Measurement of the Transverse Resistive-Wall Impedance of a LHC Graphite Collimator at Low Frequency

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HB2008, Nashville, 25-Aug-2008

Presentation overview

- Resistive wall transverse impedance in the “low frequency” regime (analytical predictions)
- Coupling impedance measurements
  - probe coil method
- Transverse impedance measurements setup and results
  - Laboratory Measurement
  - Numerical Simulations

Resistive wall transverse impedance in the low frequency regime

- Definition of the regime of interest - LHC
- Analytical predictions

Motivation and Regime definition

Resistive wall transverse impedance

Benchmarking of available **analytical predictions** with **laboratory measurements** and numerical **simulations**

Prediction of beam impedance effect of **LHC phase 1 collimators** on total **LHC budget**

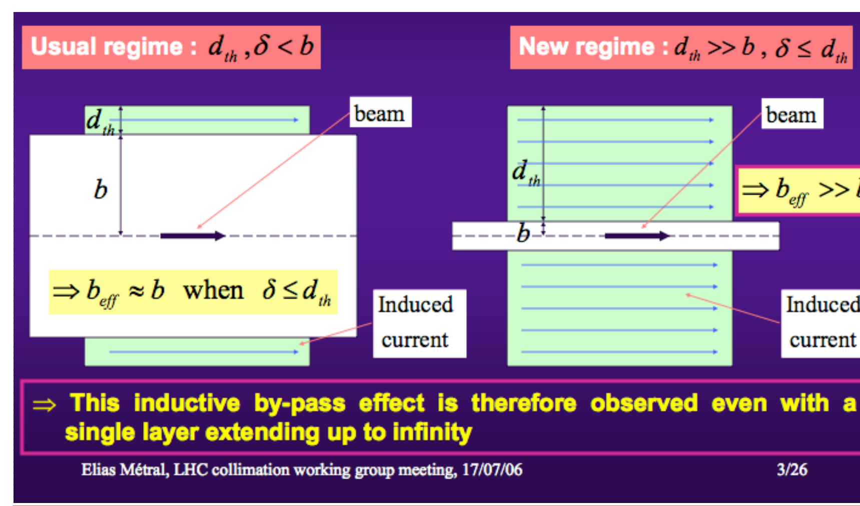
Contribute to the **development** of LHC **phase 2 collimators** for reaching nominal luminosity

→ **Studies Motivation**

Beam **distance** from the wall
<
Wall **thickness**

Skin depth < Wall **thickness**

→ **Studies 'regime' of interest** →



In the case of LHC collimator: this means going down to frequencies of the order of the first LHC betatron unstable frequency , ~ 8 kHz

Analytical predictions in the regime of interest

The complex transverse impedance depends on: **Material conductivity**, **Material thickness** (+ single or multi layering/coating), **Distance of the beam from the wall**, **Beam pipe shape** (cylindrical, collimator-like etc.)

Available analytical models:

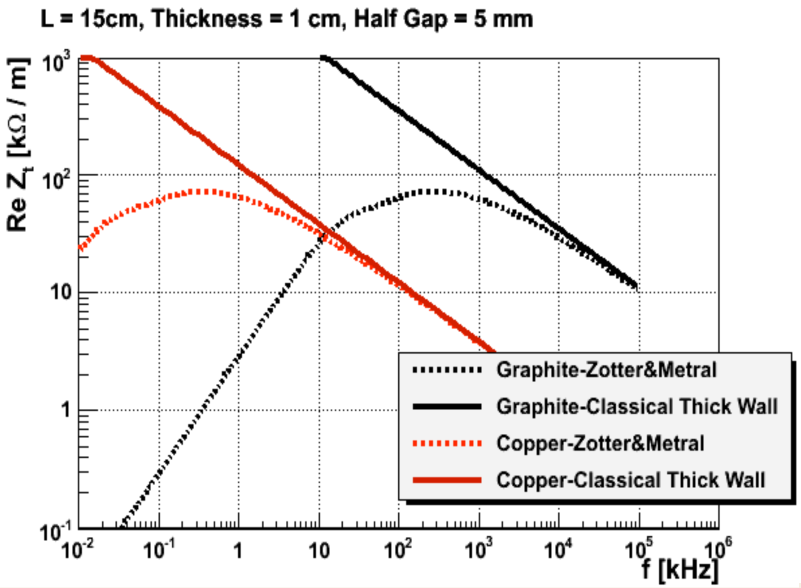
'**Classical**' Thick Wall

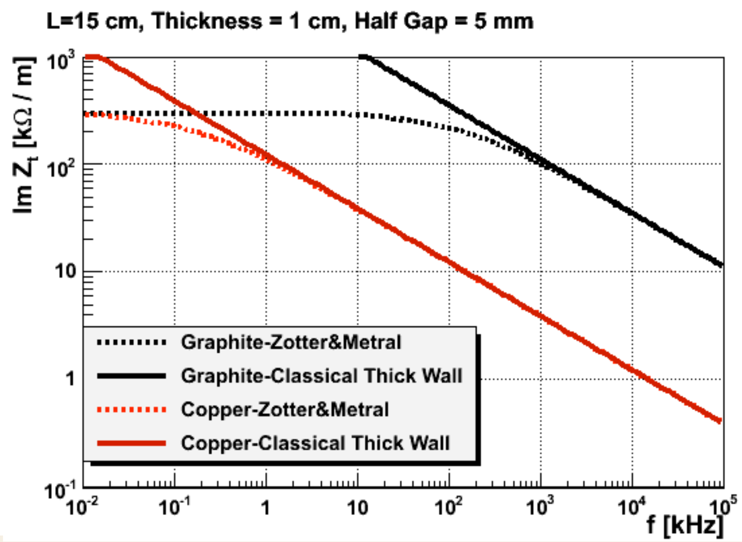
$$Z_T(\omega) = (1-i)\frac{LZ_0}{2\pi b^3}\sqrt{\frac{2}{\omega\mu_0\sigma_c}}$$

Burov - Lebedev - see e.g : **TRANSVERSE RESISTIVE WALL IMPEDANCE FOR MULTI-LAYER FLAT CHAMBERS**, Proceedings of EPAC02, Paris

Zotter - Metral see e.g., "**RESISTIVE-WALL IMPEDANCE OF AN INFINITELY LONG MULTI-LAYER CYLINDRICAL BEAM PIPE** ", Proceedings of PAC07 (and references included)

Case of rectangular plates, 15 cm long, 1 cm thick, half gap 5mm





Burov-Lebedev agrees very well with Zotter-Metral

Coupling Impedance measurements

- Coaxial wire method
- Two wires method ⟶ Probe coil method

Coaxial wire method

V.G. Vaccaro, "**Coupling Impedance Measurements**", INFN/TC-94/023 (1994)

F. Caspers in **Handbook of Accelerator Physics and Engineering**, A. Chao and M. Tinger (editors), World Scientific, Singapore (1998), p.570.

