Transverse impedance in the HL-LHC era

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R. Wanzenberg, O. Zagorodnova (DESY)

Acknowledgements: G. Arduini, V. Baglin, C. Boccard, G. Bregliozzi, R. Calaga, H. Day, L. Esposito, J. Esteban Müller, S. Fartoukh, A. Grudiev, R. Jones, R. Kersevan, N. Kos, R. de Maria, A. Mostacci, U. Niedermayer, A. Nosich, S. Redaelli, B. Salvachua, E. Shaposhnikova, R. Steinhagen, M. Taborelli, E. Todesco, S. Tomassini, G. Valentino.

Transverse impedance in the HL LHC era

- Introduction: status of the LHC impedance model in 2012
- Refining the LHC impedance model
- What is changing for HL-LHC
- Comparison between LHC & HL-LHC impedance for various configurations
- Conclusions

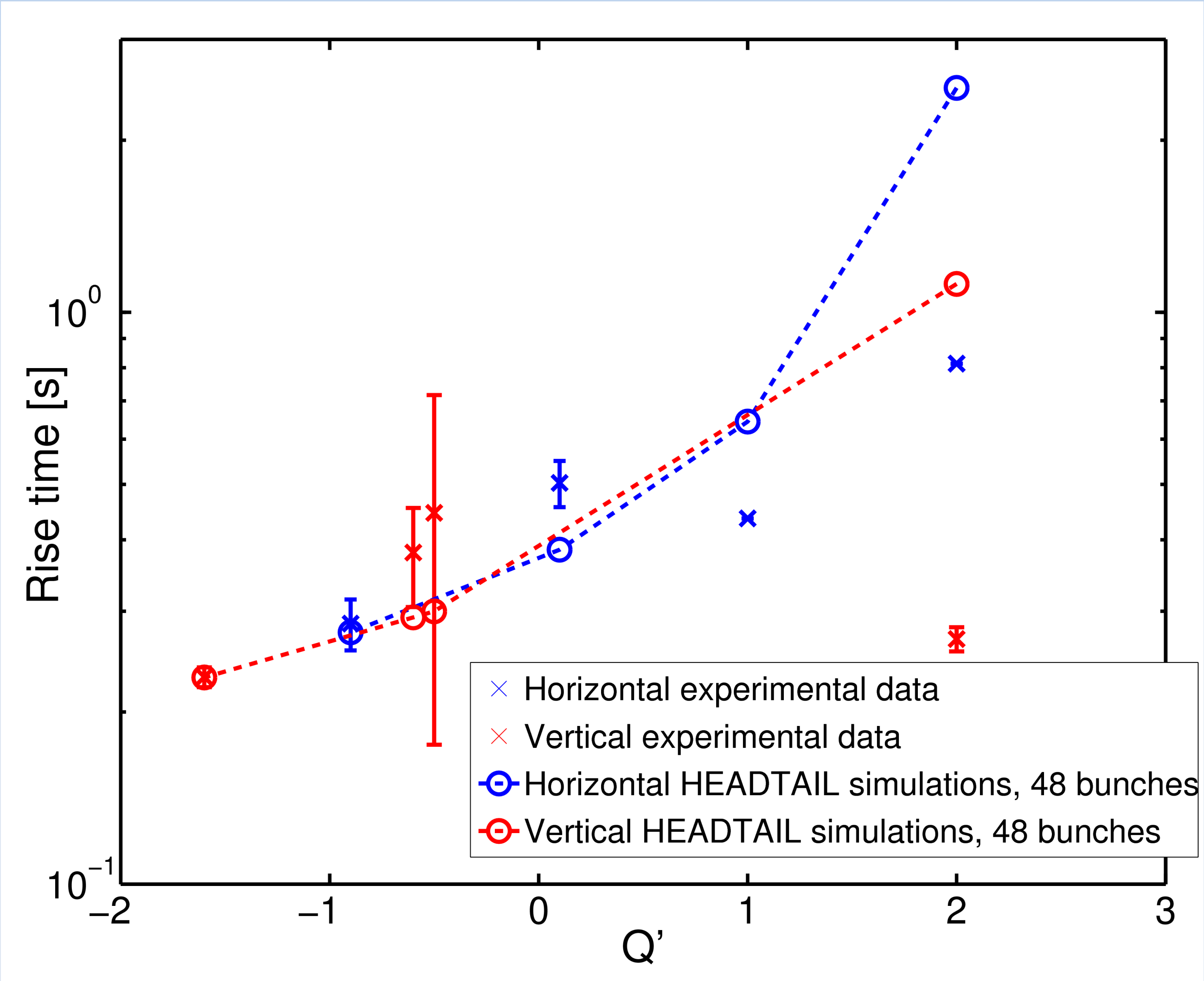
Previous status of the LHC impedance model

- Up to now, LHC impedance model included:
  - resistive-wall impedance of collimators,
  - resistive-wall impedance of beam screens and warm vacuum pipe (several different cross-sections),
  - broad-band model from design report, including pumping holes, BPMs, bellows, vacuum valves, geometric impedance of collimators (round tapers), other BI instruments.

