Update on resistive wall transverse impedance measurements at low frequency (graphite samples and PIMs)

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Acknowledgments:

O.Aberle, R.Assmann, E.Bravin, M.Giovannozzi, J.Serrano,

Motivations

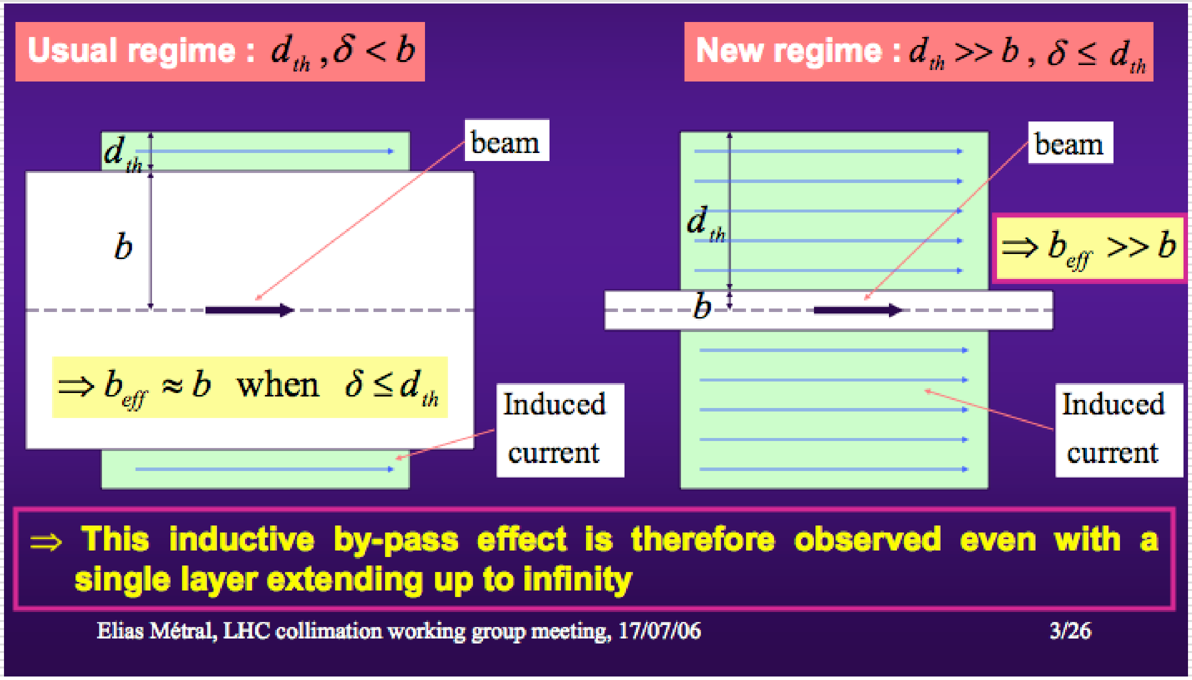
- Measurements motivated by outstanding issues
  - Benchmark most recent theories predicting resistive wall transverse impedance of poor conductor materials, at low frequency
  - Assess phase I collimator transverse impedance and support phase II design
  - verify PIMs RF fingers transverse impedance effect due to contact resistance

Theory

Resistive wall transverse impedance in a "regime" where

1. beam distance from the wall = half gap < wall thickness
2. skin depth < wall thickness

Down to frequencies of the order of the first LHC betatron unstable frequency ,
→ ~ 8 kHz

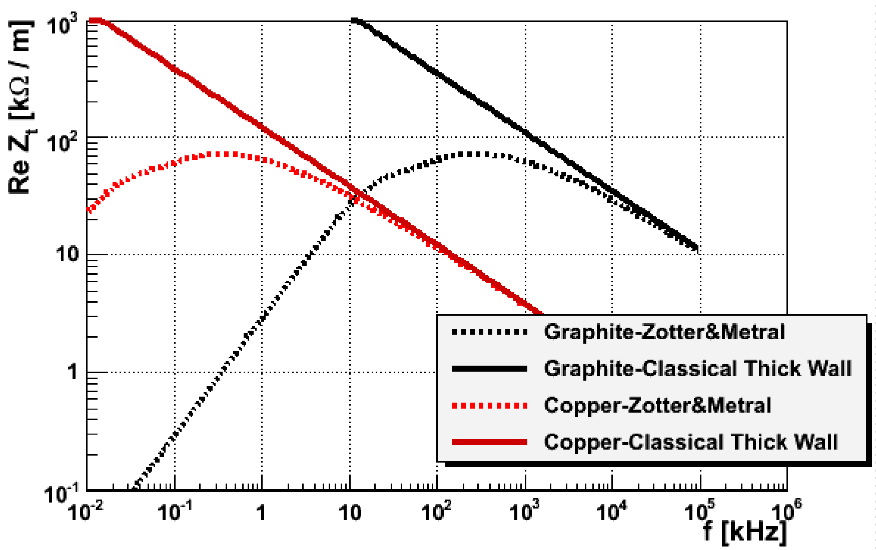


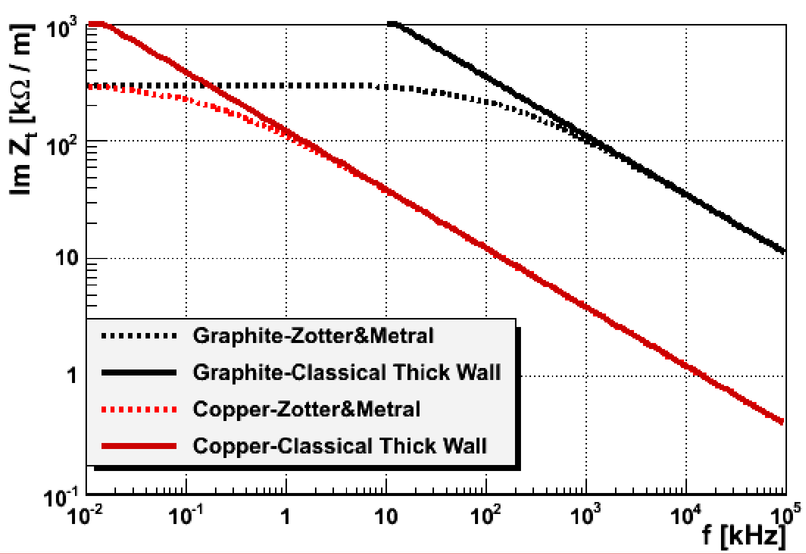
Theory

Complex transverse impedance depends on:

- Material conductivity
- Material thickness (+ single or multi layering/coating)
- Distance between the beam and the material
- Beam pipe cross section
  - cylindrical
  - collimator-like

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





MEASUREMENT

Method

Coaxial wire method to estimate transverse impedance

- single wire displaced at different transverse positions
- two wires

has low sensitivity at low frequencies

↓

Extension of two wires method:

Evaluation of the transverse impedance of a DUT by measuring the inductance variation of a probe coil