The wire is used to simulate the EM fields induced by the beam. The structure becomes a coaxial wave guide structure with TEM modes. The set up consists in some alignment system and a Vector Network Analyzer as RF source.

The longitudinal impedance can be inferred from scattering parameters analysis. In particular: the signal S21 transmitted through the wire along the Device Under Test (DUT) has to be compared to the one measured along a smooth reference beam pipe with the same length of the DUT.

$$Z_{||}(f) = -2Z_c ln\frac{S_{21}^{DUT}(f)}{S_{21}^{REF}(f)}$$

with: Z_c = Line impedance

d = Wire diameter

D = Inner pipe diameter (or distance between plates)

Transverse impedance from longitudinal impedance variation

$$Z_{\perp}(x,\omega) \simeq \frac{c}{\omega}\frac{Z_{||}(x) - Z_{||}(x=0)}{x^2}$$

This is practically impossible at low frequencies due to the small measurable signals

Transverse impedance - double wire method

G.Nassibian ,F.Sacherer "**METHODS FOR MEASURING TRANSVERSE COUPLING IMPEDANCE IN CIRCULAR ACCELERATORS**", NIM. 159(1979)

An oscillating beam induces on the beam pipe EM fields E and B. Neglecting the E field, the transverse impedance results:

① $$Z_T = \frac{i}{\beta I \Delta} \int_0^{2\pi R} (\vec{v} \times \vec{B})_T ds$$

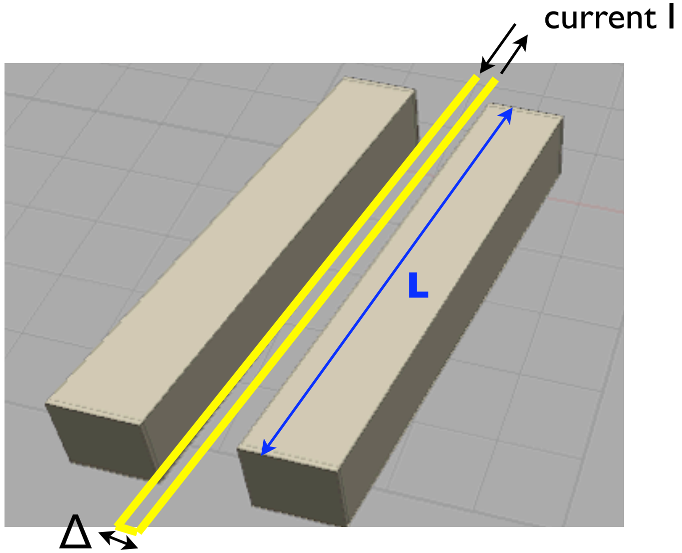
$\pm\Delta = \text{beam oscillation amplitude}$

$\beta = v/c$

$I = \text{beam current}$

The source of the resulting deflecting force (that can induce instabilities) is the dipole moment I·Δ. The same effect arises substituting the beam with two wires separated by Δ and powered with opposite current I or by a loop.

The field B induced by the loop on the surroundings, acts back generating a voltage in the loop. As a consequence the loop impedance changes. Measuring such impedance change allows to calculate the induced B and the related transverse impedance.



$$V = j\omega BL\Delta = Z_B \cdot I$$

$$Z_{loop} = Z_0 + Z_B \text{ with } Z_0 = \text{loop reference impedance}$$

$$\Rightarrow \quad Z_B = Z_{loop} - Z_0 \text{ can be measured}$$

$$\Rightarrow \quad B = \frac{IZ_B}{j\omega L\Delta}$$ ②

① + ② ⇒ $$Z_T = \frac{c\, Z_B}{\omega \Delta^2}$$

Transverse impedance - probe coil method

At low frequencies, the sensitivity of a 2-wires or a single loop setups is very low.

Better accuracy can be achieved substituting the loop with a multi-turn coil

F.Caspers, **http://lhcp.web.cern.ch/lhcp/LCC/LCC_2001-08c.pdf**

F.Caspers, A.Mostacci,L.Vos **http://lhcp.web.cern.ch/lhcp/LCC/LCC_2002-01.htm#main3a**

F.Caspers, A.Mostacci, U.Iriso .**Bench Measurements of Low Frequency Transverse Impedance**, CERN-AB-2003-051-RF

In summary, the method consists in measuring the variation of the probe coil impedance in the presence of a device under test compared to a reference measurement

$$\vec{Z}_{TR}^{meas} = \frac{c}{\omega} \frac{\vec{Z}_{coil}^{DUT} - \vec{Z}_{coil}^{REF}}{N^2 \Delta^2}$$

Δ = coil width

N = number of coil windings

DUT = Device Under Test

REF = Reference material with known impedance

N.B. : geometric part of impedance is equal for the two materials. The **results can be plotted in two ways**:

→ $\vec{Z}_T(\omega) = \vec{Z}_{meas}(\omega) = \vec{Z}_{RW}^{DUT} - \vec{Z}_{RW}^{REF}$ **THAT CAN BECOME NEGATIVE**

→ $\vec{Z}_{RW}^{DUT}(\omega) = \vec{Z}_{meas} + \vec{Z}_{RW}^{REF}$

Laboratory Measurements Planning and Setup

Staged approach

It was planned to tackle the problem in **stages**, from simple cases to a LHC collimator assembly

1. **Sample graphite plates**

2. **Stand-alone jaws**

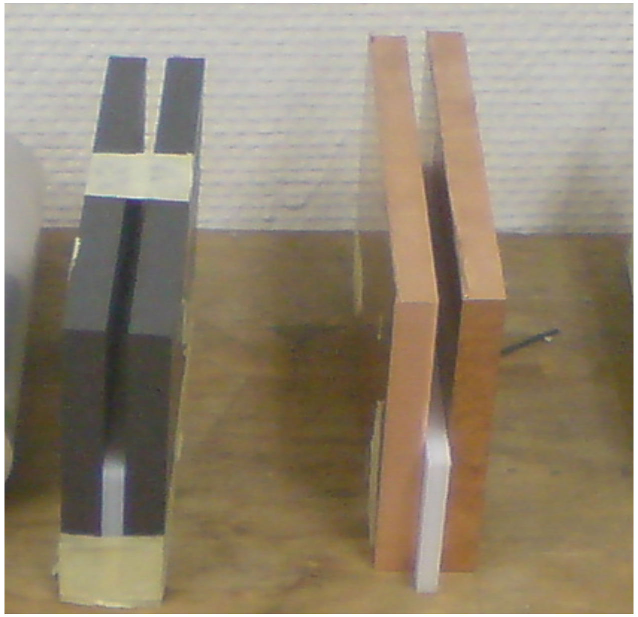
measurements with actual LHC collimators material and dimensions Requires long coil (>= 1.2 m)