  All weighted by local beta functions.
- Model was initially designed to account well for coupled-bunch instabilities → low frequency (from 8KHz to 40 Mhz) impedance.

”Old” LHC impedance model: coupled-bunch instabilities simulations vs measurements

- 12+36 bunches at 450GeV/*c*, coupled-bunch instability rise times measured vs. simulations (beam 2) (May 2011)



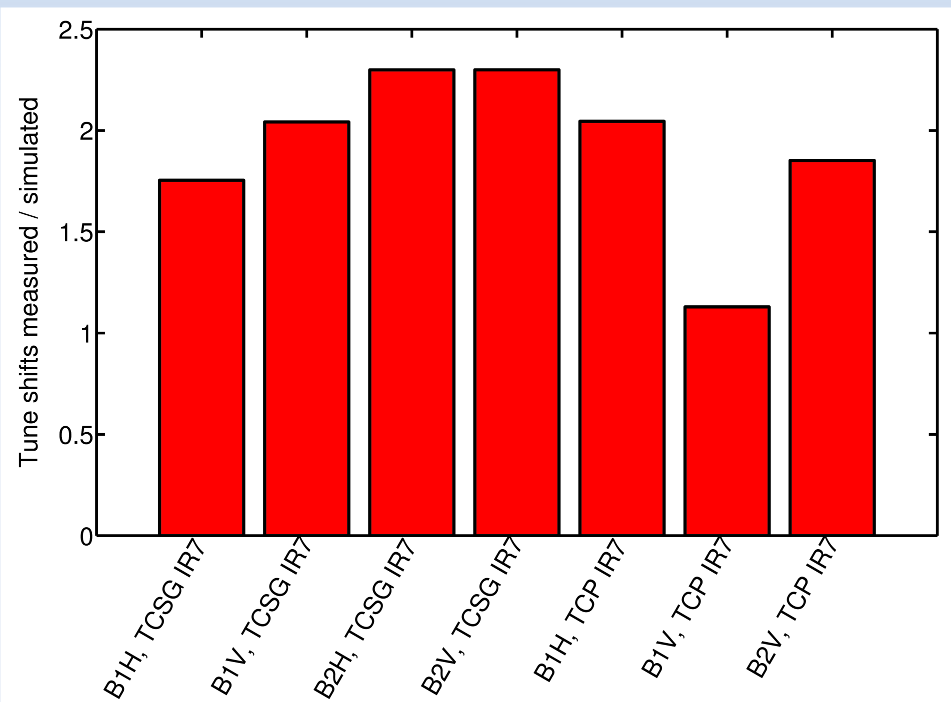
→ measured rise times were well reproduced by the model.

Note: at 3.5 TeV/c, measurements rather at a factor 2-3 from the model, but higher uncertainty on chromaticity because octupole feed-down errors were not taken into account...

