Update on the HL-LHC impedance budget

N. Biancacci

CERN, 19-11-2014

HL-LHC WP 2 Task 2.4

Acknowledgements:
A.Grudiev, R. Bruce, R. Calaga, F. Caspers, O. Frasciello, J. Kuczerowski, A. Lechner, A. Marcone, E.Métral, A.Mostacci, N. Mounet, A. Passarelli, B.Salvant, J. Uythoven, C. Vollinger, M. Zobov and all the equipments groups.

Outline

- **Review of LHC impedance model Vs measurements**
  - HEADTAIL vs DELPHI computations,
  - Effect of finite length on LHC collimators,
  - Effect of geometrical impedance of collimators,
  - Effect of increase of resistivity in collimator jaws,

- **HL-LHC impedance reduction strategy**
  - Update of the collimators database,
  - Mo/MoC scenarios vs CFC and coatings.

- **HLLHC impedance model**
  - Longitudinal impedance
  - Vertical/Horizontal dipolar impedance

- **HLLHC vs LHC impedance model**

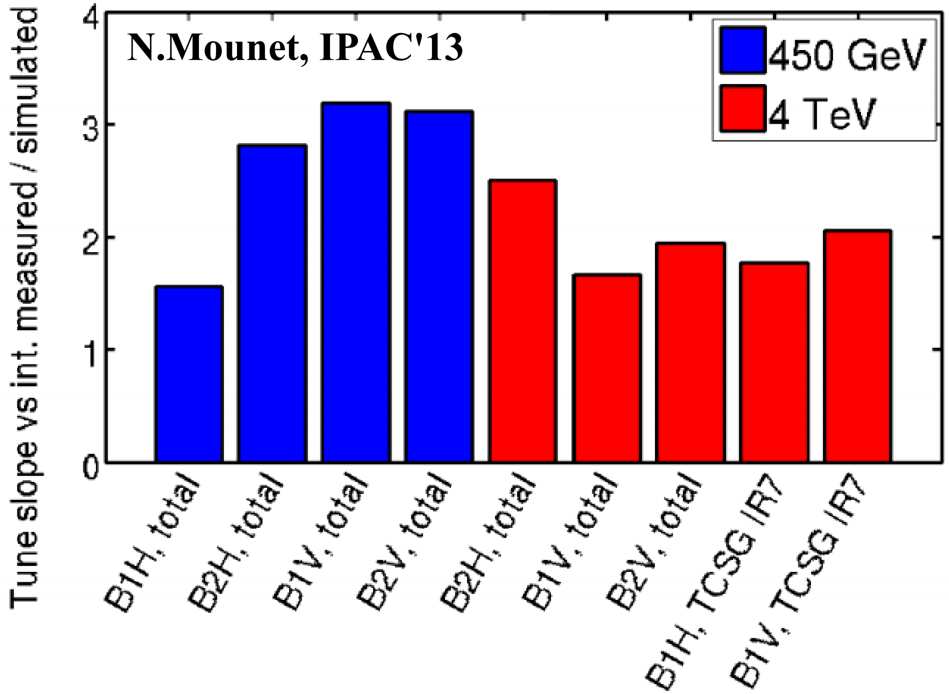
- **Challenging devices:**
  - TDI,
  - TCTP,
  - Crab Cavities.

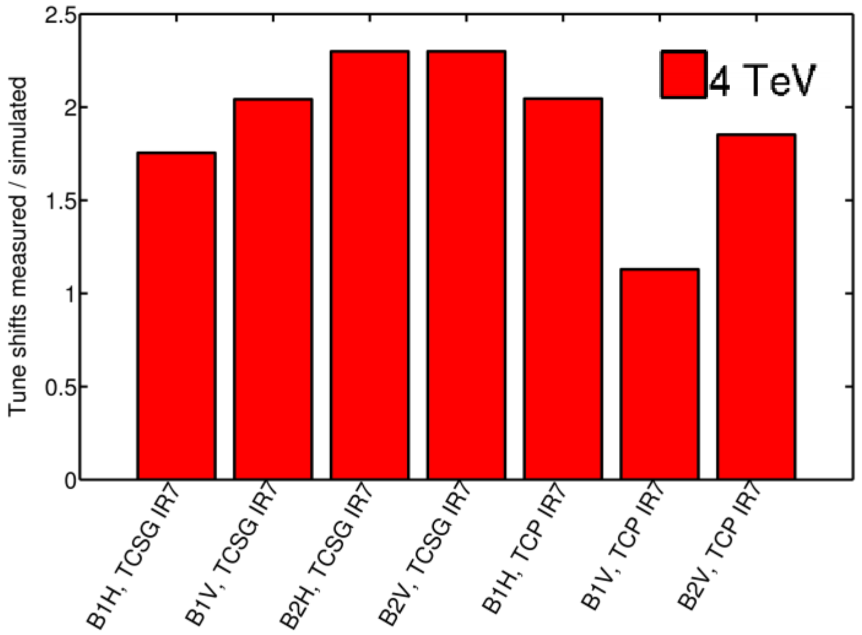
- **Impedance induced heating overview.**

- **Conclusions and outlook**

Measurements Vs Model

Observations in 2013:





- **450 GeV** → Factor ~**3** Measurement Vs HEADTAIL simulations.
- **4 TeV** → Factor ~**2** Measurement Vs HEADTAIL simulations.

Measurements Vs Model

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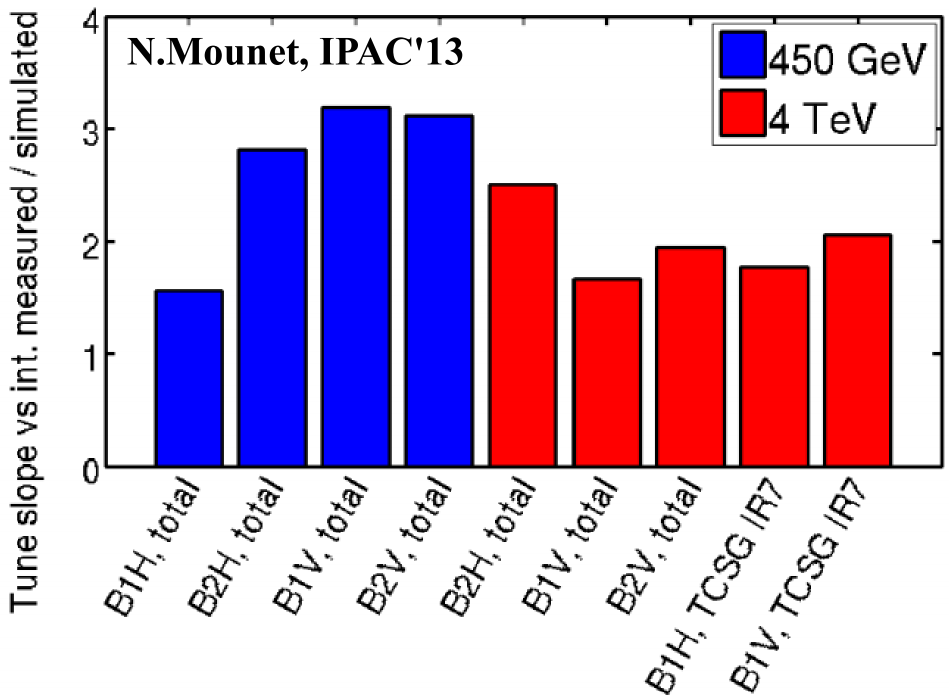

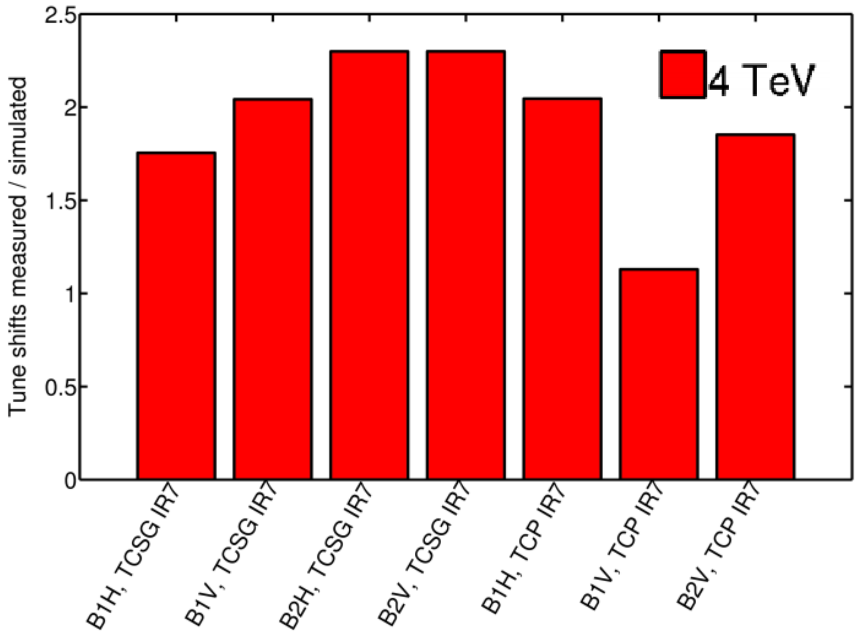

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Possible explanations:

1. Collimators: finite jaws length effect.
2. Collimators: geometrical impedance.
3. HEADTAIL/DELPHI: model convergence.
4. Collimators: Effect of radiation on jaws conductivity during the years.
5. Collimators: Graphite anisotropy.
6. Theory: Non linear terms in the impedance.

HEADTAIL: macroparticle tracking simulations
DELPHI: analytical Vlasov solver for headtail modes.

Measurements Vs Model

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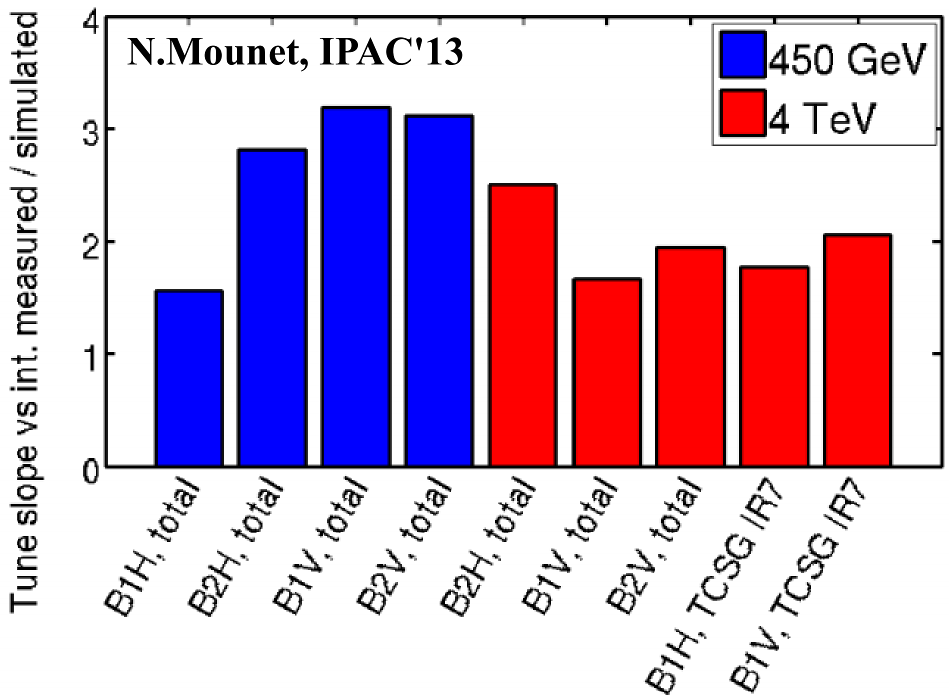

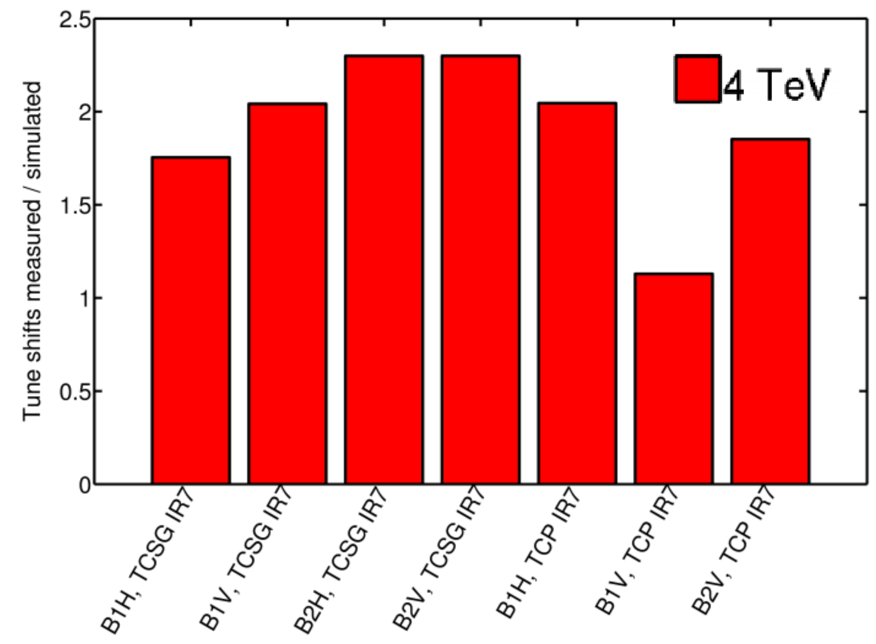

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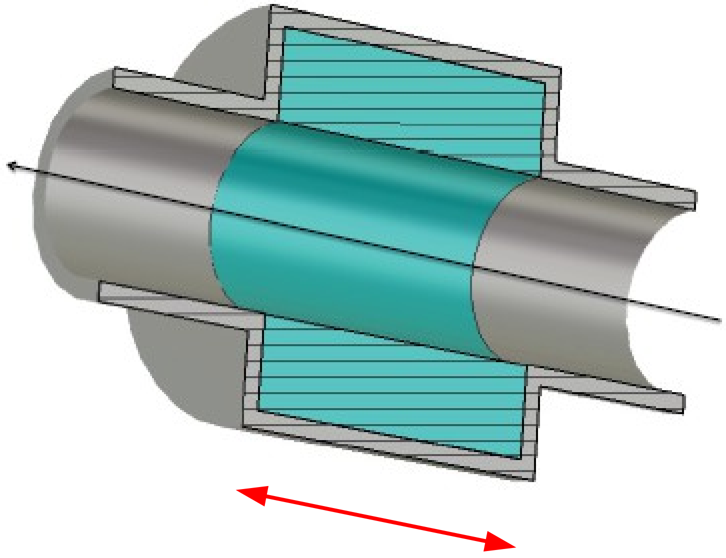
Not treated here...

Measurements Vs Model

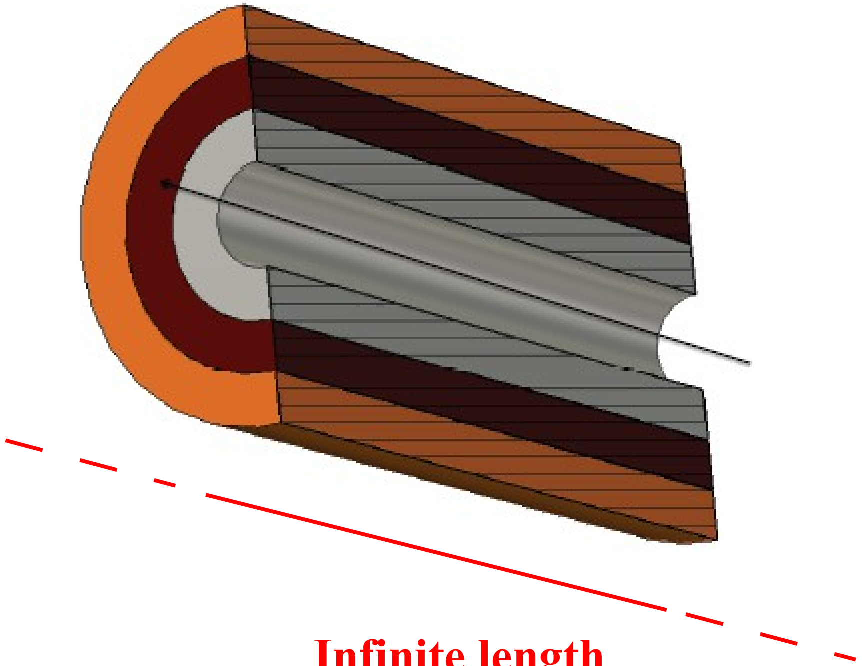
1. Collimators: finite jaws length effect.

- Collimators are modeled as infinite long flat multi-layer planes. → Is this a good approximation?

In other words:
"What is the effect of **finite length** on impedance Vs the 2D **infinite length** approximation?"



Finite length

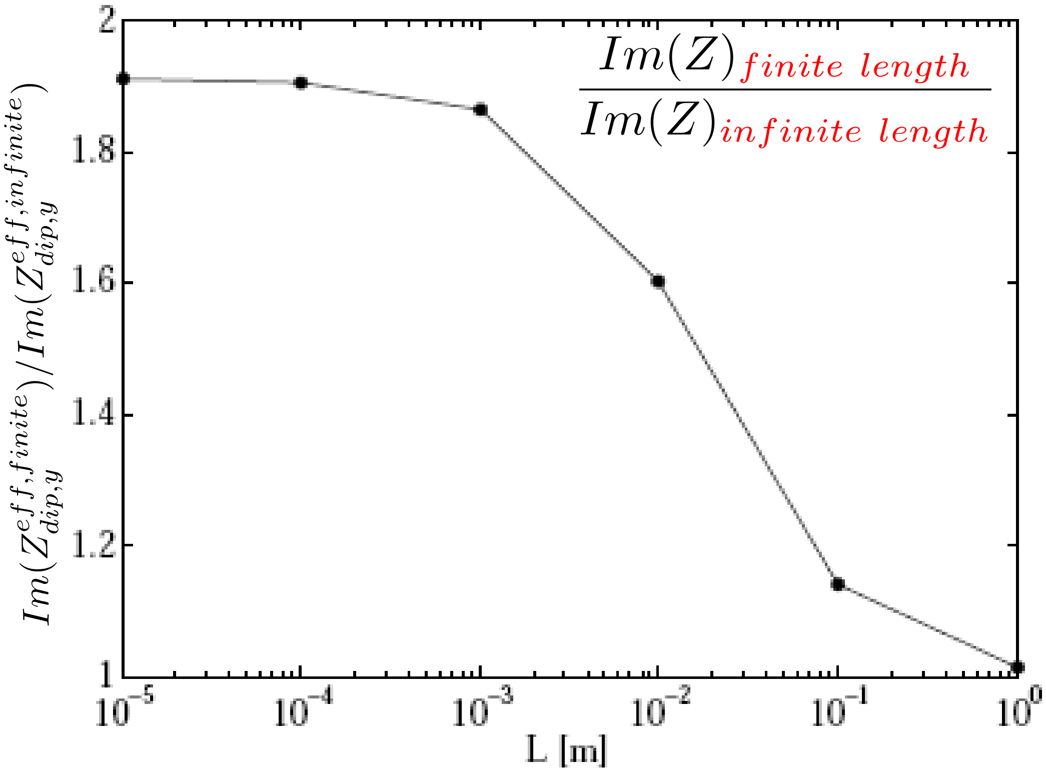


Infinite length

Measurements Vs Model

1. Collimators: finite jaws length effect.

- EM problem solved applying the Mode Matching technique [1].
- Calculated the **effective** impedance for different lengths.
- Calculated ratio with infinite length.



Example of dipolar impedance of a carbon collimator (resistivity=1e-6, gap=50mm)

[1] N.Biancacci, PhD thesis

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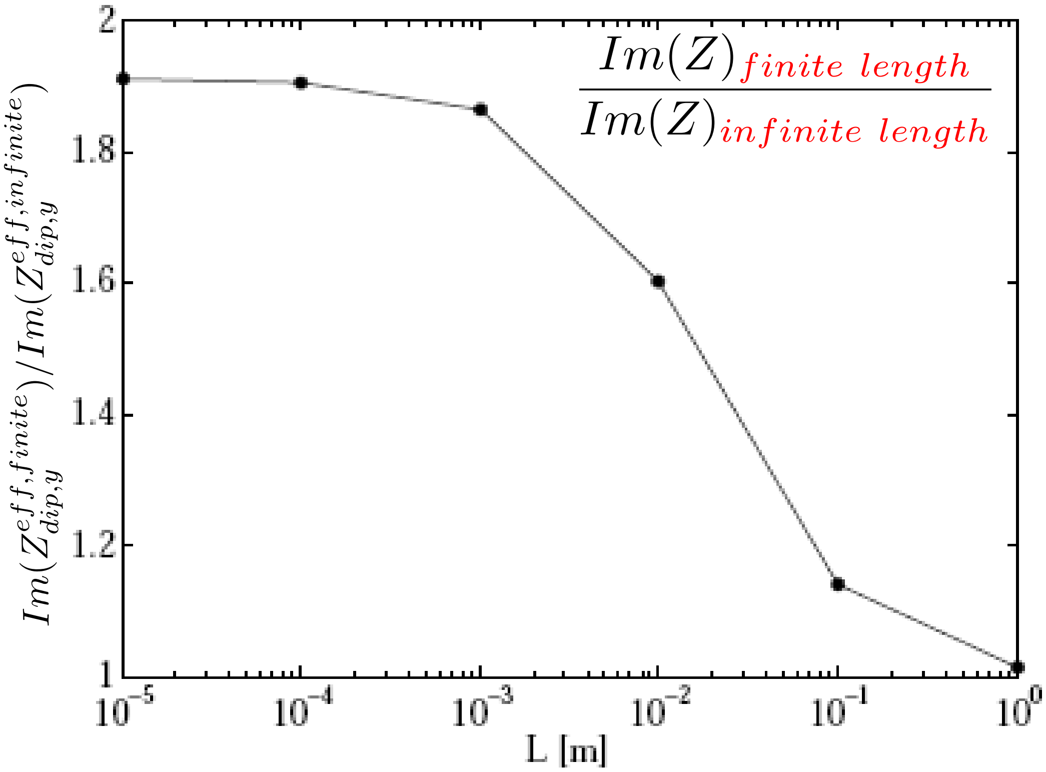

Example of dipolar impedance of a carbon collimator (resistivity=1e-6, gap=50mm):

- Relative increase of the low frequency reactive impedance only for very narrow lengths.
- Negligible effect for long devices (meters).

