Impedance simulations of FCC interconnects and measurements on LHC TCDQ blocks

Diego Ferrazza

Acknowledgements: Benoit Salvant , Nicolò Biancacci,
David Amorim, Edoardo Bonanno

Introduction

PURPOSE OF 1ST STUDY:

- ***Presently there are many studies for the design of FCC.***
- ***The 1st simple model of impedance for the beam stability was developed.***
- ***Starting from the LHC impedance model and its datasheet, the elements with the biggest impedance for the FCC were simulated, like:***
    1. ***Collimators***
    2. ***Beam screen***
    3. ***Shielded bellows***
- ***The impedance of the FCC shielded bellows at the interconnects between two magnets was calculated.***

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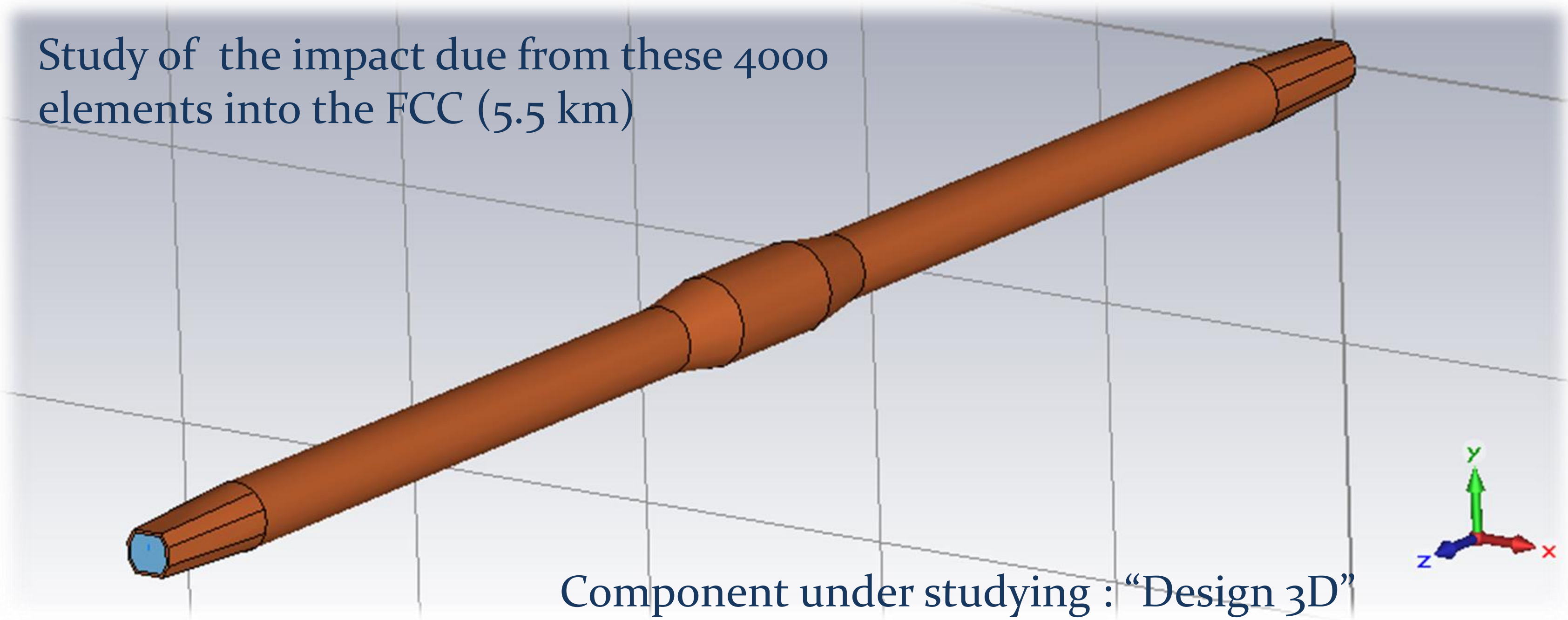
FCC interconnect between two magnets

Study of the impact due from these 4000 elements into the FCC (5.5 km)



Component under studying : “Design 3D”

Summary of the study

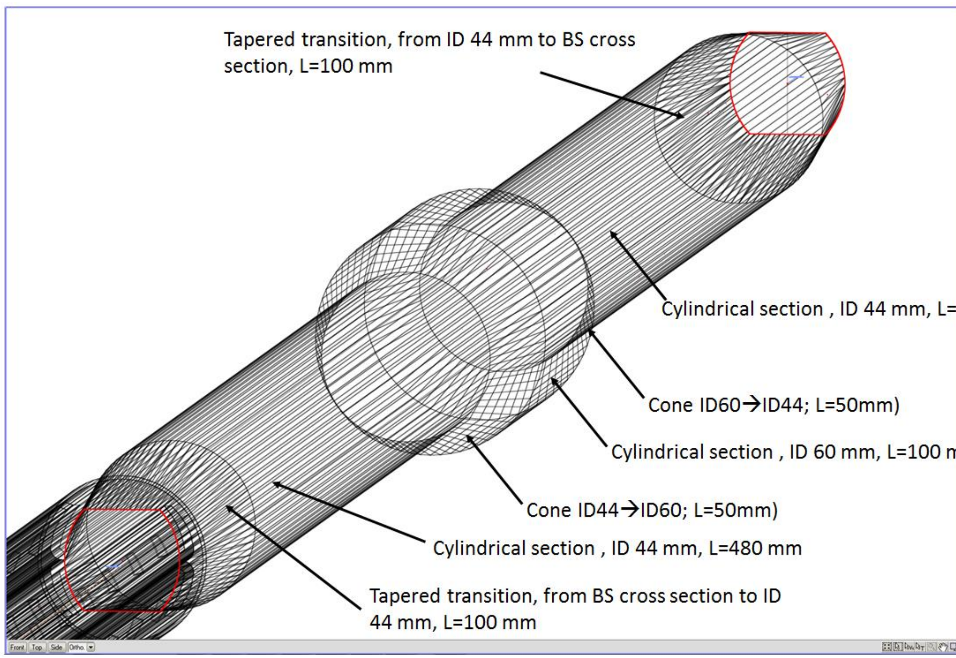
- Data of the component and design
- Modes study
- Longitudinal impedance
- Transverse impedance
- Shunt impedance
- Conclusion

Data for the start of this study.

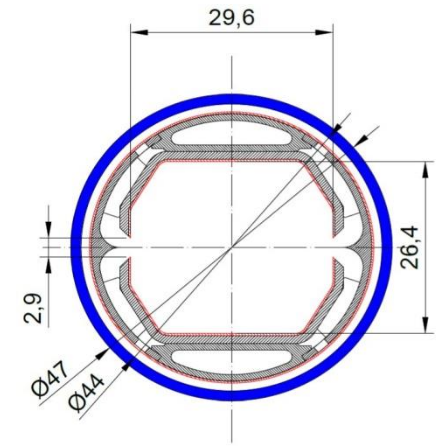
DATA SHEET

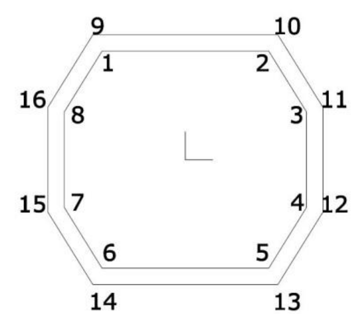
Material	$\rho(50K)\ [\Omega \cdot m]$	Thickness [mm]
Copper (annealed)	$0.75 \cdot 10^{-9}$	0.3

DIMENSIONS OF THE COMPONENT



REAL CROSS SECTION AND USED CROSS SECTION AT THE START AND THE END OF THIS COMPONENT, REDESIGNED WITH AUTOCAD

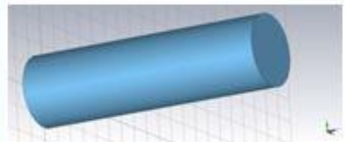
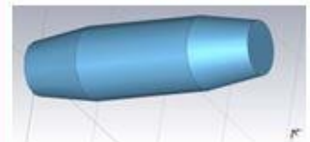
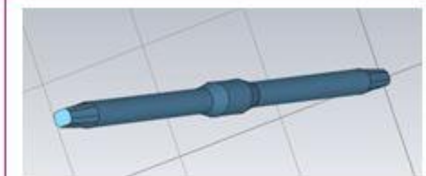




	X	Y
1	-10.185	13.2
2	10.185	13.2
3	14.8	5.8
4	14.8	-5.8
5	10.185	-13.2
6	-10.185	-13.2
7	-14.8	-5.8
8	-14.8	5.8
9	-11.295	15.2
10	11.295	15.2
11	16.8	6.38
12	16.8	-6.38
13	11.295	-15.2
14	-11.295	-15.2
15	-16.8	-6.38
16	-16.8	6.38