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

MEASUREMENT

Formulas

Measured quantity: the complex impedance of a coil in the presence of a perturbing material

From measurements:

$\vec{Z}^{DUT}(\omega)$ low conductivity material (graphite)

$\vec{Z}^{REF}(\omega)$ high conductivity material (copper)

$$\vec{Z}_T(\omega) = \frac{c}{\omega}\,\frac{\vec{Z}^{DUT}(\omega) - \vec{Z}^{REF}(\omega)}{N^2\Delta^2}$$

# of turns (N) **Coil width** (Δ)

N.B. : geometric part of impedance is equal for the two materials

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

We apply a simple data processing to plot : $\vec{Z}_{RW}^{graphite}(\omega) = \vec{Z}_{meas}(\omega) + \vec{Z}_{RW}^{copper}(\omega)$

Stages

Towards completion

1. **Sample graphite plates**
   - Test measurement method sensitivity at low frequencies
   - Test 2 different instruments for the coil impedance determination
     - Vector network analyzer
     - LCR impedance meter
   - Test coils differing in
     - Length and width
     - Number of windings

Starts now

2. **Stand-alone jaws**
   - measurements with actual LHC collimators material and dimensions
     - Requires long coil (>= 1.2 m)

From Jan 08

3. **Collimator assembly**
   - Measurements with LHC available collimator prototype(s)
     - Requires even longer coil (>=1.4m)
     - Use of collimator control system: once the coil is well aligned, the jaw position will be precisely known

Setup

DUTs and References

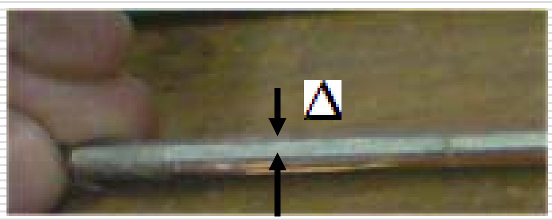
Vector Network Analyzer (VNA)

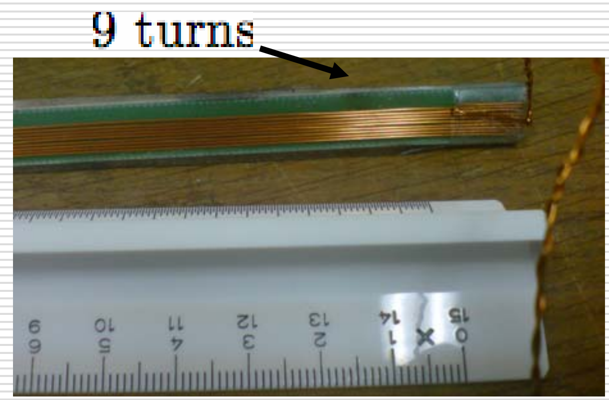
Coils

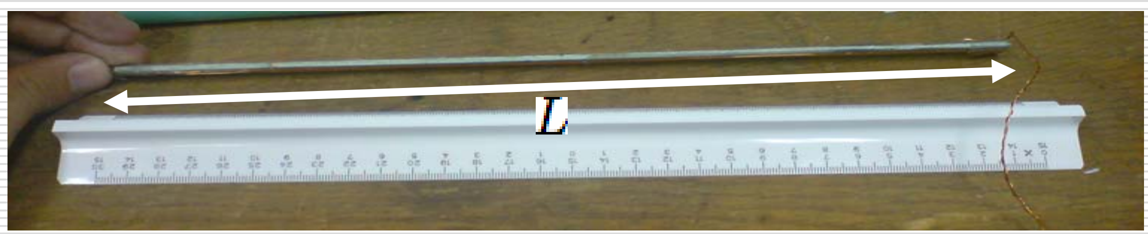
The two “best” coil prototypes produced and tested until now:

	Wire Diameter [mm]	Length (L) [cm]	Width (Δ) [mm]	N turns
COIL #1	0.5	30	2.5	9
COIL #2	0.5	45	4.5	19

COIL #1



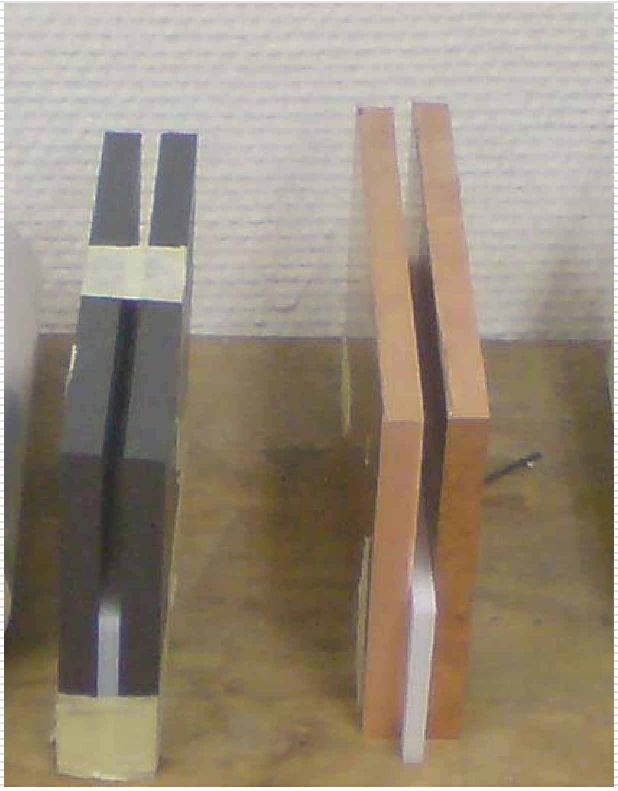




Plates

Graphite (DUT) and Copper (REFERENCE) plates

$$10 \text{ cm} \times 15 \text{ cm} \times 1 \text{ cm}$$



REMARKS

Understanding (and appreciating …) the results

- VNA and LCR are two different instruments measuring the coil impedance with two different methods

- Each set of measurements normally implies realignment of graphite and copper plates

- The measurements that will be presented were taken
  - with copper and graphite plates shown earlier
  - during several weeks (many manipulations and different conditions in between)

REMARKS

Understanding (and appreciating …) the results

- In almost all results two plots will be presented:

1. **"RAW DATA"**

$$\vec{Z}_T(\omega) = \frac{c}{\omega}\frac{\vec{Z}^{DUT}(\omega) - \vec{Z}^{REF}(\omega)}{N^2\Delta^2}$$

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

2. **"PROCESSED DATA"**

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

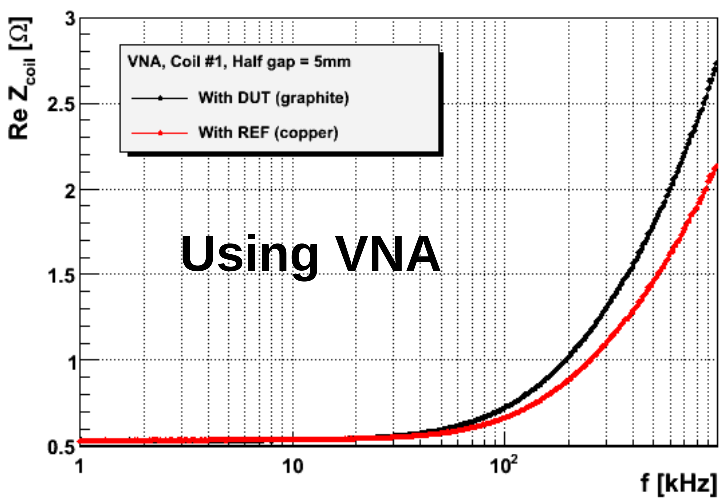
This assumes RW transverse impedance of copper as known.