3. **Collimator assembly**

Measurements with LHC available collimator prototype(s)Requires even longer coil (>=1.4m)

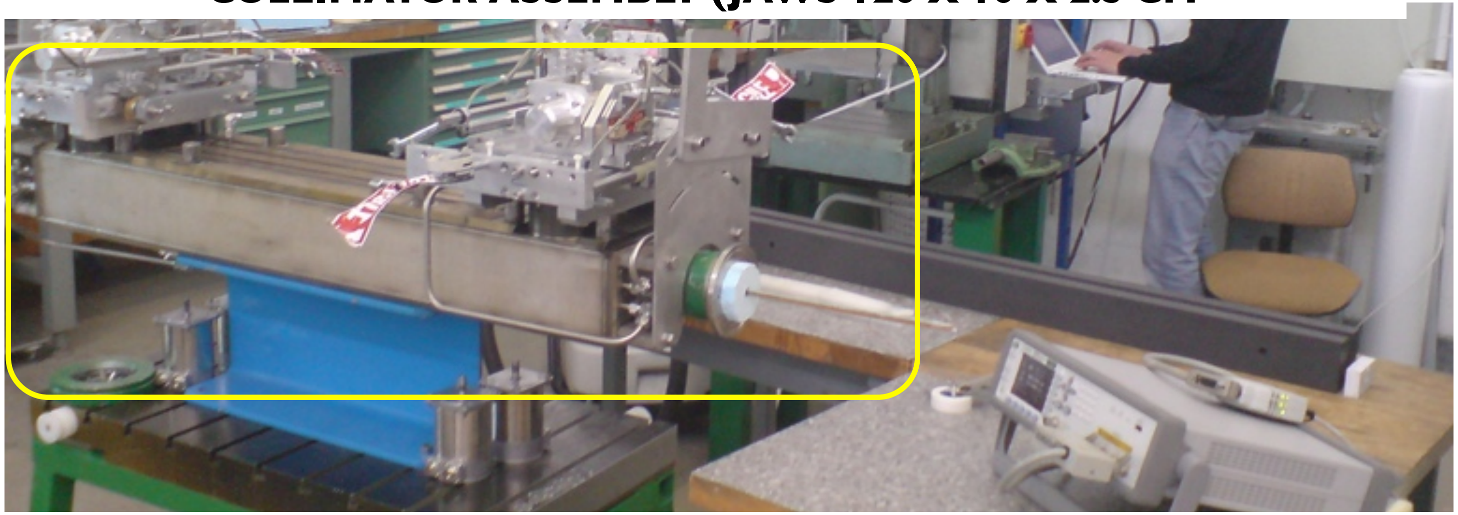
Devices under test

SAMPLE PLATES 15 X 10 X 1 CM



STAND-ALONE JAWS 120 X 10 X 2.5 CM

COLLIMATOR ASSEMBLY (JAWS 120 X 10 X 2.5 CM

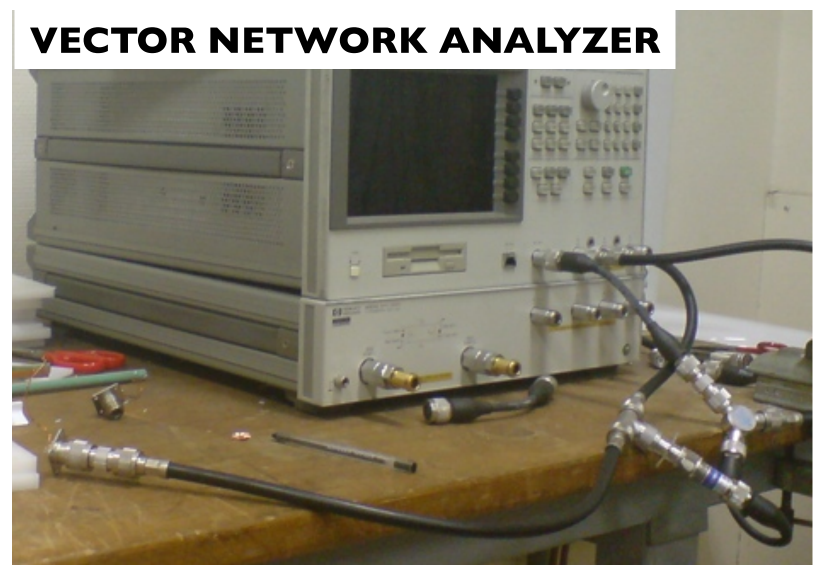


Coils, Vector Network Analyzer and LCR

Setup used in our measurement campaigns

HAND-MADE COILS

- different lengths
- different number of turns
- different widths



Sample plates

Geometry and material properties of the three different measurement stages

Stage	Geometry			Mat.	ρ_c
	L [cm]	h [cm]	t [cm]		[$\mu\Omega\cdot$m]
1	15	10	1	graph.	14
2	120	6.6	2.5	graph.	14
3	160 *, 120 **	6.6	2.5	CFC	7

*collimator in which the CFC jaws are assemble

**reference jaws and analytical calculations.

For each measurement stage at least two different probe coils were fabricated, differing in length, number of turns N and width Δ. Typical parameters were

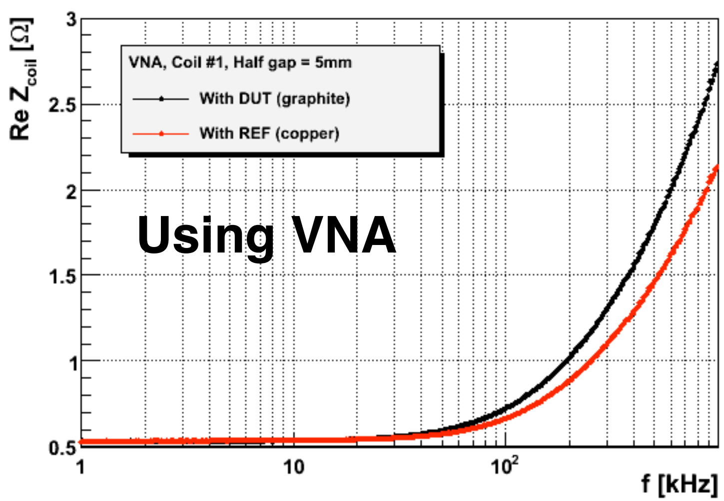
Δ>= 2.5 mm

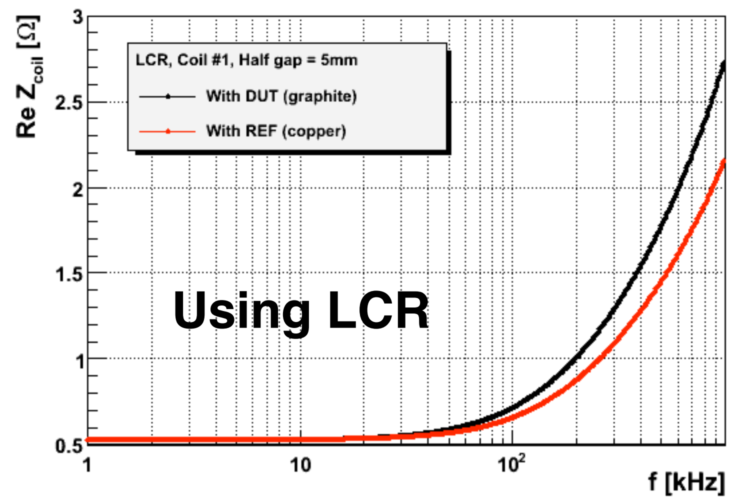
5 <=N <= 14.