CST simulations: EIGENMODE Solver

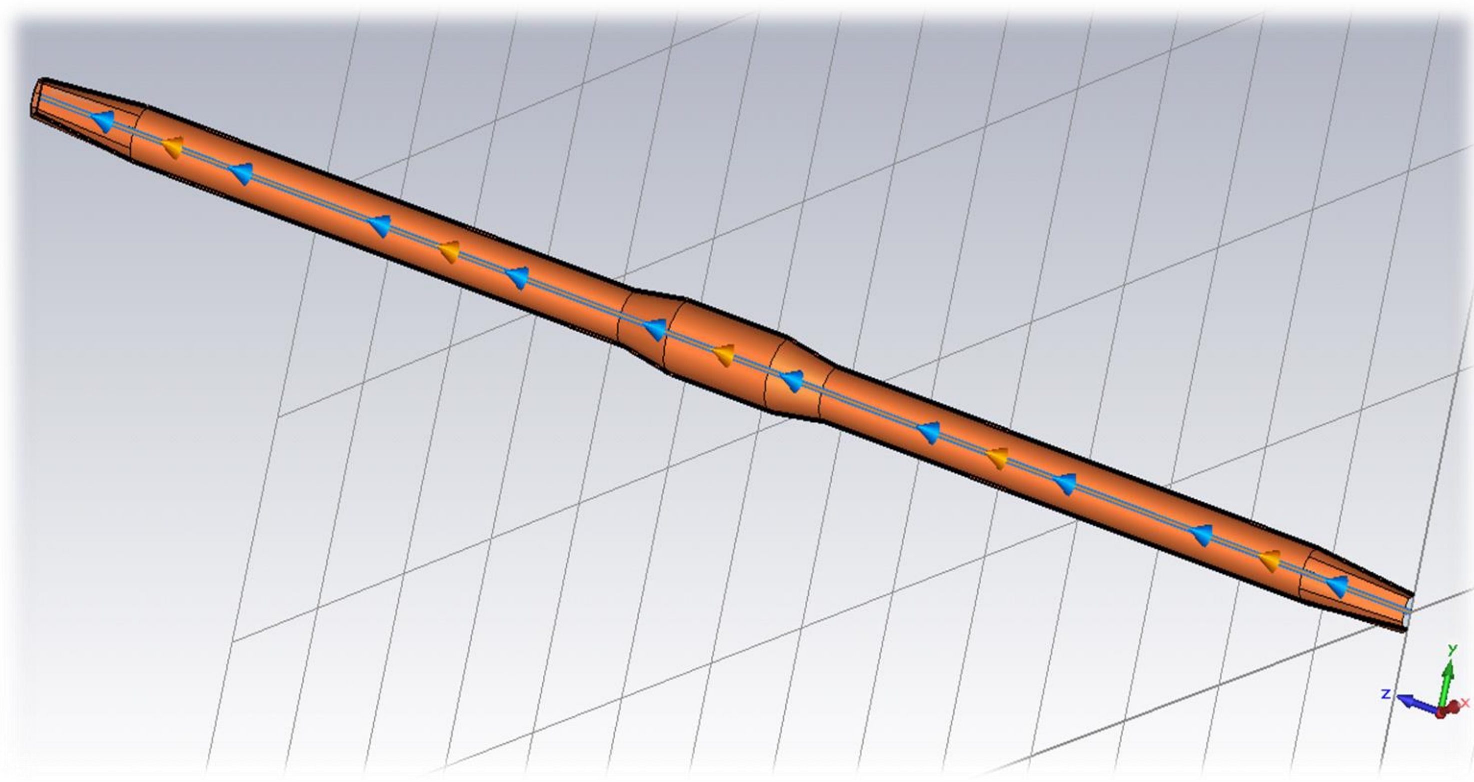
Table of the resonance frequencies of different calculations and simulations.

Modes	Calculated			
TE_{111}	$3.022\ [GHz]$	$3.023\ [GHz]$	$3.064\ [GHz]$	$3.058\ [GHz]$
TE_{112}	$3.289\ [GHz]$	$3.290\ [GHz]$	$3.411\ [GHz]$	$3.379\ [GHz]$
TE_{113}	$3.692\ [GHz]$	$3.692\ [GHz]$	$3.864\ [GHz]$	$3.746\ [GHz]$
TM_{010}	$3.825\ [GHz]$	$3.825\ [GHz]$	$3.917\ [GHz]$	$3.918\ [GHz]$
TM_{011}	$3.898\ [GHz]$	$3.898\ [GHz]$	$4.180\ [GHz]$	-
TM_{012}	$4.108\ [GHz]$	$4.108\ [GHz]$	-	-
TE_{114}	$4.190\ [GHz]$	$4.191\ [GHz]$	$4.365\ [GHz]$	-

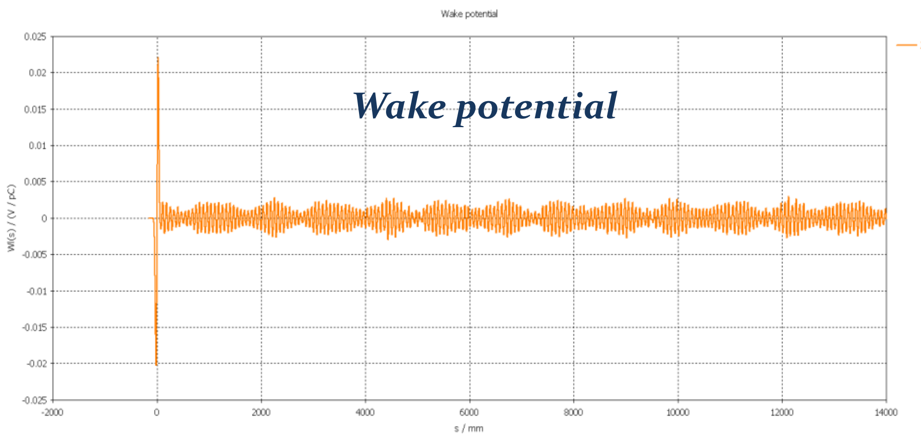
- In sequence from right there are the simulation like: cylindrical cavity ‘l = 200 mm and a = 30 mm’, only the cavity of the interconnect and at the end the results of whole element.
- In the whole component the frequency after the mode TM_{010} isn’t the TM_{011}, there is the beginning of resonances modes inside the long parts too.
- There are seven modes TE from 3.995[GHz] to 4.102[GHz] the range of frequency calculated.

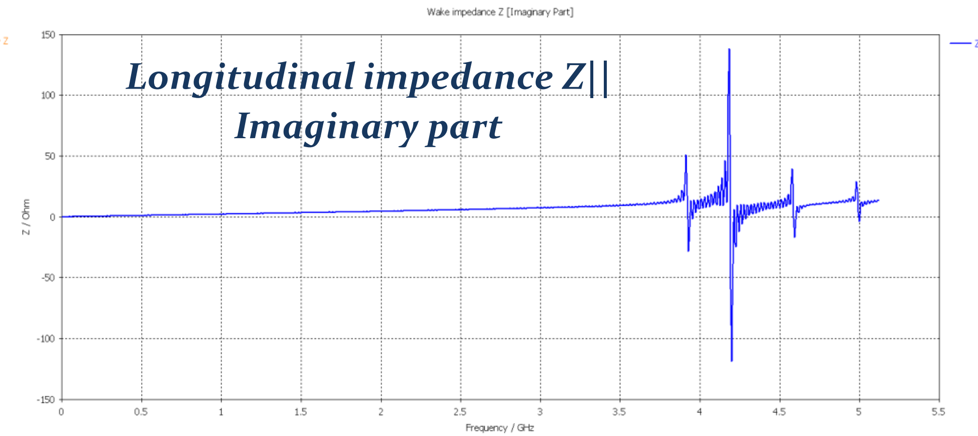
CST simulations: WAKEFIELD Solver

FIRST CONFIGURATION, THE BEAM COORDINATES ARE ***(x = 0 , y = 0) [mm]***



RESULTS





Rectifying Im(Z||) like (n= f/ f_{rev}), with f ∈ (0.001 , 4) [GHz] and

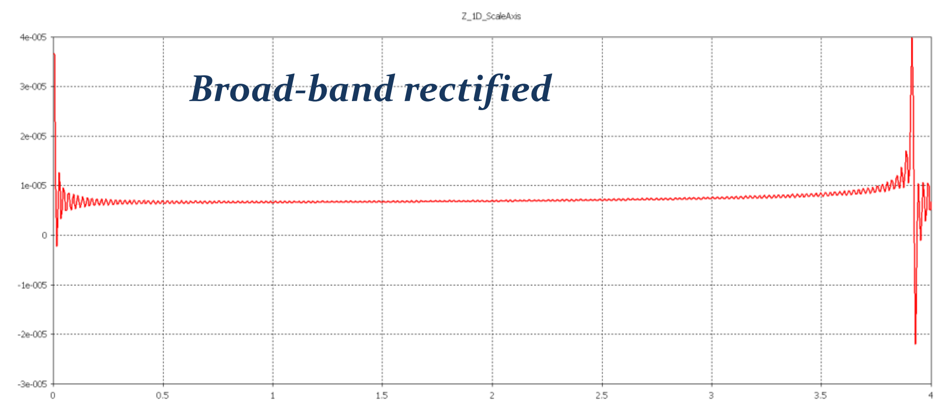
$$f_{rev}(FCC) = \frac{f_{rev}(LHC)}{3.70} = 3040\ Hz \quad \textbf{where} \quad 3.70 = \frac{length(FCC)}{length(LHC)} = \frac{100\ Km}{27\ Km}$$