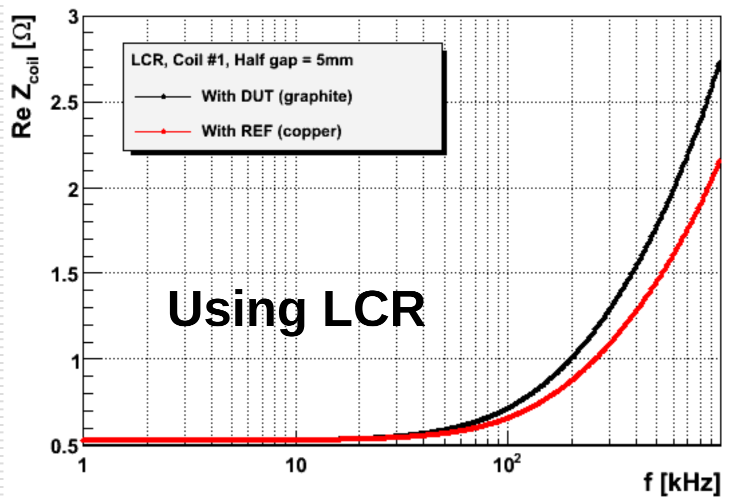
→ assumption is surely correct down to the frequency where classical thick wall and new theories agree for copper (< 10KHz in the plots presented here, I.e. half gap = 5mm)

RESULTS

Signals as measured by the two instruments

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

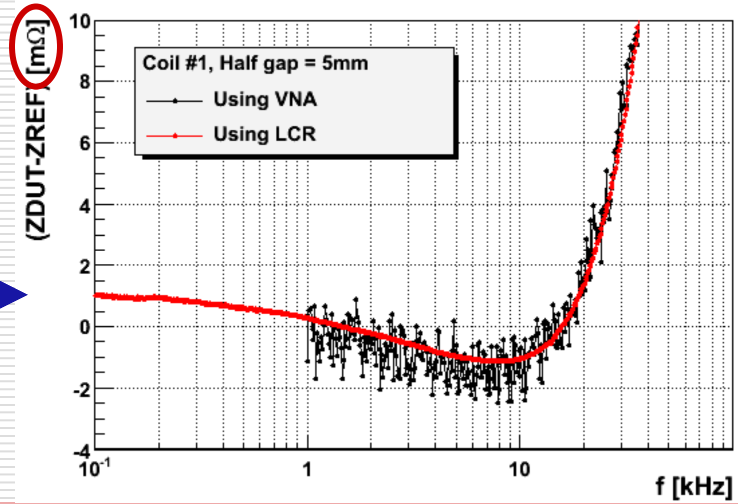




Looking at the difference

ZDUT-ZREF at low frequencies:

noise may become ~ =signal !

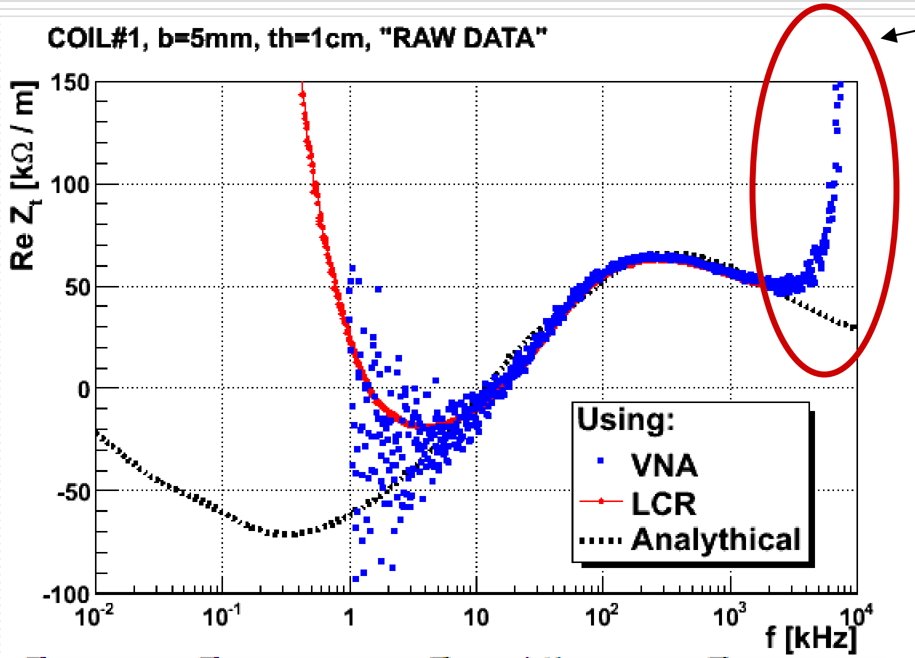


Compare instruments - VNA vs LCR

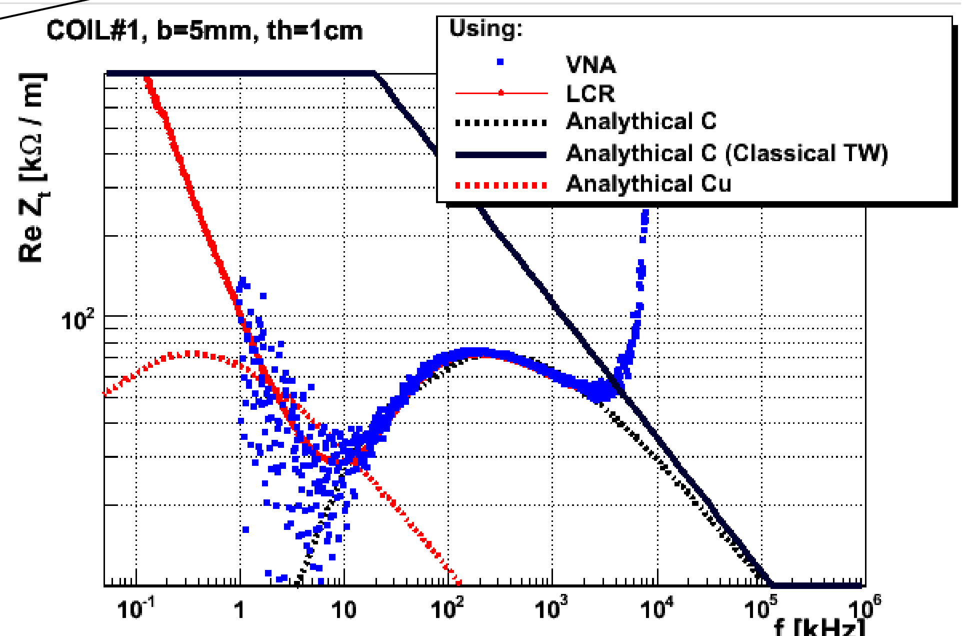
LCR results less noisy

- to compare the two instruments in a rigorous 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