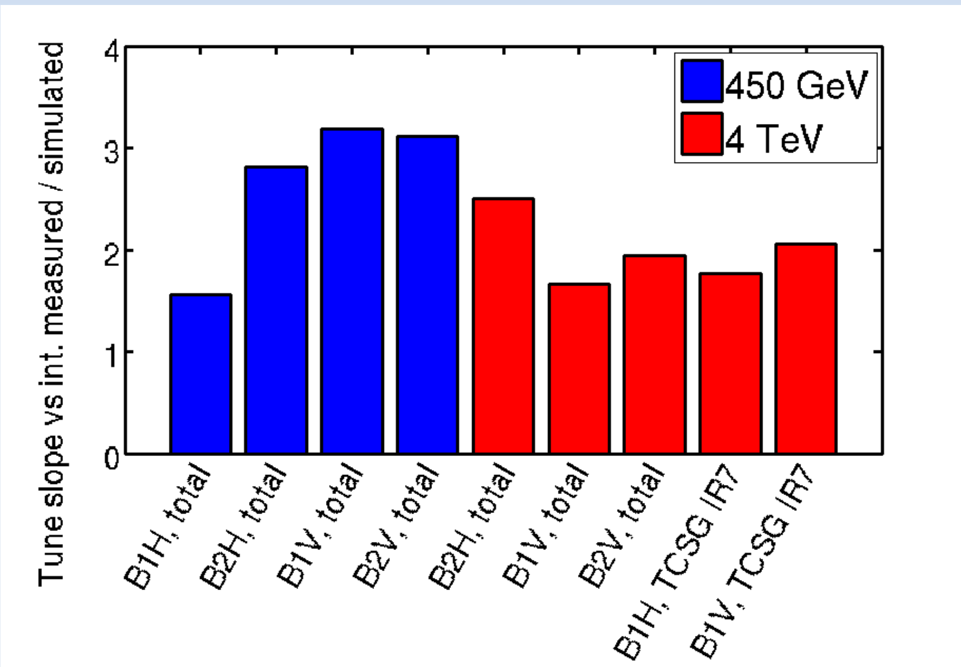
"Old" LHC impedance model: tune shifts simulated / measurements

- Tune shifts measurements when moving collimator families at 4TeV (*Q' ~ 1-5*)
  → compare tune slope w.r.t. intensity between simulations & measurements:

Collimator tune shifts (2012)



Total tune shifts (2012)