The longitudinal impedance for once component is: ➡

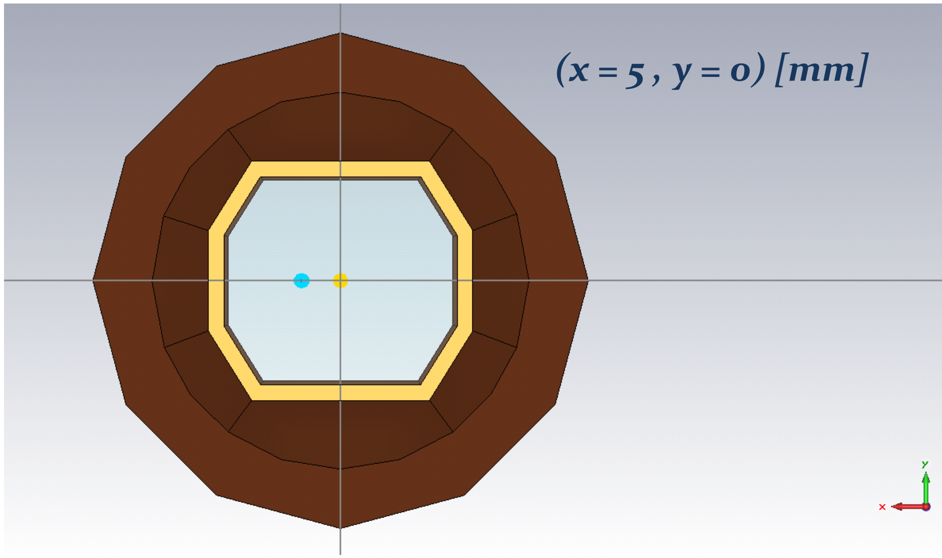
$$Im\left(\frac{Z_{||}}{n}\right) = 7 \cdot 10^{-6}\ [\Omega]$$

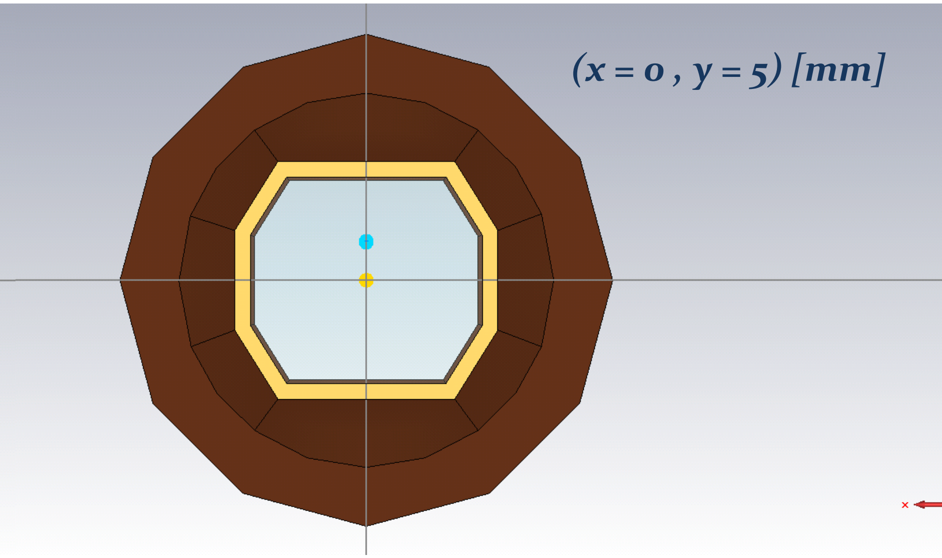
The longitudinal impact in whole FCC is: ➡

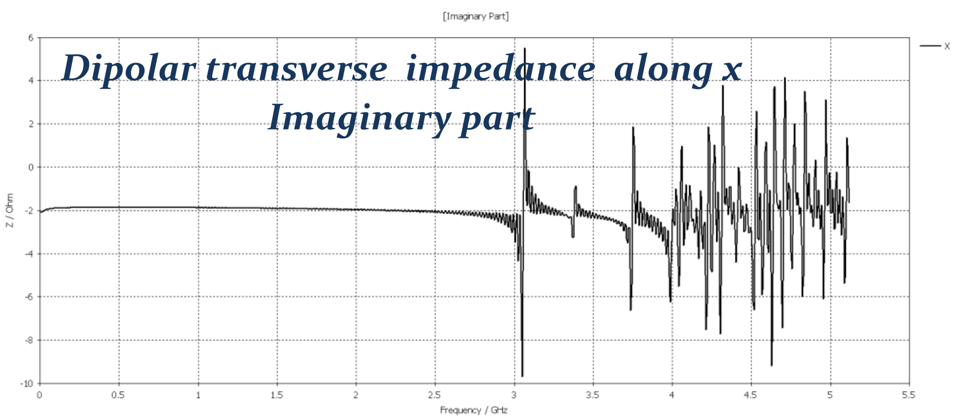
$$Im\left(\frac{Z_{||}}{n}\right)_{tot} = 7 \cdot 10^{-6} \cdot 4000 = 28\ [m\Omega]$$

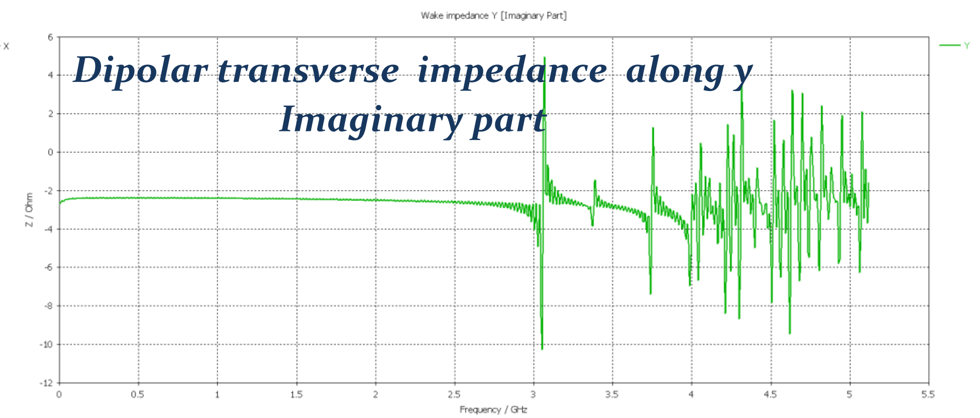


SECOND CONFIGURATION, THE BEAM COORDINATES:









