Update on the HL-LHC impedance budget

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CERN, 15-10-2014

HL-LHC WP 2 Task 2.4

Acknowledgements: B.Salvant, E.Métral, N. Mounet, O. Frasciello, M. Zobov, A.Mostacci, J. Uythoven, A. Lechner, A. Marcone, R. Bruce.

Outline

- Status of the LHC impedance model Vs measurements.

- Possible explanation for the LHC model discrepancy Vs measurements:
  - Finite length of collimators
  - Geometrical impedance contribution
  - Aging of collimators

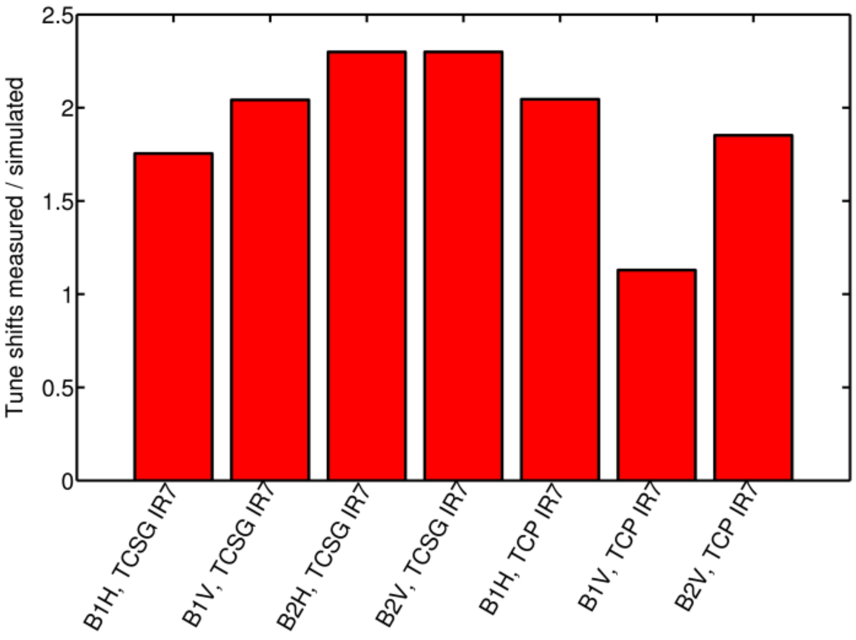
- HL-LHC impedance reduction strategy:
  - Mo/MoC jaws
  - TCT low frequency mode
  - TDI re-design

- Conclusions and outlook

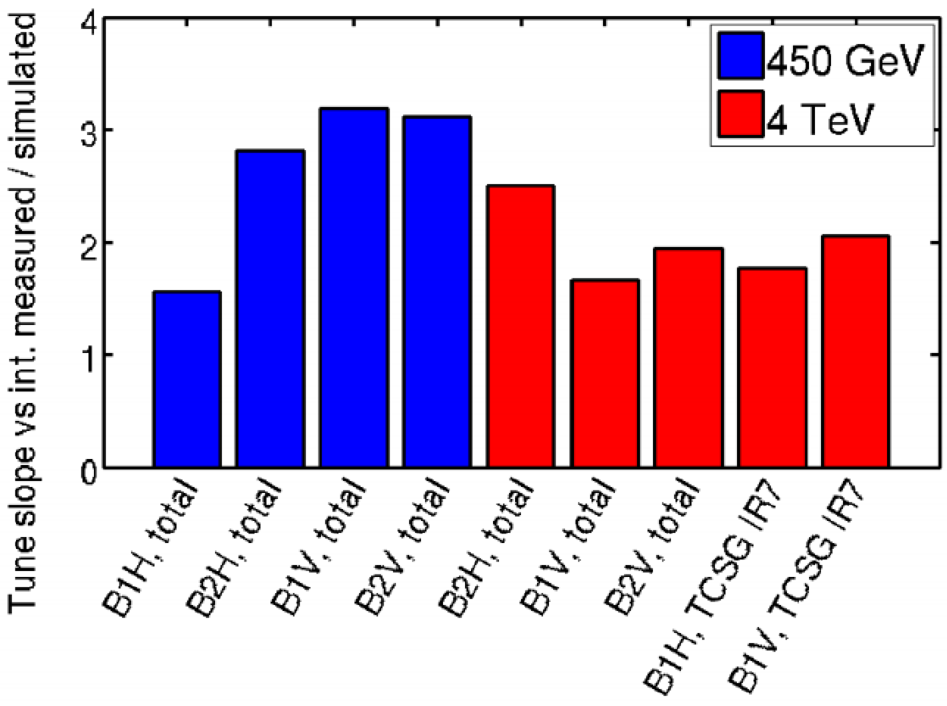
Measurements Vs Model

Observations:

- Factor ~3 discrepancy between measured and simulated tune shifts Vs intensity at 450 GeV.
- Factor ~2 discrepancy between measured and simulated tune shifts Vs intensity at 4TeV.



Courtesy of N.Mounet



Possible explanations:

1. Effects of finite length on collimator impedance model.
2. Collimator geometrical impedance contribution.
3. Effect of radiation on jaws conductivity during the years.