The higher N, the higher the measurement sensitivity, but the lower the frequency of the first coil self-resonance (i.e. the lower the upper limit of the measurable frequency band).

VNA versus LCR

Example of measured signals: **real part of coil impedance in the presence of copper and graphite**

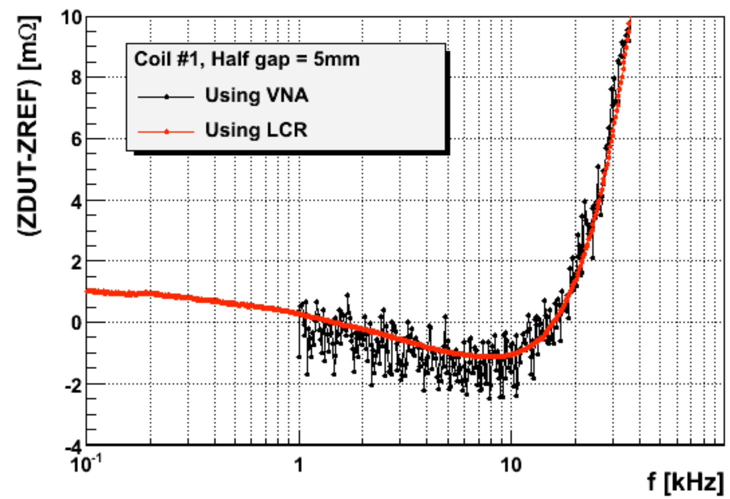




Looking at the difference

ZDUT-ZREF at low frequencies:

noise may become ~ =signal !

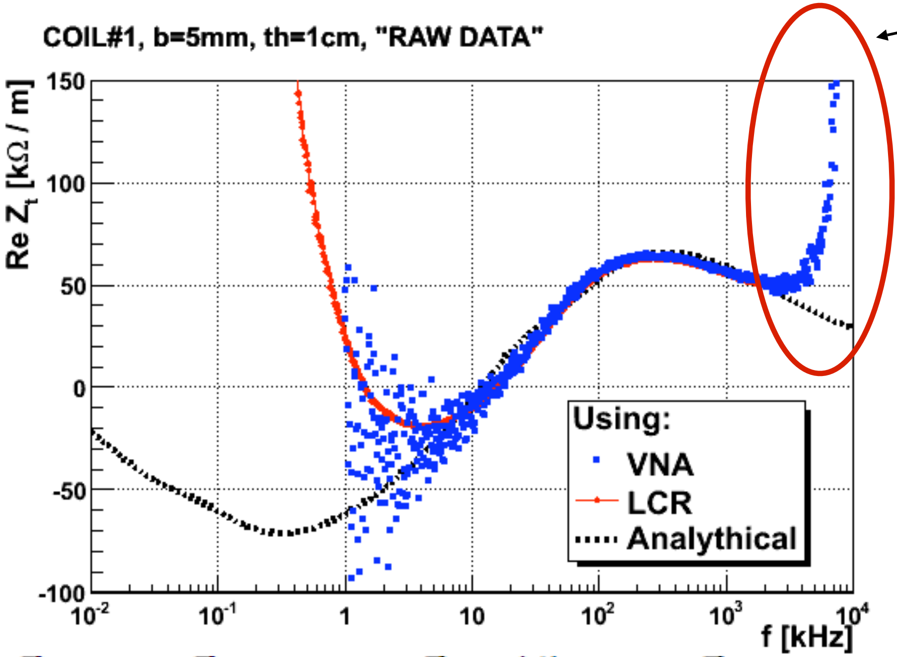


VNA versus LCR

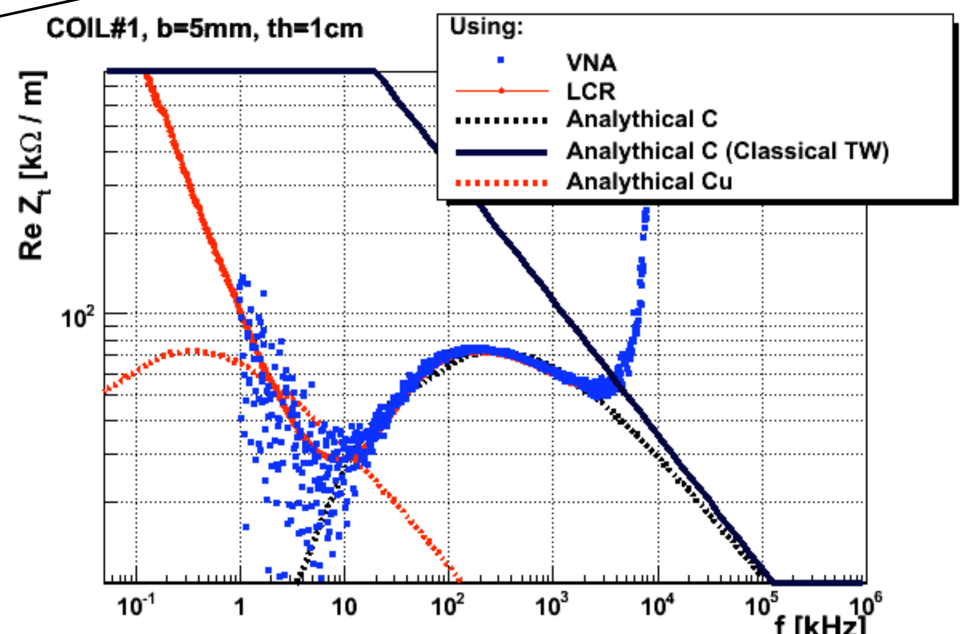
LCR results less noisy

- to compare the two instruments in a proper way one should check the real averaging time of the two instruments
- In the all the following plots: we used the LCR only

First coil resonance -->Method not anymore valid



$$\vec{Z}_T(\omega) = \vec{Z}_{meas}(\omega) = \vec{Z}^{graphite}_{RW}(\omega) - \vec{Z}^{copper}_{RW}(\omega)$$



$$\vec{Z}^{graphite}_{RW}(\omega) = \vec{Z}_{meas}(\omega) + \vec{Z}^{copper}_{RW}(\omega)$$