RESULTS: $Im(Z_{\perp x}) \cdot 5 \cdot 10^{-3} = 1.90\ [\Omega]$

➡ $Im(Z_{\perp x}) = 0.38\ [K\Omega/m]$

➡ $Im(Z_{\perp x})_{tot} = 0.38 \cdot 4000 = 1.52\ [M\Omega/m]$

RESULTS: $Im(Z_{\perp y}) \cdot 5 \cdot 10^{-3} = 2.40\ [\Omega]$

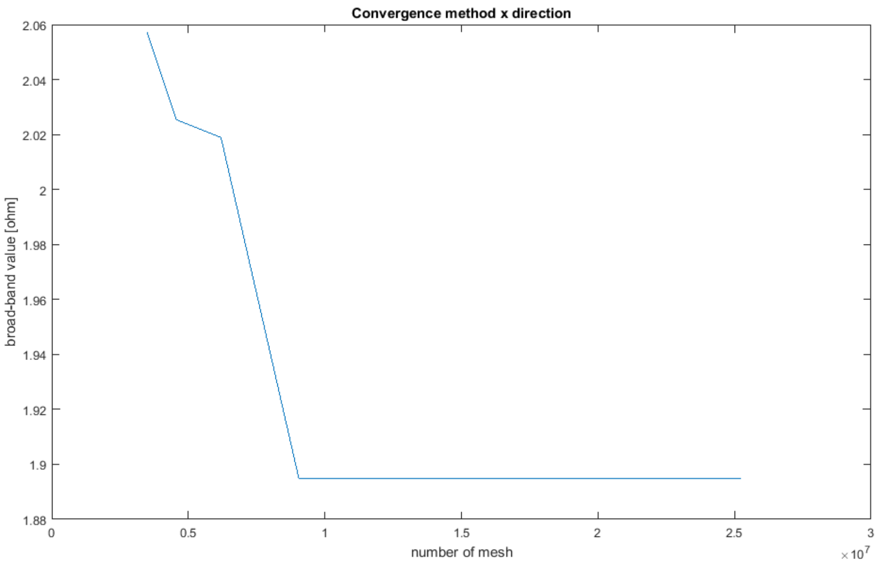
➡ $Im(Z_{\perp y}) = 0.48\ [K\Omega/m]$

➡ $Im(Z_{\perp y})_{tot} = 0.48 \cdot 4000 = 1.92\ [M\Omega/m]$

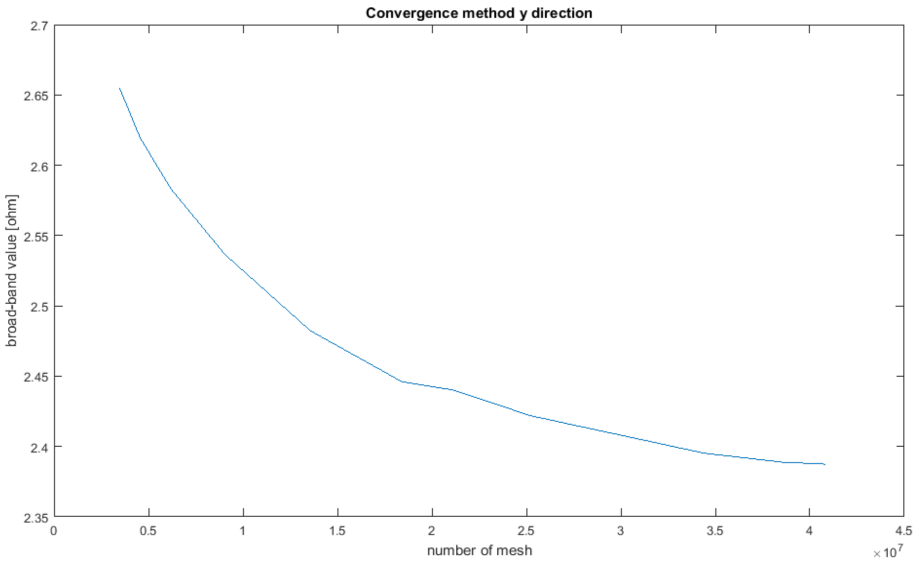
Convergence tests

- THE TRANSVERSE IMPEDANCE RESULTS SHOWN BEFORE WERE CONFIRMED WITH CONVERGENCE TESTS
- THE BROAD-BAND IMPEDANCE WAS CHECKED WITH CONVERGENCE INCREASING STEP BY STEP THE NUMBER OF MESH, FOR BOTH DIRECTIONS

Beam coordinates (x = 5 , y = 0) [mm]



Beam coordinates (x = 0, y = 5) [mm]



Shunt impedance calculation

- *By definition the shunt impedance in any direction was defined like* $\frac{R_s}{Q} = \frac{|V|^2}{2\omega_{res}W}$ *, where* W *is the energy stored in the cavity and* V *defined for a finite component like:* $V = \int_{z_0}^{z_l}[E(\omega) + (v \times B(\omega))] \cdot e^{j\frac{\omega_{res}}{v}z} dz$
- *Q is the quality factor and for the 1st mode* $Q = 86802$ *, evaluated with eigenmode post processing.*
- *From the Panofsky-Wenzel theorem in terms of impedance:* $\boldsymbol{Z}_{\perp}(\boldsymbol{\omega}) = \frac{c}{\omega_{res}} \nabla_{\perp} \boldsymbol{Z}_{||}(\boldsymbol{\omega})$.
- *The relations above give a pure parabolic trend between the longitudinal and dipolar transverse shunt impedance:* $R_{s||} = R_{s\perp}\left(\frac{\omega_{res}}{c}\right)^2 d^2\ [\Omega]$ *where d is the transverse displacement like x or y.*

Shunt impedance convention from theory to simulations:

Theoretical formula

$$R_{s||} = R_{s\perp} \left(\frac{\omega_{res}}{c}\right)^2 d^2 \ [\Omega]$$

Eigenmode convention

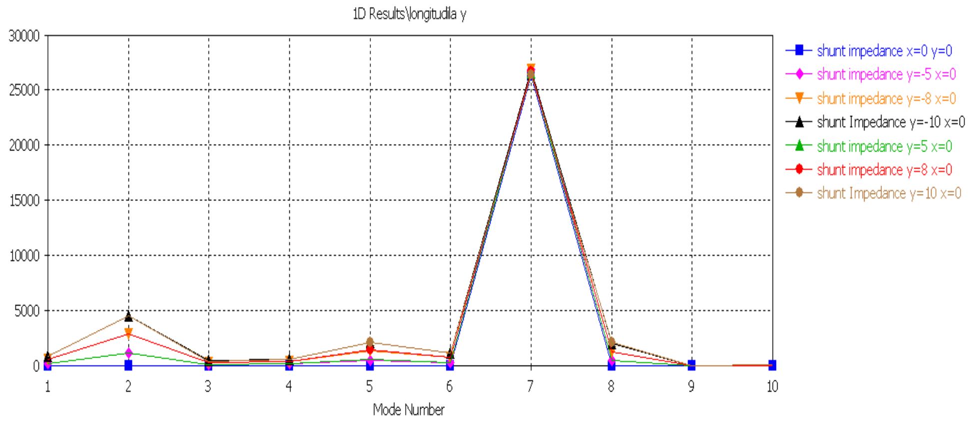
$$R_{s||}{}^{E} = R_{s\perp}{}^{E} \left(\frac{\omega_{res}}{c}\right)^2 d^2 \ [\Omega]$$

Wakefield convention

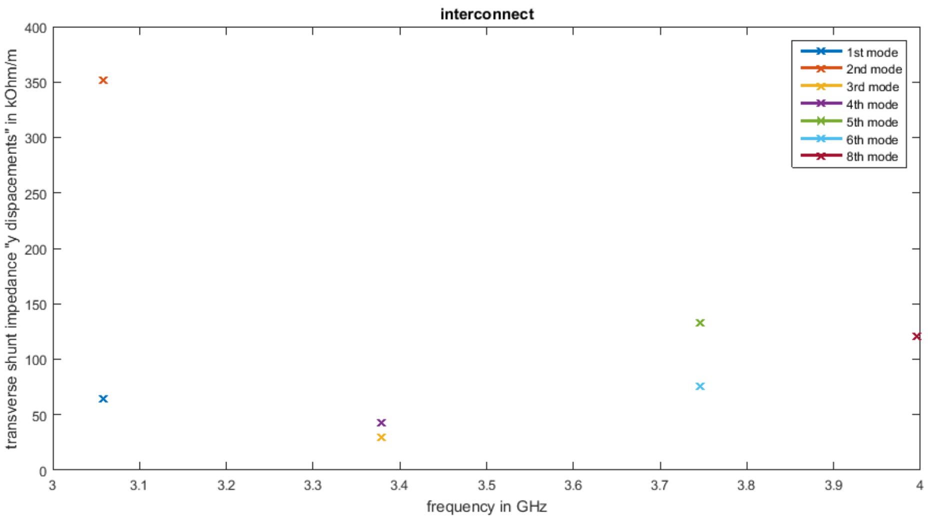
$$R_{s||} = R_{s\perp}{}^{W} \left(\frac{\omega_{res}}{c}\right) d^2 \ [\Omega]$$

Where $R_{s\perp}{}^{E} = 2R_{s\perp}[\Omega]$ *and* $R_{s\perp}{}^{W} = R_{s\perp}\left(\frac{\omega_{res}}{c}\right)\left[\frac{\Omega}{m}\right]$ *, usually the wakefield convention for the transverse shunt was used.*

Longitudinal shunt impedance
y displacement eigenmode convention $R_{s||}{}^{E}$ $[\Omega]$



Transverse shunt impedance
y direction wakefield convention $R_{s\perp}{}^{W}$ $[\Omega/m]$



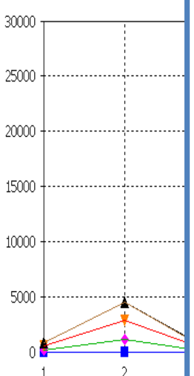
Shunt impedance convention from theory to simulations:

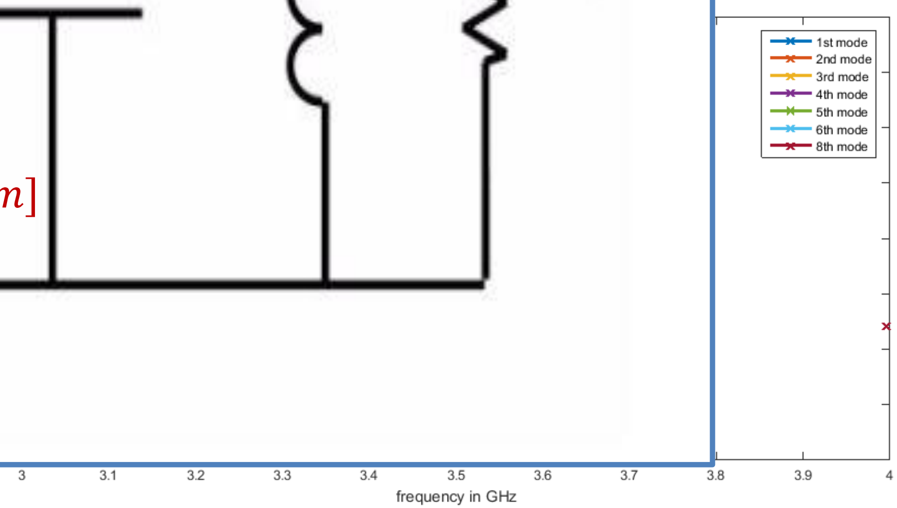
Th

$R_{s||}$ ...]