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

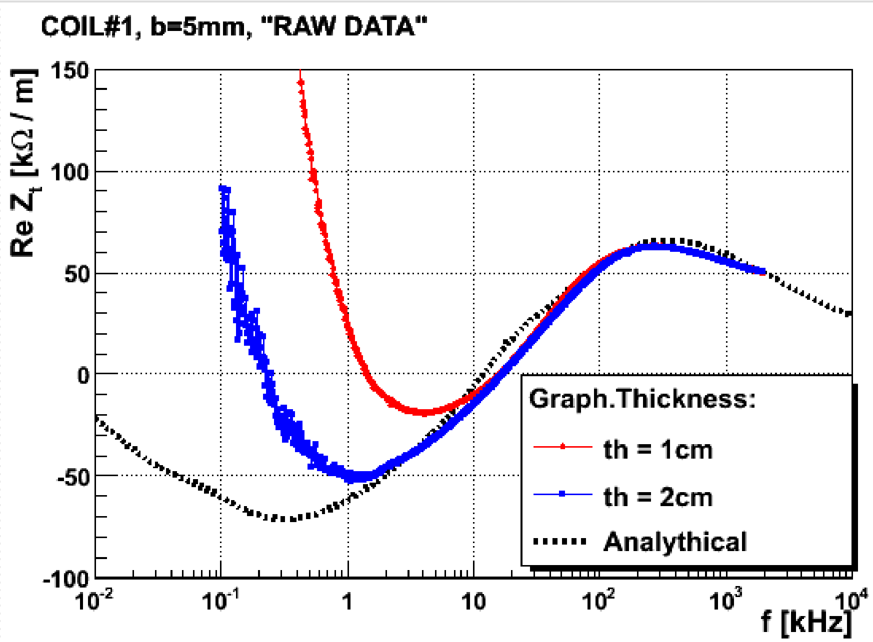


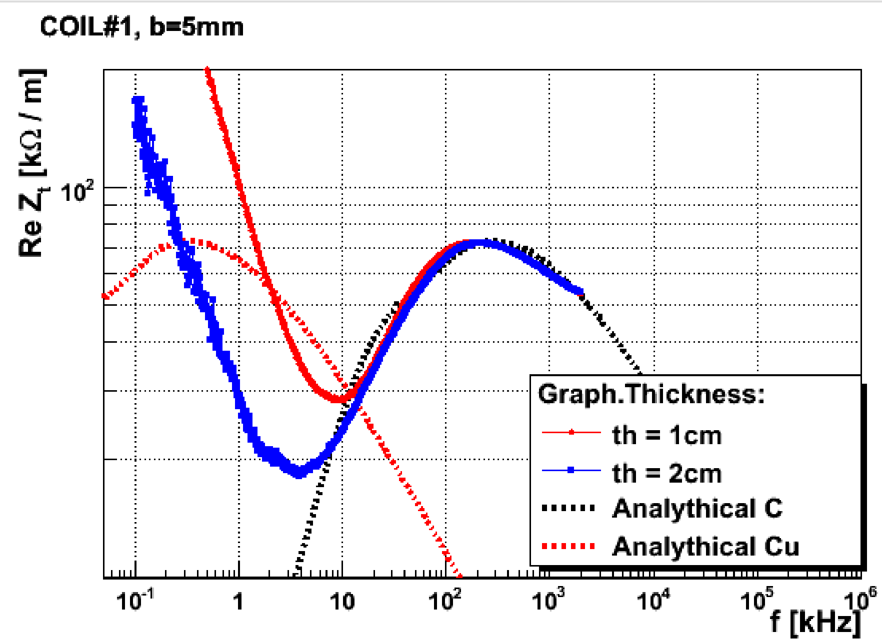
$$\vec{Z}^{graphite}_{RW}(\omega) = \vec{Z}_{meas}(\omega) + \vec{Z}^{copper}_{RW}(\omega)$$

Measure different thicknesses

- with 1 cm thickness:
  - skin depth > thickness and theory not valid anymore?

--> this is not confirmed by the next slide





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

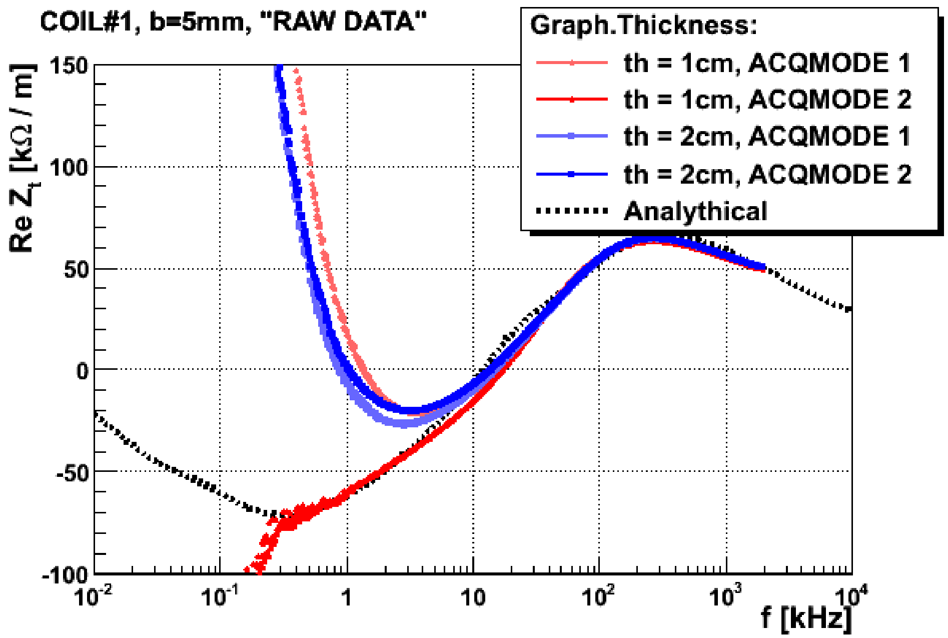
$$\vec{Z}_{RW}^{graphite}(\omega) = \vec{Z}_{meas}(\omega) + \vec{Z}_{RW}^{copper}(\omega)$$