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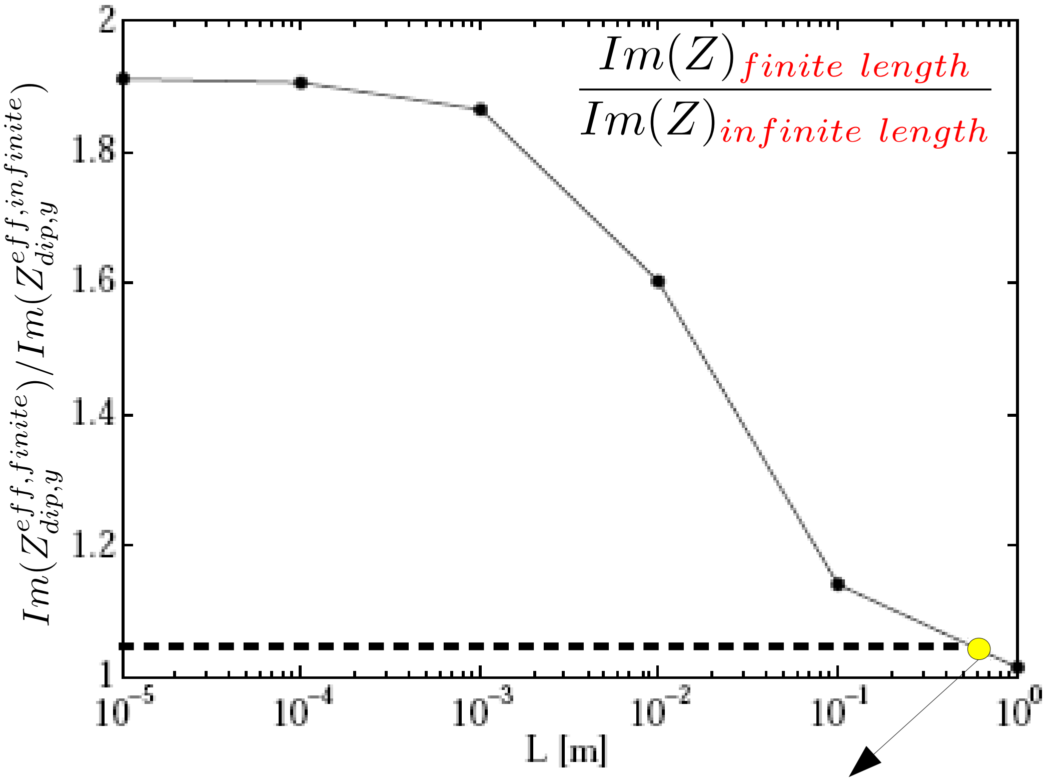

Collimator length >= 60cm

Example of dipolar impedance of a carbon collimator (resistivity=1e-6, gap=50mm):

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- Negligible effect for long devices (meters).

Few % increase in **tune shift** for the LHC collimators

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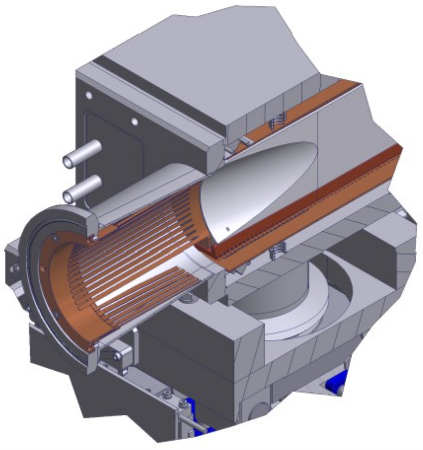
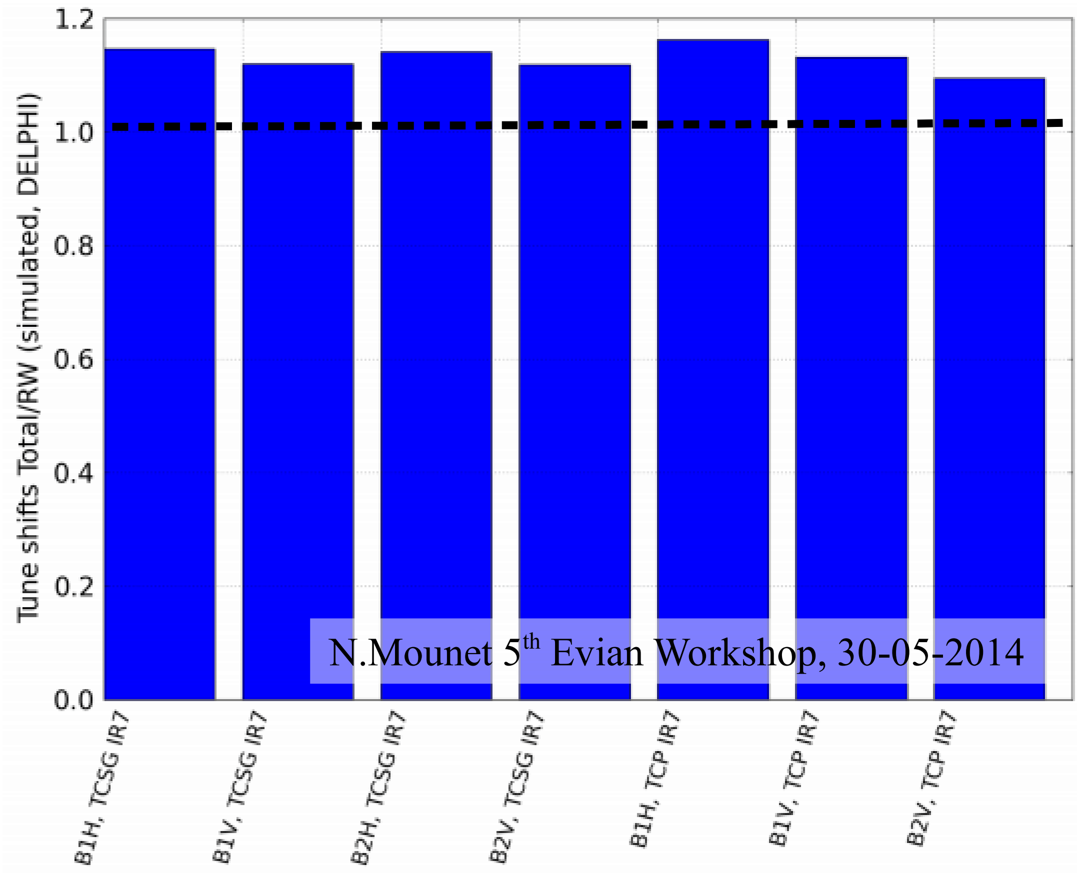
Measurements Vs Model

2. Collimators: geometrical impedance.

- Geometrical collimator impedance from 3D models
- Close collaboration with LNF-INFN





+10-15% increase in the tune shift.

Details in O.Frasciello previous talk.

Update of LHC model Vs Measurement ratio:
4 TeV → Factor ~**1.8** Measurement Vs DELPHI.

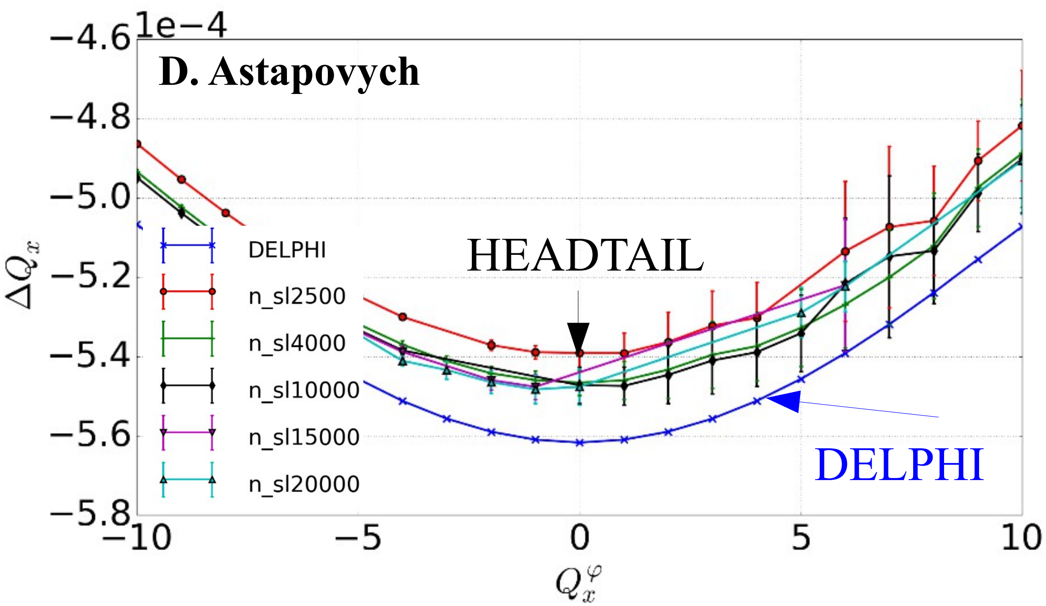
Measurements Vs Model

3. HEADTAIL/DELPHI: model convergence

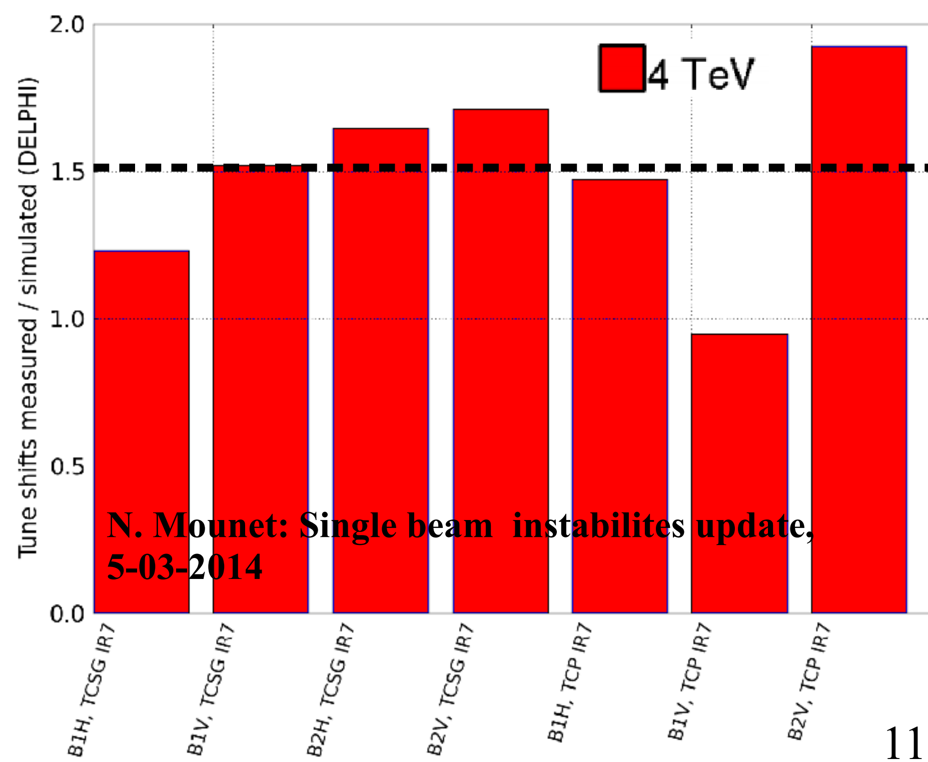
Convergence test:

- **~20%** disagreement in old Model vs Measurement tune shift ratio due to convergence issues.
- Study of HEADTAIL convergence to DELPHI → within few percents.

Update of LHC model Vs Measurement ratio:
4 TeV → Factor ~**1.5** Measurement Vs DELPHI.



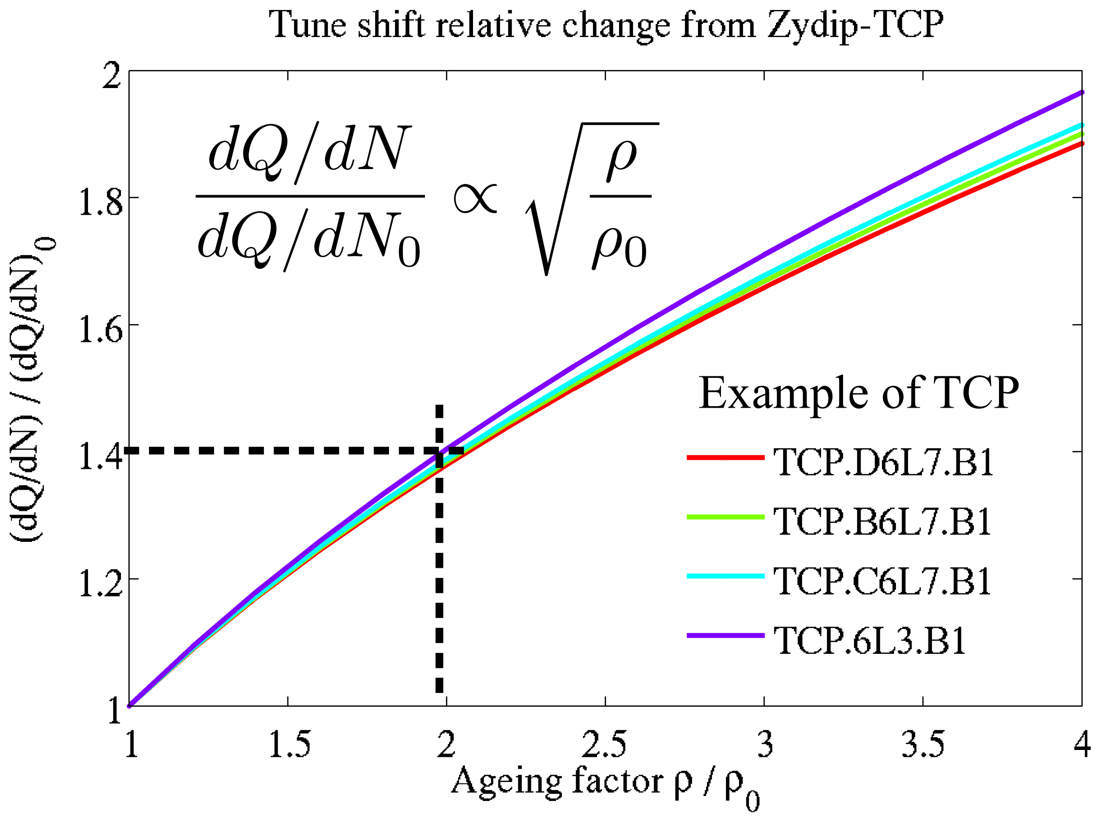
Measurement Vs DELPHI



Measurements Vs Model

4. Collimators: Effect of radiation on jaws conductivity during the years.

- The primary and secondary collimators are more exposed to radiation → resistivity growth? [1]
- "Aging" the CFC in TCP and TCSG increasing the resistivity by a factor: $\text{Aging factor} = \rho/\rho_0$



[1] A.I.Ryazanov et al. CERN-ATS-Note-2010-042 MD

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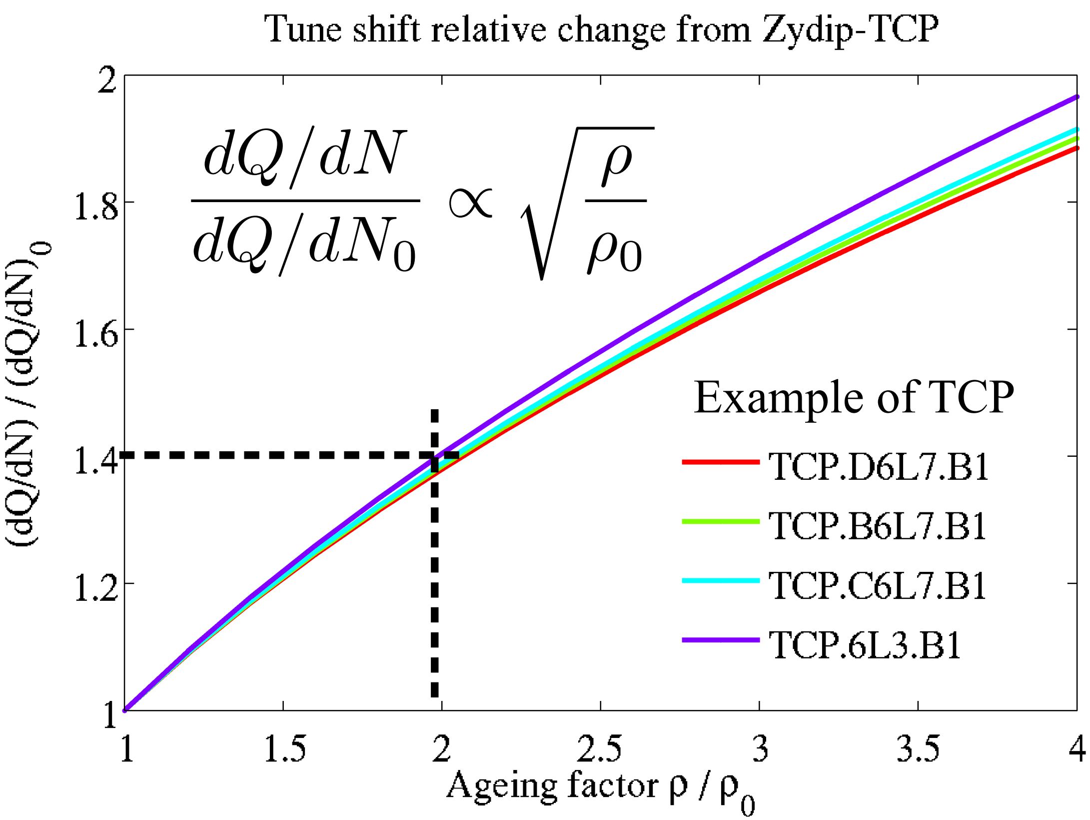


For example, a factor **2** in resistivity

↓

Factor **+1.4** in tune shift

↓

4 TeV → Factor ~**1** Measurement Vs DELPHI.

But....

Hypothesis to be checked with measurements!

[1] A.I.Ryazanov et al. CERN-ATS-Note-2010-042 MD

HL-LHC impedance

- Current LHC transverse impedance model **not compatible** with HL-LHC operational parameters in terms of beam stability. → *Details in E.Métral talk after.*
- Need of an **impedance reduction** strategy.
- Different approaches wrt impedance frequency range:
  - Low frequency (below ~ 10 MHz) → Transverse damper improvements.
  - High frequency (above ~10 MHz) → Higher conductivity materials for collimator jaws.

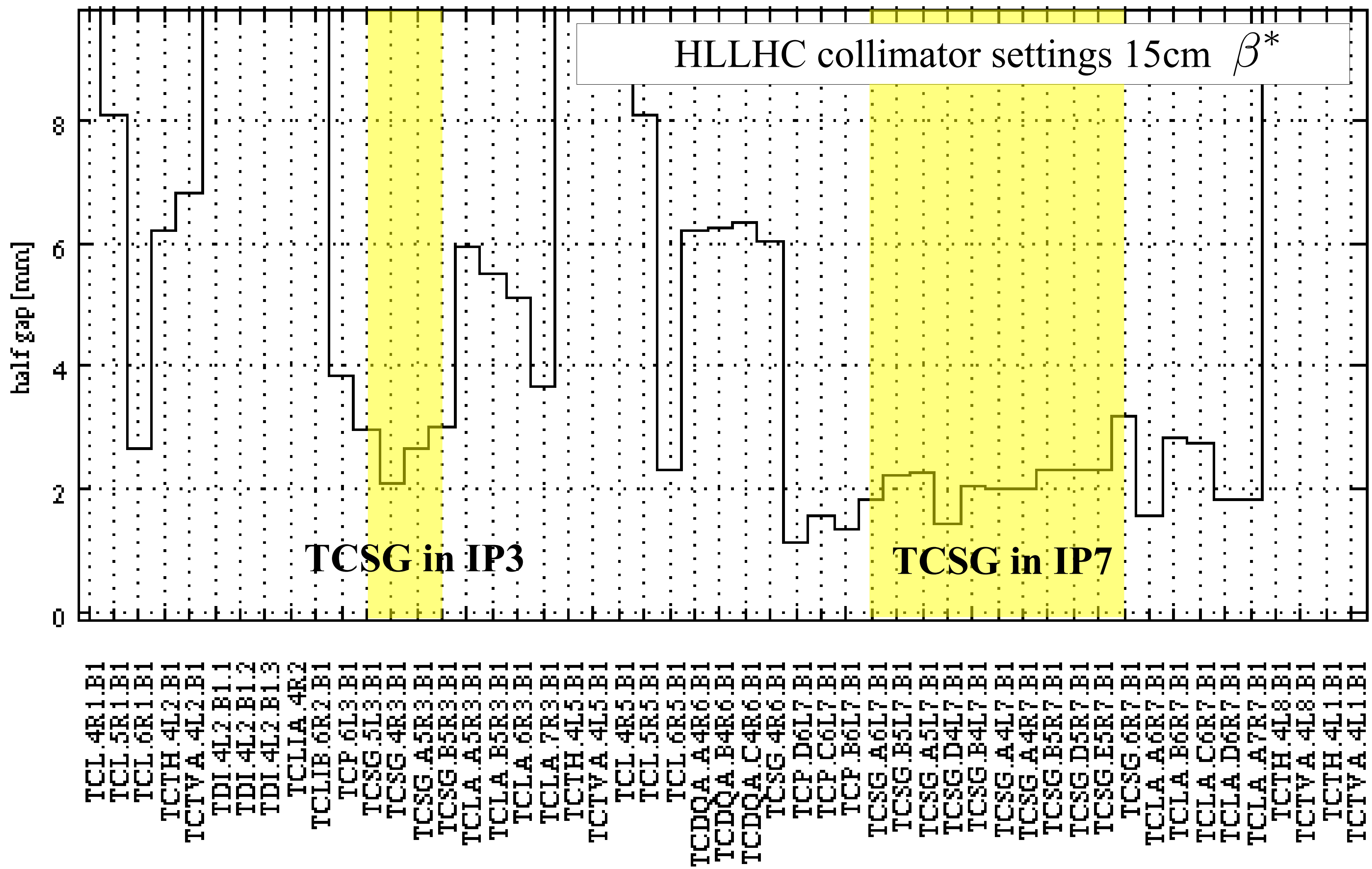
Current material in IP3 and IP7	→	CFC Tatsuno AC150 $\rho_{DC} = 5\mu\Omega \cdot m$
New proposed materials	→	Molybdenum-Carbon (MoC) $\rho_{DC} = 1\mu\Omega \cdot m$ Molybdenum (Mo) $\rho_{DC} = 53.5n\Omega \cdot m$

- Transverse impedance reduction scenarios:

MoC only	Mo only	CFC + Mo coating	MoC + Mo coating

Collimator impedance reduction

Impedance reduction scenarios applied to Secondary collimators in IP3 and IP7 → very small gap.