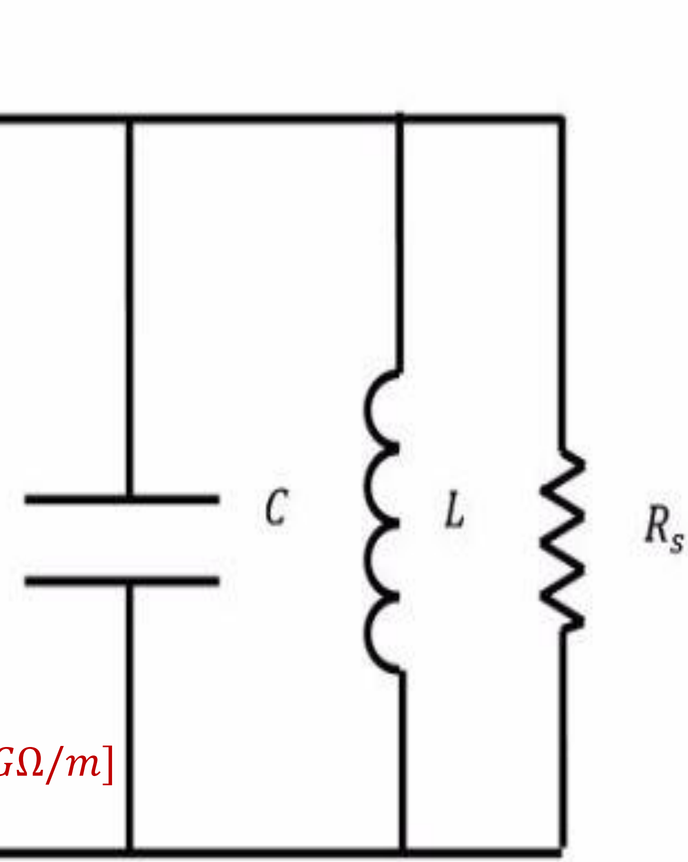
Where R ... *ıs used.*

y disp ... $_{s\perp}{}^{W}$ *[Ω/m]*





Electric equivalent circuit



Transverse impedance definition:

$$Z(\omega)_{\perp} = \frac{f_{res}}{f}\frac{R_{s\perp}}{1+jQ\left(\frac{f}{f_{res}}-\frac{f_{res}}{f}\right)}$$

if $f = f_{res}$ ➡ $Z(\omega)_{\perp} = R_{s\perp}$

For the 1st resonant mode:

$$Z(\omega_{res})_{\perp tot} = 0.35 \cdot 10^{6} \cdot 4000 = 1.4[G\Omega/m]$$

Conclusion

The comparison between the impedance values of these 4000 components and the impedances of same elements (red rectangle) in the LHC particle accelerator was done. Considered that the FCC is 3.70 times longer than the LHC:

- *The longitudinal contribution* $Im\left(\frac{Z_{||}}{n}\right)_{tot} = 28\ [m\Omega]$ *is bigger than* $Im\left(\frac{Z_{||}}{n}\right)_{LHC}$
- *The transverse impedance* $Im(Z_{\perp y})_{tot} = 1.92\ [M\Omega/m]$ *is almost double of* $Im(Z_{\perp})_{LHC} \cdot 3.70$

Below the datasheet of the LHC used for the check:

element	Ref.	b	$\mathrm{Im}(Z/n)$	$\mathrm{Im}(Z_{\perp})$
		mm	Ω	MΩ/m
Pumping slots	[23]	18	0.017	0.5
BPM's	[24]	25	0.0021	0.3
Unshielded bellows		25	0.0046	0.06
Shielded bellows		20	0.010	0.265
Vacuum valves		40	0.005	0.035
Experimental chambers		-	0.010	-
RF Cavities (400 MHz)		150	0.010	(0.011)
RF Cavities (200 MHz)		50	0.015	(0.155)
Y-chambers (8)	[25]	-	0.001	-
BI (non-BPM instruments)		40	0.001	0.012
space charge @injection	[2]	18	-0.006	0.02
Collimators @injection optics		4.4 ÷ 8	0.0005	0.15
Collimators @squeezed optics		1.3 ÷ 3.8	0.0005	1.5
TOTAL broad-band @injection optics			0.070	1.34
TOTAL broad-band @squeezed optics			0.076	2.67

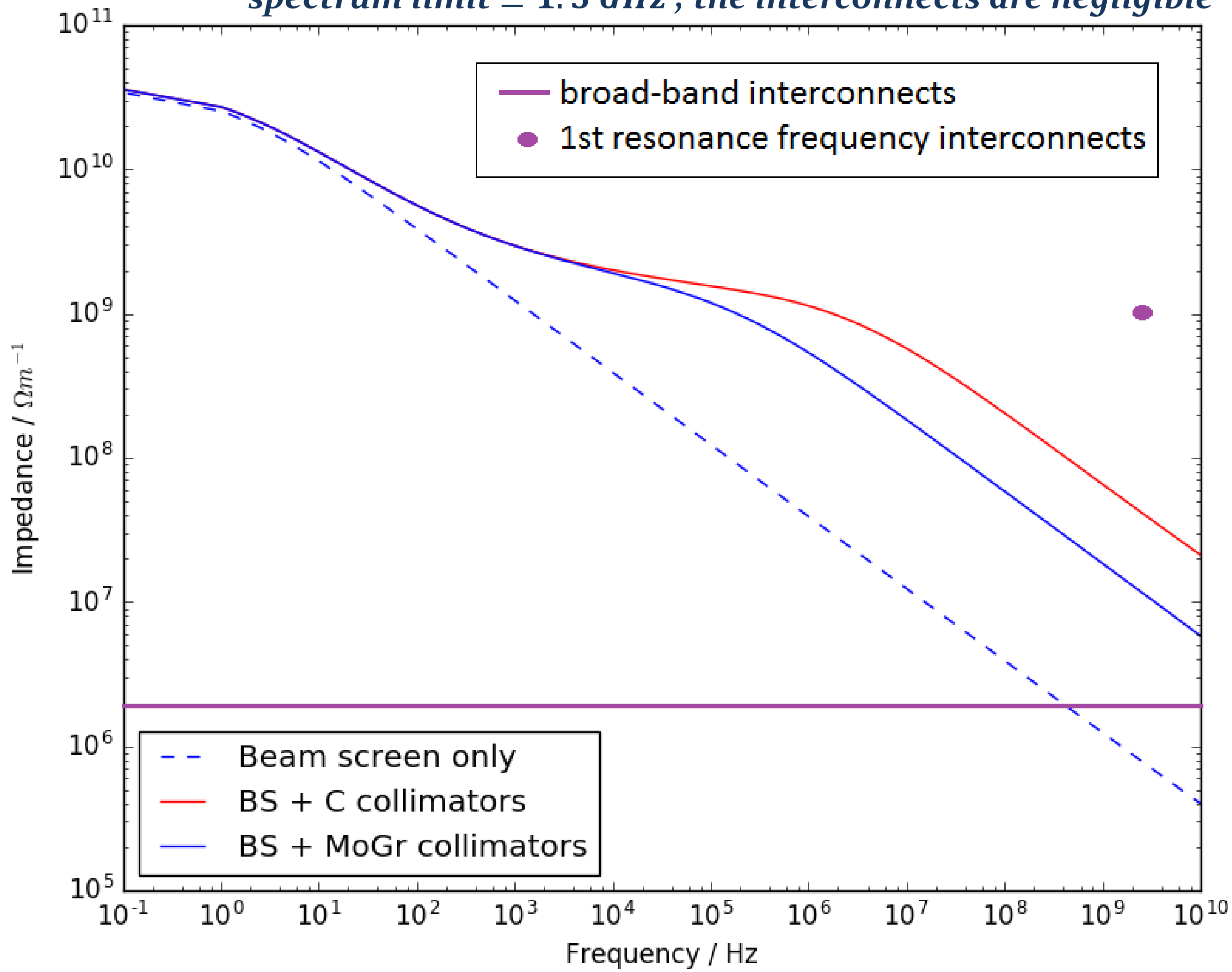
Conclusion

The com… s of same element… 3.70 times longer t…

- *The l…*
- *Inst… $_C \cdot 3.70$*

Below th…

Good news: *In the 1st and simple FCC impedance model, under the beam spectrum limit $\cong 1.5\ GHz$, the interconnects are negligible*