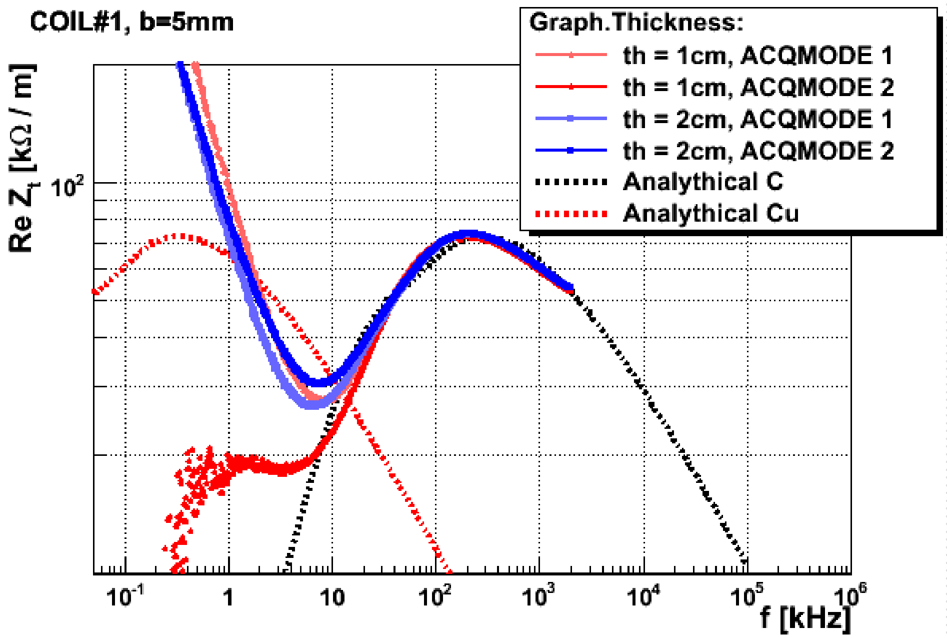
RESULTS

Change LCR acquisition mode

Averaging time (at each freq.) ACQMODE1 < Averaging time ACQMODE2

- In ACQMODE 2 dependence on thickness is opposite than previous slide
- In ACQMODE 1 dependence on thickness disappears
- In ACQMODE 2 , thickness 1cm : perfect agreement with theory down to 1 kHz! (we need to understand how we reached this … and reproduce!)





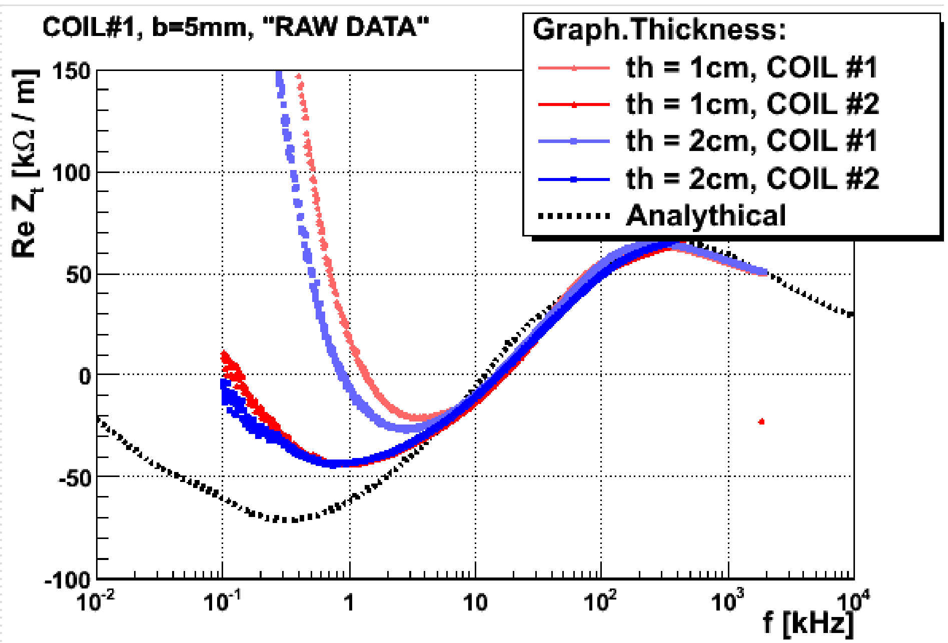
$$\vec{Z}_T(\omega) = \vec{Z}_{meas}(\omega) = \vec{Z}_{RW}^{graphite}(\omega) - \vec{Z}_{RW}^{copper}(\omega)$$

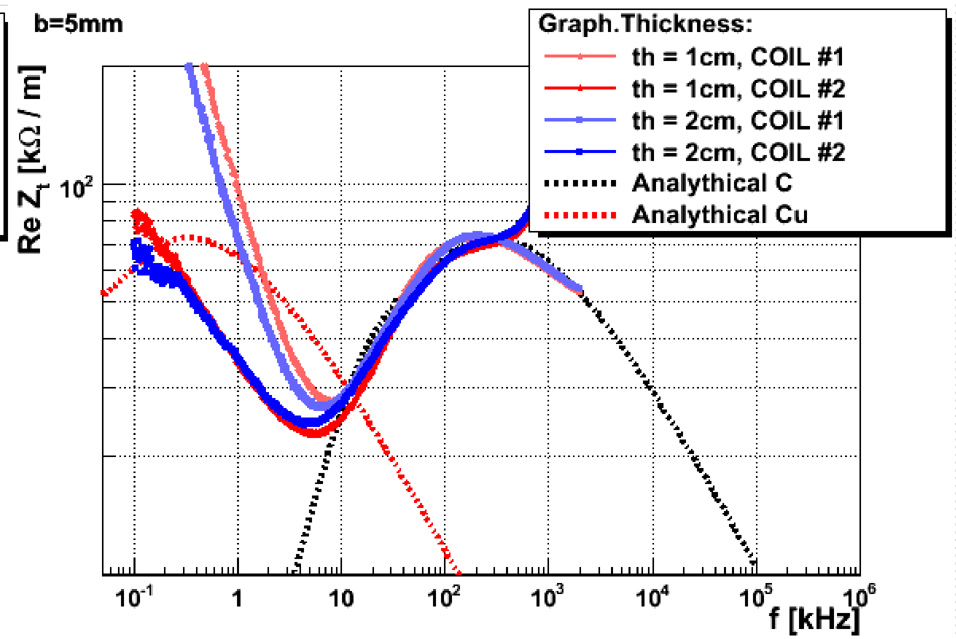
$$\vec{Z}_{RW}^{graphite}(\omega) = \vec{Z}_{meas}(\omega) + \vec{Z}_{RW}^{copper}(\omega)$$

RESULTS

Compare coils

- All measurements taken in ACQMODE1 (fastest)
- As expected: COIL #2 (19 turns) better than COIL #1 (9 turns)
    - Drawback: first coil resonance at lower frequency (~1.5MHz)