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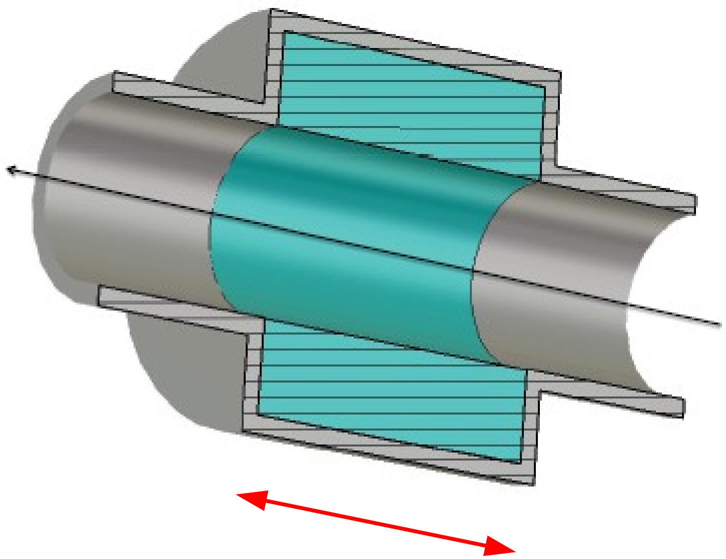
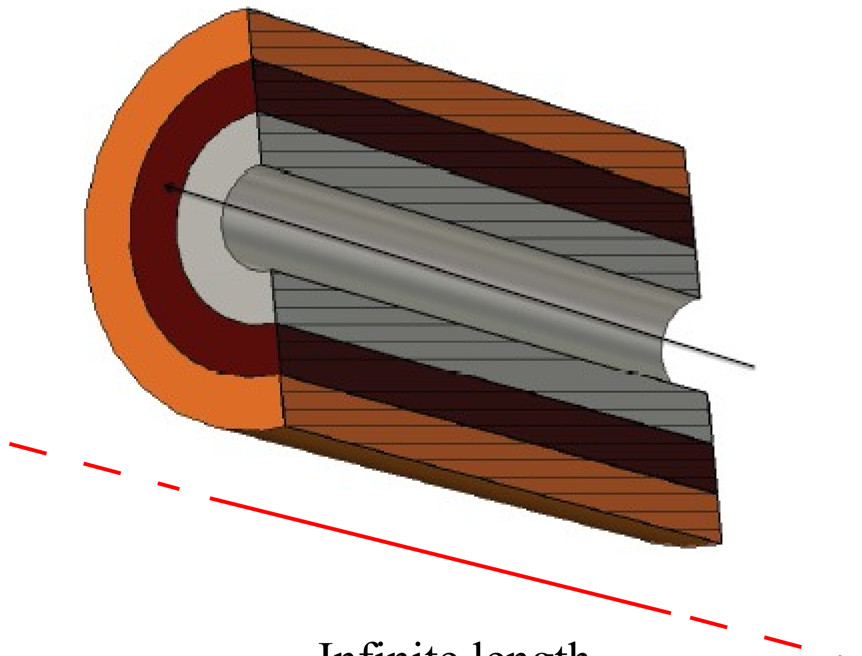
In other words:

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



Finite length



Infinite length

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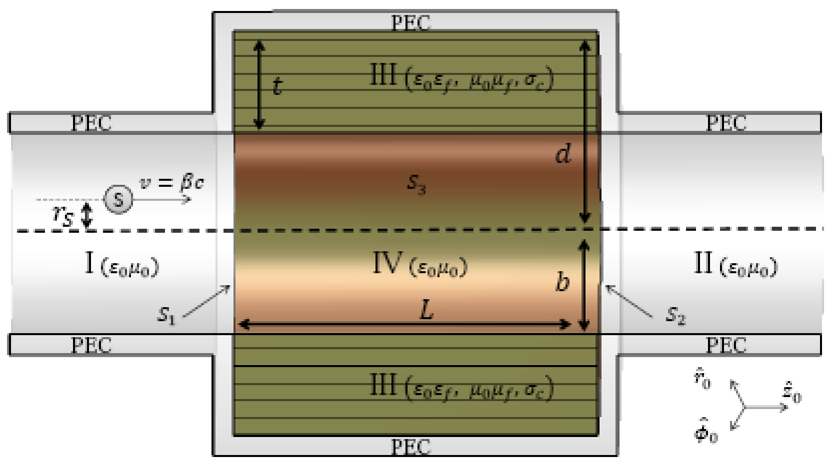

We applied the Mode Matching method in order to solve the related EM problem:

1) Decompose EM fields in sub-volumes.

2) Match opportunely the EM fields at the surfaces in between.

3) Compute ratio between the impedance of finite length Vs the infinite length approximated one.

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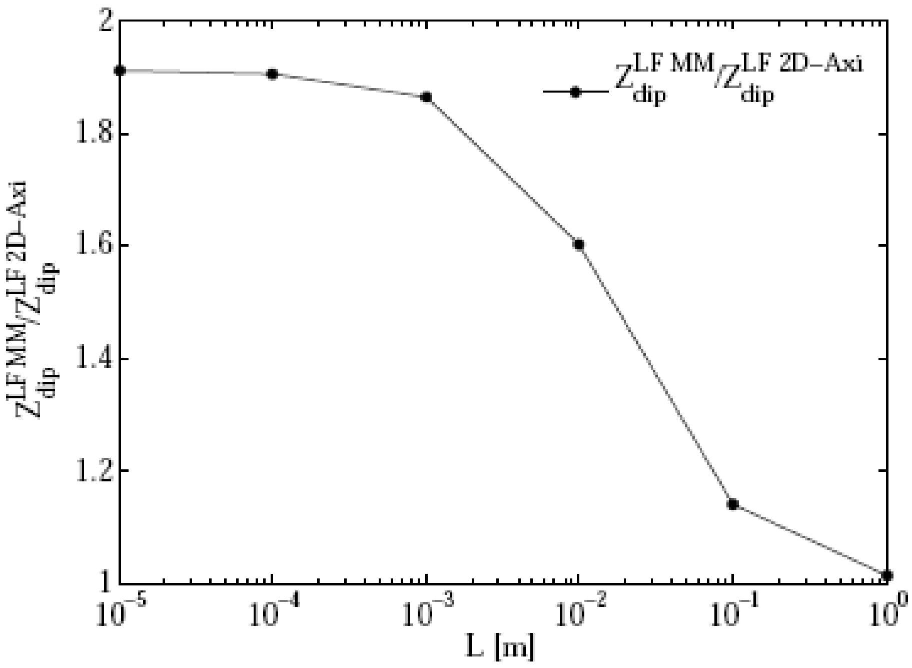