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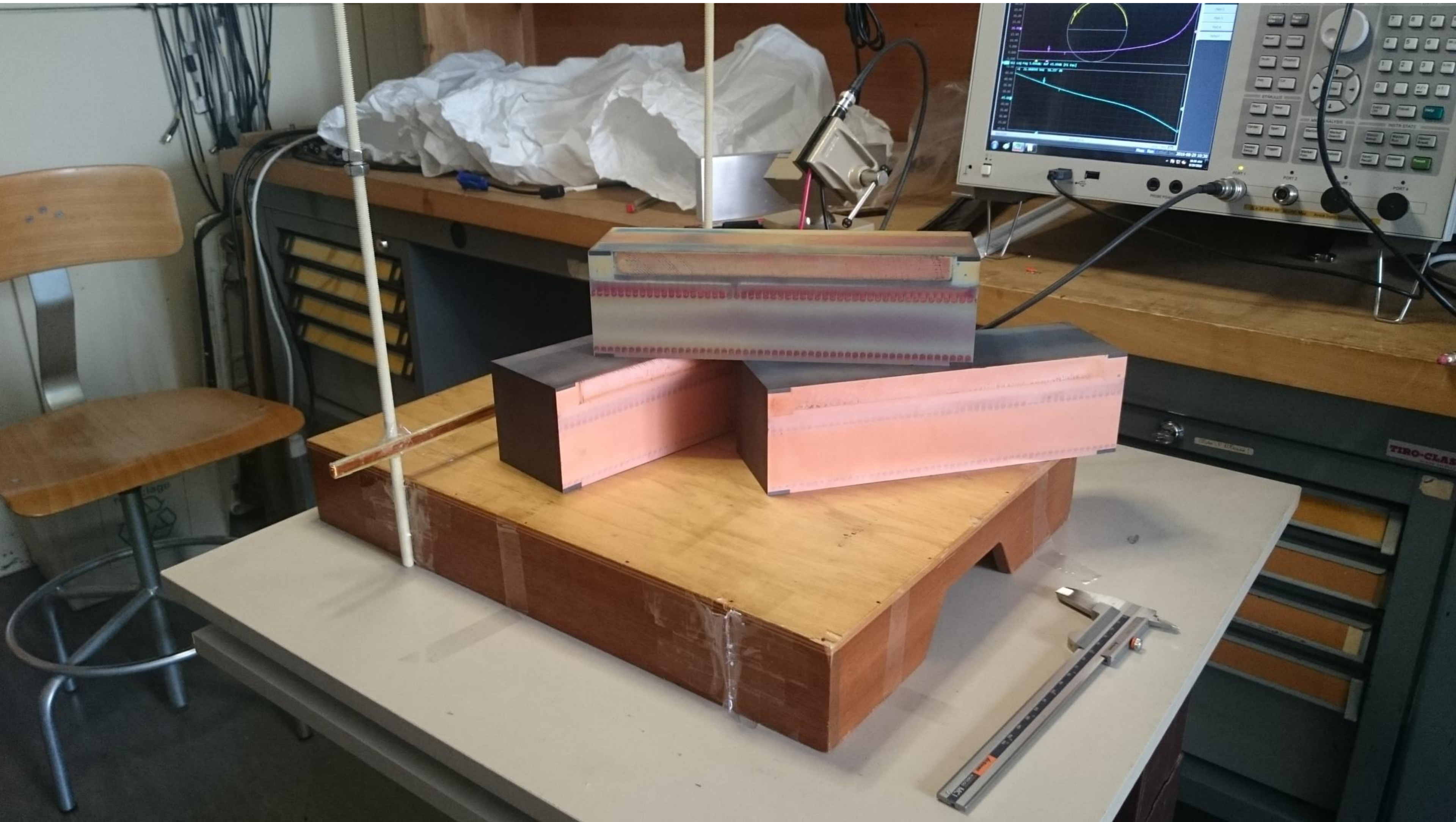
TDCQ impedance measurements



Summary of the study

- Used theoretical method
- Measurement structure and tools
- Design LHC-TCDQ
- Measurements and cross check
- Conclusions

Used theoretical method
Bench measurements of low frequency transverse impedance

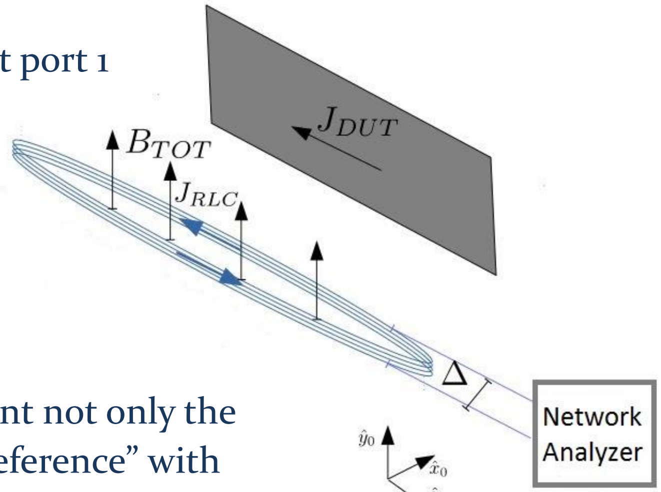
We are interested in the dipolar transverse impedance component $[Z^{dip}(\omega)]$, that can be found for low frequencies thanks to the relation with the electric impedance $[Z]$ of the device under test "DUT".

$$Z^{dip}(\omega) = \frac{c}{\omega}\frac{Z}{N^2\Delta^2}$$

Nassibian-Sacherer : Methods for measuring transverse coupling impedances in circular accelerators

- In lab it was possible to measure the electric impedance of the DUT by using only one S-Parameters of the Network analyzer.

$$Z = Z_o\frac{1+s_{11}}{1-s_{11}}$$ Where $$Z = \frac{V_1}{I_1}$$ Is the input impedance at port 1

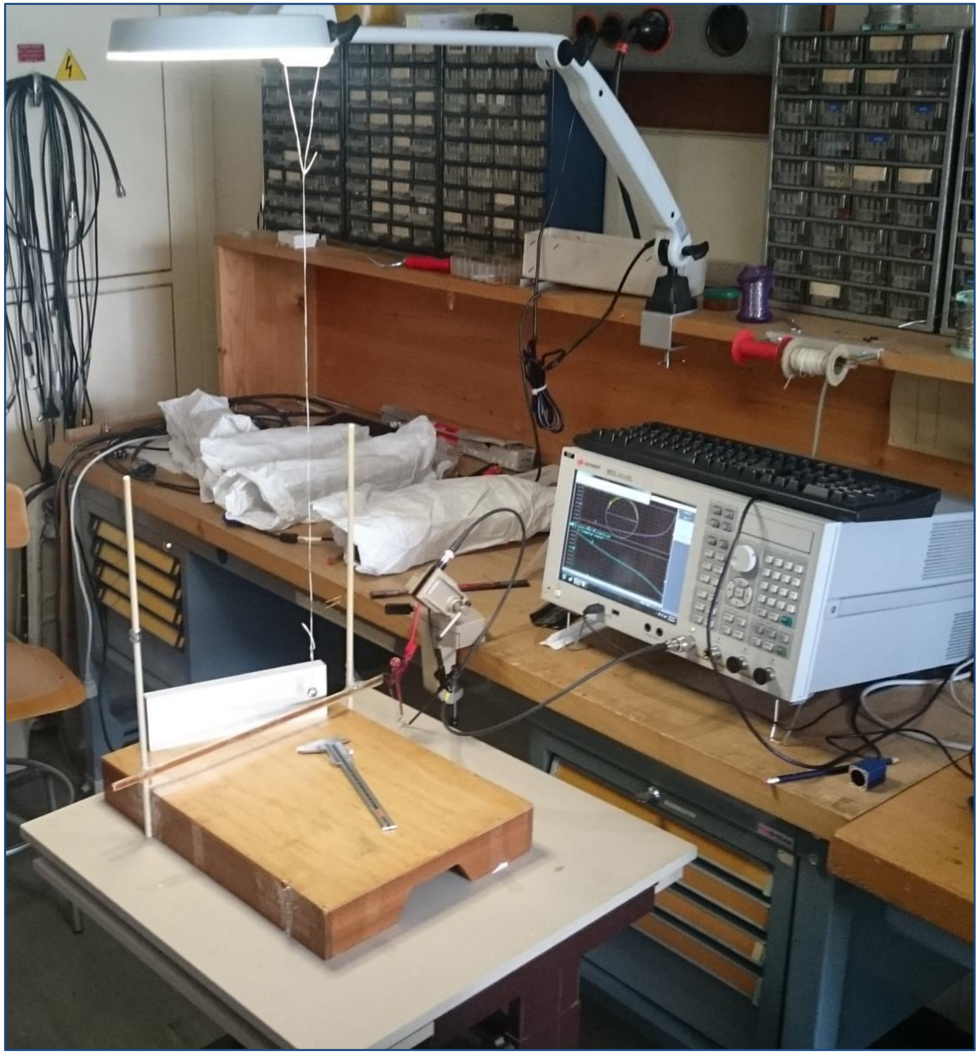


- where N and Δ shown in the figure are respectively the number of the turns and the width of the antenna which represents the beam.

- During the measurements the S-Parameters has taken in account not only the DUT but also the environment. Thus by using a known "DUT reference" with the same dimensions of our DUT, it is possible to do a differential measure that will delete the environment contribution:

$$Z^{dip}(\omega) = \frac{c}{\omega}\frac{Z^{DUT} - Z^{ref(DUT)}.}{N^2\Delta^2}$$

Measurement structure and tools



The measurements have been done with different blocks in different displacements. The chosen reference for them was the loop centre. It was mandatory to bear in mind that it was almost impossible to determine the loop centre without touching the loop itself.