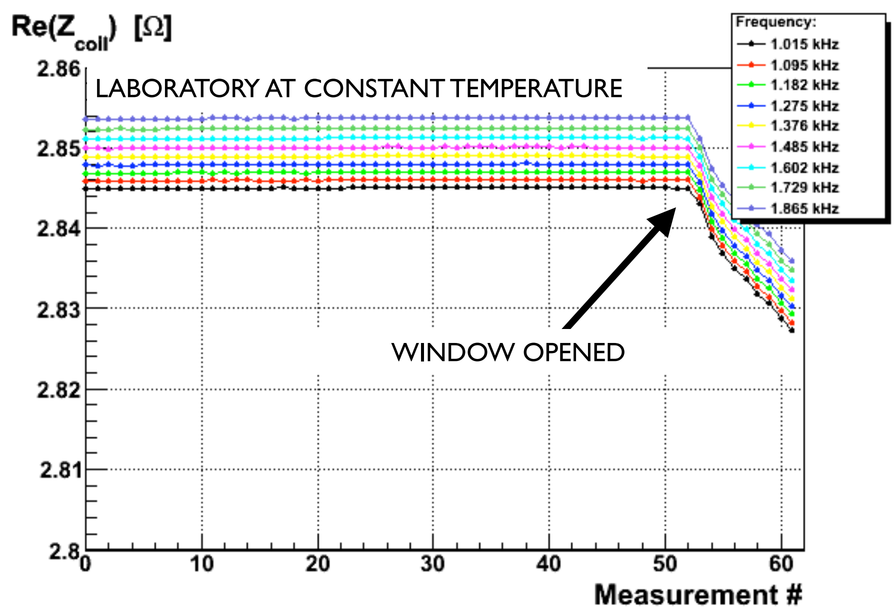
N.B. : rise of measured impedance below 10KHz (i.e. disagreement w.r.t. to theory) discussed in the next slide

Effect of temperature

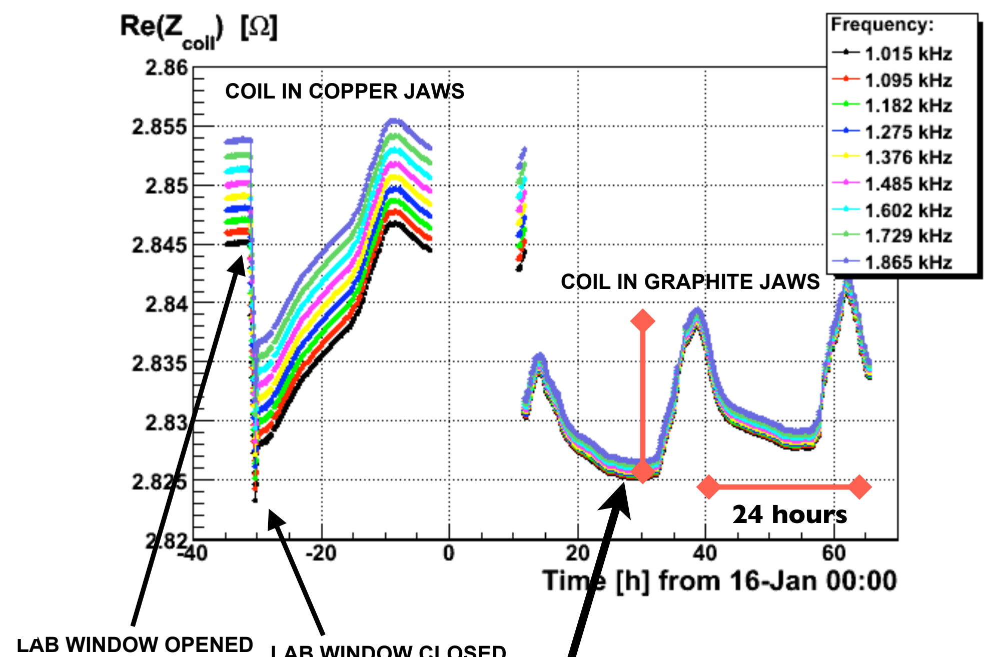
The disagreement between measurements and theory below 10KHz showed-up as some systematic drift rather than something systematic or statical. After some brainstorming we decided to investigate temperature effects on the meas. results

CONSECUTIVE MEASUREMENTS OF THE COIL IMPEDANCE WITHOUT CHANGING ITS SURROUNDING MATERIALS FOCUSING ON LOW FREQUENCIES

FIRST OBSERVATION OVER FEW MINUTES



SYSTEMATIC STUDIES OVER FEW DAYS



VARIATION DUE TO NORMAL TEMPERATURE CYCLING (~ 2 DEG) IN A TEMPERATURE CONTROLLED LAB

CONCLUSION:

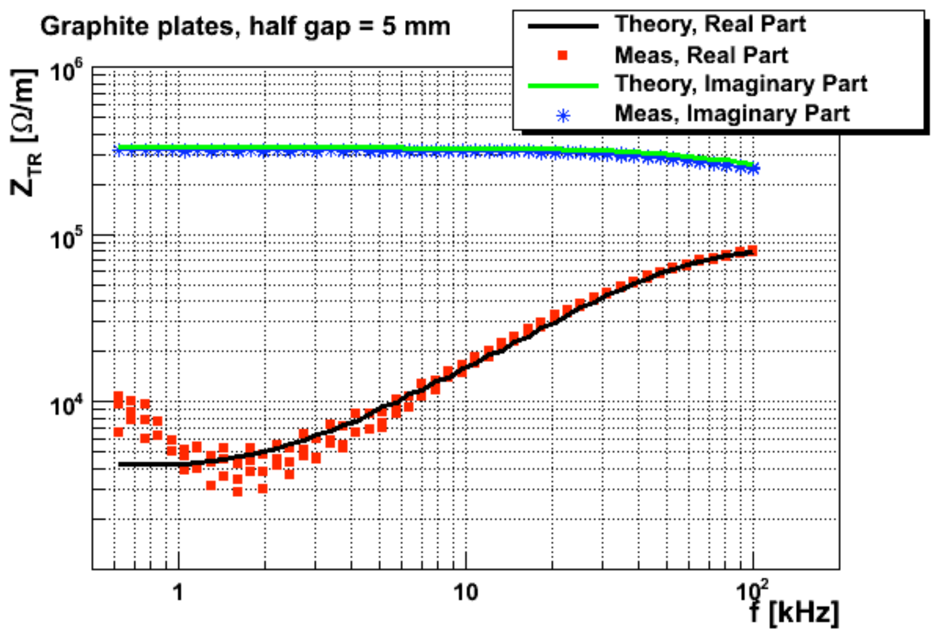
-**temperature effect can become >= signal !**