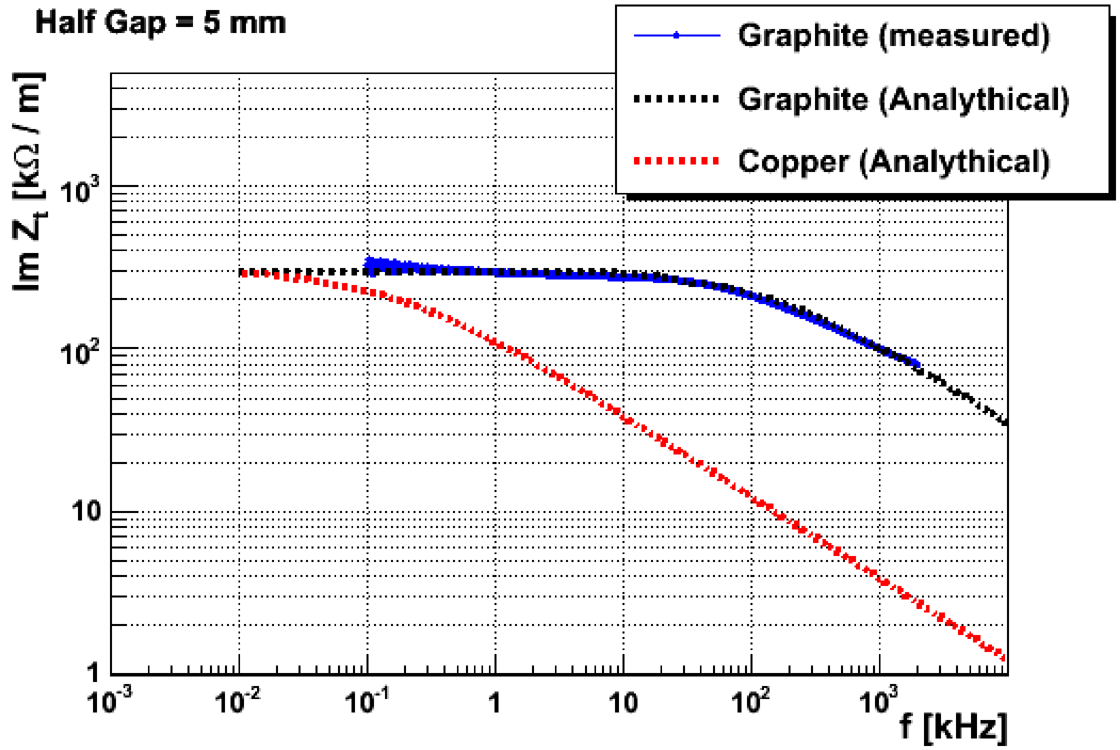
$$\vec{Z}_T(\omega) = \vec{Z}_{meas}(\omega) = \vec{Z}^{graphite}_{RW}(\omega) - \vec{Z}^{copper}_{RW}(\omega)$$

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

RESULTS

Imaginary part of Zt

Imaginary part fits very well with theory, in all the measurements we performed



Plug In Modules - (PIMs)

PIMs were designed with RF fingers

- to reduce their longitudinal coupling impedance at high frequency,
- may represent a problem due to their contact resistance = transverse impedance at low frequency

We are measuring them with the same method used for poor conductor materials

- to verify if/how the contact resistance varies when they are in their nominal position at “cold” (i.e. during LHC operation)

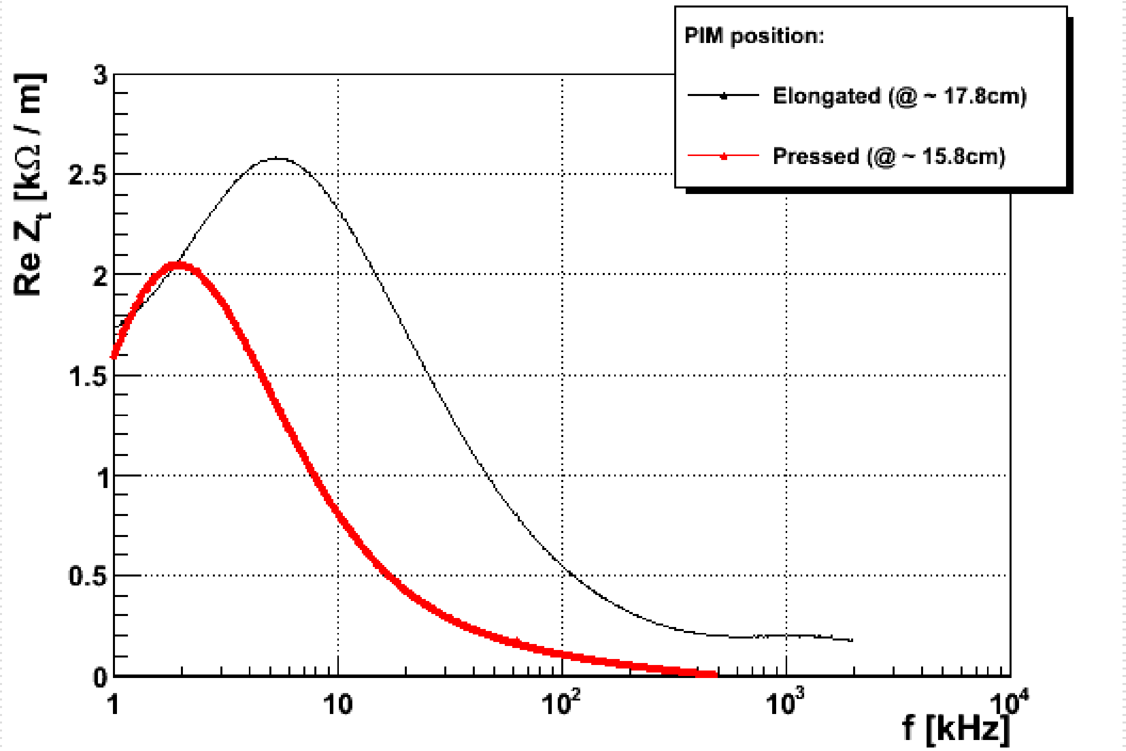
Gap is large w.r.t to graphite tests → Requires a “bigger” coil

- Two coil prototypes already tested

We have preliminary results indicating that we can measure transverse impedance changes due to PIM extension

PIMS

Preliminary results



Poor conductor materials - Collimators

Preliminary results using sample graphite plates

- carried out with different instruments, different coils, different measurement conditions
- exhibit good sensitivity and reproducibility
- show excellent agreement w.r.t theory down to 10 kHz
- below 10 kHz more studies are needed
  - improve alignment and gap setup
  - understand dependence on LCR acq. Modes