The problem has been solved by using the shadow to determine the loop centre without affecting the results.

The work is in progress for a new and more efficient measurement structure (thanks to I.L.Garcia)

Loop data sheet

N	$\Delta\ [m]$
20	$6{,}25 \cdot 10^{-3}$

Data measures

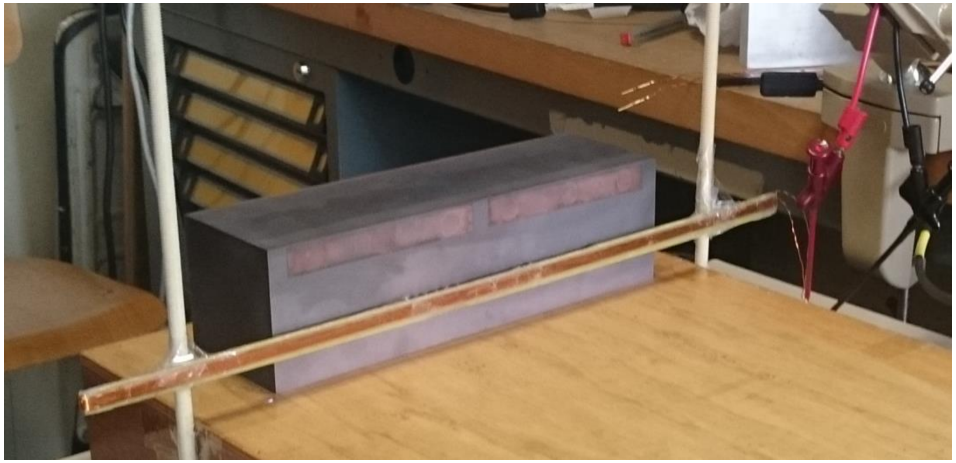
$f.band\ [MHz]$	$disp.\ [mm]$
$from\ 0\ to\ 1$	$6 - 8 - 10$

Design LHC TCDQU and aluminium reference

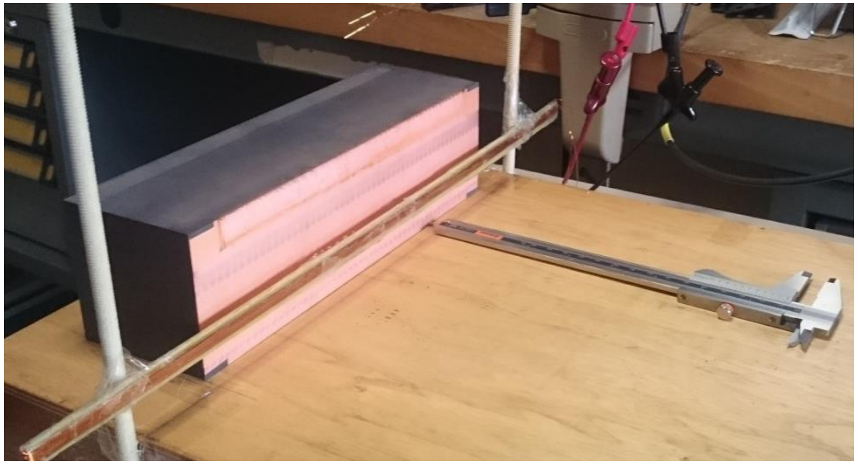
Reference design:

- The reference was made of aluminium
- The TCDQU back side was all graphite
- The TCDQU front side is formed by a little copper thickness and by a graphite layer

Spare TCDQ back:

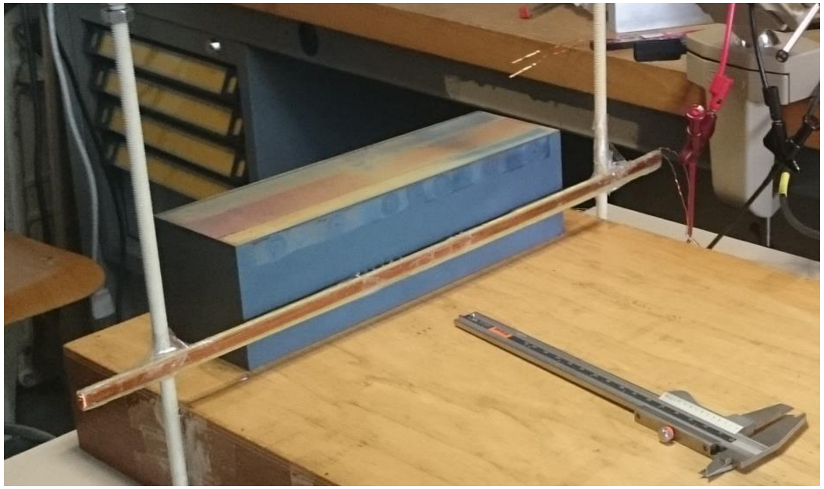


Spare TCDQ front:

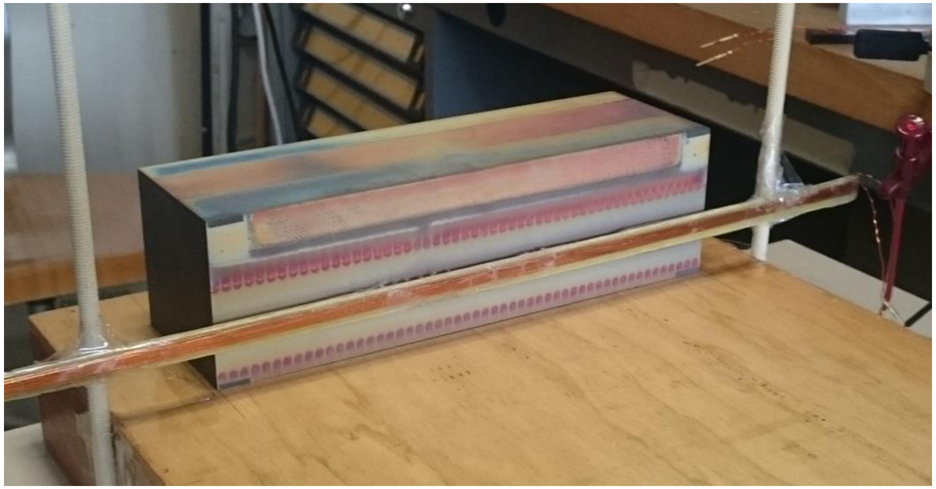


Design LHC TCDQ and aluminium reference

Used TCDQ back:



Used TCDQ front:



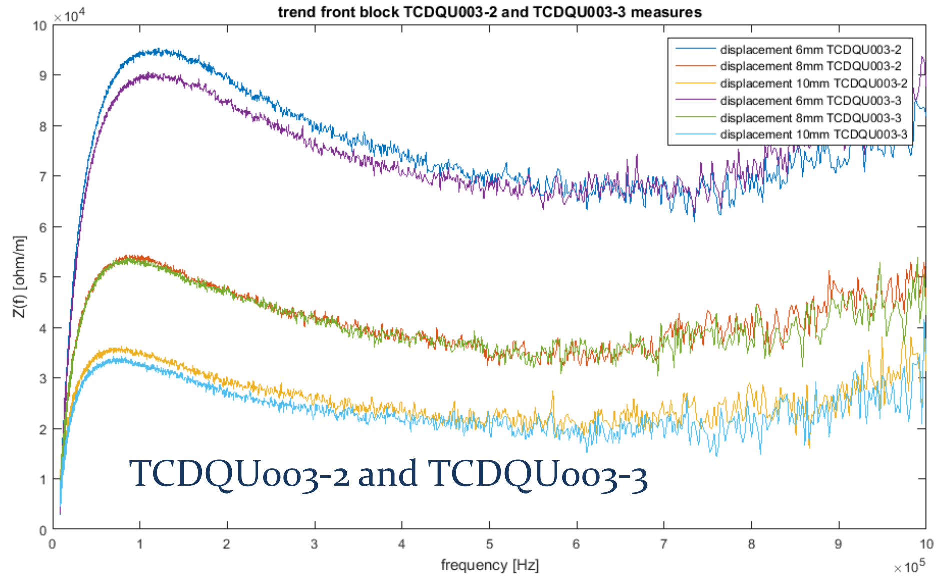
We used two references TCDQ and the TCDQ from the LHC for the measurements:

