Intermediate frequencies: skin depth in Cu comparable to Cu thickness => maximum impedance effect of Cu
  - High frequencies: graphite takes over currents => impedance

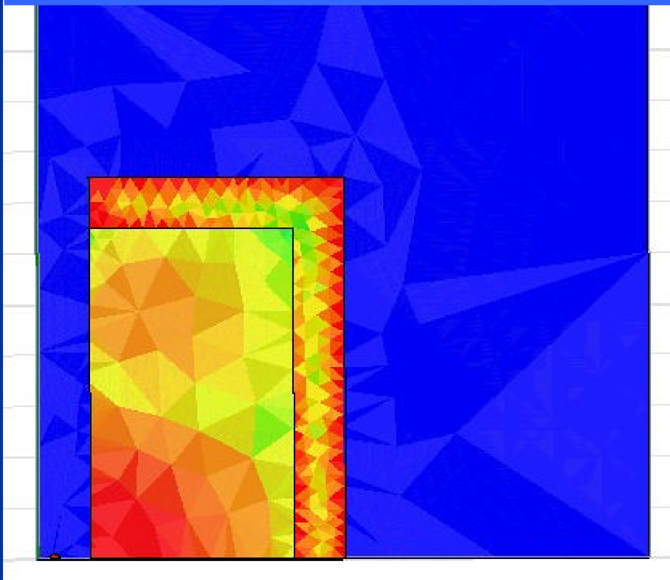
1 Hz: most of current and impedance in Cu



100 Hz: skin depth in Cu comparable to thickness

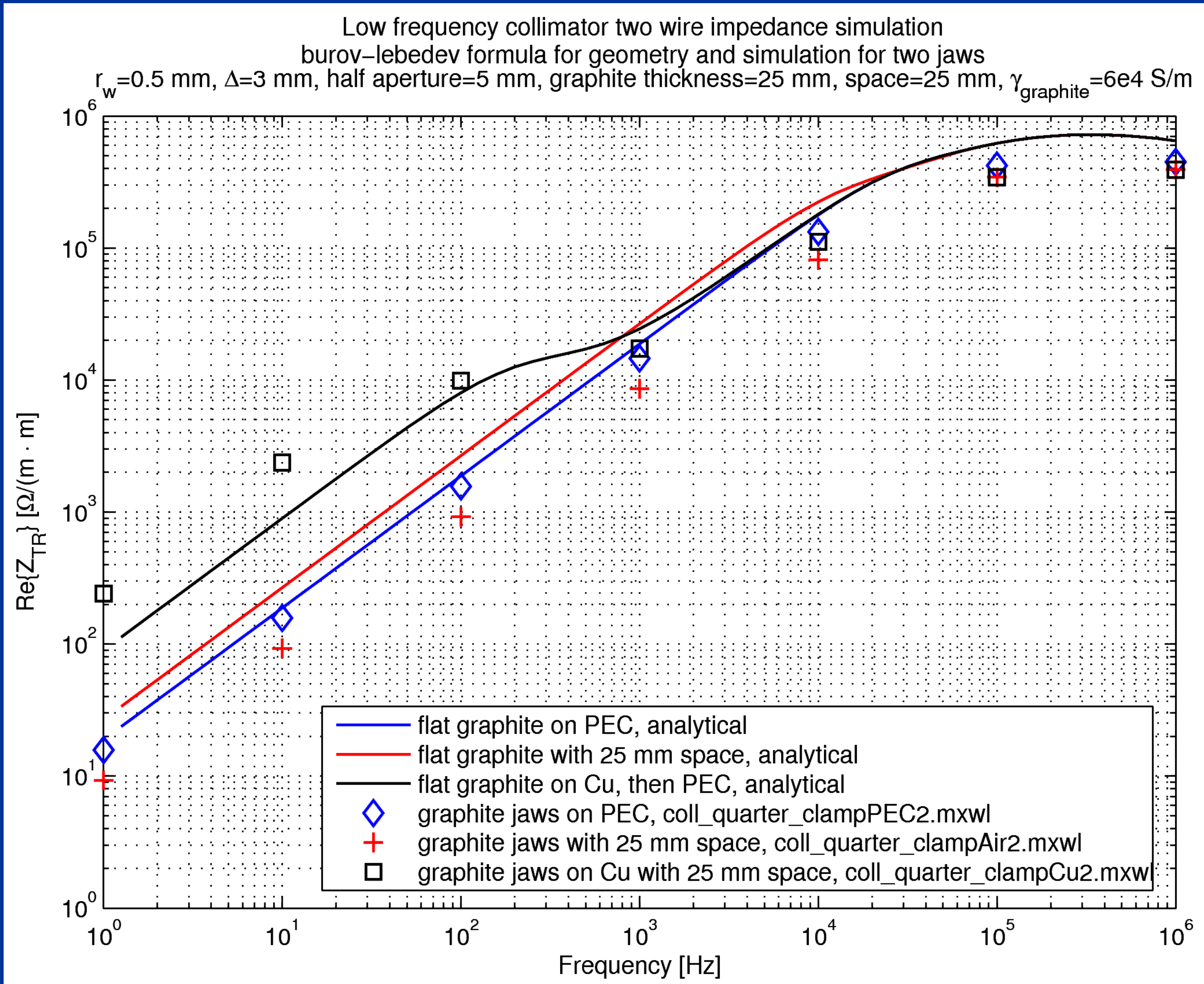


100 kHz: graphite takes over current



Results – collimator cross-section

- ZTR shows the characteristics of both an isolated graphite block and a copper block at a larger distance from the beam
- ZTR is dominated by the graphite above 10 kHz and by the copper below a few 100 Hz
- A three-layer analytical calculation shows a similar behaviour



Summary

- The low-frequency solvers of commercial simulation packages can be used for evaluating the collimator transverse impedance at low frequencies
- Very good agreement between the simulation and the Burov-Lebedev formula was obtained for structures with rotational symmetry
- Preliminary results for a structure with graphite blocks as for the current bench measurements as well as for a slice of an LHC graphite collimator were given
- The latter showed characteristics of both the metallic support structure (low frequencies) and the graphite jaws (high frequencies)