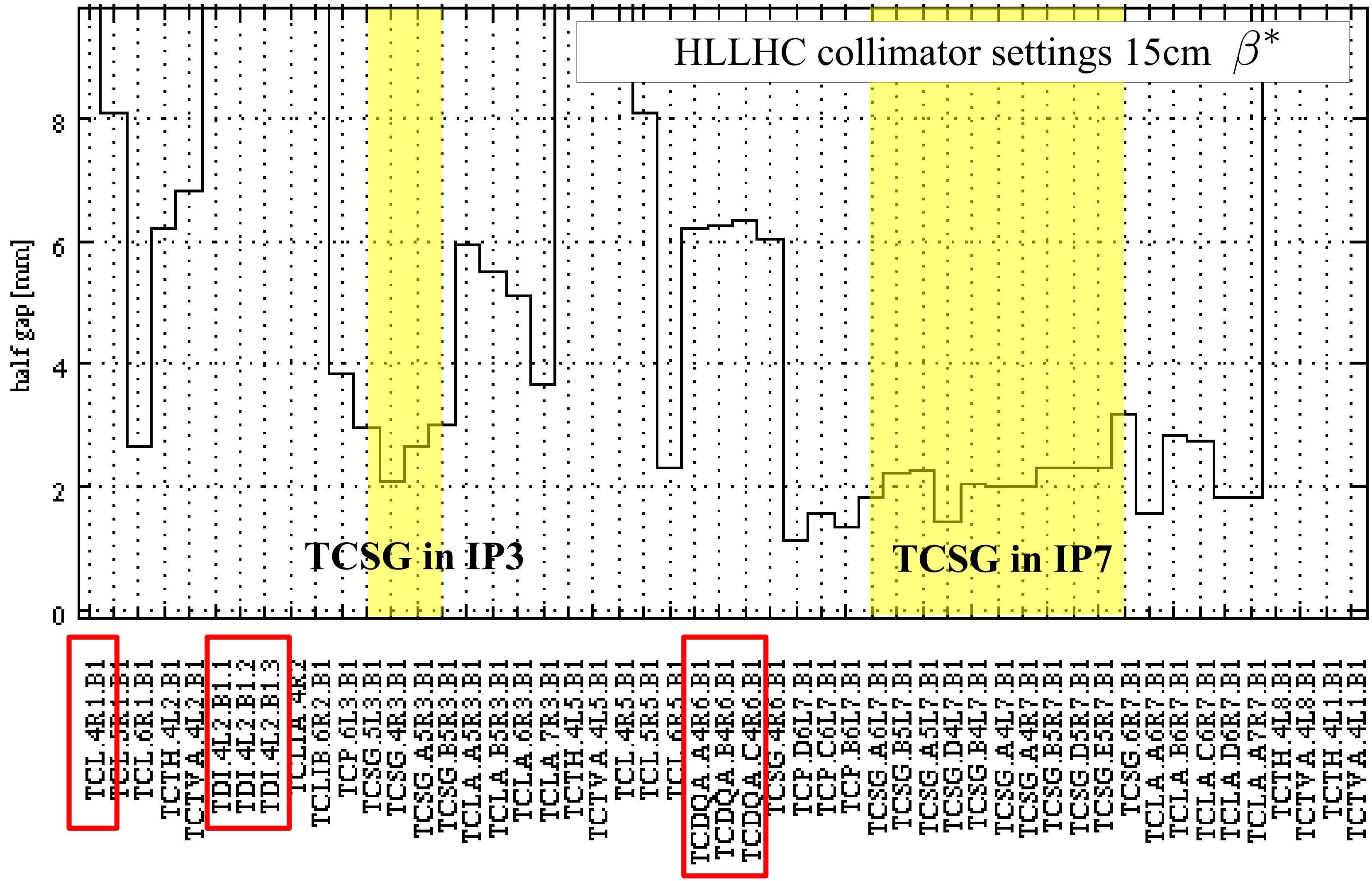


Collimator impedance reduction

Impedance reduction scenarios applied to Secondary collimators in IP3 and IP7 → very small gap.

NB: Beforehand, the collimator impedance model was **updated**.

- ✔ Added TCL4 and TCDQ coating.
- ✔ TDI split in 3 blocks.



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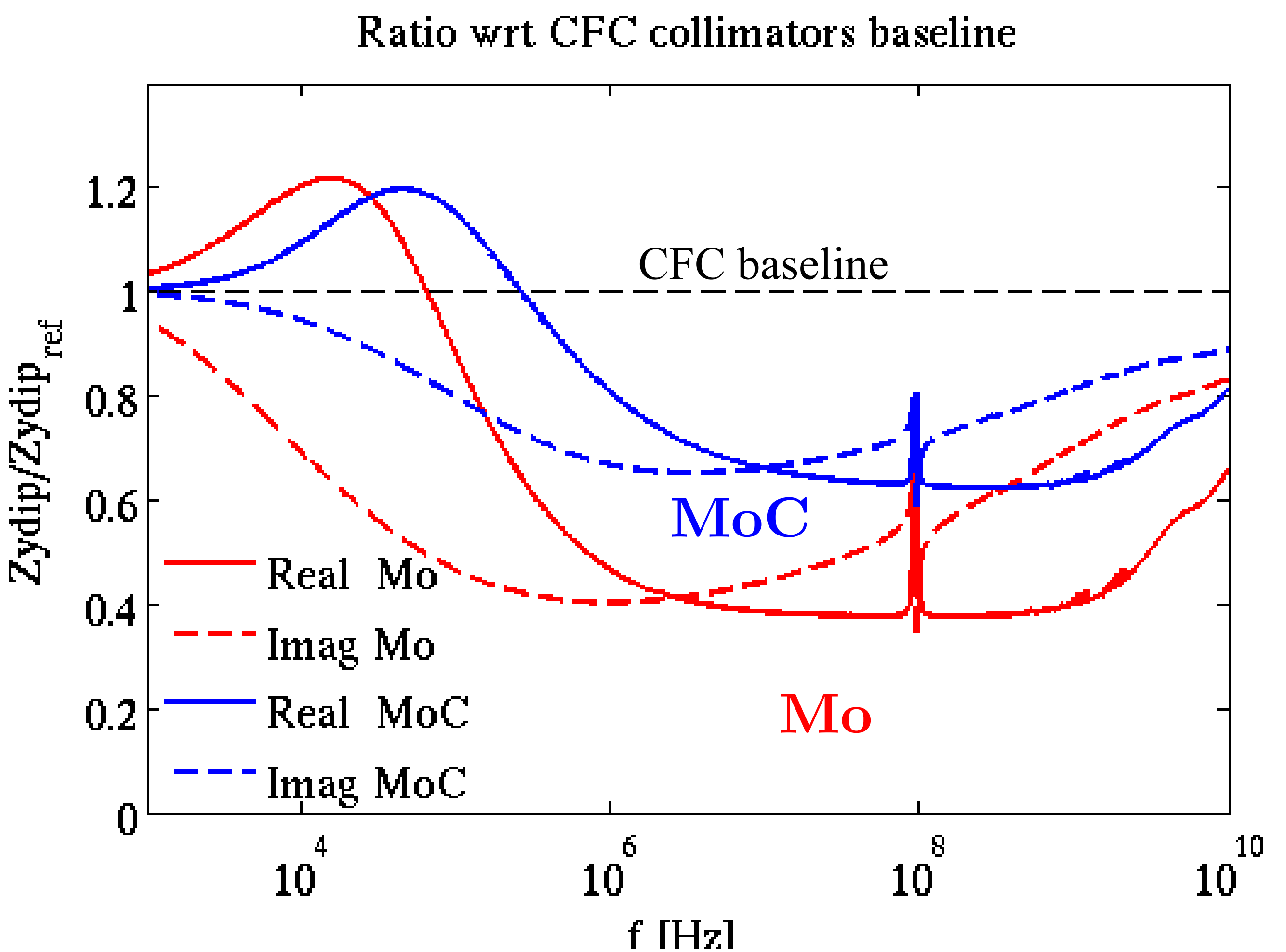

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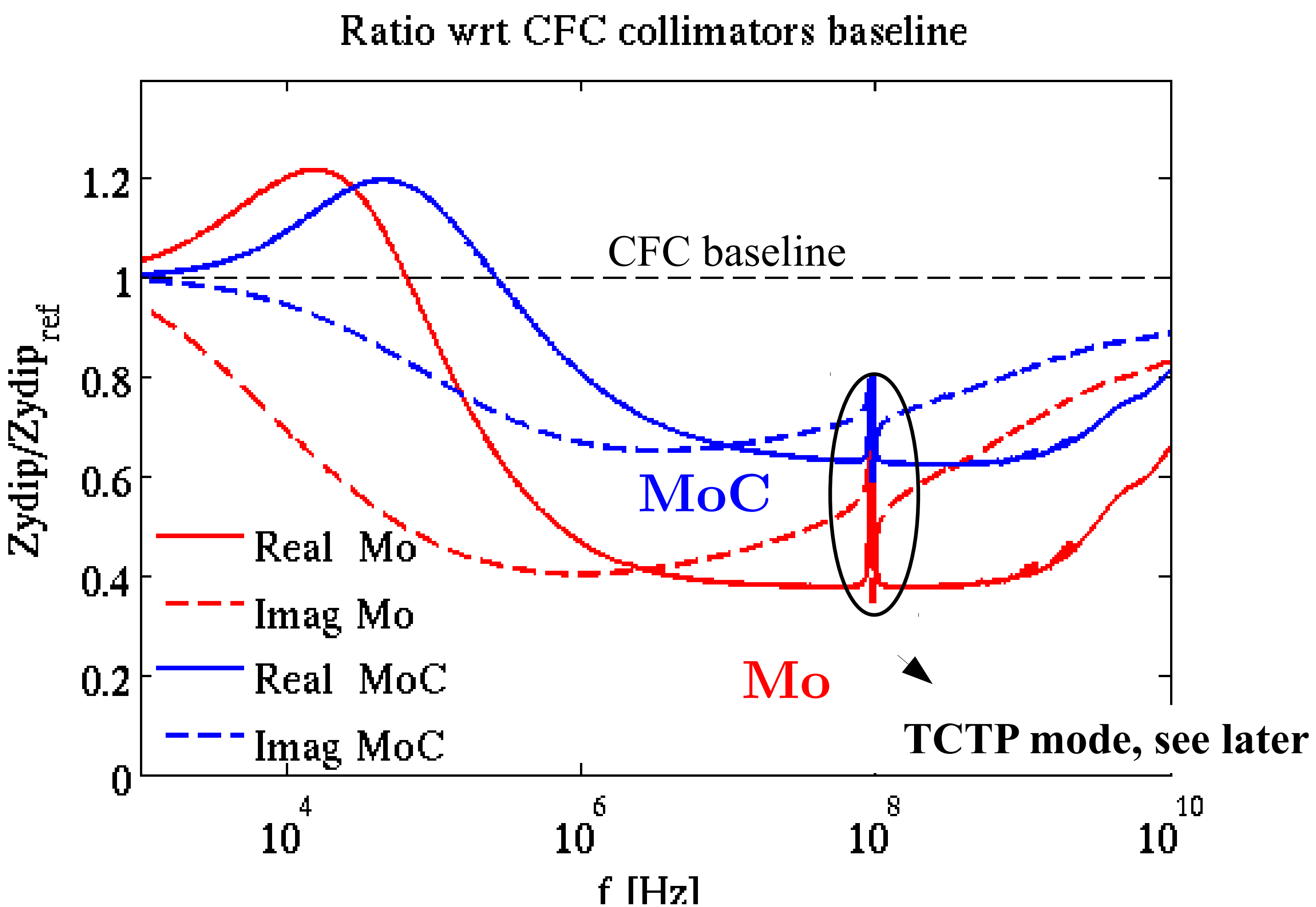

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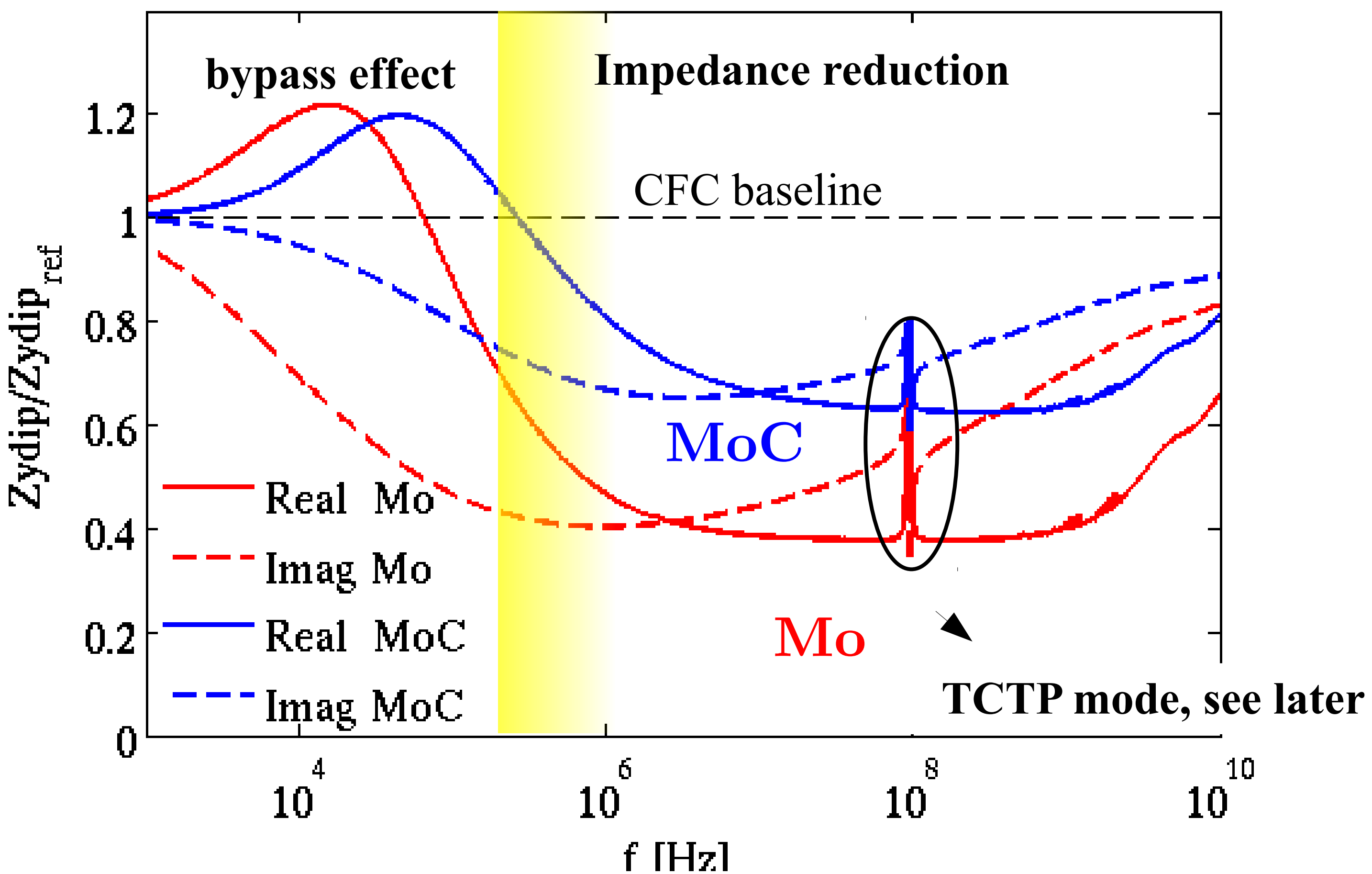
Ratio wrt CFC collimators baseline



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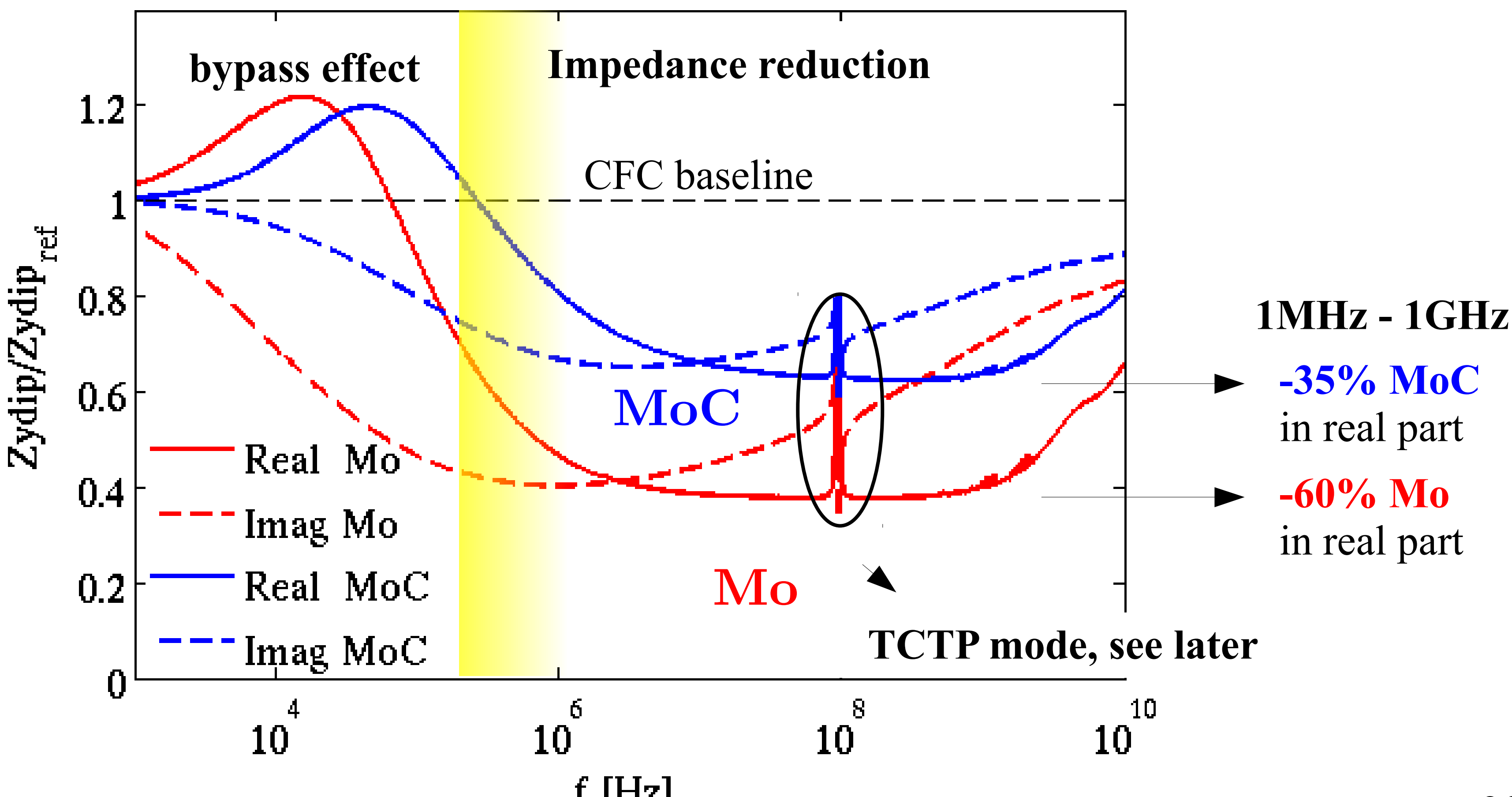

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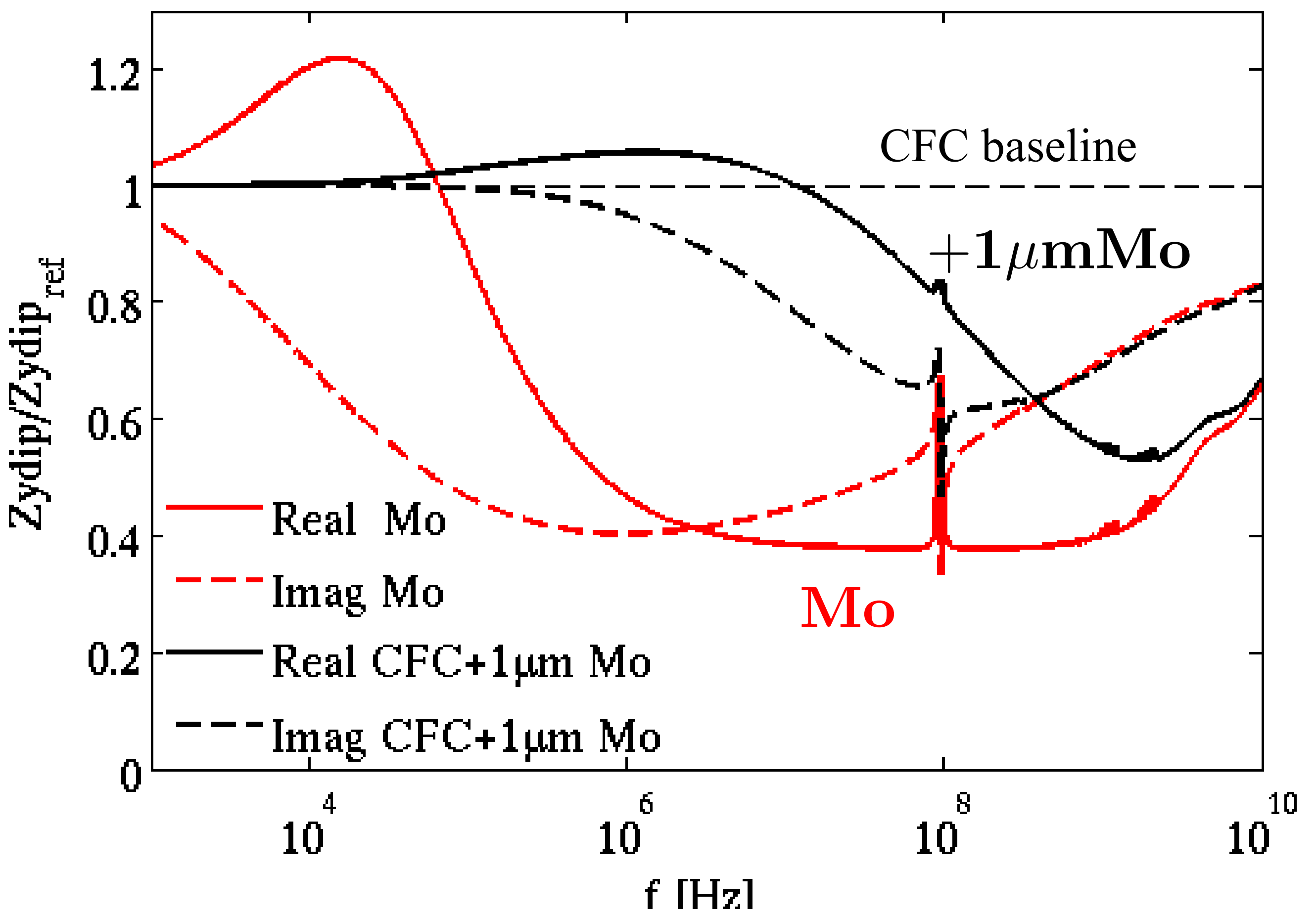