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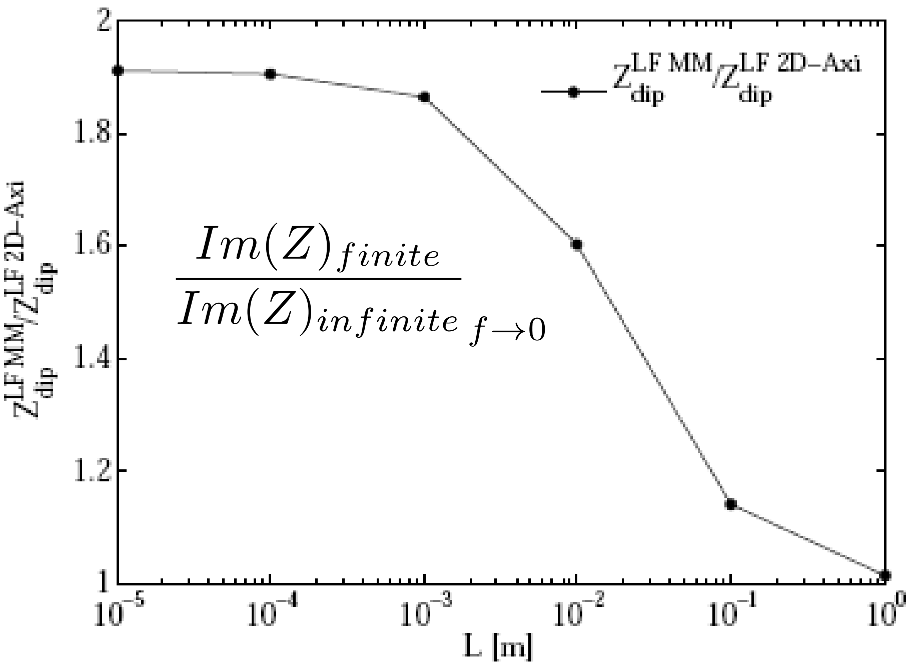

Example of dipolar impedance of a carbon collimator (resistivity=1e-6):

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

Negligible for the LHC collimators

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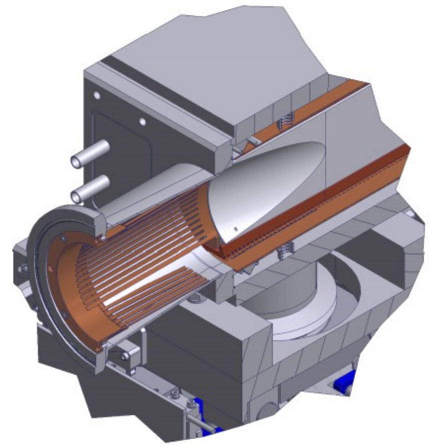

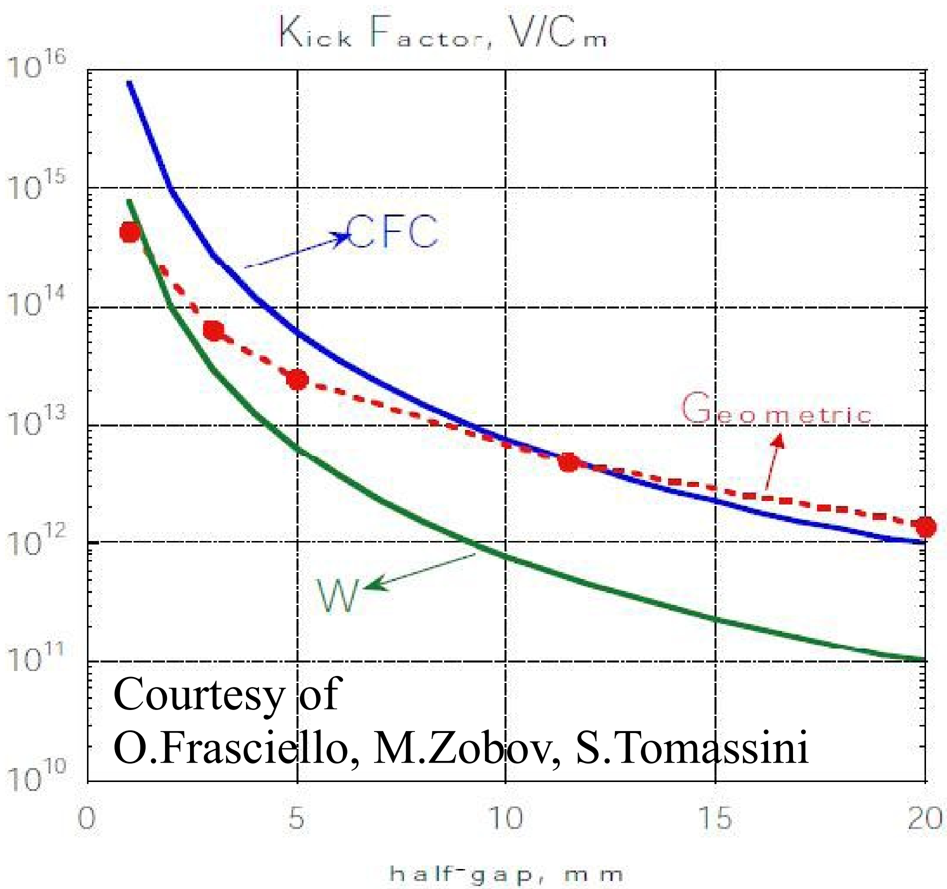

Geometrical flat transitions accounted with G.Stupakov formula:

$$Z_T = j\frac{Z_0 w}{4}\int \frac{(g')^2}{g^3}\,\mathrm{d}z$$

Results:

- Strong impact for CFC collimators above 8mm half gap..
- Strong impact for W (tungsten) collimators all over the gap range.