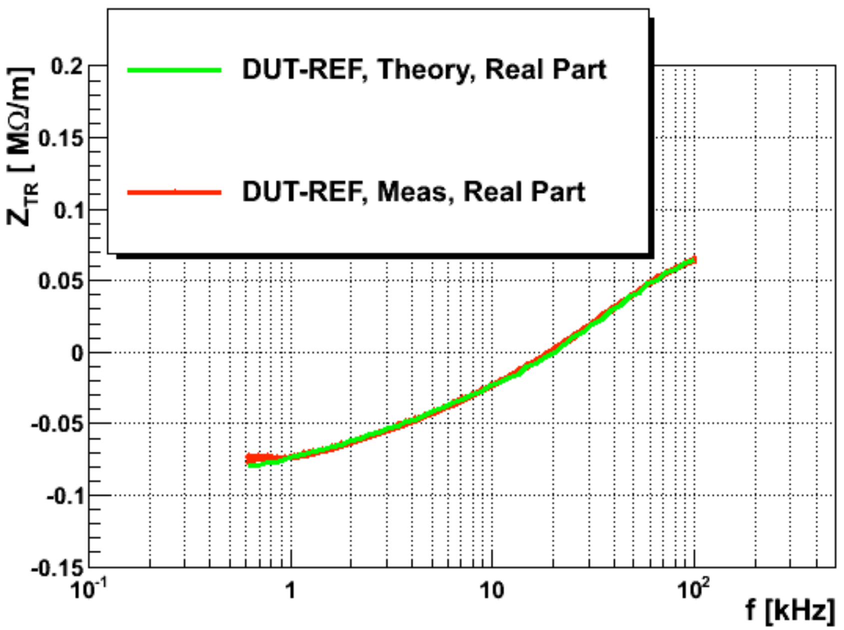
-making **QUICK** measurements in order to have **minimum T drift between REF and DUT meas** was fundamental to achieve the results presented later

Laboratory Measurements Results

Sample Plates

Example of measurement results compared to theory



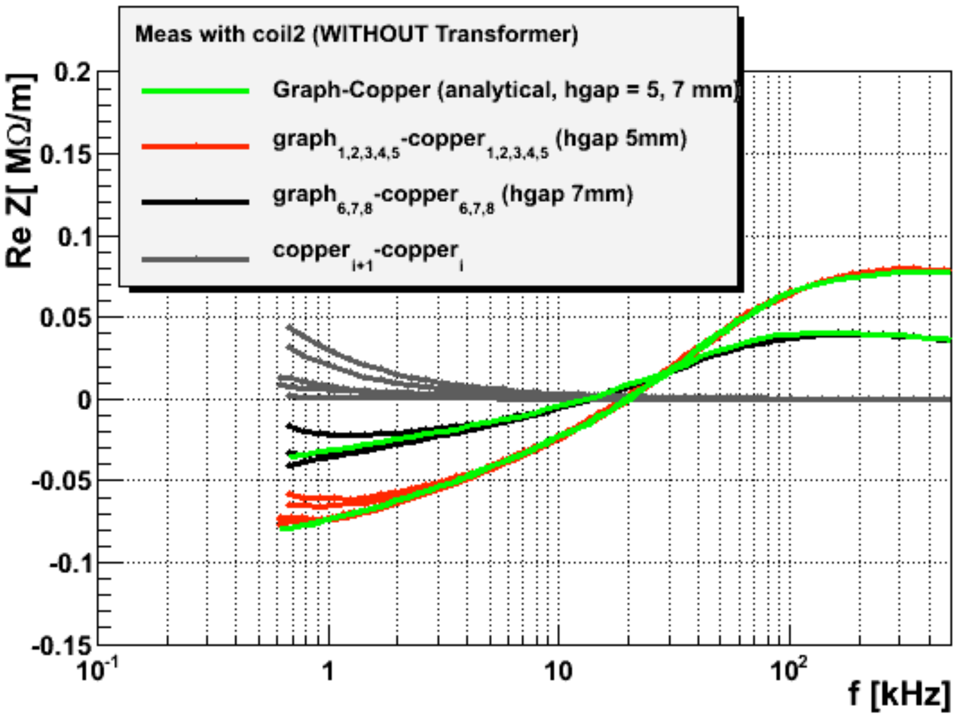


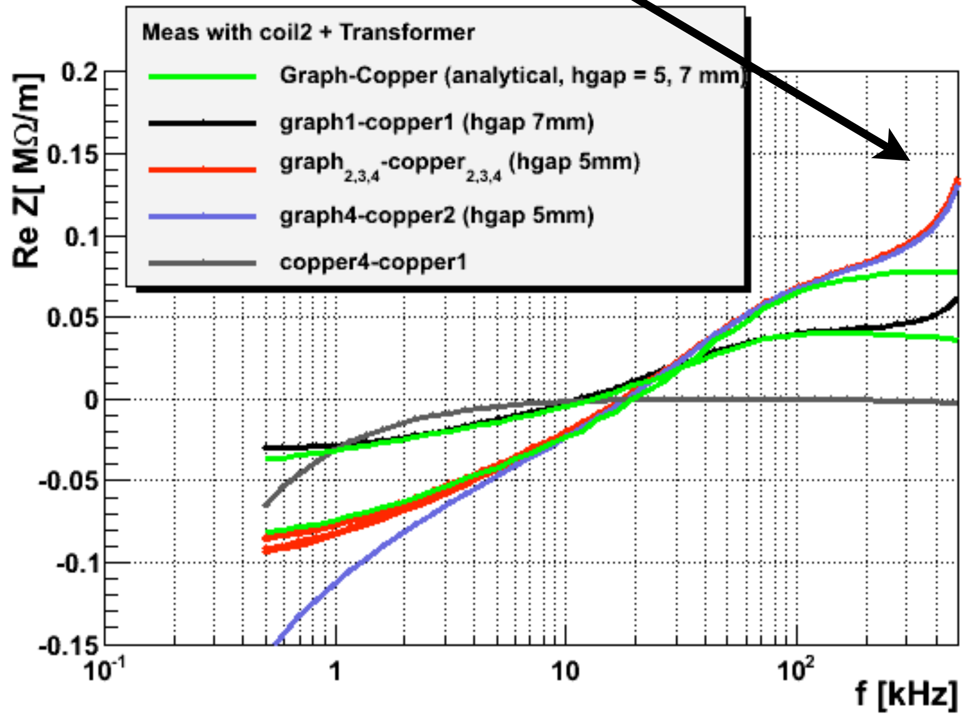
The same type of agreement has been achieved for many measurements with different gaps, different coils.