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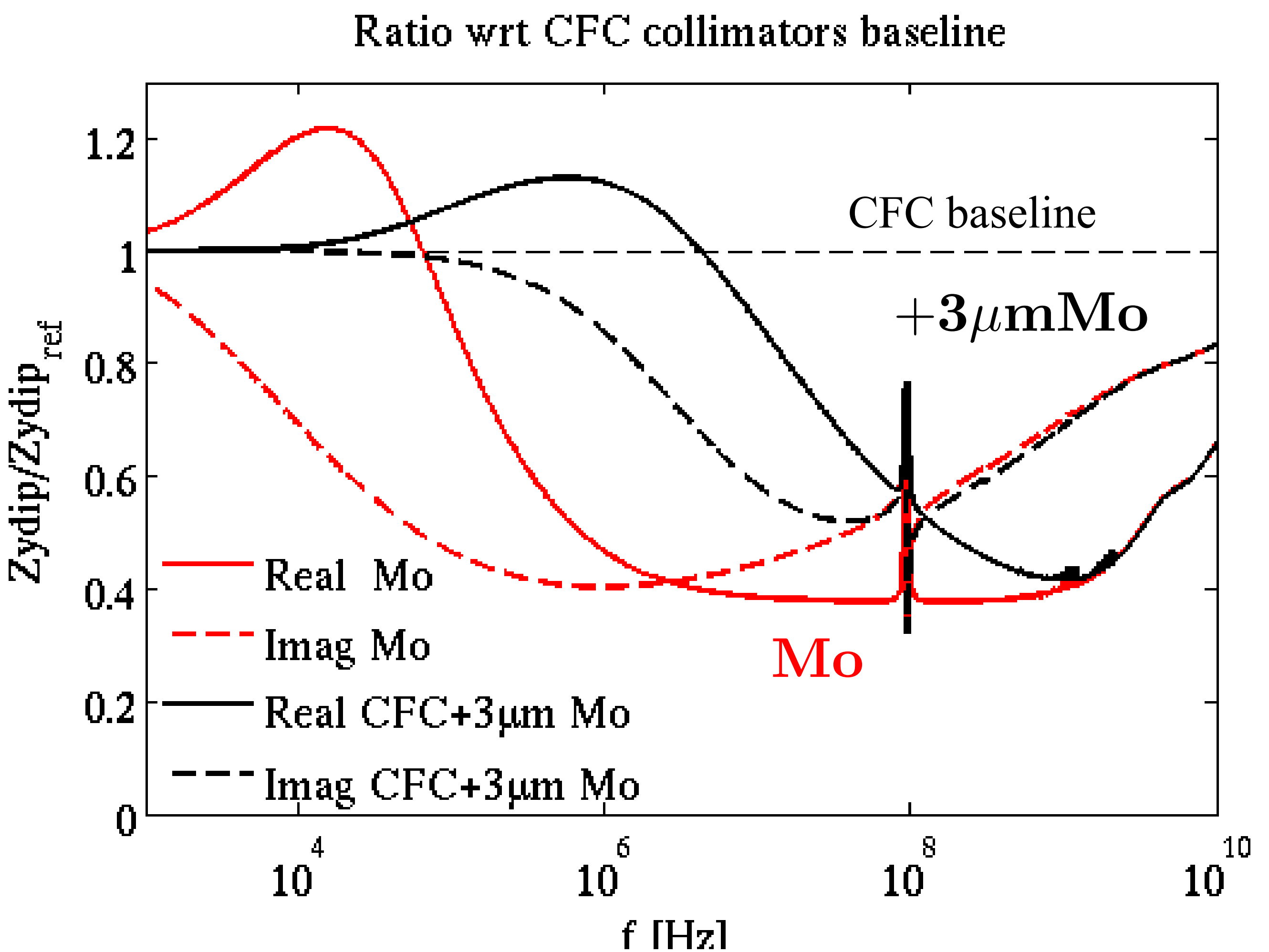

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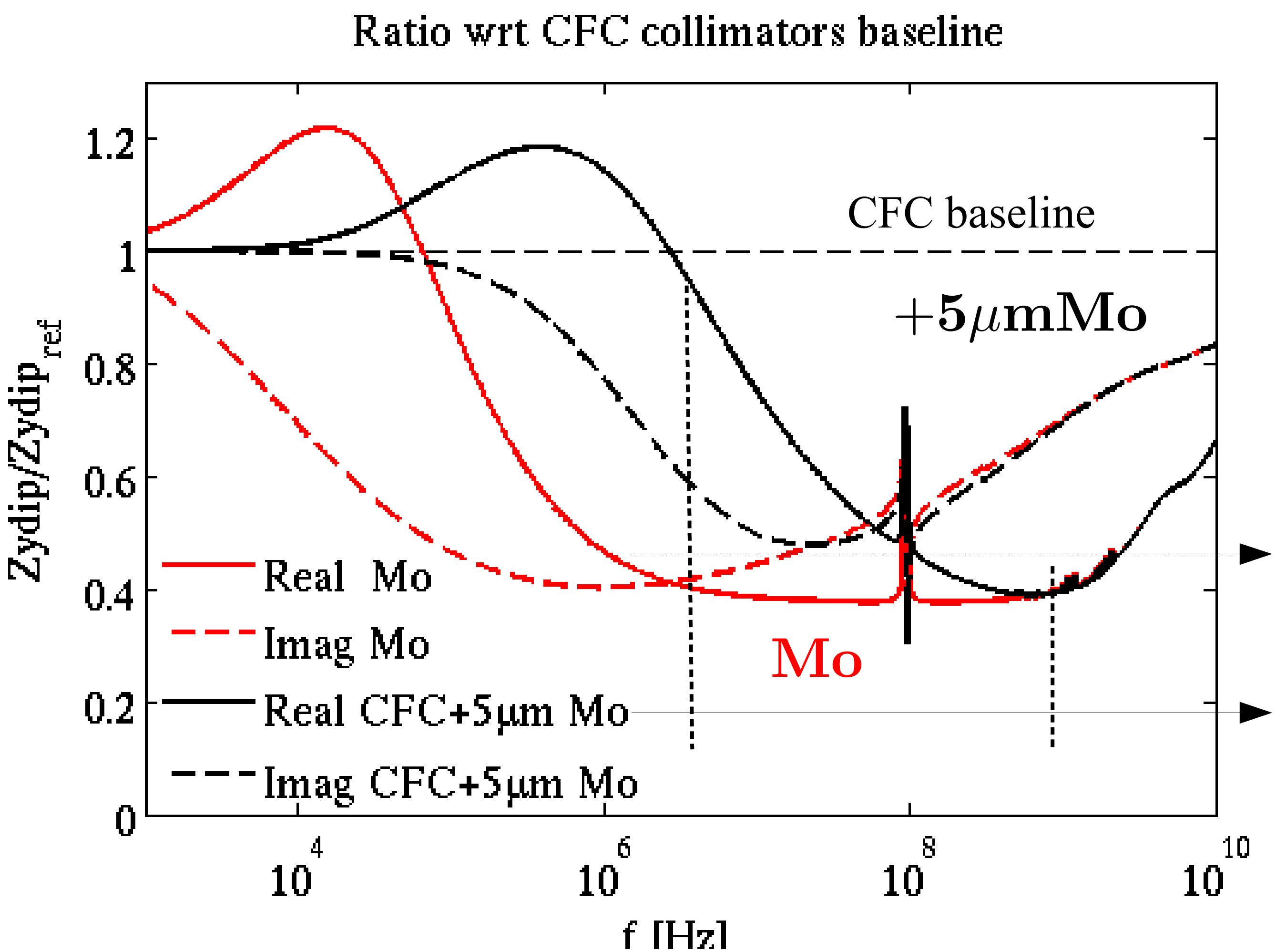

-50% → -30%
imag part

-5% → -60%
real part

Collimator impedance reduction

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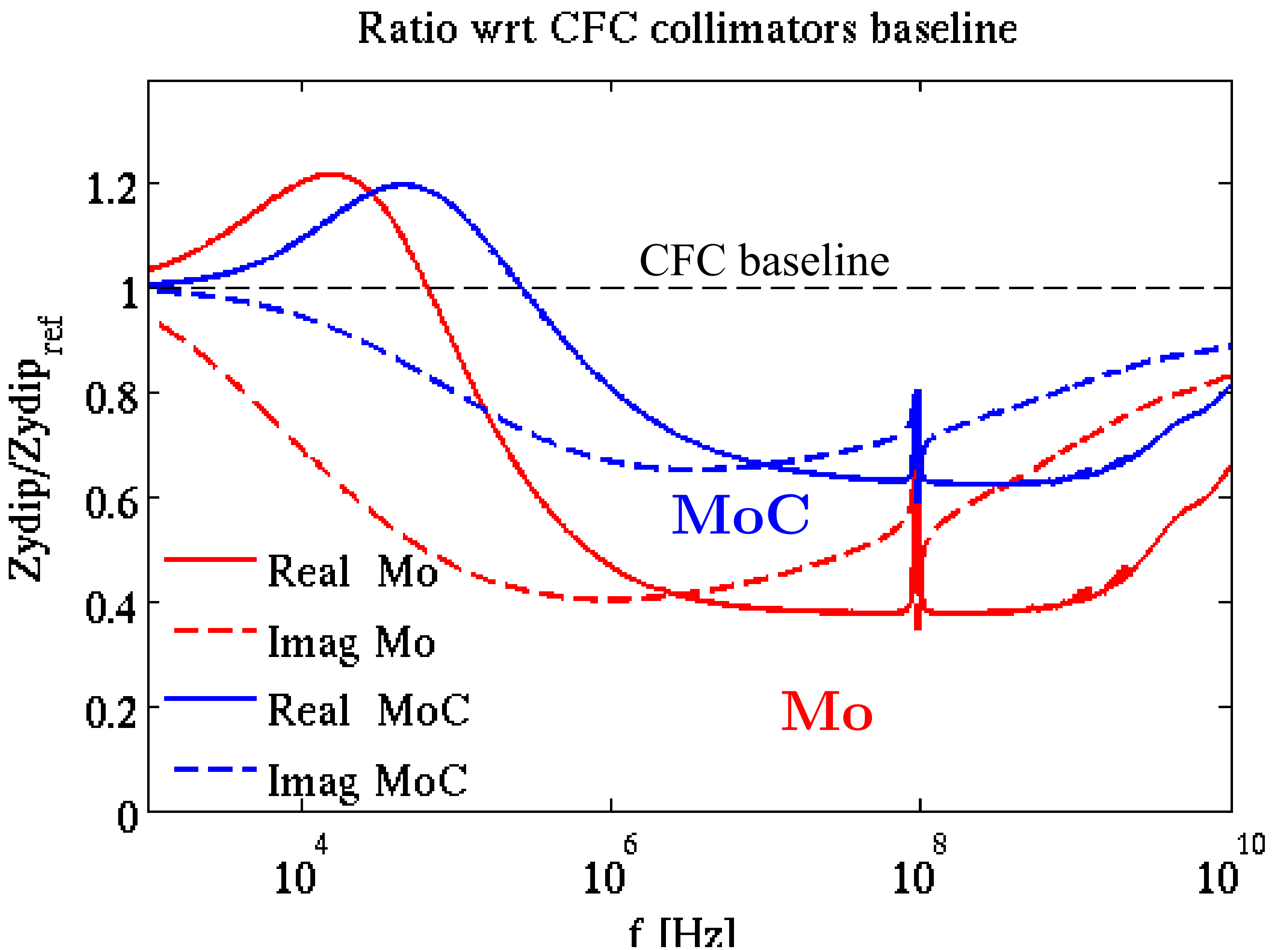

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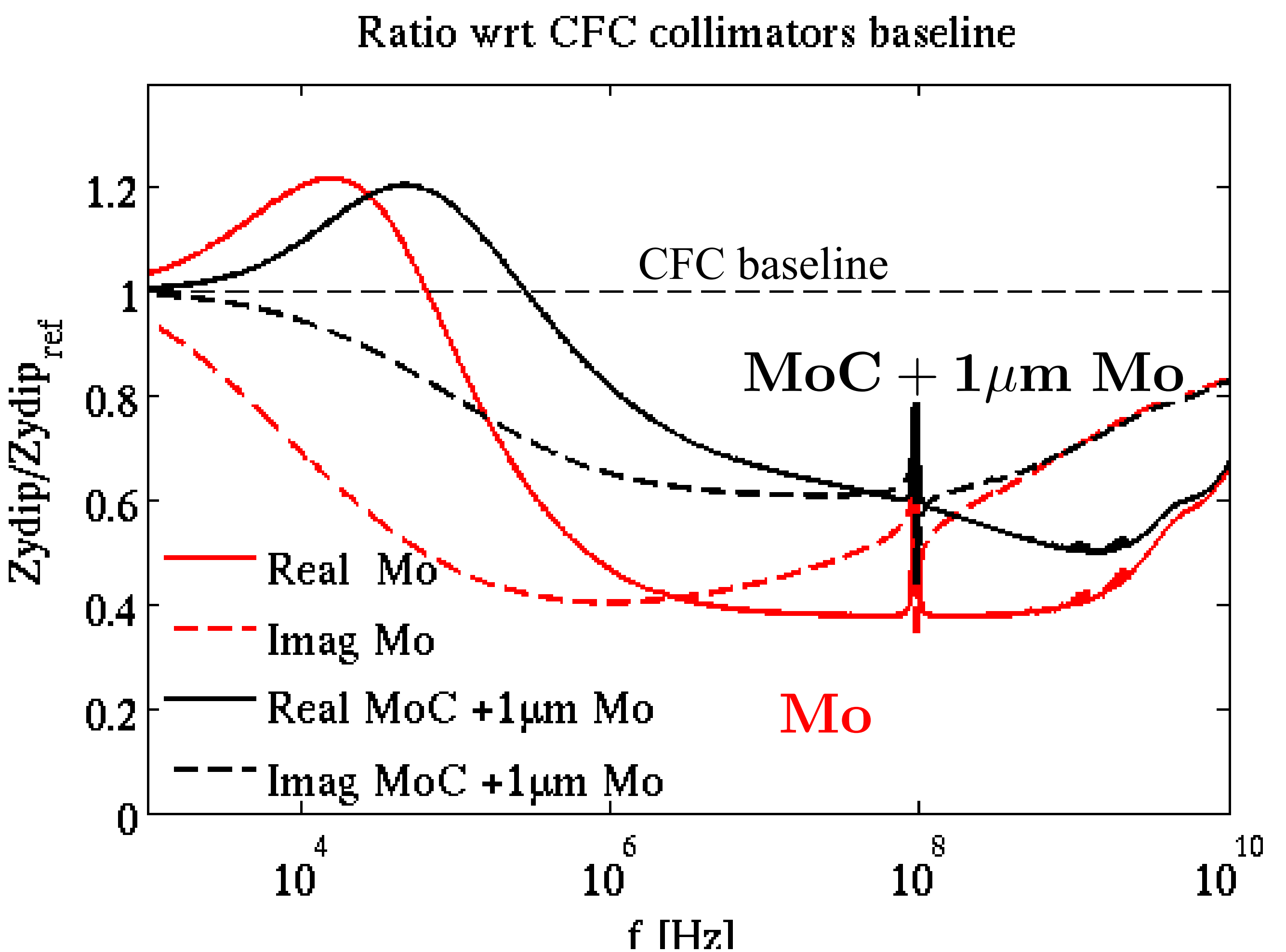

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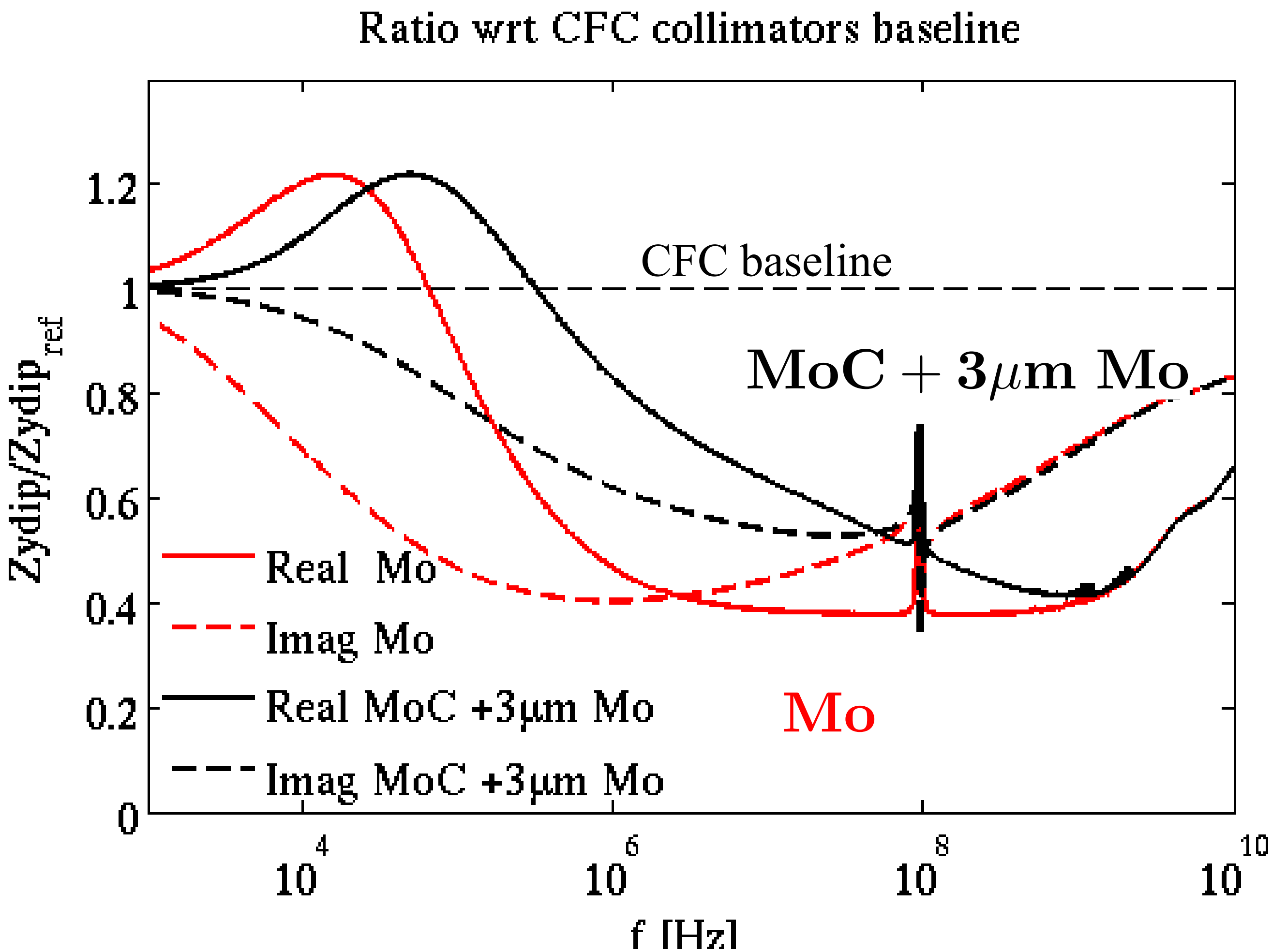

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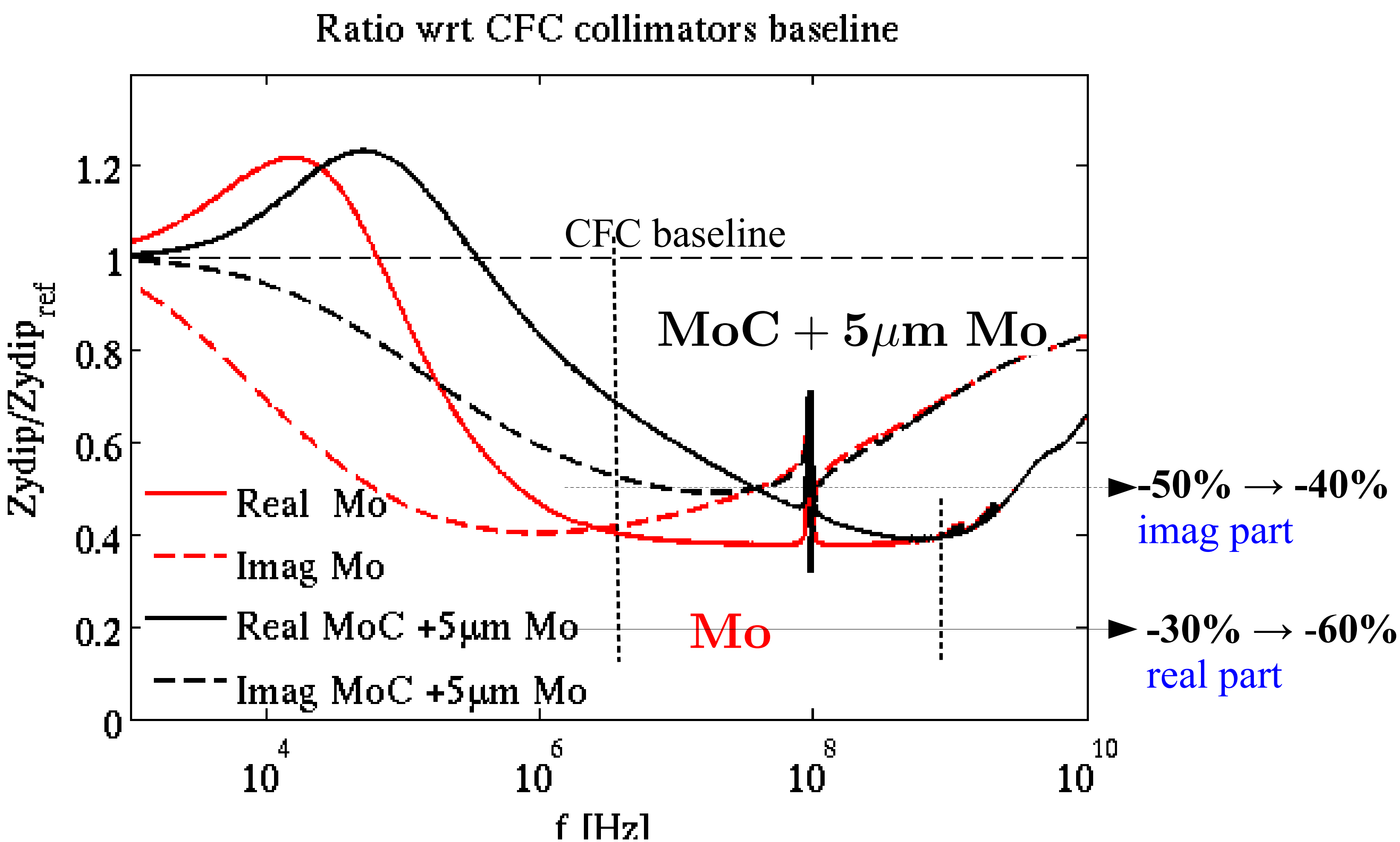

Collimator impedance reduction

1MHz - 1GHz

MoC only	**-35%** in real part **-40%** → **-20%** in imaginary part
Mo only	**-60%** in real part **-60%** → **-40%** in imaginary part
CFC + **5um** Mo coating	**-5%** → **-60%** in real part **-50%** → **-30%** in imaginary part
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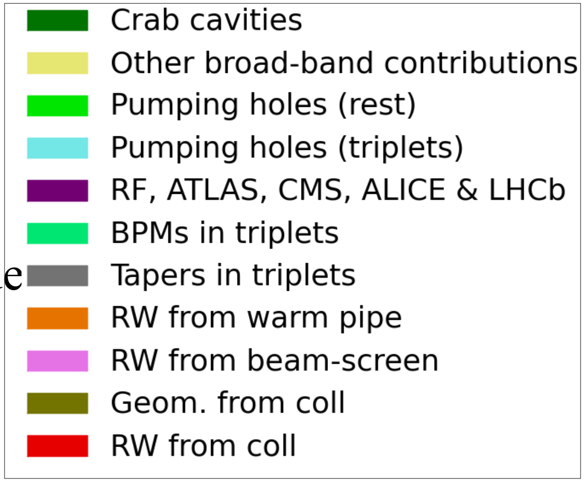
Preferred solution for the moment in terms of beam stability.