Upto 20-30% at 1 GHz!

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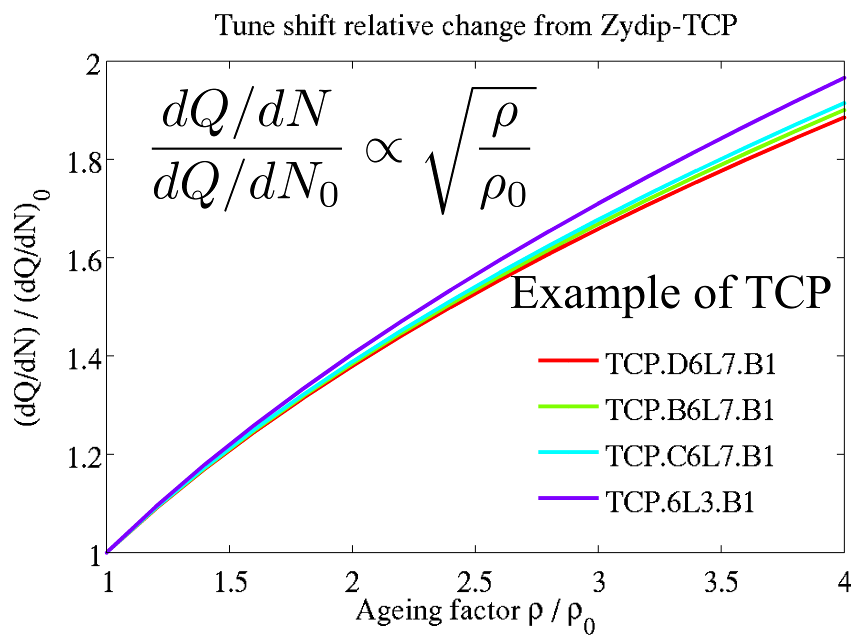
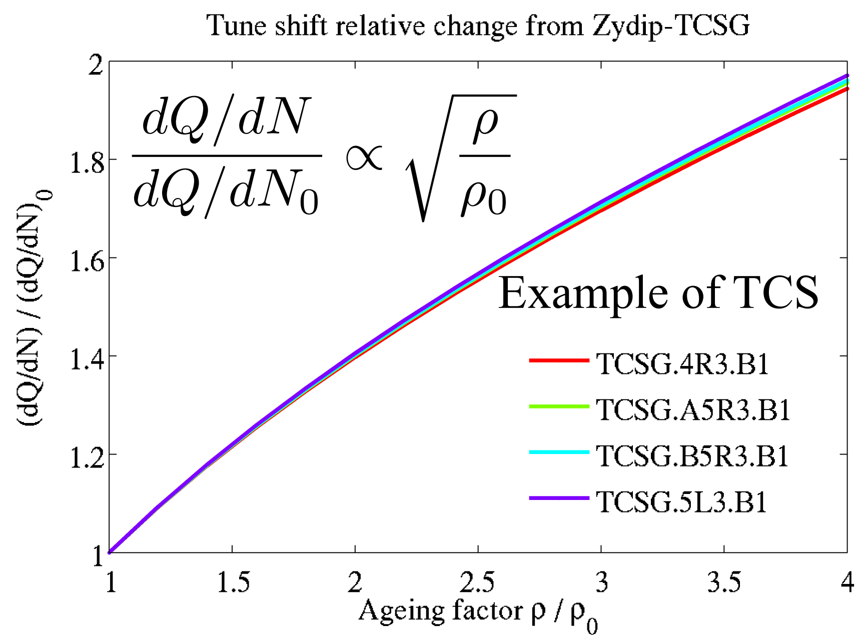
- The primary and secondary collimators are more exposed to radiation.
- Studied the effect of "aging" the CFC in TCP and TCSG increasing the resistivity by a factor:

$$\text{Aging factor} = \rho/\rho_0$$





Strong impact. Confirmation is needed through updated conductivity measurements.

Molybdenum jaws

HL-LHC impedance reduction strategy:

1. New Molybdenum jaws in IP3 and IP7 → Impedance reduced of order of magnitude!

Possible different material scenarios:

1. MoC: Molybdenum Carbon only.
2. Mo: Molybdenum only.
3. Mo coating on CFC.
4. MoC on CFC.

Studied the HL-LHC impedance model with 15 cm round optics.