Sample Plates

Again with sample plates: investigate possible improvements by using a transformer ⇒ enhance the absolute value of the probe coil impedance

Conclusion: not significant improvement + lower frequency first coil self resonance





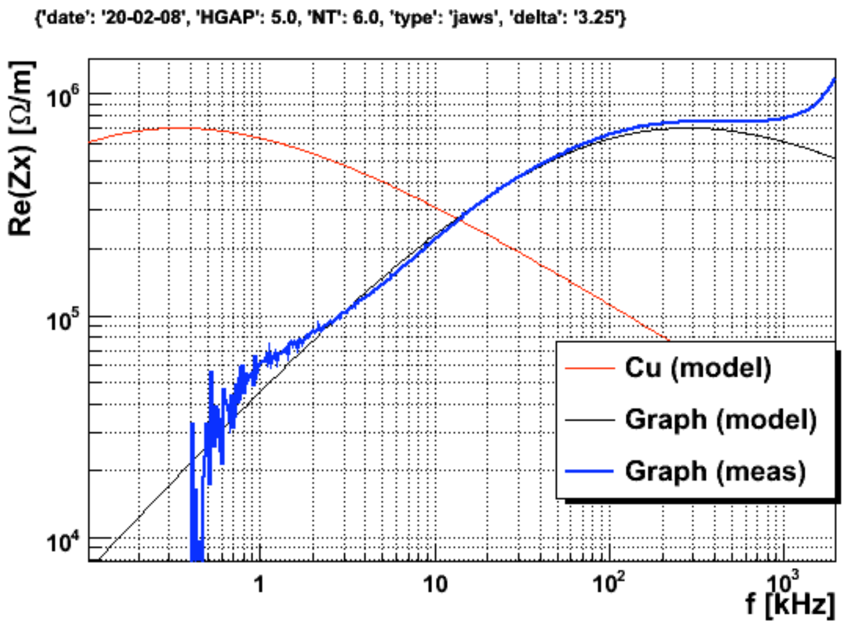
In any case: excellent example of **measurement accuracy and reproducibility with 2 different gaps**

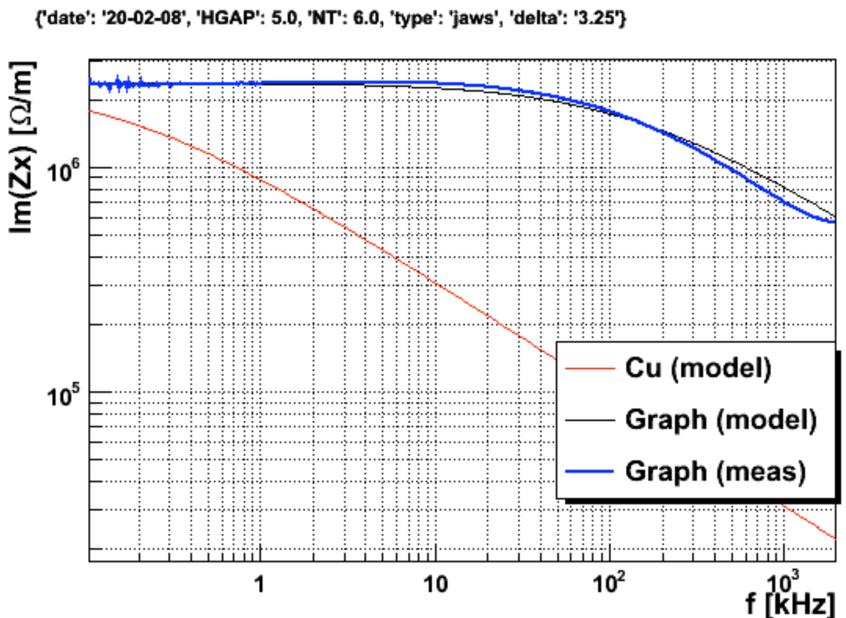
Stand-alone jaws

The signal is larger than for small sample plates, but:

- alignment more critical
- long coil fabrication more difficult

Conclusion: excellent **agreement** with theory





Also in this case the results were reproduced in different conditions, different gaps, different coils (see also next slides)

Collimator Assembly

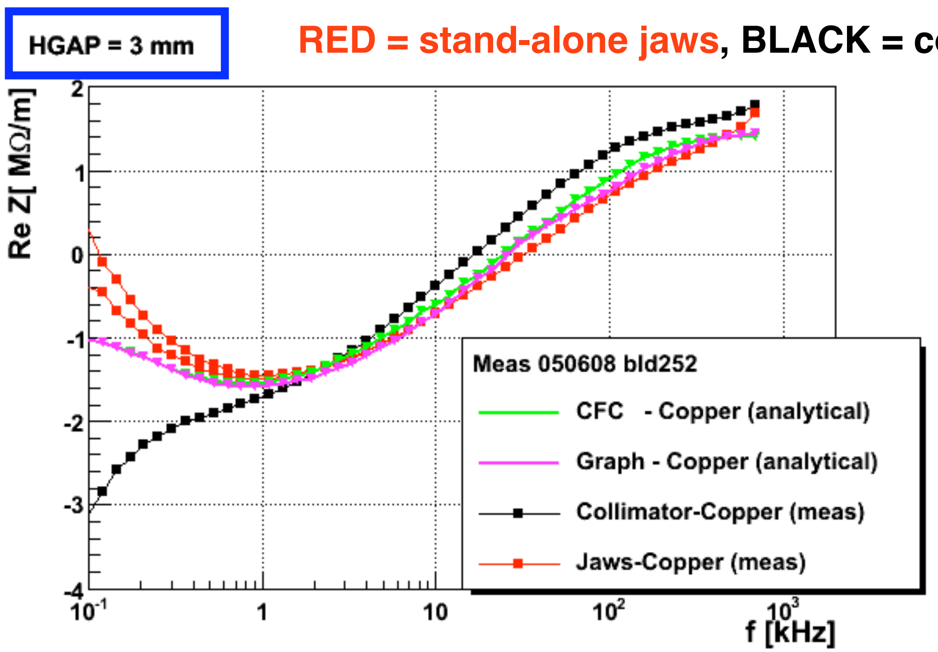
Measurements of a **LHC collimator prototype**

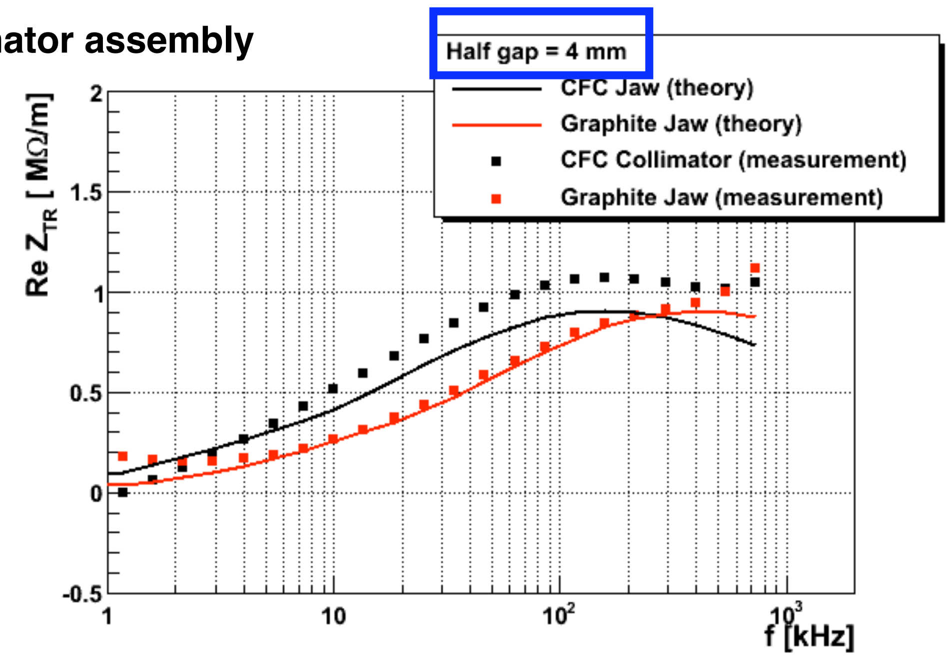
- the measurement if much more complicated due to difficult access for positioning and aligning the coil