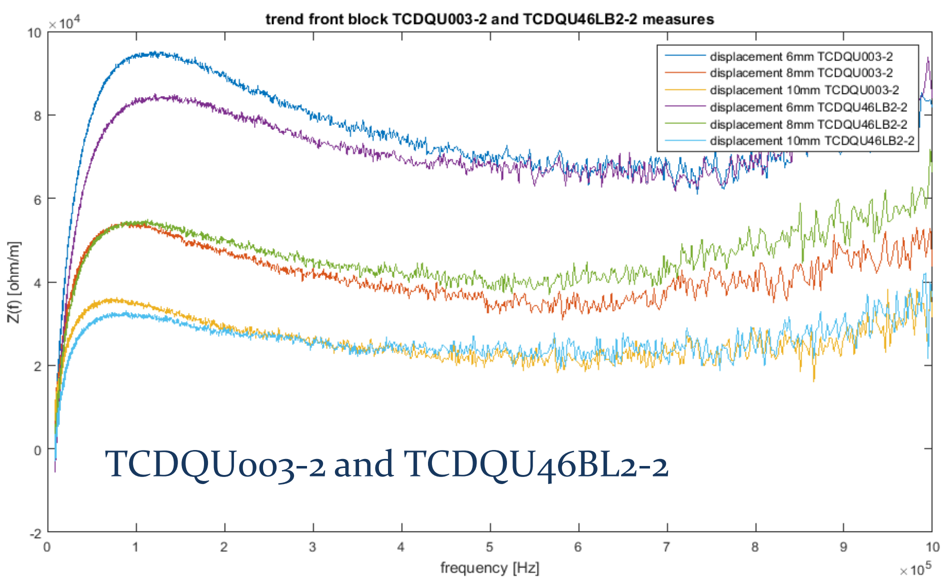
- 1st Reference TCDQU003-2
- 2nd Reference TCDQU003-3
- 1st Used TCDQU46LB2-2

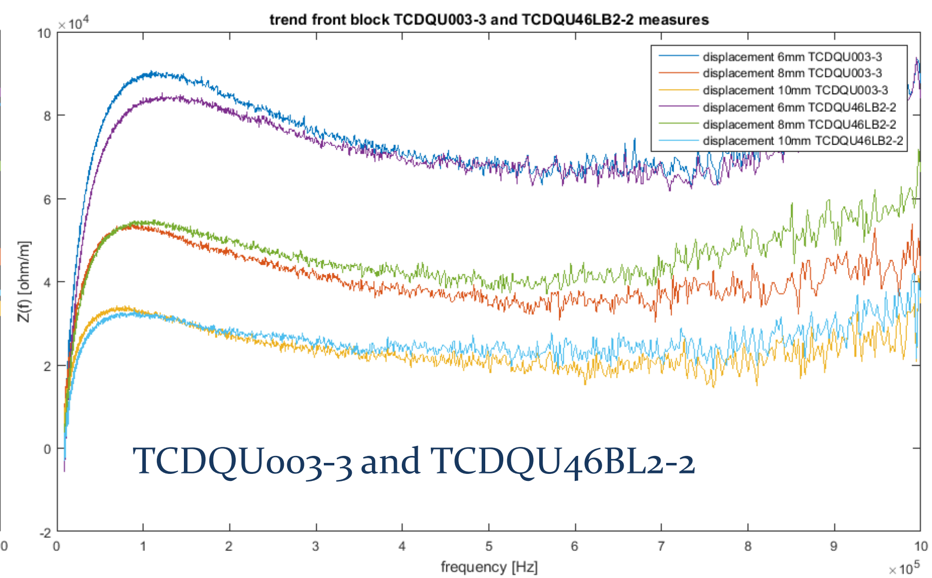
Front measurements and cross checks: charts

Starting from the figure on the right side:

- TCDQU003-2 and TCDQU003-3 check
- TCDQU003-2 and TCDQU46BL2-2 check
- TCDQU003-3 and TCDQU46BL2-2 check



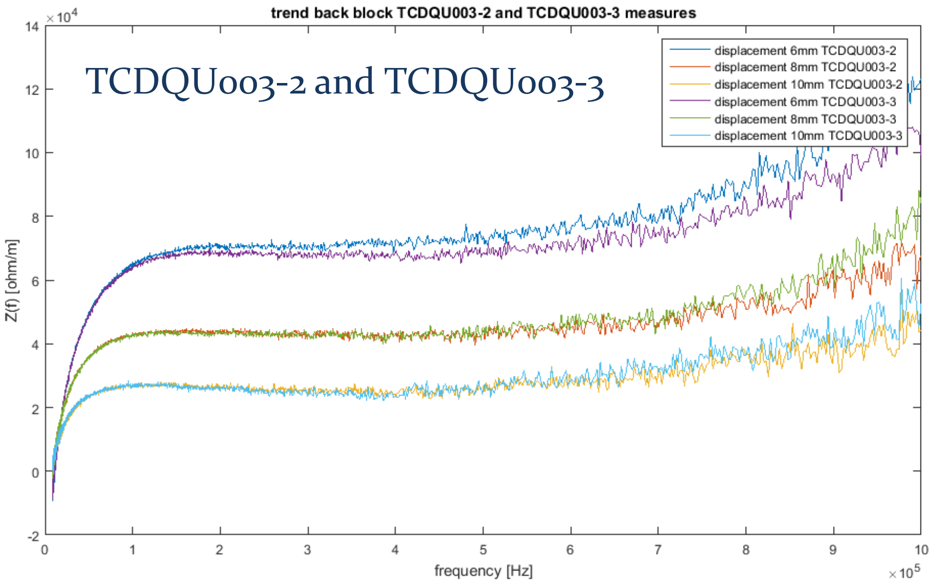


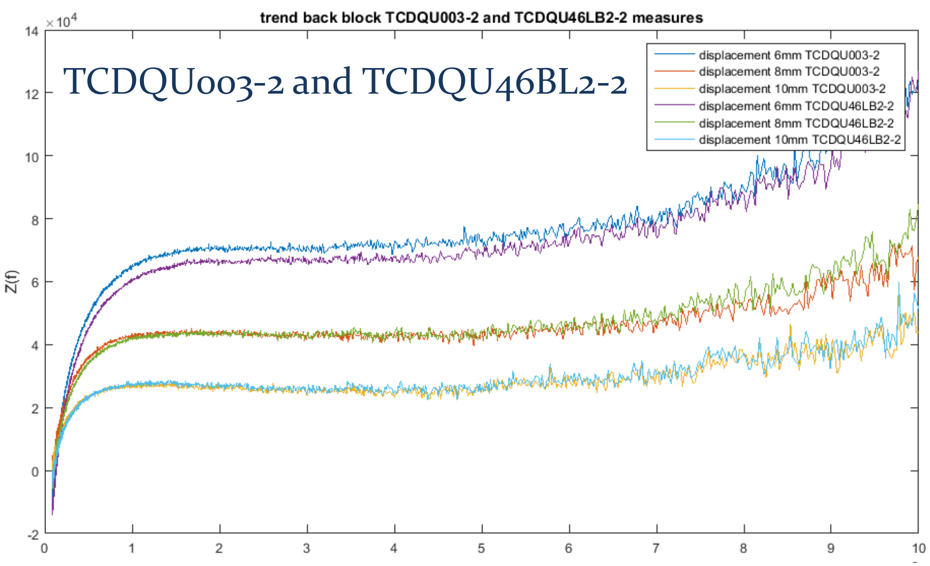


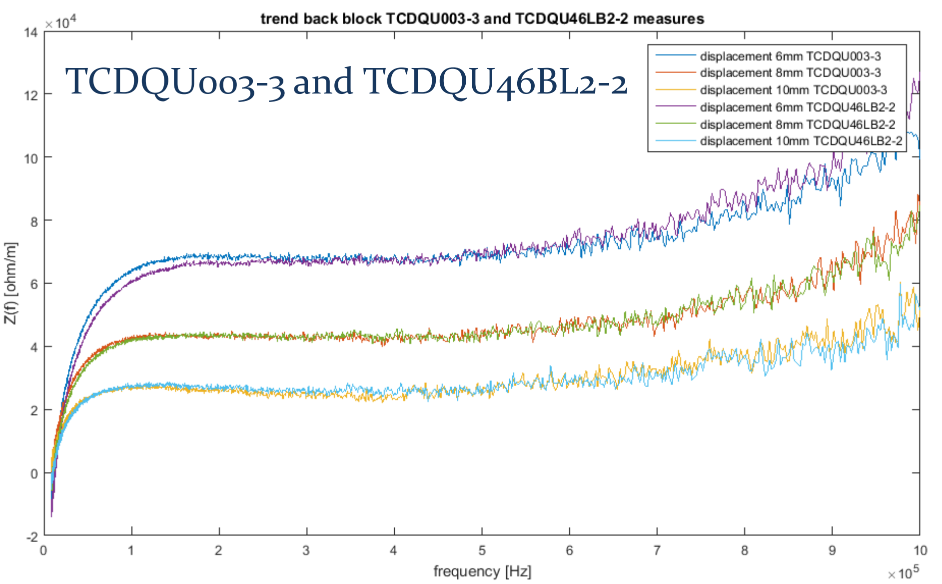
Back measurements and cross checks: charts

Starting from the figure on the right side:

- TCDQU003-2 and TCDQU003-3 check
- TCDQU003-2 and TCDQU46BL2-2 check
- TCDQU003-3 and TCDQU46BL2-2 check







Conclusions

As we can denote from the previous graphs the only difference between spare TCDQ and used TCDQ is the colour.

The impedance didn't have variation and therefore the resistivity of coating and bulk.

Ongoing work:

- Thesis writing….
- Inferring resistivity value comparing measurements with ImpWake2D simulations

THANK YOU ALL