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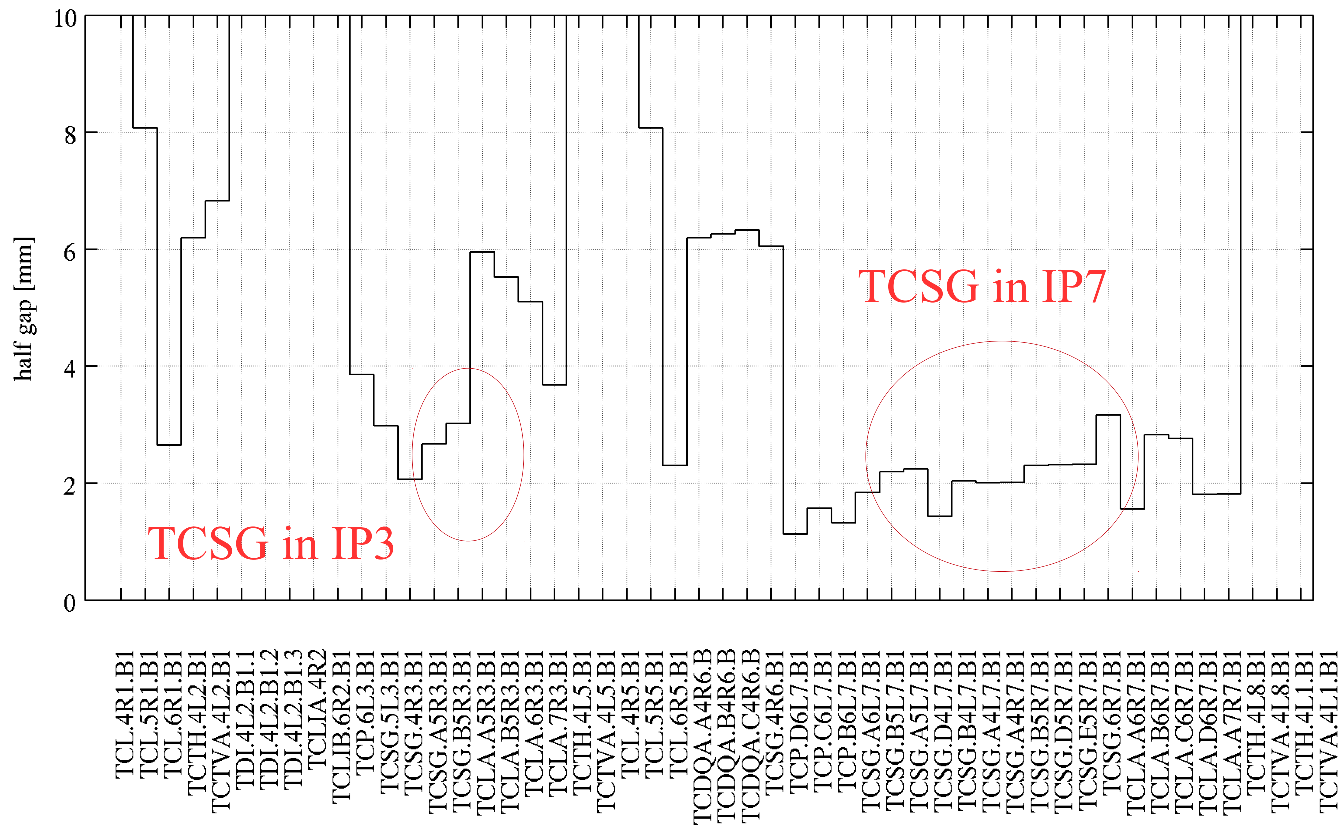

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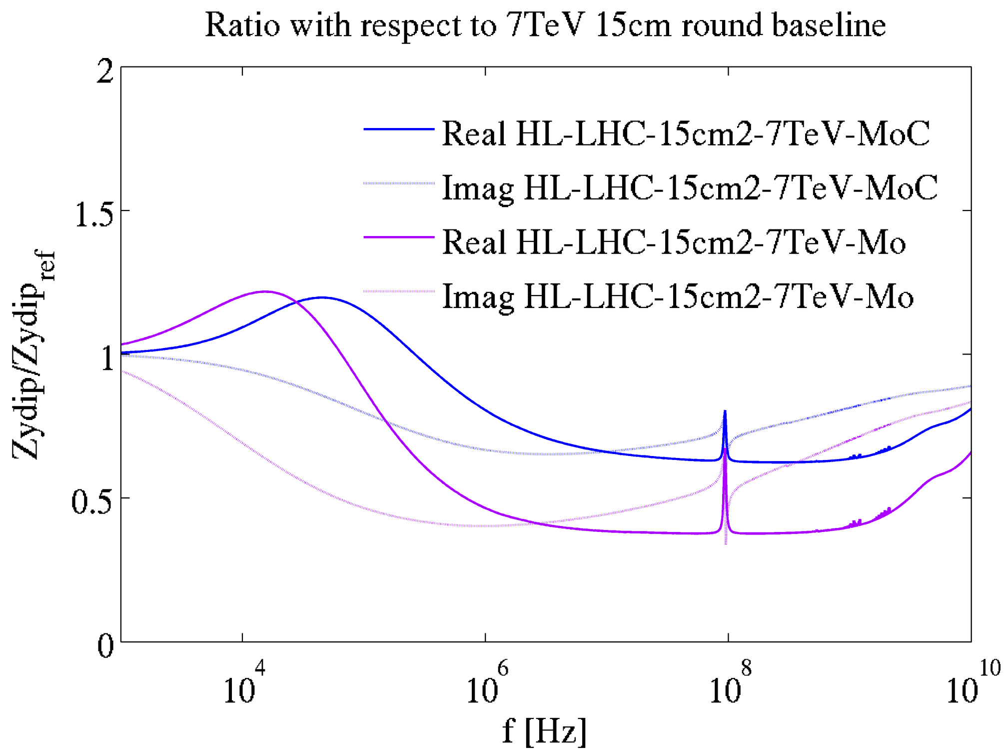