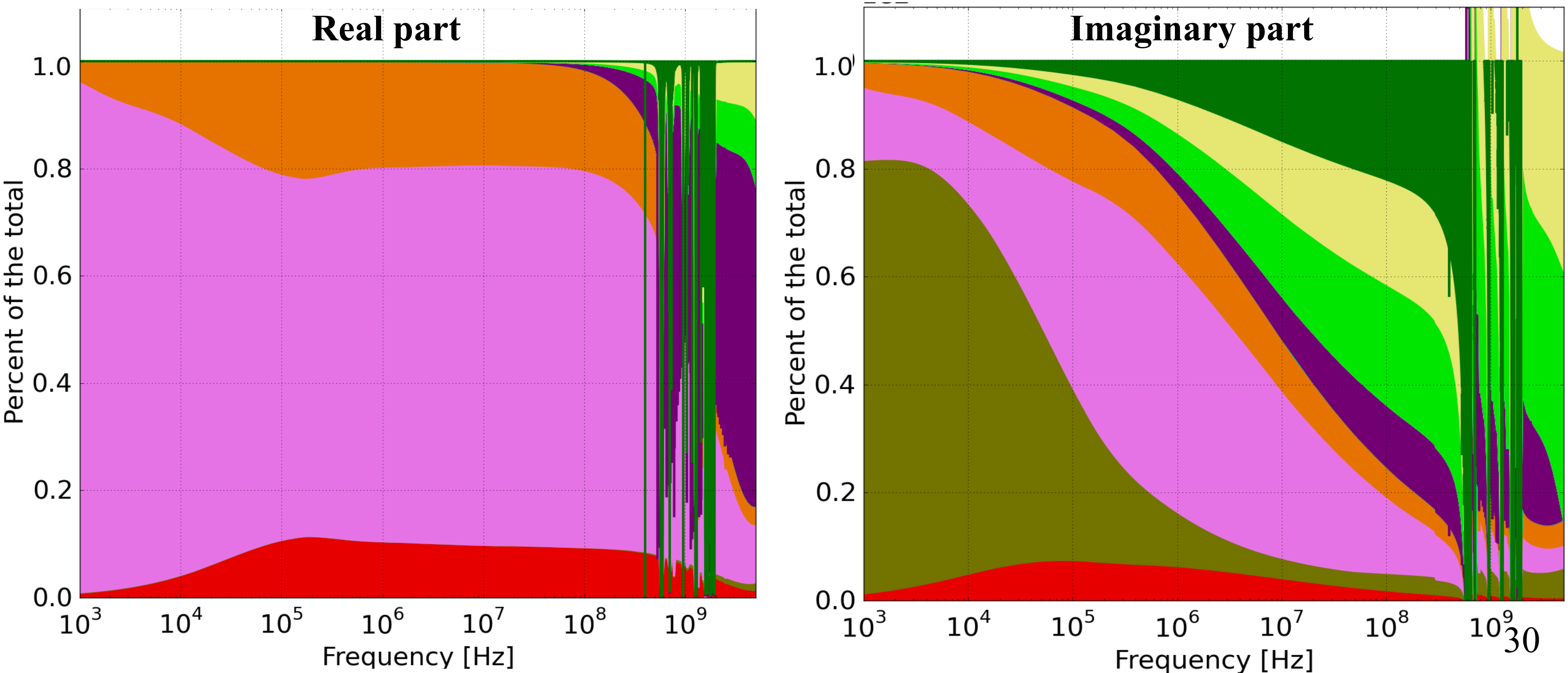
→ *Details on stability in E.Métral talk after.*

HL-LHC impedance

Longitudinal impedance

- HLLHC in the case of Mo collimator jaws.
- Real part: Strong beam screen contribution below 100MHz
  Experimental beam pipes, BNL CCs and RF dominate the high freque
  impedance as pumping holes and broad band impedances.
- Imaginary part: low frequency dominated by collimator geometrical impedance. Pumping holes and broad band mainly high frequency.





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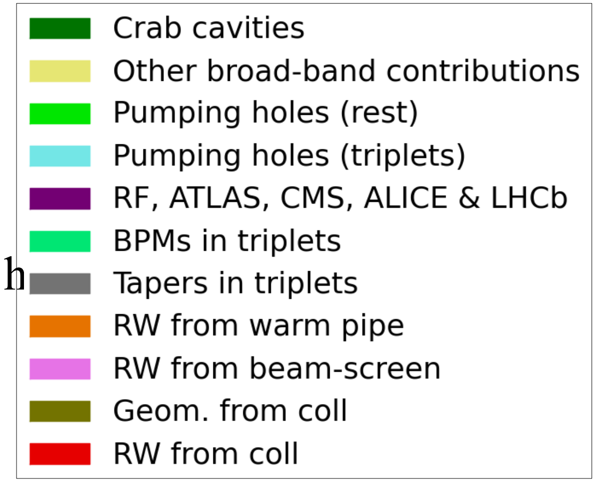
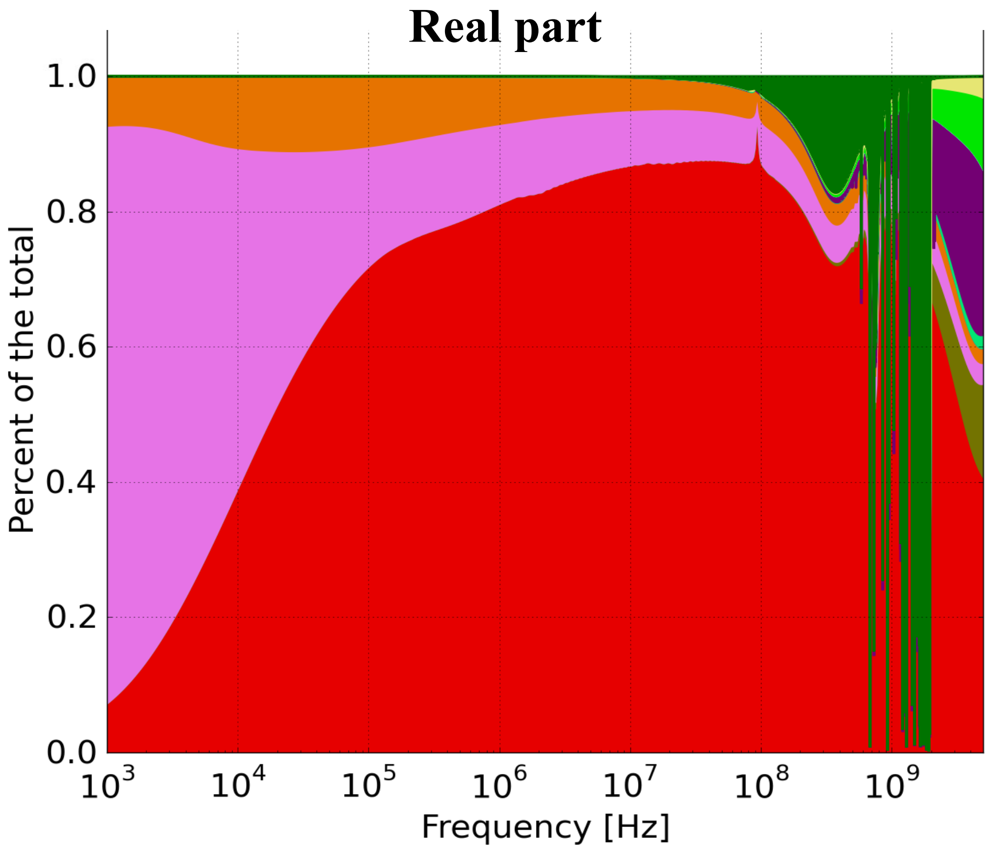
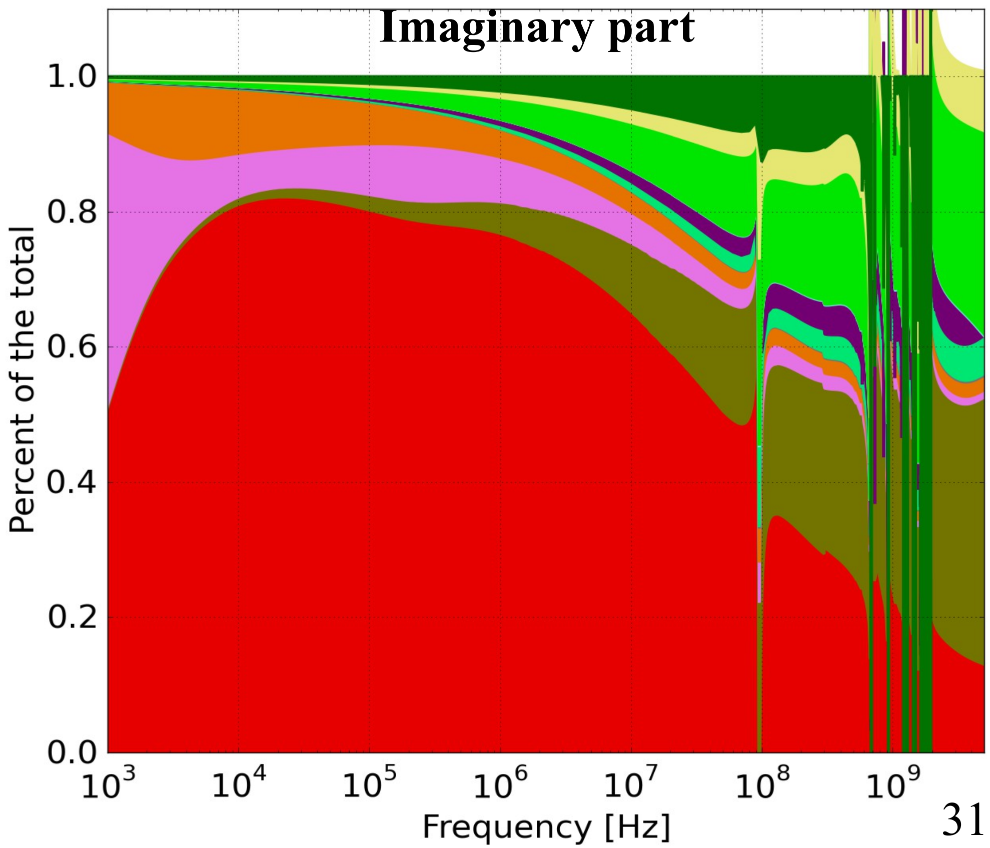


Vertical dipolar impedance

- HLLHC in the case of Mo collimator jaws.
- Real part: Low frequency dominated by beam screens. Collimators main source up to GHz (80% of total). BNL CC HOMs h
- Imaginary part: Collimator dominated up to 10 MHz. Geometrical collimator impedance contribution higher from 10-100 MHz.
- Horizontal impedance is similar.

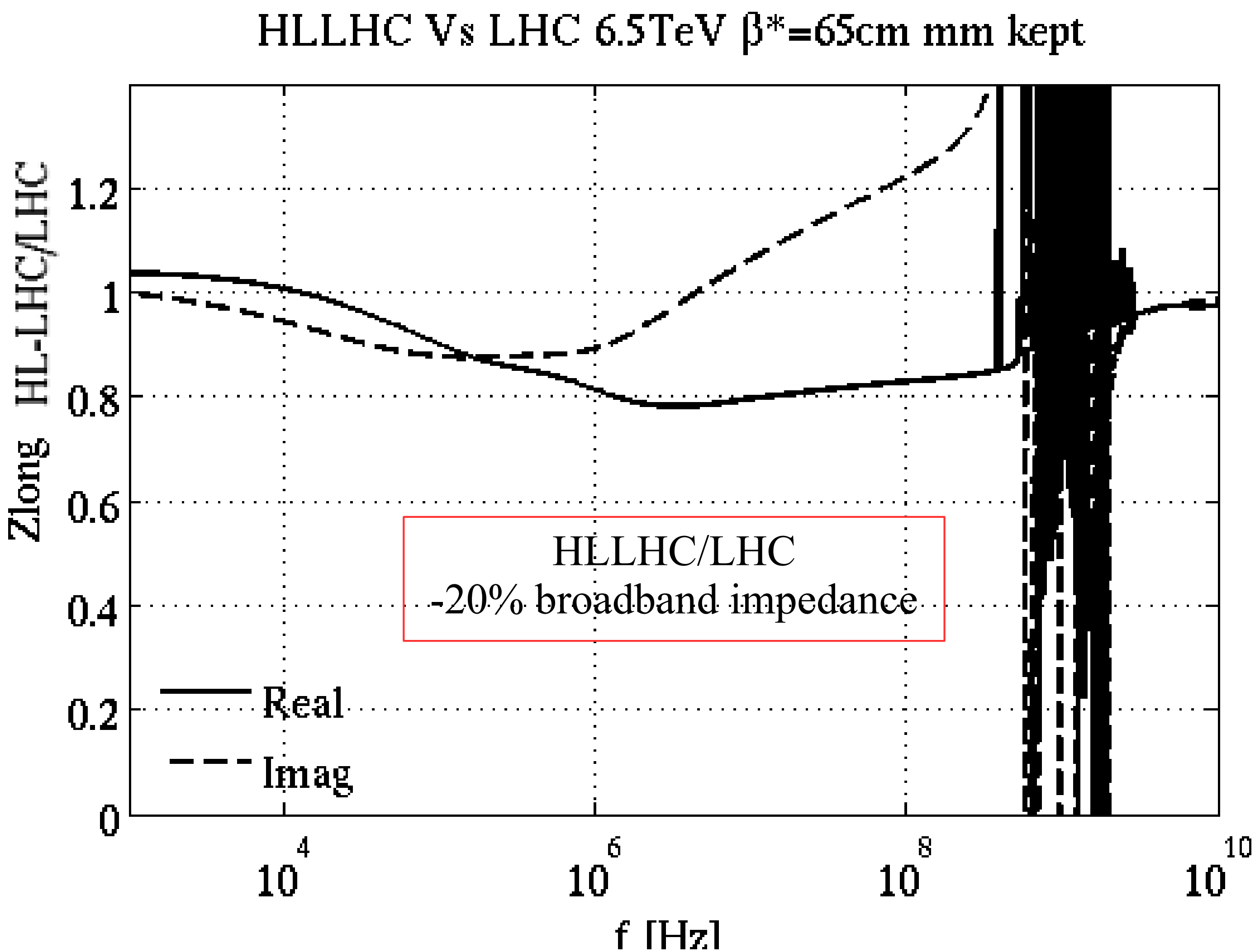




HL-LHC vs LHC impedance

HLLHC vs LHC: **Longitudinal impedance**

- HLLHC in the case of Mo collimator jaws.
- LHC 6.5 TeV, 65cm β^* optics.



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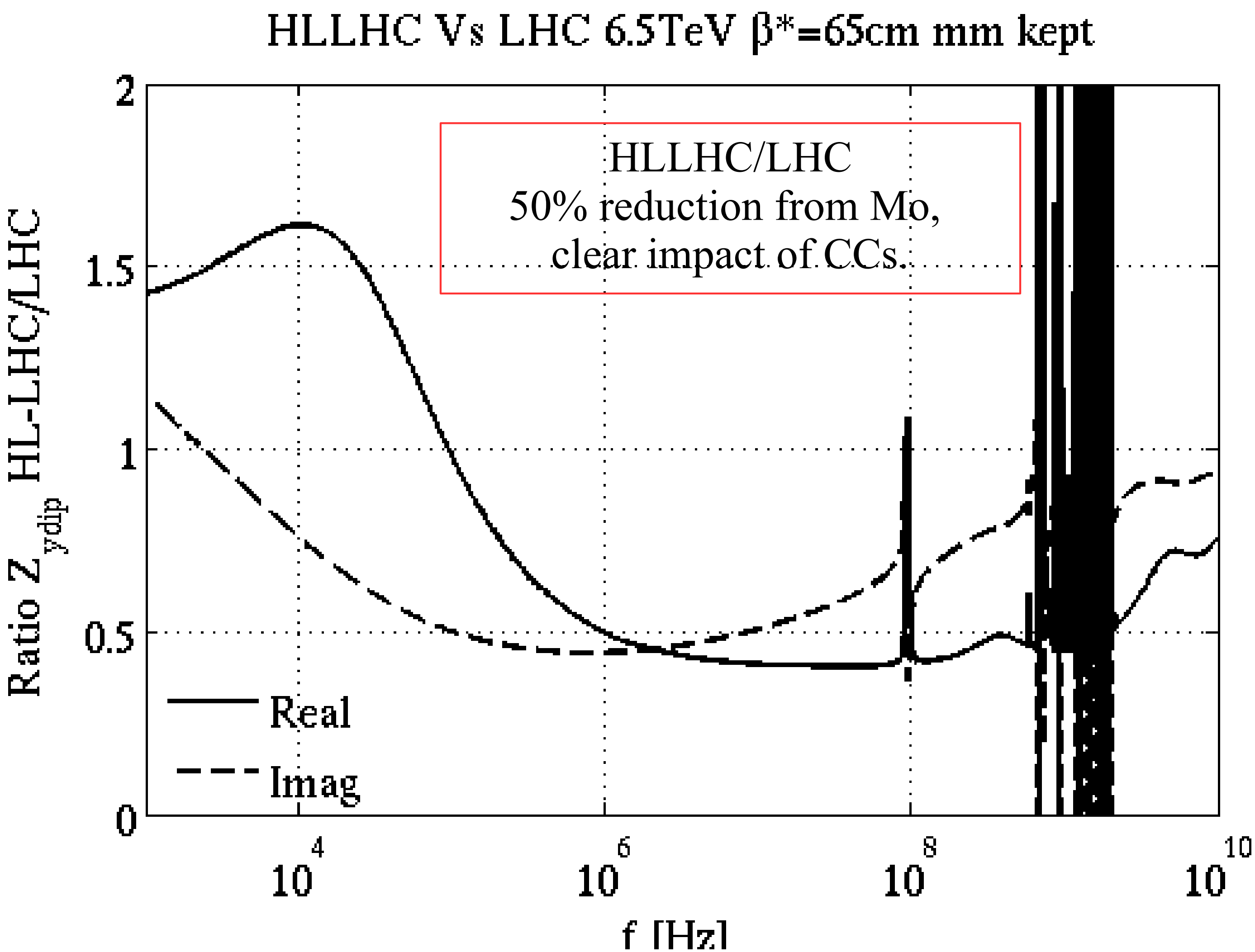
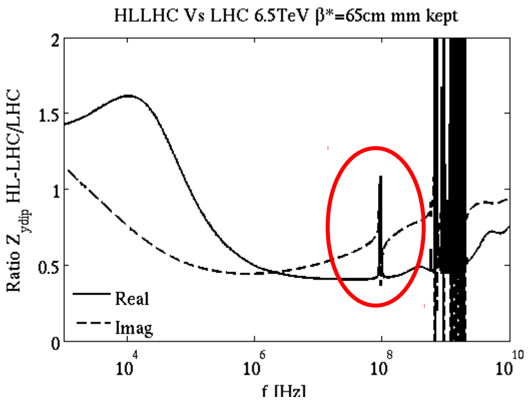
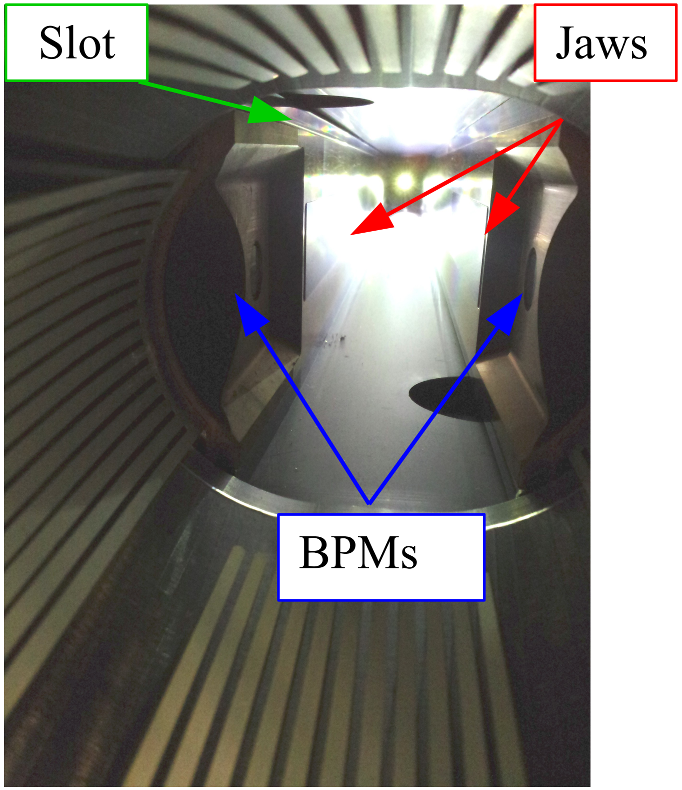


TCT – TCSG trapped mode

New TCT-TCSG collimator design: relevant for HLLHC
1. Model with integrated **BPM** buttons introduces open **slot** along the **jaws**
2. Predicted a trapped mode at ~**100 MHz**.
3. DELPHI simulations for LHC → Small impact on stability.
4. Tentative of mode damping with ferrite.





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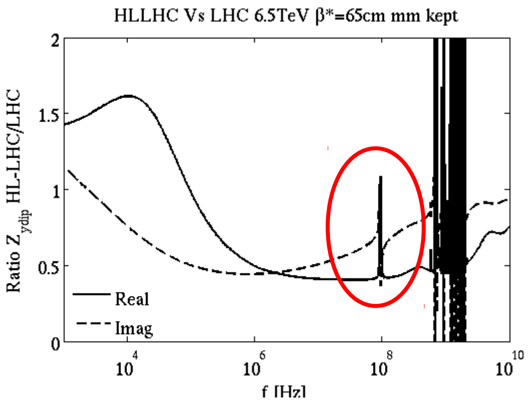
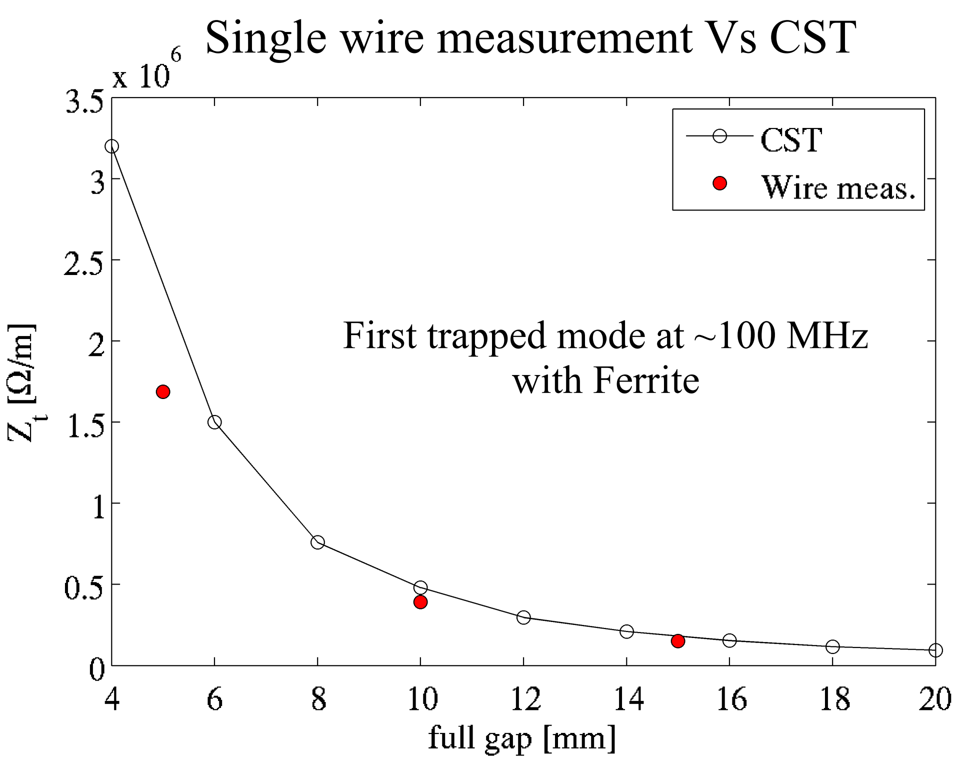
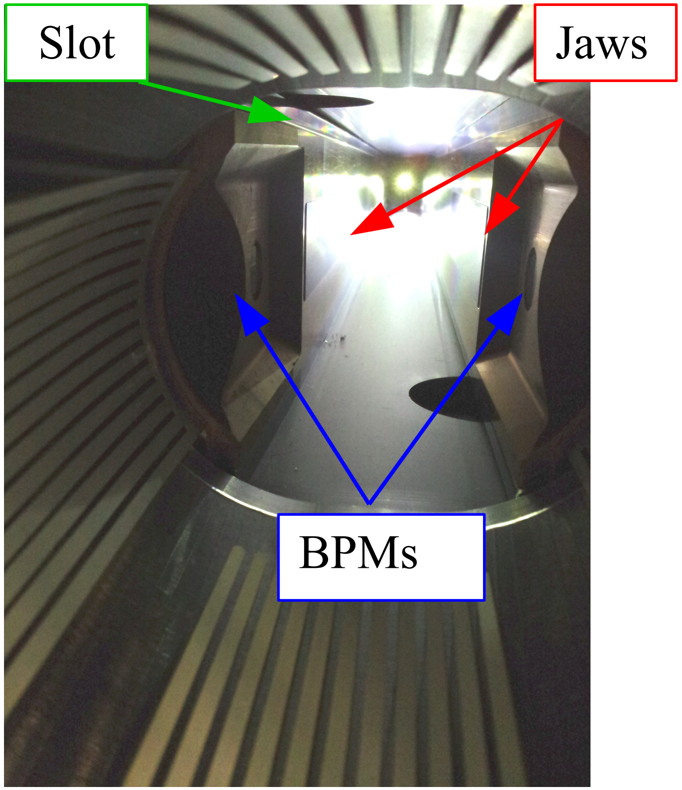
Impedance bench measurements:

1. Confirmed presence of the mode
2. Good agreement between CST simulation and wire measurements (Zt Vs gap)
3. Simulations ongoing with INFN-LNF colleagues.