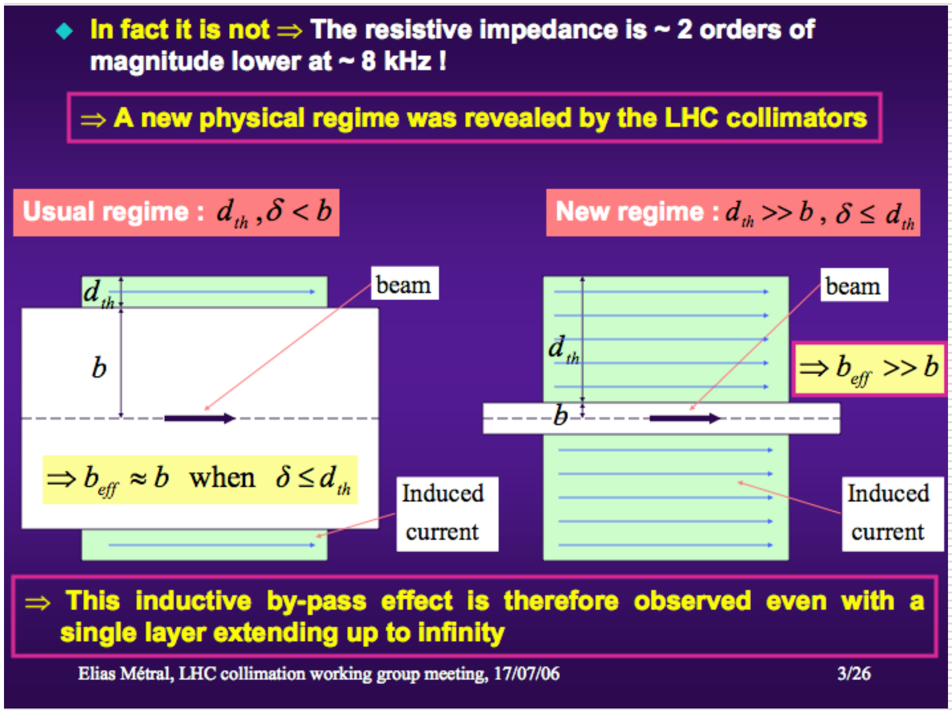
NEXT :

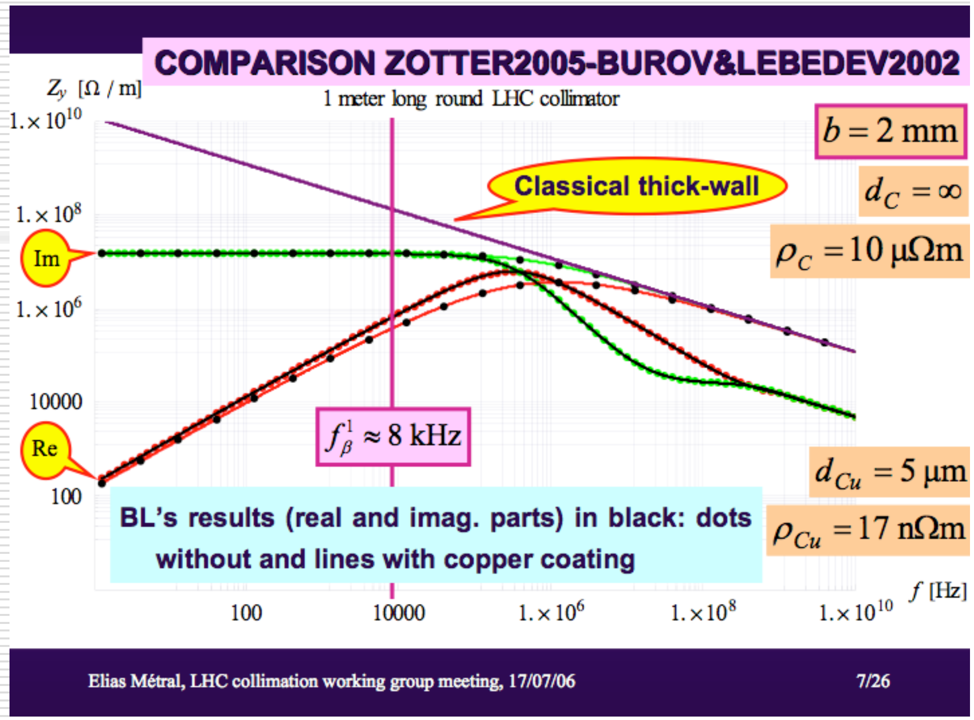
- Measure stand alone jaws and collimator assembly
- In both cases: scan gap amplitudes

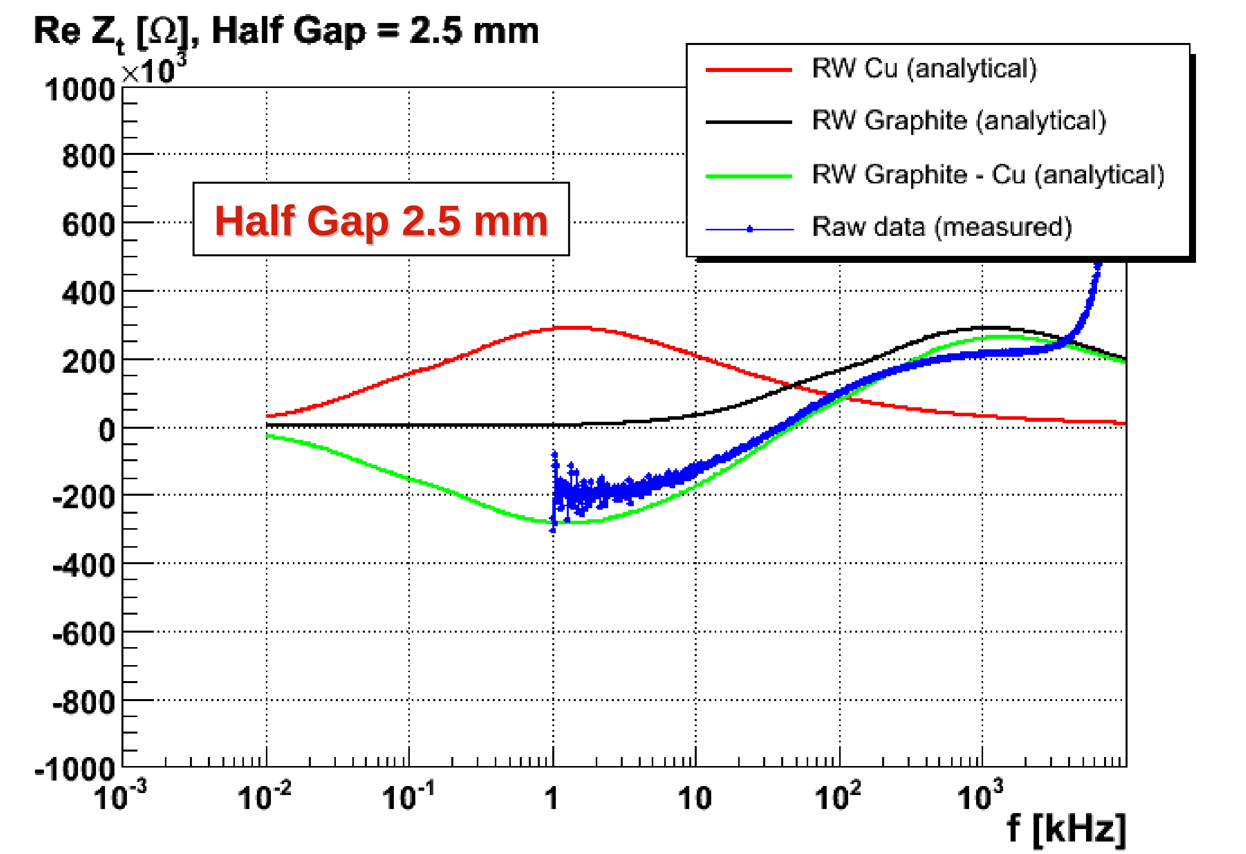
PIMs

- Establish a procedure for systematic measurements
  - Different PIM elongations
  - Remove single RF fingers and detect effect (?)