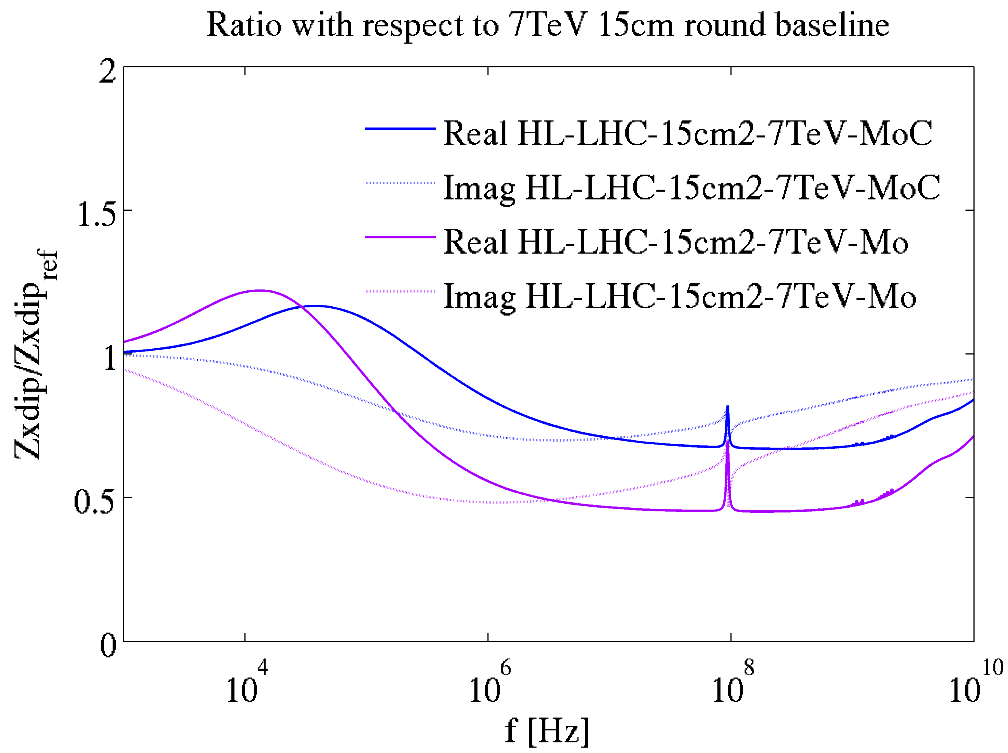

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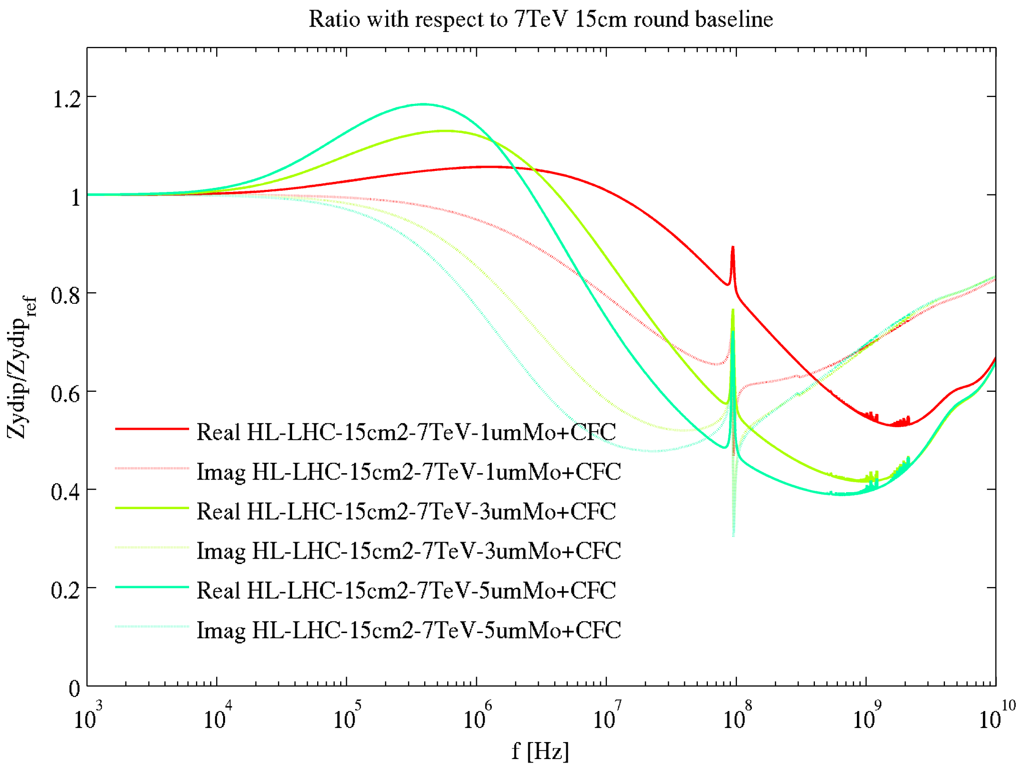