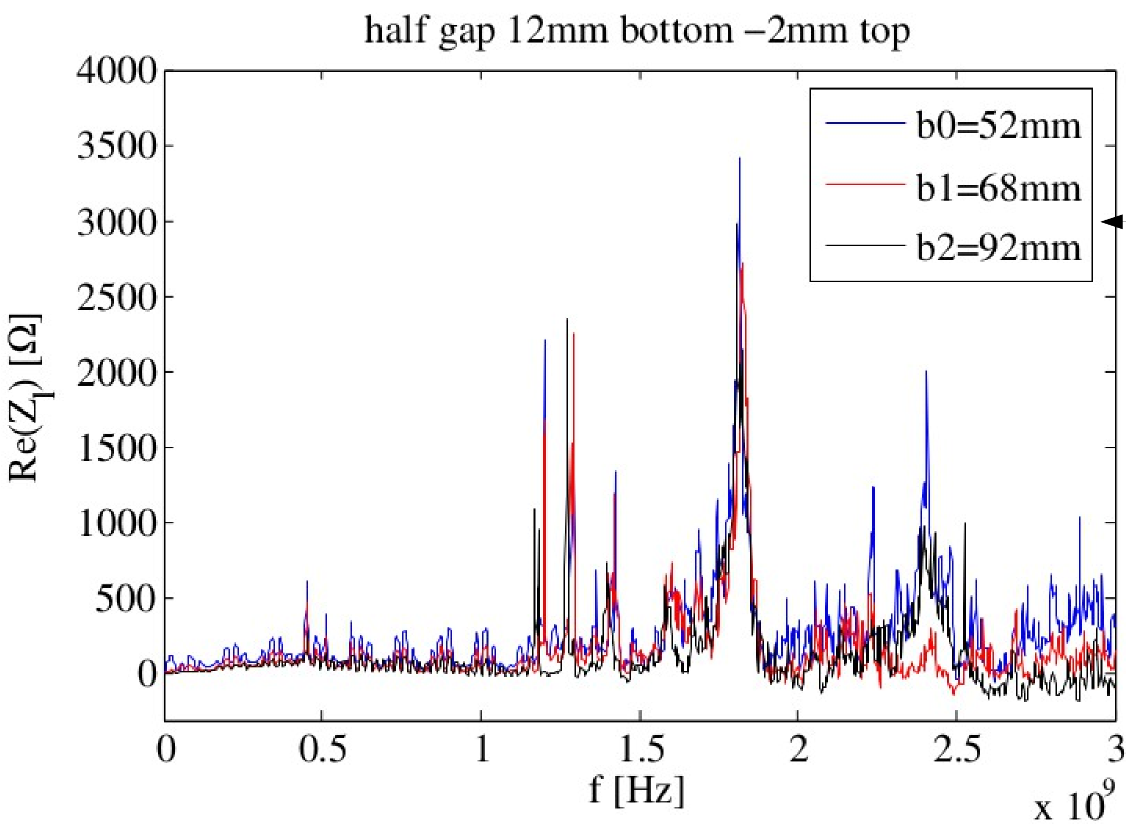


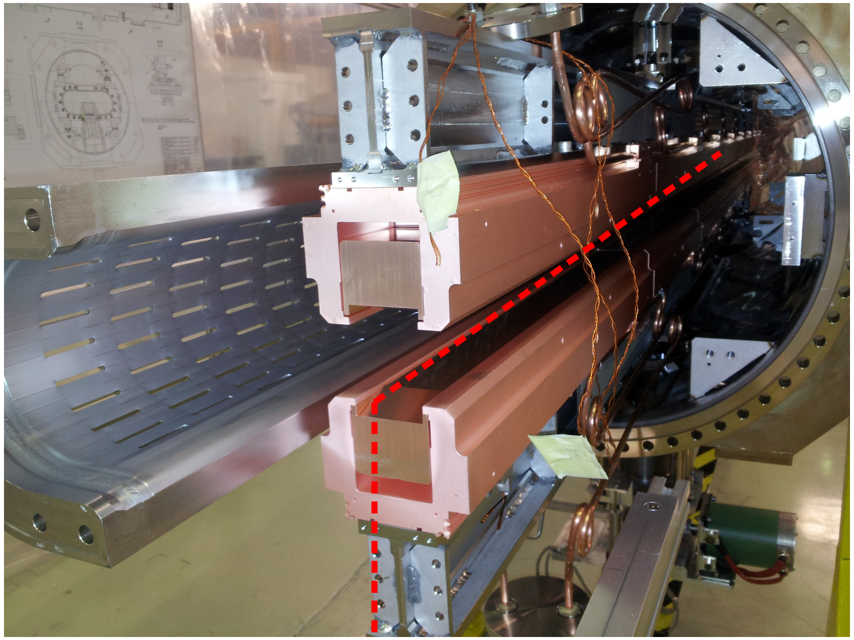


TDI impedance

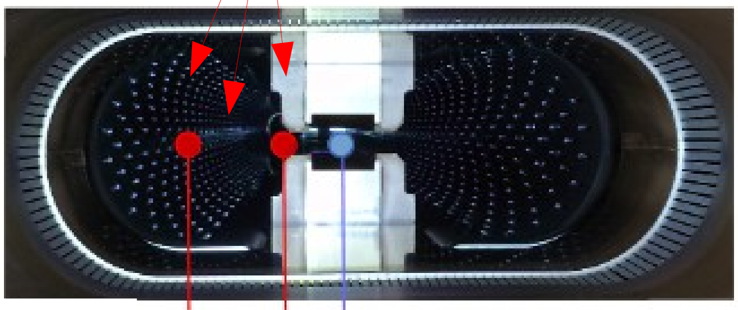
Present TDI design:
1. Presence of many harmful trapped modes.
2. Heating issues.

Impedance single wire measurements:
1. Long device → Strong and successful team effort!
2. Most of the trapped modes characterized.
3. Update comparison with simulations ongoing.





wire positions



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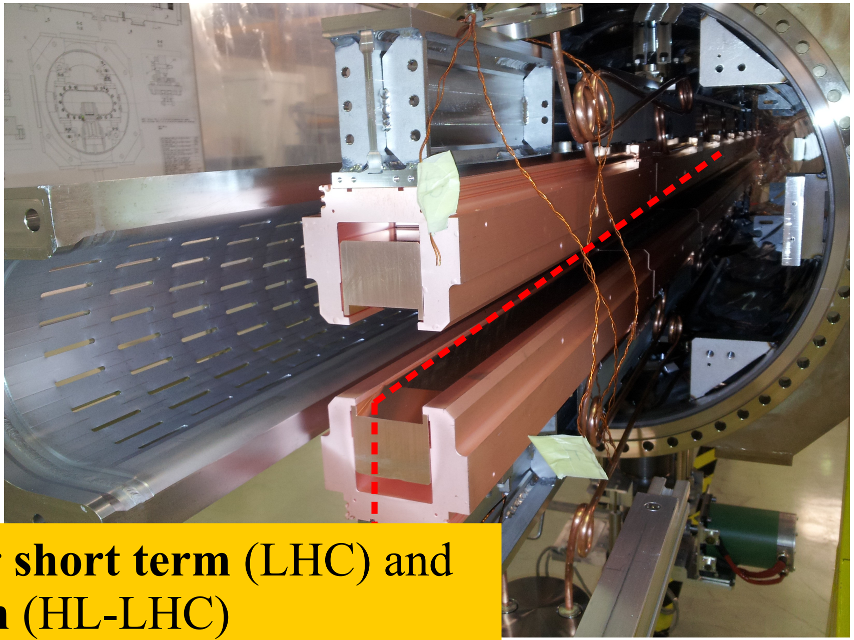
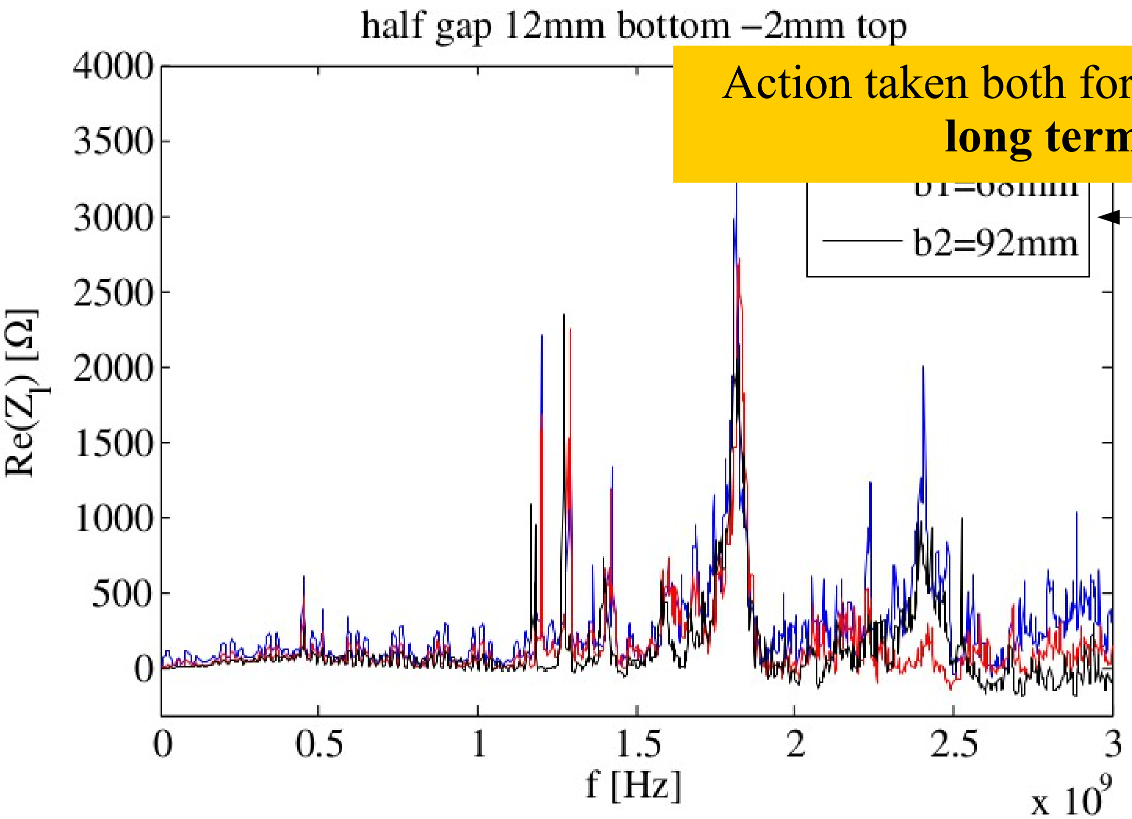
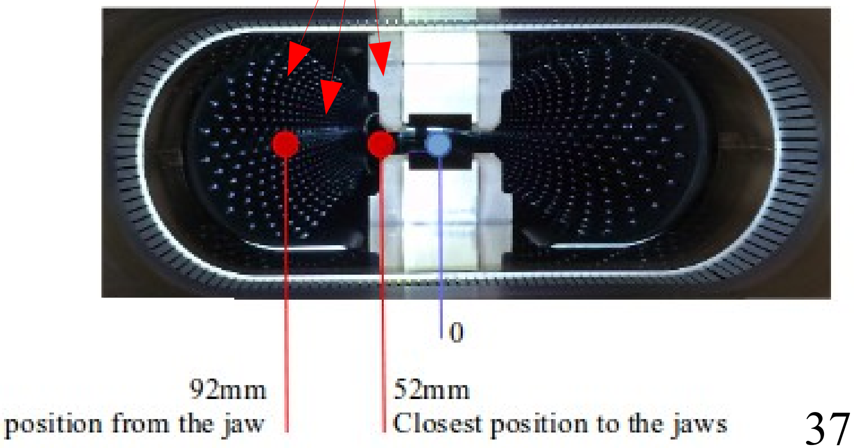
Impedance single wire measurements:
1. Long device → Strong and successful team effort!
2. Most of the trapped modes characterized.
3. Update comparison with simulations ongoing.





Action taken both for **short term** (LHC) and **long term** (HL-LHC)

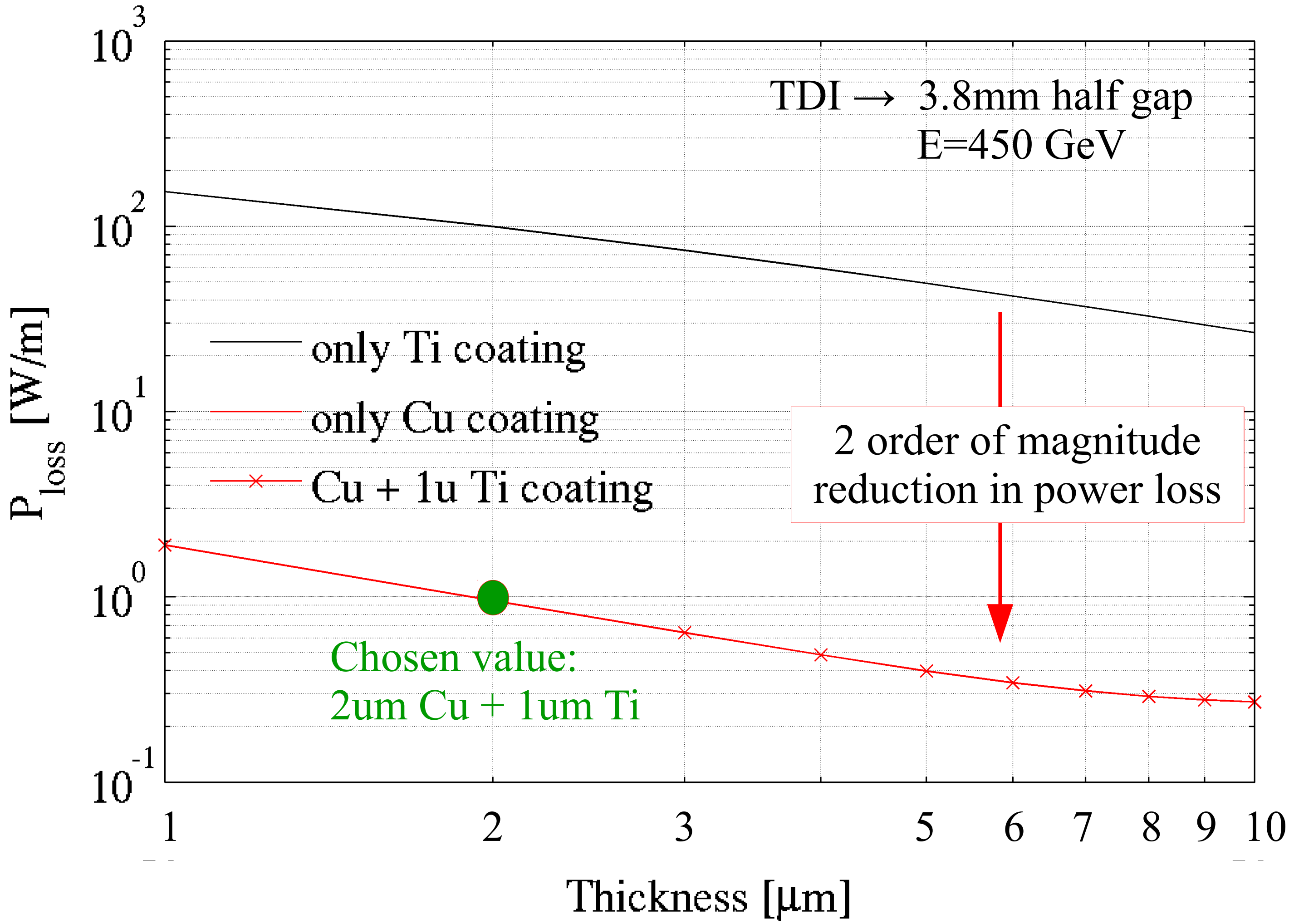
wire positions



TDI impedance

Short term solution: post-LS1 mitigation

1. Change of the beam screen from copper to stainless steel → more robustness
2. Coating of 1um Titanium + 2um Copper on hBN jaws → strong power loss reduction

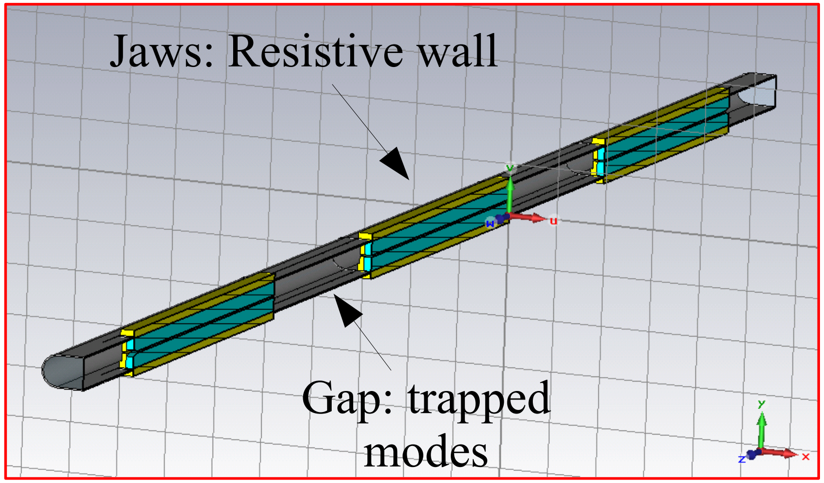


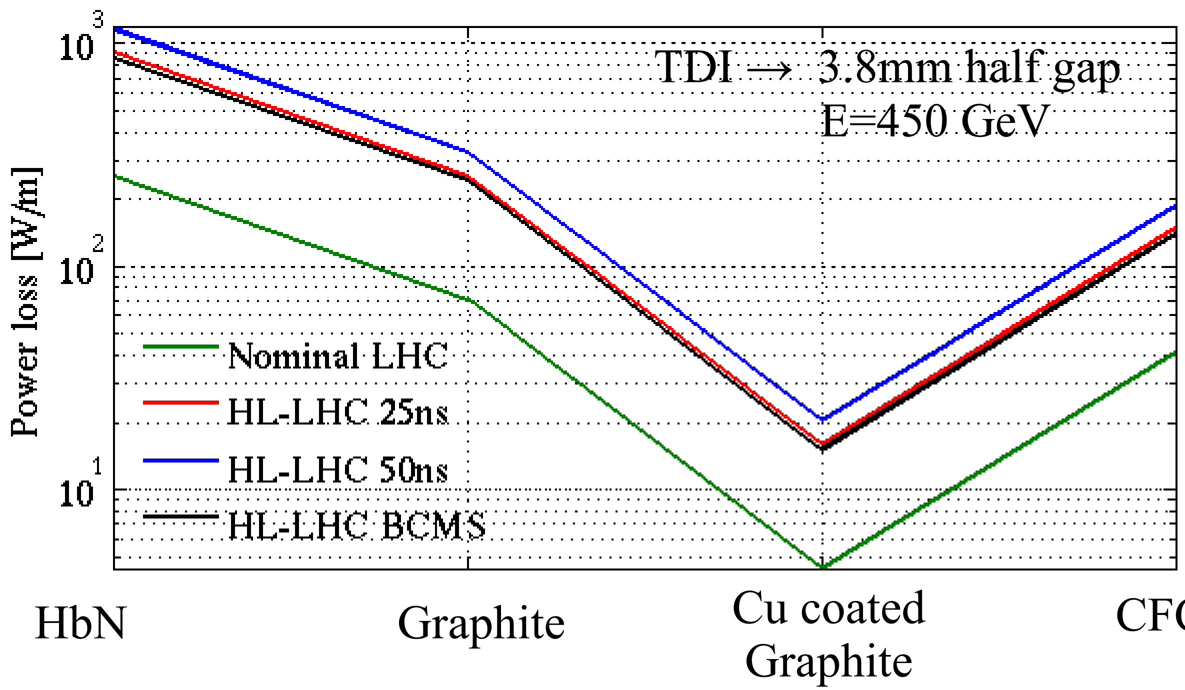
TDI impedance

Long term solution: Device re-design

A new TDI design is foreseen with 3 module segmentation for mechanical reasons. Impedance concerns about:

- number of segmented modules
- optimization of tapered transitions
- trapped modes between modules
- quality of contacts between jaws and screen
- heating
- surface coatings





Interplay between impedance, mechanics, vacuum, cooling, etc... Challenging and exciting design!

See also D.Wollmann talk

Crab Cavities

- Devices used to kick the colliding beams in order to improve the geometrical overlapping.
- Main RF transverse mode at 400MHz gives kick to the beam.
- Many other Higher Order Modes (HOMs). → strong effort to reduce them!
- Simulated data updated with latest HOM list

Double 1/4-wave

BNL
(DQW)

RF Dipole

ODU/SLAC (RFD)

4-Rod

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Thanks in particular to
Silvia Verdu Andres, Binping Xiao, Ben Hall, Zenghai Li and Rama!