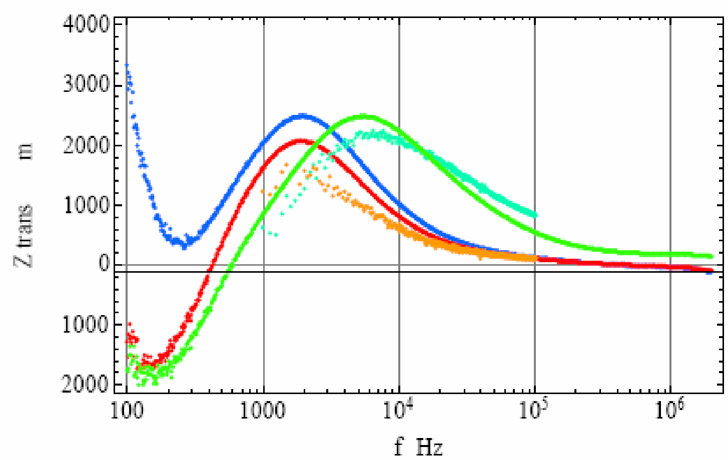
SPARE


In fact it is not ⇒ The resistive impedance is ~ 2 orders of magnitude lower at ~ 8 kHz !
⇒ A new physical regime was revealed by the LHC collimators
Usual regime : $d_{th}, \delta < b$
New regime : $d_{th} >> b$, $\delta \le d_{th}$
d_{th}
b
beam
$\Rightarrow b_{eff} \approx b$ when $\delta \le d_{th}$
Induced current
d_{th}
b
beam
$\Rightarrow b_{eff} >> b$
Induced current
⇒ This inductive by-pass effect is therefore observed even with a single layer extending up to infinity
Elias Métral, LHC collimation working group meeting, 17/07/06
3/26


COMPARISON ZOTTER2005-BUROV&LEBEDEV2002
Z_y [Ω / m]
1 meter long round LHC collimator
$1. \times 10^{10}$
$1. \times 10^{8}$
$1. \times 10^{6}$
10000
100
Im
Re
Classical thick-wall
$f_\beta^1 \approx 8$ kHz
$b = 2$ mm
$d_C = \infty$
$\rho_C = 10$ μΩm
$d_{Cu} = 5$ μm
$\rho_{Cu} = 17$ nΩm
BL's results (real and imag. parts) in black: dots without and lines with copper coating
100
10000
$1. \times 10^{6}$
$1. \times 10^{8}$
$1. \times 10^{10}$
f [Hz]
Elias Métral, LHC collimation working group meeting, 17/07/06
7/26


Re Z_t [Ω], Half Gap = 2.5 mm
×10^3
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
10^-3
10^-2
10^-1
1
10
10^2
10^3
f [kHz]
Half Gap 2.5 mm
RW Cu (analytical)
RW Graphite (analytical)
RW Graphite - Cu (analytical)
Raw data (measured)

Measurement of the transverse impedance of a PIM (23.11.2007)
with respect to a reference copper tube

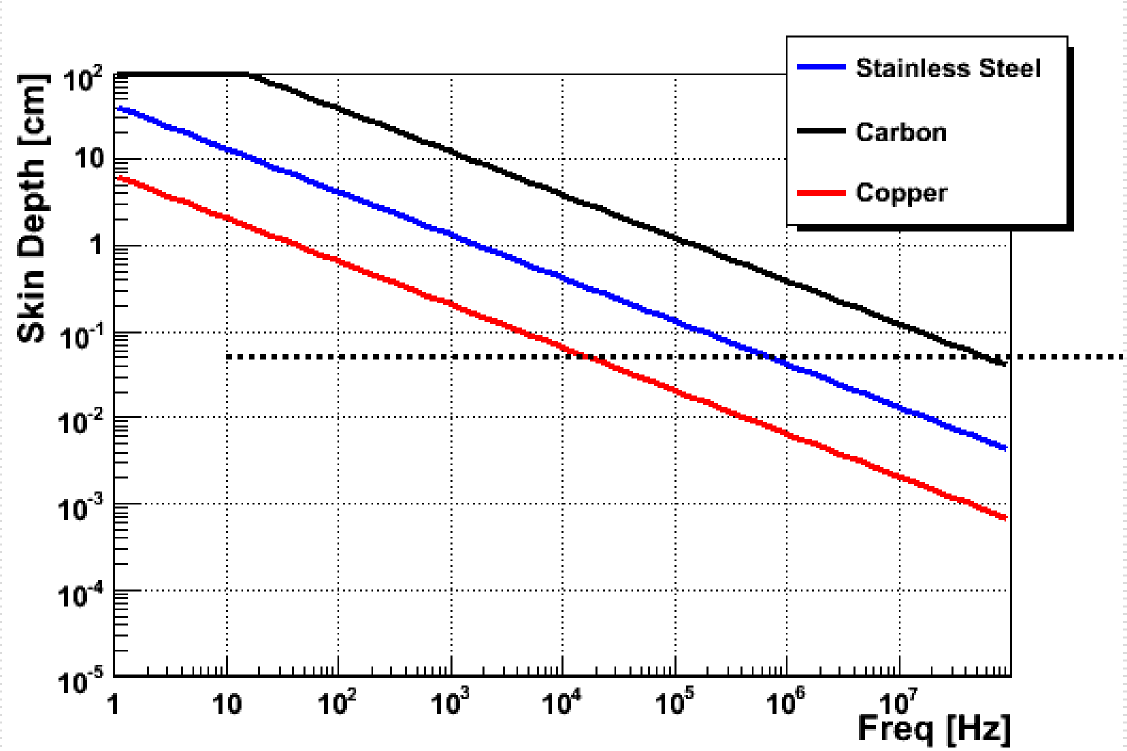


LCRmeter with 1.6 cm wide coil

In green: PIM fully open (~18 cm) -> several RF contacts clearly disconnected
In blue : PIM half open (~16 cm) -> RF contacts "look" all connected (to be confirmed with DC resistance measurement done in parallel)
In red : PIM closed (~15.5 cm)

Vector Network Analyzer with 2.25 cm wide coil

In light blue : PIM fully open (~18 cm) -> several RF contacts clearly disconnected
In orange : PIM closed (~15.5 cm)



Skin Depth [cm]
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1
10
10^2
10^3
10^4
10^5
10^6
10^7
Freq [Hz]
Stainless Steel
Carbon
Copper