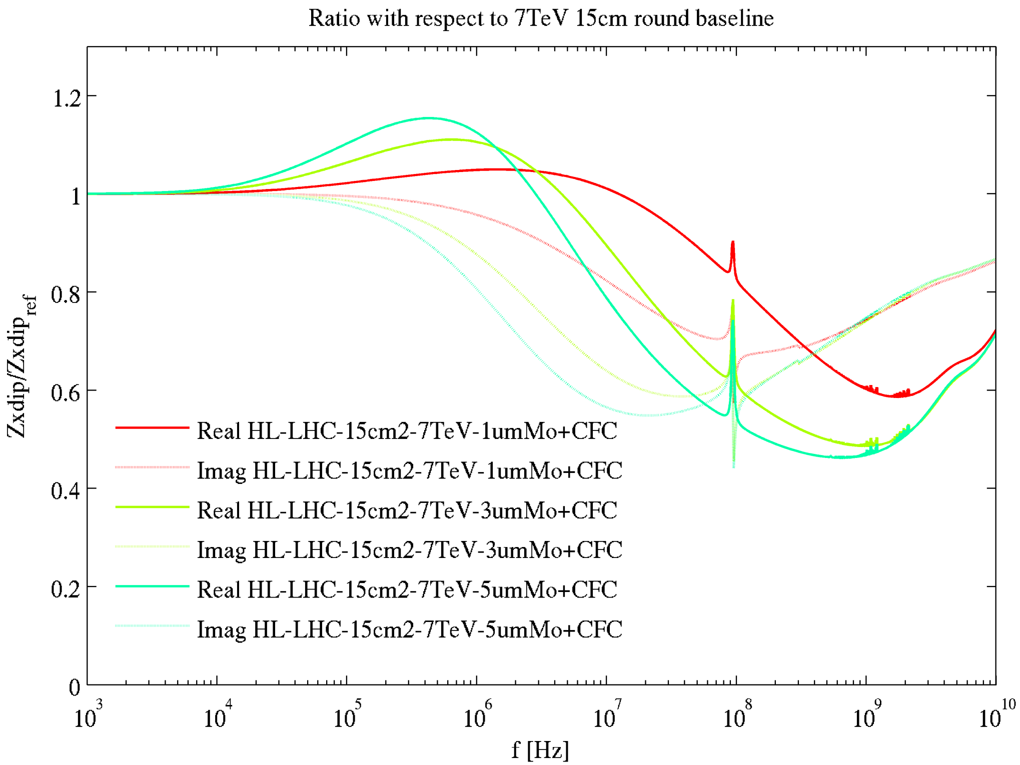

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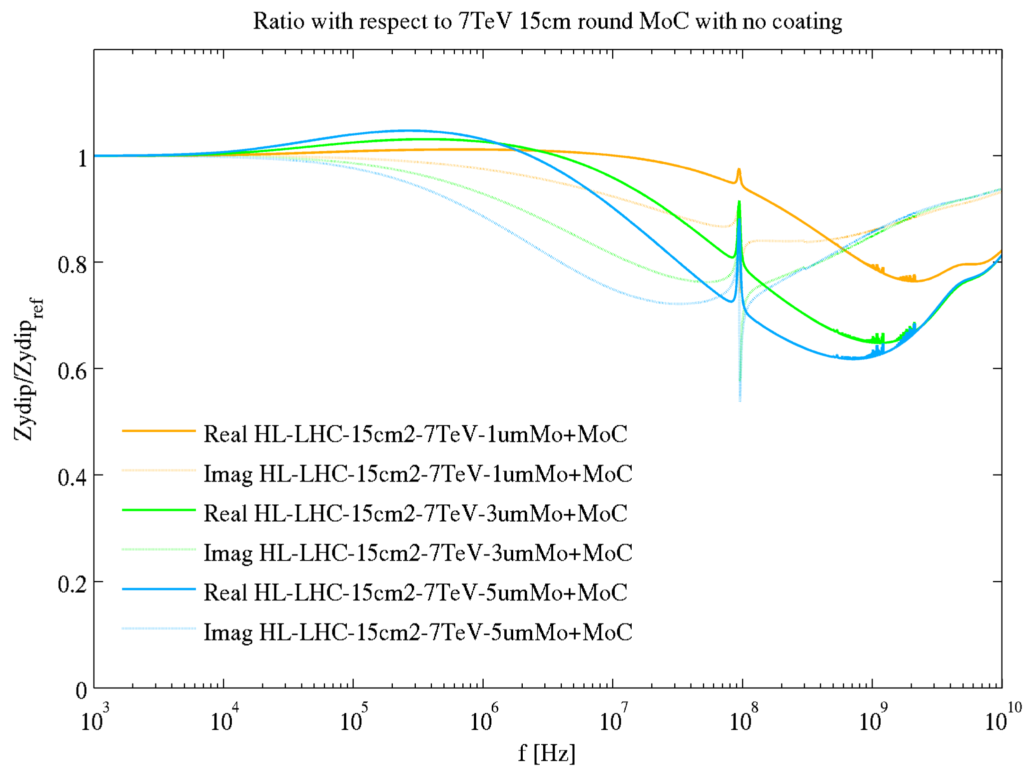
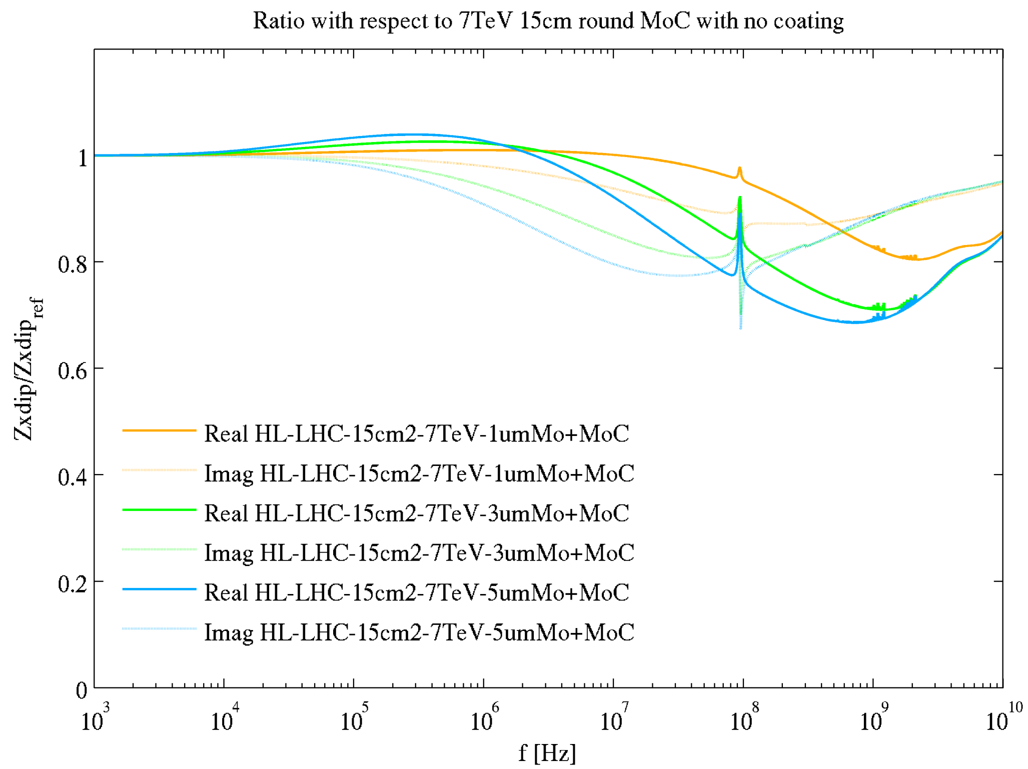
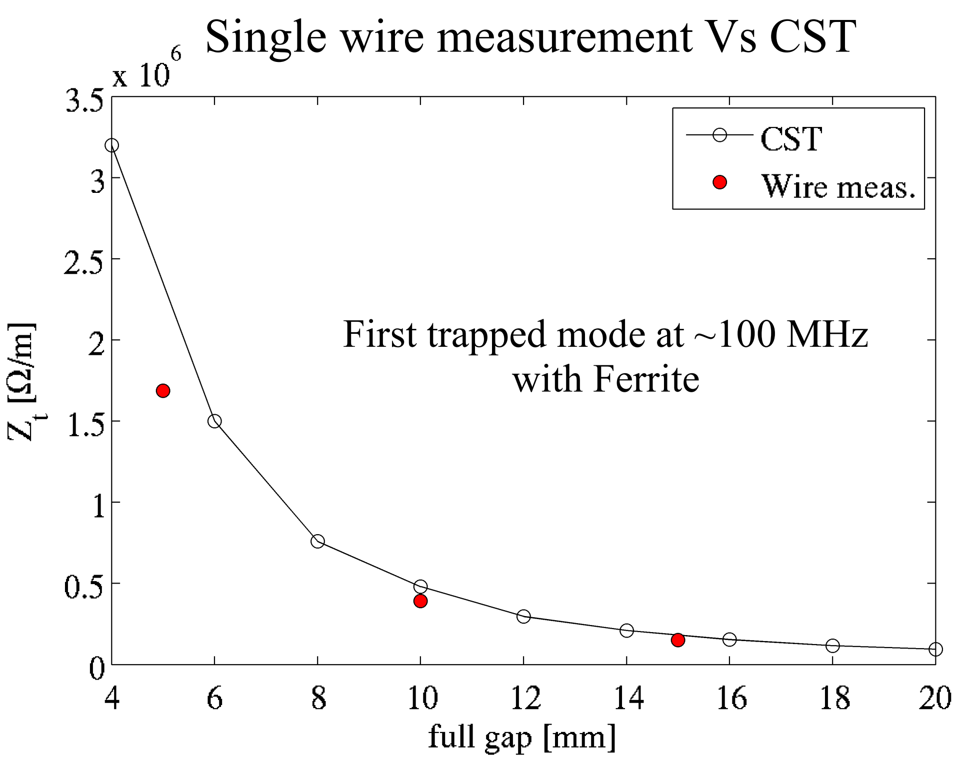