Double 1/4-wave

BNL (DQW)

RF Dipole

ODU/SLAC (RFD)

4-Rod

BNL (DQW) and ODU/SLAC (RFD)

- Main transverse modes (> 100 kOhm/m in circuit convention):

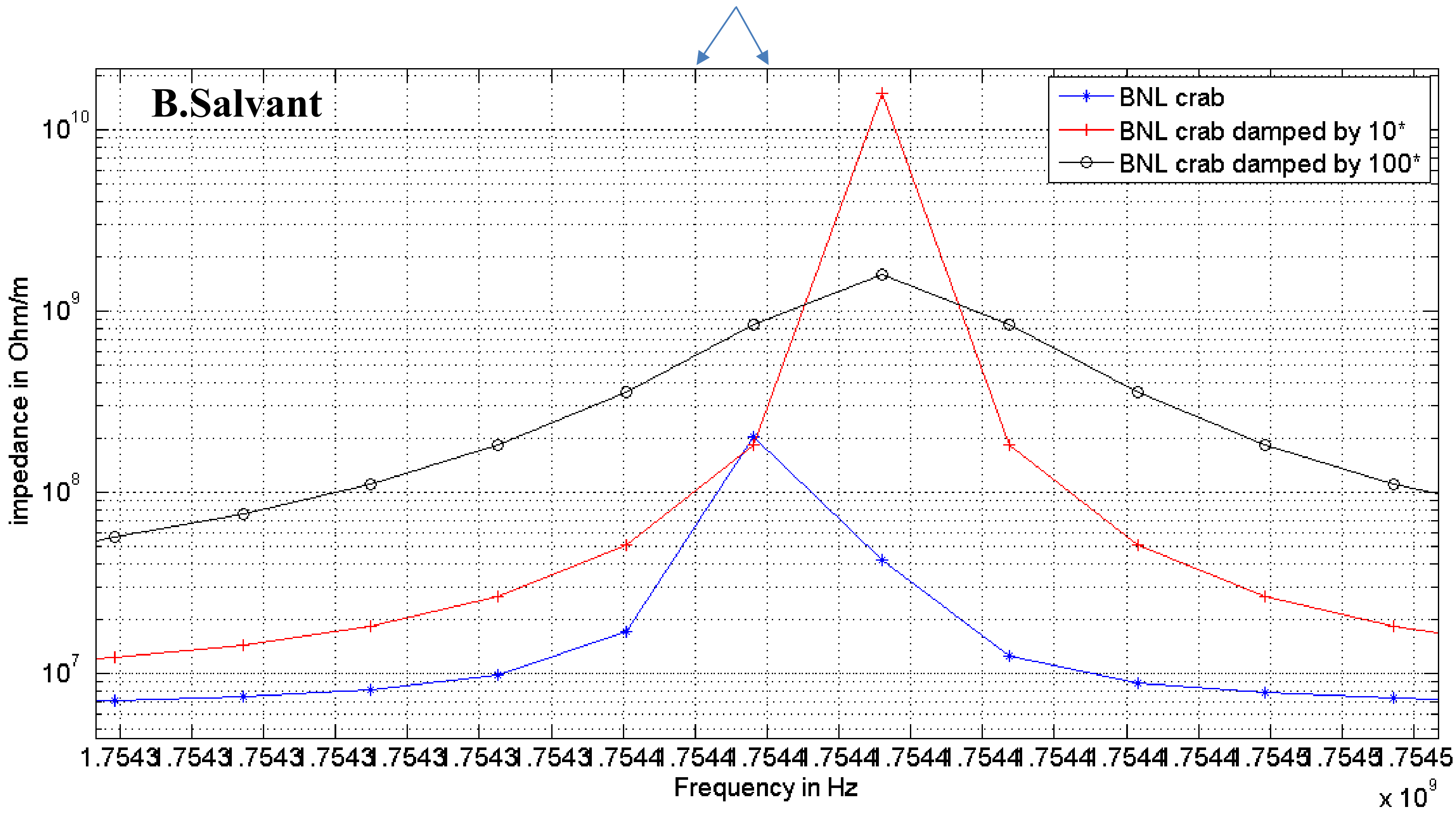
f (GHz)	Q	R (Ohm/m) per half cavity	plane	Deltaf in kHz
0.400	6.66E+09	5.98E+12	V	-
0.685	1880	4.67E+05	H	365
0.927	8600	1.38E+06	H	108
1.30	6540	3.73E+05	V	200
1.50	10800	2.67E+05	H	140
1.66	24200	3.14E+05	H	69
1.75	5800	2.57E+05	H	301
1.75	4160000	1.81E+08	H	0.4
1.84	9990	3.34E+05	V	185
1.86	26400	4.17E+05	H	70
1.86	88200	1.56E+06	V	21
1.92	102000	1.85E+06	H	18
1.96	54400	1.15E+05	H	36

f (GHz)	Q	R (Ohm/m) per half cavity	plane	Deltaf in kHz
0.4			V	
0.634	672	1.64E+05	H	940
1.27	1790	1.63E+05	V	707
1.48	78200	2.29E+06	H	19
1.48	1710	1.95E+05	V	870
1.72	109000	6.18E+05	H	16
1.77	93700	3.10E+06	H	19
1.88	432000	4.89E+05	H	4
1.96	413000	4.01E+06	V	5
1.96	1150000	1.77E+07	H	2
1.99	4260000	1.33E+08	H	0.5
2.00	586000	1.11E+07	H	3

→ Largest amplitude modes have a very thin width (~400 Hz) and are less likely to be hit by a revolution frequency (11kHz for LHC and 44 kHz for SPS)

Issue with sampling for very peaked modes

Unstable modes



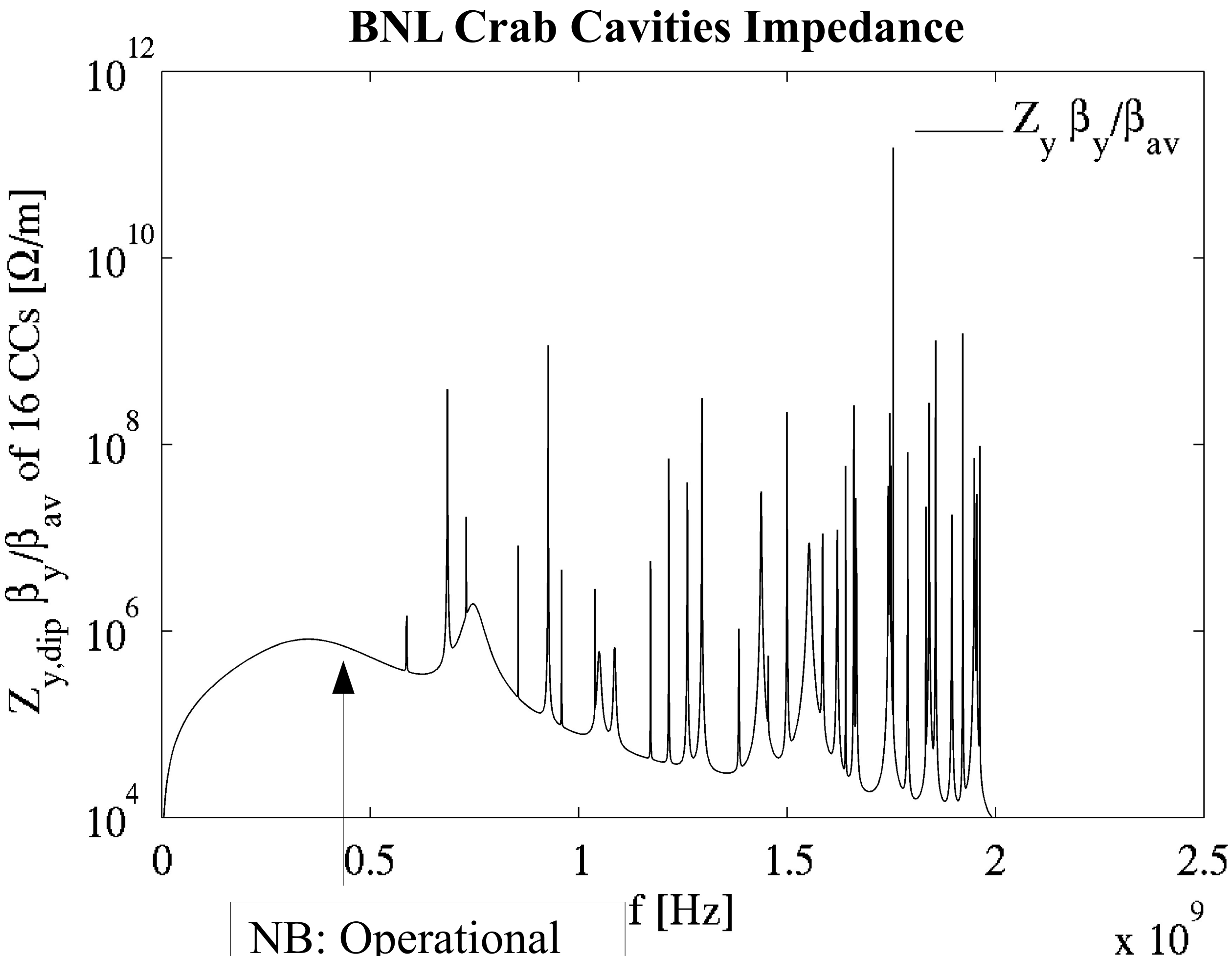
→ DELPHI takes already 12h for the simulations.

→ Need to increase sampling for impedance, and include all unstable modes

→ Need also to move the frequency to the unstable mode as otherwise we could miss it

→ Highest mode: 400 Hz width for 11 kHz sampling...

Criterion for threshold on HOMs



NB: Operational mode at 400 MHz damped. Q=1, R/Q constant.

As from [1,2] in a single mode test case:

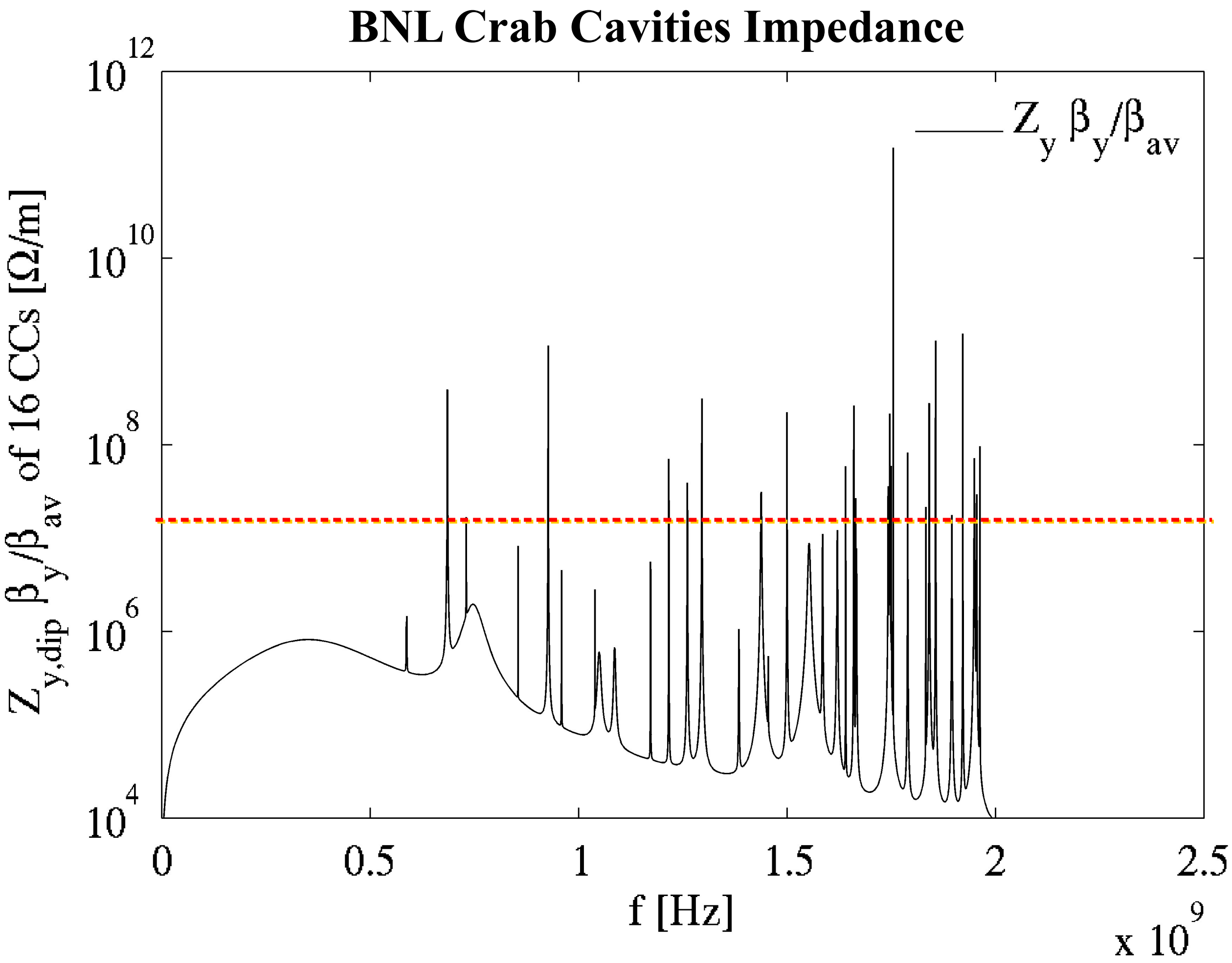
$$\frac{\beta_y}{\beta_{av}} R_\perp^{sh} \ll 1G\Omega/m$$

With
$$\beta_y \simeq 3600\ m$$
$$\beta_{av} \simeq 70\ m$$
$$\ll \rightarrow \frac{1}{50}$$

→ *Details on procedure on E.Métral talk after*

[1]: F.Zimmermann, 3rd LHC-ILC crab synergy meeting, 2008.
[2]: E.Métral, PAC09.

Threshold on HOMs



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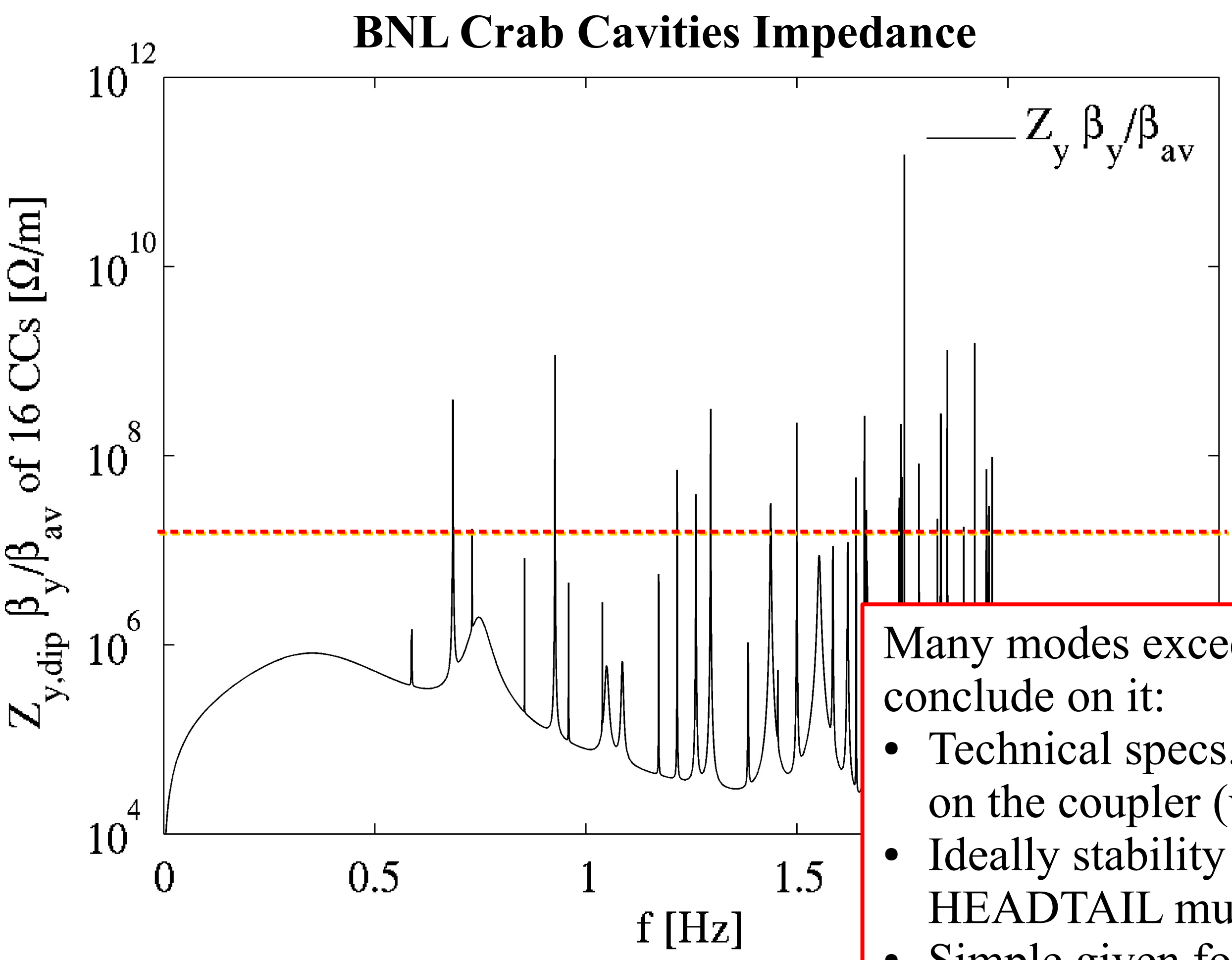


As from [1,2] in a single mode test case:

$$\frac{\beta_y}{\beta_{av}} R_{\perp}^{sh} \ll 1G\Omega$$

With

$$\begin{cases} \beta_y \simeq 3600\ m \\ \beta_{av} \simeq 70\ m \\ \ll \to \dfrac{1}{50} \end{cases}$$

Many modes exceed threshold, but this is not enough to conclude on it:

- Technical specs. on HOM → Already huge effort done on the coupler (very compact design).
- Ideally stability should be checked with DELPHI and HEADTAIL multibunch.
- Simple given formula can be a starting point for more accurate studies.

[1]: F.Zimmermann, 3rd LHC-ILC crab synergy meeting, 2008.
[2]: E.Métral, PAC09.

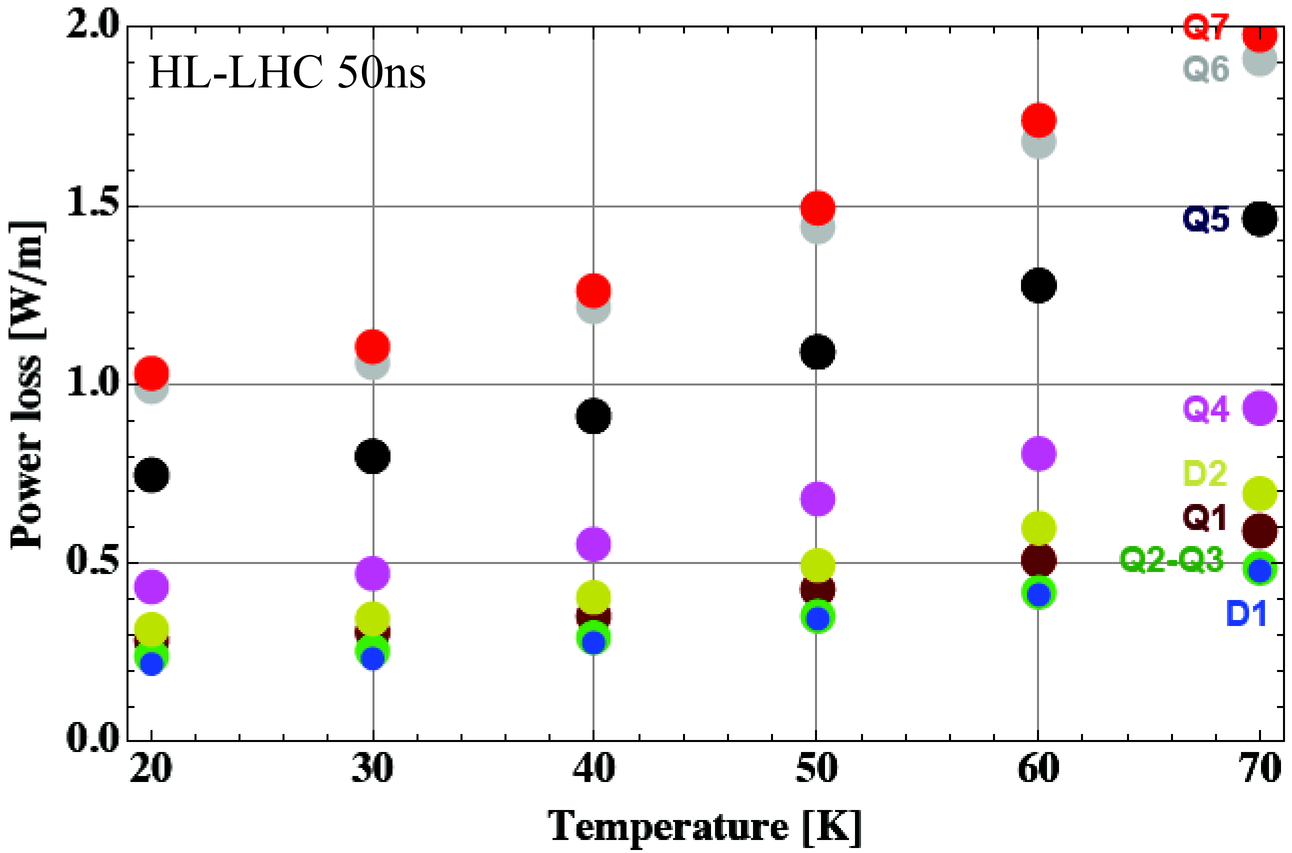
Impedance, SPS related details: N. Biancacci tomorrow talk

Heating

Equipment with RF fingers	Negligible for conforming RF finger
Experimental beam pipes	Negligible for ATLAS, > 100 W for CMS, LHCb and ALICE if beam lines overlap impedance.
BPMs in triplets	0.2W/m for 50ns beams assuming no 2 beam interference and Cu coating.
Collimators with BPMs and mode damping ferrites	~100 W of which ~7 to the ferrites, ~6 to RF fingers. Should be acceptable.
Injection kickers (MKI)	~125-190 W/m as the pre-LS1 one. Heat transfer improvements and power loss reduction are planned.
Crab cavities	kW range. We should be able to fine tune the HOMs to not overlap beam spectral lines.
Injection protection dump (TDI)	New design under study to avoid **kW** dissipation.
Beam syncrothron monitor BSRT	Heated in LS1. New design and usability **to be assessed** for HL-LHC.
Beam screens	Accounting weld, magnetoresistance, 2 beams impedance. Concern for Q7: 2W/m. Cryo general limit at 3.8W/m.

Heating

Expected heat loads for beam screens as a function of the temperature.



G. Iadarola's talk

Beam screens	Accounting weld, magnetoresistance, 2 beams impedance. Concern for Q7: 2W/m. Cryo general limit at 3.8W/m.

Conclusions and next steps

LHC impedance model Vs measurements

Factors:

Few % → Finite length
+20% → Geometrical impedance of collimators
+20% → DELPHI/HEADTAIL convergence
Updated ratio → Factor ~**1.5**
Compensation: an increase in resistivity (factor 2: from 5uOhm.m → 10uOhm.m) would explain ~40% of the impedance missing. It would be great to measure it!

HL-LHC impedance reduction scenarios

Mo and Mo+MoC coating scenarios: most suitable for impedance reduction for beam stability. Impedance reduced of ~50% both in longitudinal and in transverse wrt LHC.