What could explain a difference w.r.t the measured stand-alone jaws:

- jaws material graphite (jaws) and CFC (collimator assembly)
- possible influence of components of the assembly including RF contact

RED = stand-alone jaws, BLACK = collimator assembly





Conclusion: in all analyzed results the measured impedance is larger than the model

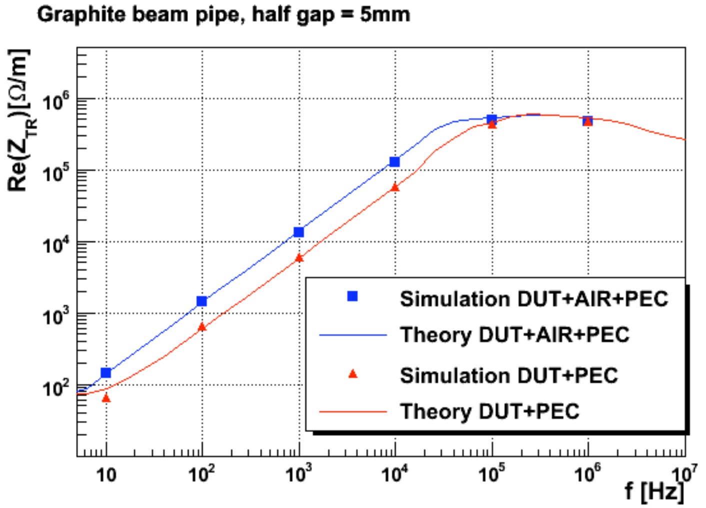
➠ the assembly does have an influence, effect can be quantified in 10-20 %

Numerical Simulations

Ansoft Maxwell Simulations

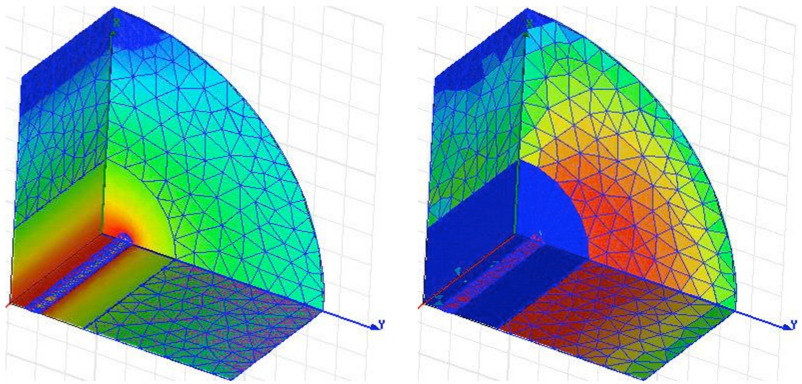
T.Kroyer, **"Simulation of the Low-frequency Collimator Impedance"**, CERN-AB-Note-2008-017

The commercial numerical tool Ansoft Maxwell has been used to simulate the 2 wires setup (with no problem of sensitivity!) and calculate the real part of the transverse impedance by integrating the effect of eddy currents on the material.



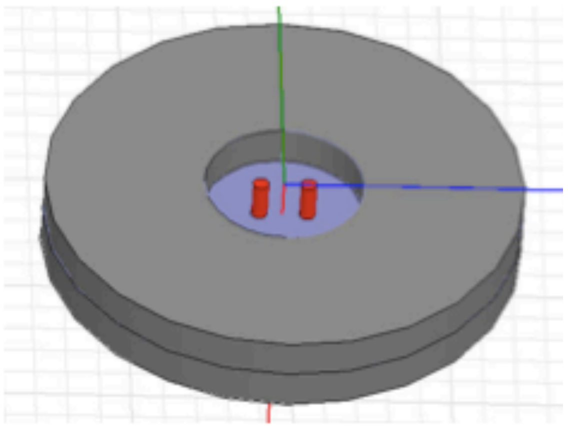
Results in excellent agreement with theory and measurements

The simulations give the additional information about fields and image current distributions



(a) Magnetic field. (b) Current density.

Figure 3: The field solutions in a round structure at 1 Hz. Logarithmic scaling is used for the color coding.



Conclusions

- Outlook and final remarks

Outlook

The measurement campaign aiming at bench-marking novel analytical theories in a ‘low frequency’ regime was successful:

- the measurement results (and the numerical simulations) agree very well with theory down to f=1kHz

The method and the challenges related to the measurements has been discussed

Even accounting for the effect of the collimator assembly on the RW impedance, the impact of the collimation system on the total LHC impedance and all the corresponding analysis of beam stabilities is valid, see:

E.Metral et al., "**Transverse impedance of LHC collimators**", Proceedings of PAC07

All these studies are already contributing to the design proposals for the LHC phase 2 collimation

we do have preliminary results of prototype materials/geometries (like “Waffle” copper plates, “Litz wires”)

Remarks

-Analytical calculations and numerical simulations:

infinitely long structures

-Measurements:

devices with finite length

-The laboratory experiments have the hypothesis that only Eddy currents are responsible for the impedance at low frequency

-with the probe coil method we neglect the effects of lossless dielectric materials and thus the related imaginary part of the impedance.

-measurements of prototype dielectric collimators is difficult and not solved yet

Acknowledgements

AB/ABP
G.Arduini, R. Assmann, C. Carli, M.Chanel, M. Giovannozzi

AB/ATB
O. Aberle, P. Francon, Y. Kadi, R. Beltron, J. Garcia Perez
S.Perrolaz, R.Chamizo

AB/BI
E. Bravin, P. Lavanchy, T. Lefevre

AB/CO
C. Leroy-Jonckx, J. Serrano

AB/OP
S.Redaelli

AB/RF
A. Boucherie, A. Findlay, M. Morvillo, C. Rossi

TS/SU
H. Mainaud-Durand, D. Missiaen

R.Jones (The Univ. of Manchester – Cockcroft Institute)
P. Mc Intosh (Daresbury Lab)