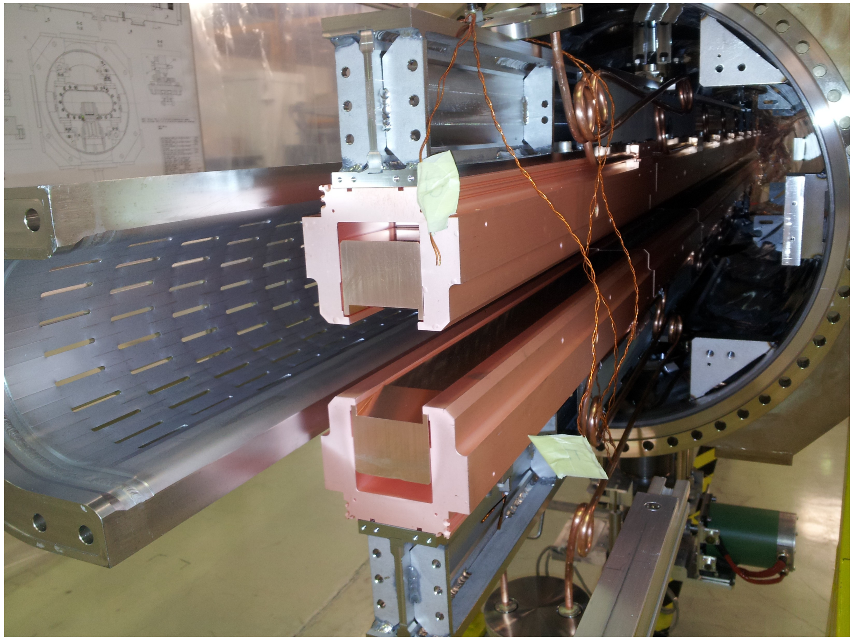
TCT – TCSG.4R6 trapped mode

Present TCT-TCSG in IP6 design:
1. Potentially harmful low frequency modes.

Impedance bench measurements:
1. Confirm the presence of the mode.
2. Parallel simulations will disentangle the nature of the mode (longitudinal Vs transverse)
3. For the moment good agreement between simulation and measurements (Zt Vs gap)
4. More simulations in collaboration with INFN-LNF will be soon available.



New TDI design



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

Impedance bench measurements:
1. Confirmed the presence of the low frequency modes.

Short term: post-LS1 mitigation:
1. Change of the beam screen from copper to stainless steel → more robustness.
2. 1um Ti + 2um Cu coating → power loss reduction.

Long term: Device re-design from scratch:
1. Iterations with the collimation and INFN-LNF group to take into account:
   - mechanical feasibility (number of modules, transition geometry, gaps, etc..)
   - impedance compatibility (transition + jaw material)

Conclusions and next steps

Update on the HL-LHC impedance model:

1. **Finite length:** crosschecked the impact of the infinite length approximation with the rigorous application of the Mode Matching → negligible impact on collimator impedance.
2. **Geometrical impedance:** high impact on tungsten jaws and on CFC ones for h.g > 8mm.
3. **Aging of collimators:** could explain why we have higher measured impedance. We would need measurements of conductivity Vs dose or some estimation.
4. **Mo-MoC scenarios:** updated alternatives for full Mo, MoC replacement of CFC jaws and coatings.
5. **TCT mode:** potentially harmful mode also in the HL-LHC scenario → DELPHI simulations planned.
6. **TDI:** short-term solution for the post-LS1 LHC. Iterative re-design ongoing!

Next steps:

1. Replacement of the BPM broadband model with accurate impedance estimations.
2. Update of the other broadband impedances (valves, Y chamber, …) from design report.
3. Update of the Crab Cavities design → impedance HOM updated list.
4. ….

Thanks!

Some material electrical properties

Material properties:

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

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