Particular devices

1. **TCT:** charcterized the 100 MHz mode: DELPHI simulation → not harmful for LHC.
2. **TDI:** short-term solution for the post-LS1 LHC. Iterative re-design ongoing!
3. **Crab cavities:** updated the HOMs impedance → concern about transverse HOM modes.

Heating

TDI being redesigned. BSRT under observation for LS2. Beam screens alone slightly above 1/2 the limit of heat load from cryogenics at 70 K. Crabs modes in the kW range if beam overlapping, detuning is advised. Suspected devices should host temperature probes to be closely monitored.

Next steps

Continuous development and update of the HL-LHC impedance model.

Thanks!

Arigato!

Appendix

Some material electrical properties

Material properties:

- Stainless steel 604L:
  $\rho_{DC} = 720n\Omega \cdot m$
- Graphite SGL R4550:
  $\rho_{DC} = 15\mu\Omega \cdot m$ $\tau_{AC} = 1.3ps$
- CFC Tatsuno AC150:
  $\rho_{DC} = 5\mu\Omega \cdot m$
- Tungsten:
  $\rho_{DC} = 54n\Omega \cdot m$ $\tau_{AC} = 0.005ps$
- Titanium (in TDI):
  $\rho_{DC} = 2.5\mu\Omega \cdot m$
- hBN:
  $\rho_{DC} = 4 \cdot 10^{12}\Omega \cdot m$
- Aluminum:
  $\rho_{DC} = 27n\Omega \cdot m$ $\tau_{AC} = 0.008ps$
- Copper:
  $\rho_{DC} = 17n\Omega \cdot m$ $\tau_{AC} = 0.027ps$
- Molybdenum:
  $\rho_{DC} = 53.5n\Omega \cdot m$ $\tau_{AC} = 0.01ps$
- Molybdenum-Carbon:
  $\rho_{DC} = 1\mu\Omega \cdot m$

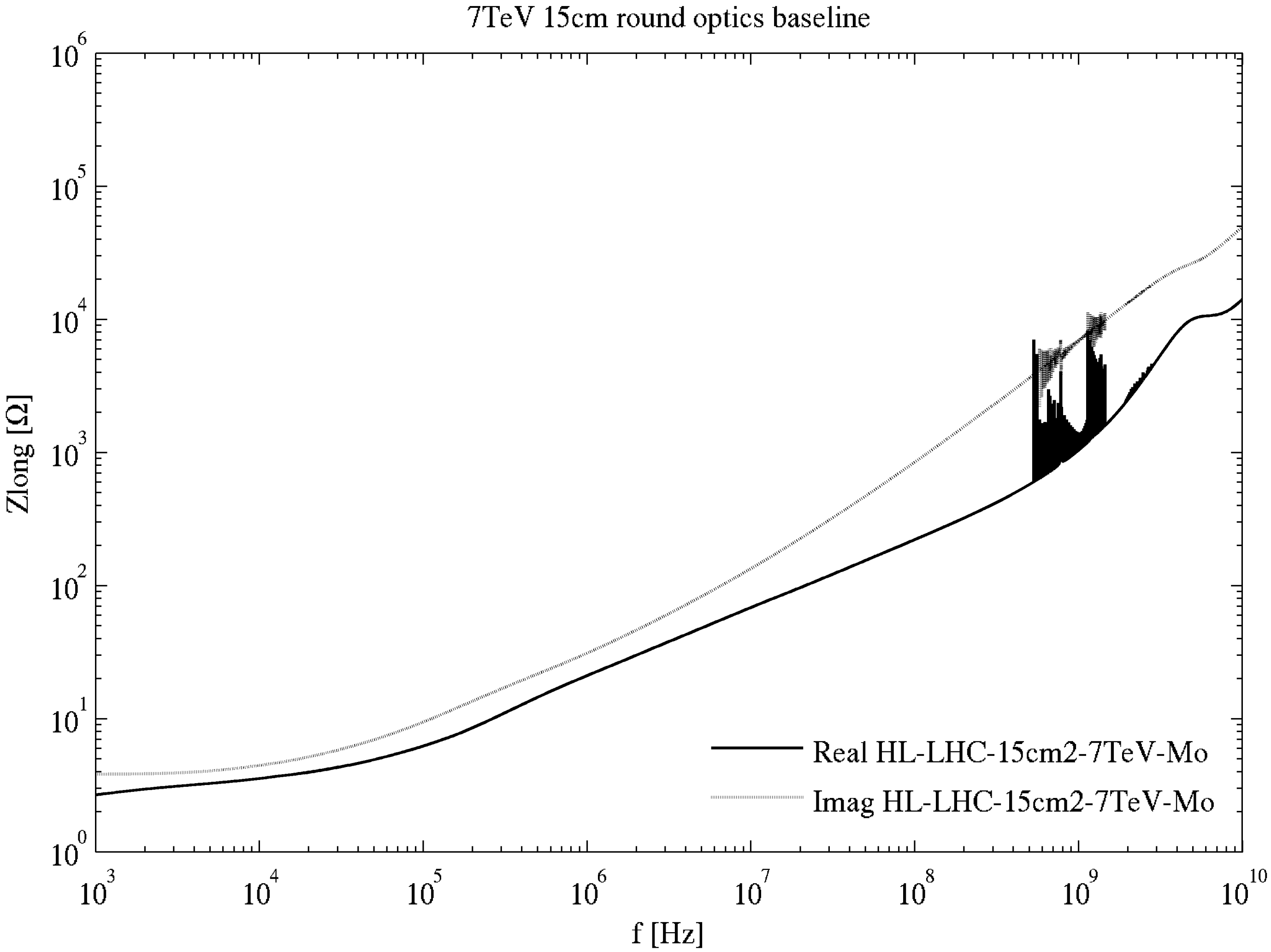
HL-LHC parameters

Parameter	Nominal LHC (design report)	HL-LHC 25ns (standard)	HL-LHC 25ns (BCMS)	HL-LHC 50ns
Beam energy in collision [TeV]	7	7	7	7
N_b	1.15E+11	2.2E+11	2.2E+11	3.5E+11
n_b	2808	2748	2604	1374
Number of collisions in IP1 and IP5 [1]	2808	2736	2592	1368
N_{tot}	3.2E+14	6.0E+14	5.7E+14	4.9E+14
beam current [A]	0.58	1.09	1.03	0.89
x-ing angle [μrad]	285	590	590	590
beam separation [σ]	9.4	12.5	12.5	11.4
β^* [m]	0.55	0.15	0.15	0.15
ε_n [μm]	3.75	2.50	2.50	3
ε_L [eVs]	2.50	2.50	2.50	2.50
r.m.s. energy spread	1.13E-04	1.13E-04	1.13E-04	1.13E-04
r.m.s. bunch length [m]	7.55E-02	7.55E-02	7.55E-02	7.55E-02
IBS horizontal [h]	80 -> 106	18.5	18.5	17.2
IBS longitudinal [h]	61 -> 60	20.4	20.4	16.1
Piwinski parameter	0.65	3.14	3.14	2.87
Total loss factor R0 without crab-cavity	0.836	0.305	0.305	0.331
Total loss factor R1 with crab-cavity	(0.981)	0.829	0.829	0.838
beam-beam / IP without Crab Cavity	3.1E-03	3.3E-03	3.3E-03	4.7E-03
beam-beam / IP with Crab cavity	3.8E-03	1.1E-02	1.1E-02	1.4E-02
Peak Luminosity without crab-cavity [$cm^{-2} s^{-1}$]	1.00E+34	7.18E+34	6.80E+34	8.44E+34
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [$cm^{-2} s^{-1}$]	(1.18E+34)	19.54E+34	18.52E+34	21.38E+34
Events / crossing without levelling and without crab-cavity	27	198	198	454
Levelled Luminosity [$cm^{-2} s^{-1}$]	-	5.00E+34 [5]	5.00E+34	2.50E+34
Events / crossing (with leveling and crab-cavities for HL-LHC) [8]	27	138	146	135
Peak line density of pile up event [event/mm] (max over stable beams)	0.21	1.25	1.31	1.20
Leveling time [h] (assuming no emittance growth) [8]	-	8.3	7.6	18.0
Number of collisions in IP2/IP8	2808	2452/2524 [7]	2288/2396	0[4]/1262
N_b at LHC injection [2]	1.20E+11	2.30E+11	2.30E+11	3.68E+11
n_b / injection	288	288	288	144
N_{tot} / injection	3.46E+13	6.62E+13	6.62E+13	5.30E+13
ε_n at SPS extraction [μm] [3]	3.40	2.00	< 2.00 [6]	2.30

HL-LHC vs LHC impedance

Longitudinal impedance

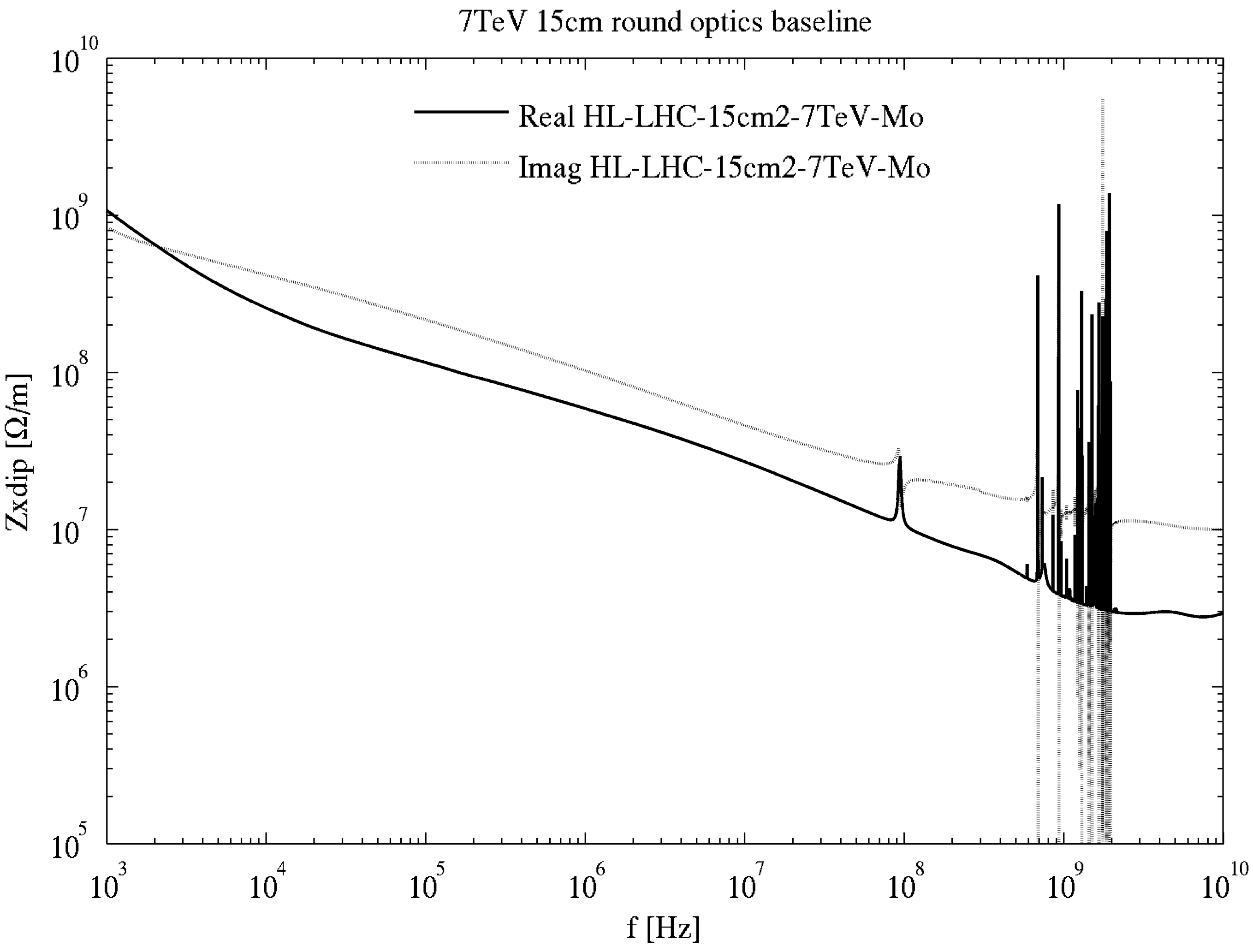
- HLLHC in the case of Mo collimator jaws,



HL-LHC vs LHC impedance

Horizontal dipolar impedance

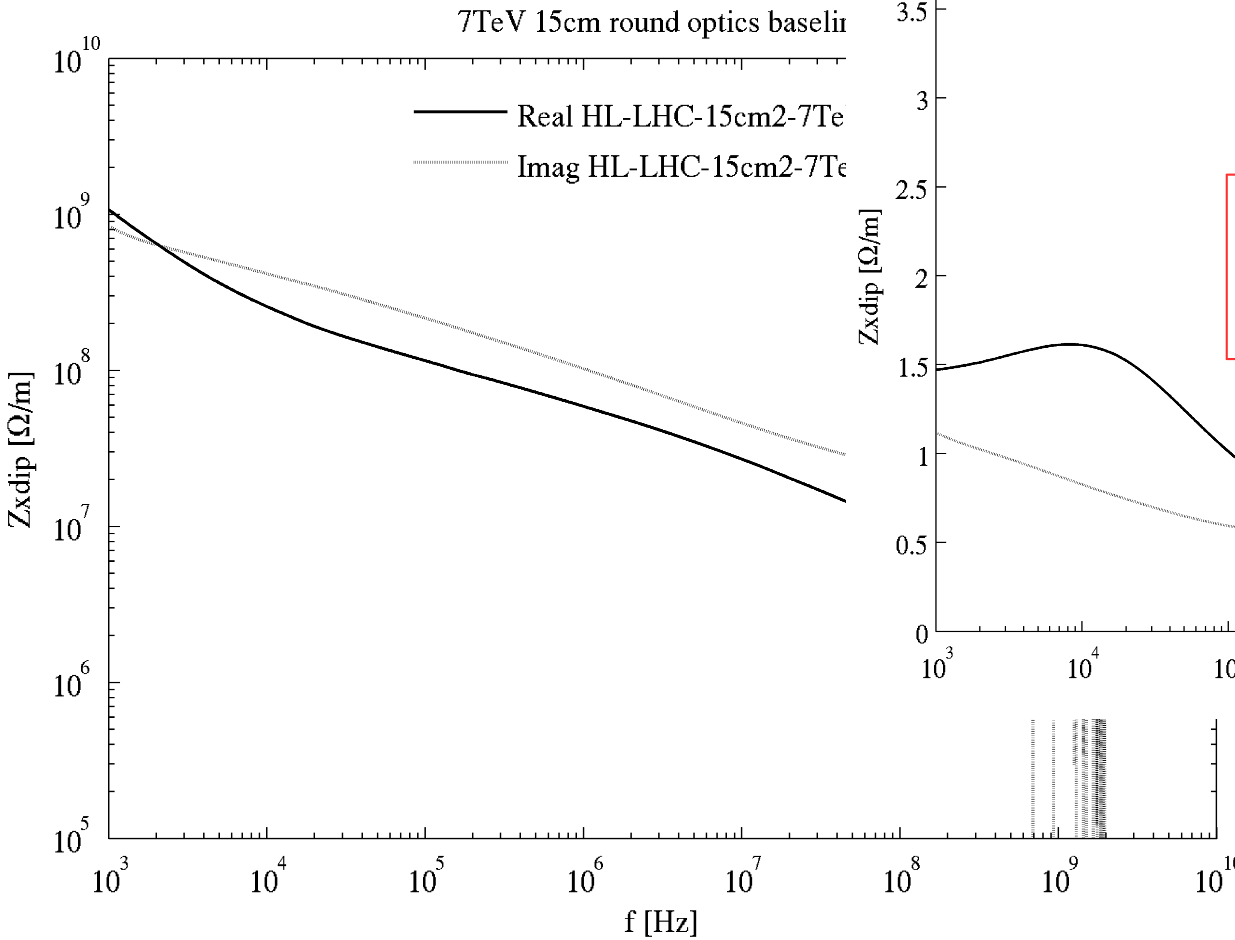
- HLLHC in the case of Mo collimator jaws,

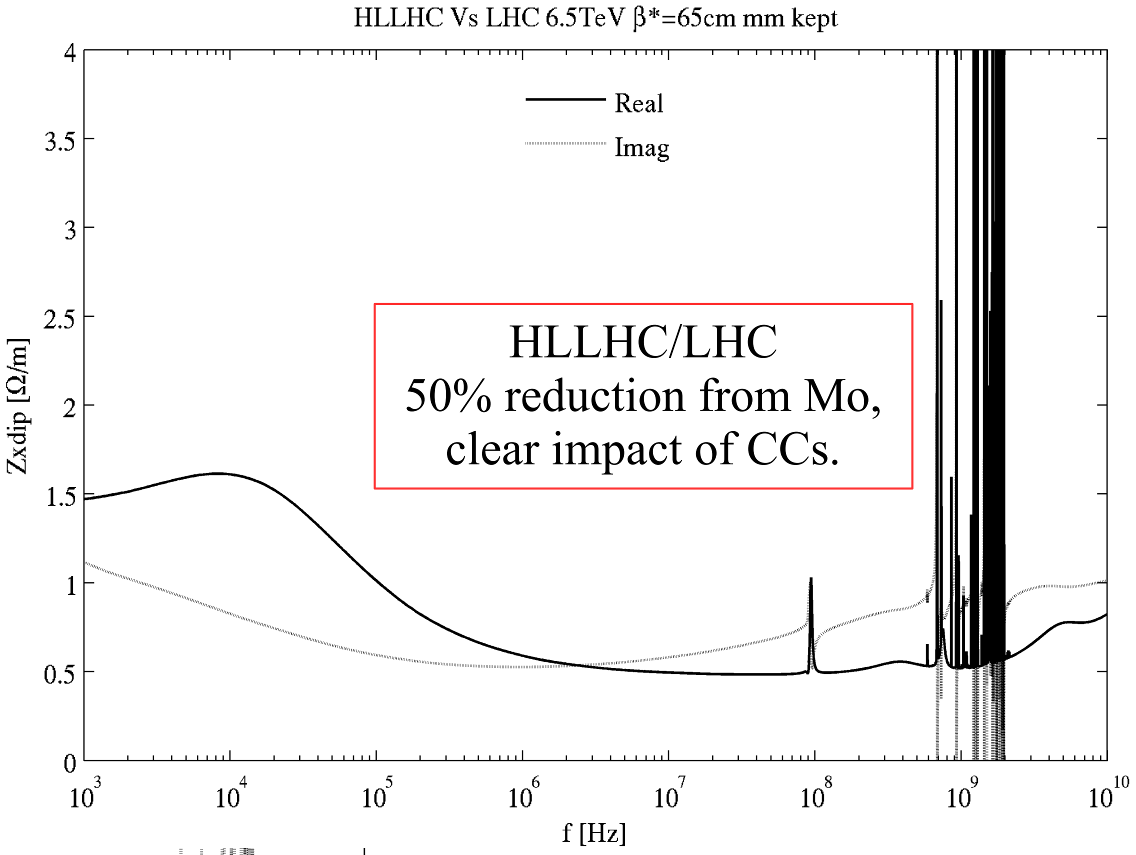


HL-LHC vs LHC impedance

Horizontal dipolar impedance

- HLLHC in the case of Mo collimator jaws,
- LHC 6.5 TeV, 65cm beta star optics..

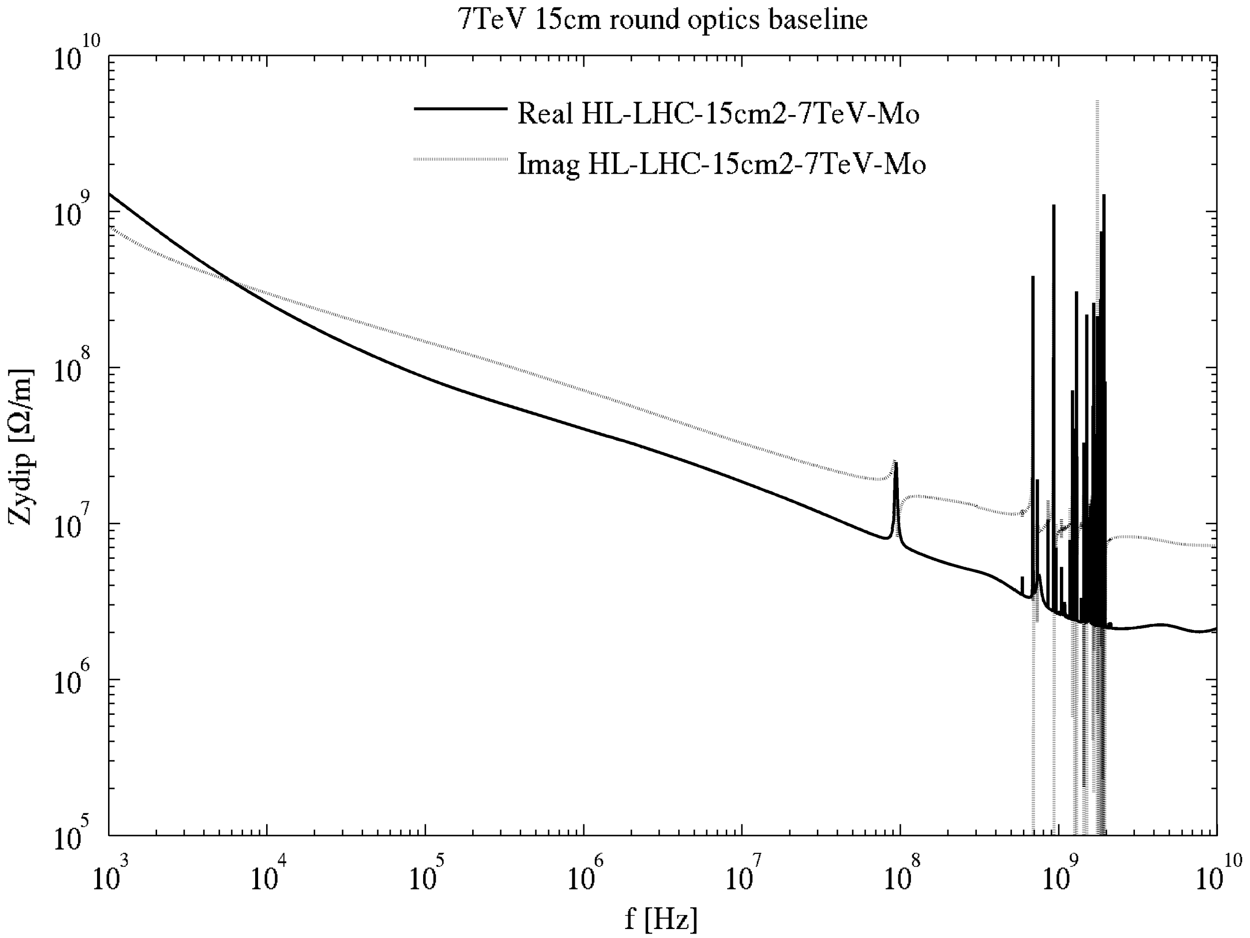




HL-LHC vs LHC impedance

Vertical dipolar impedance

- HLLHC in the case of Mo collimator jaws,



HL-LHC impedance

Horizontal dipolar impedance

- HLLHC in the case of Mo collimator jaws,