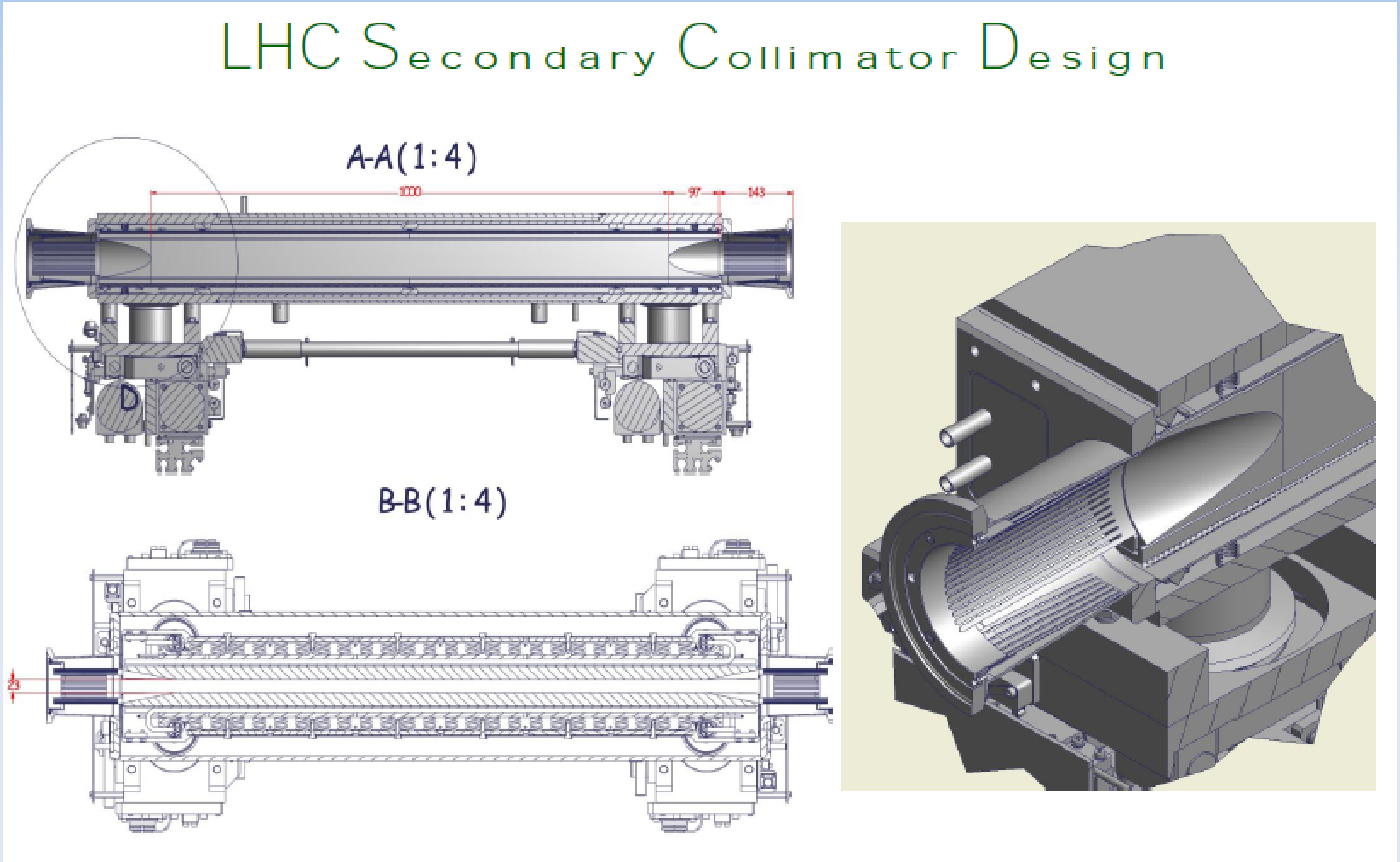


→ Discrepancy factor around 2 (3 at injection energy),
→ model had to be refined for single-bunch (high frequency, i.e. ~Ghz) effects.

Refining the LHC impedance model

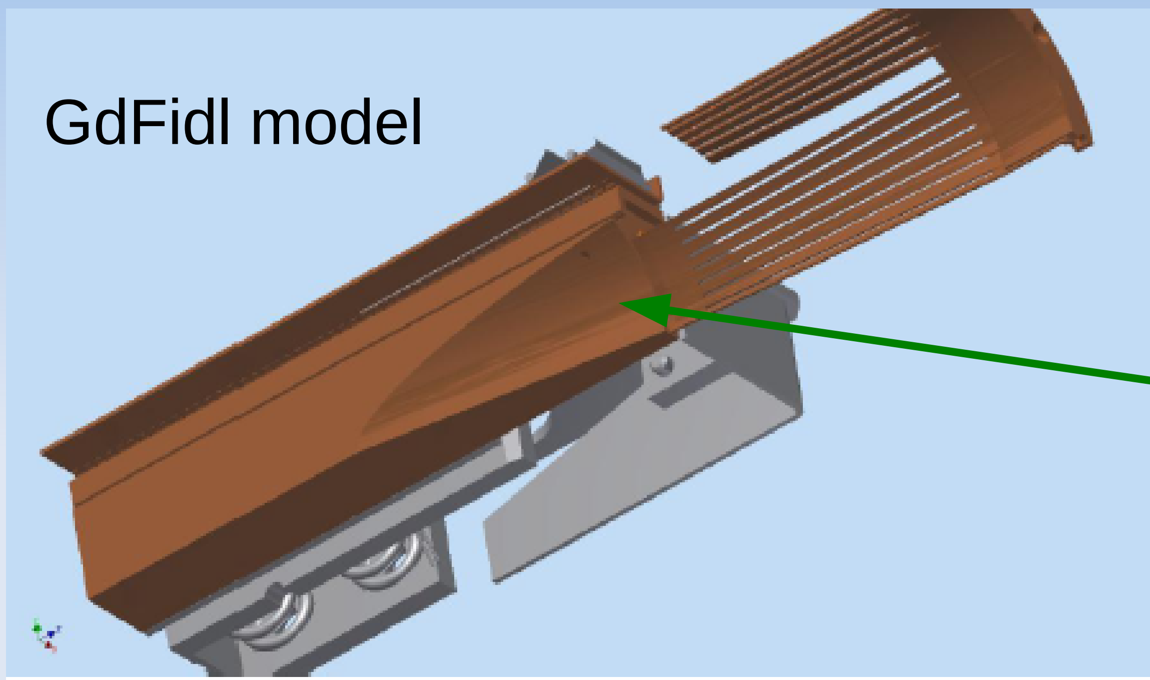
- Updates / additions to the LHC model:
  - geometric impedance of collimators re-evaluated from Stupakov formula (pessimistic, maybe by factor 2), geometric wake function directly from GdFidl computations (M. Zobov & O. Frasciello - INFN),
  - refine resistive-wall impedance of beam screens and warm vacuum pipe, including NEG for the latter, effect of weld for the former (C. Zannini),
  - pumping holes impedance re-evaluated thanks to S. Kurennoy formula & A. Mostacci,
  - details of the triplet region (tapers – Yokoya formula, BPMs from B. Salvant),
  - Broad-band and high order modes of RF cavities (E. Haebel et al, CERN sl-98-008), CMS (R. Wanzenberg, LHC Project Note 418), ALICE and LHCb experimental chambers (B. Salvant).

Geometric impedance of current collimators



M. Zobov, O. Frasciello, S. Tomassini (INFN)

Geometric impedance of current collimators



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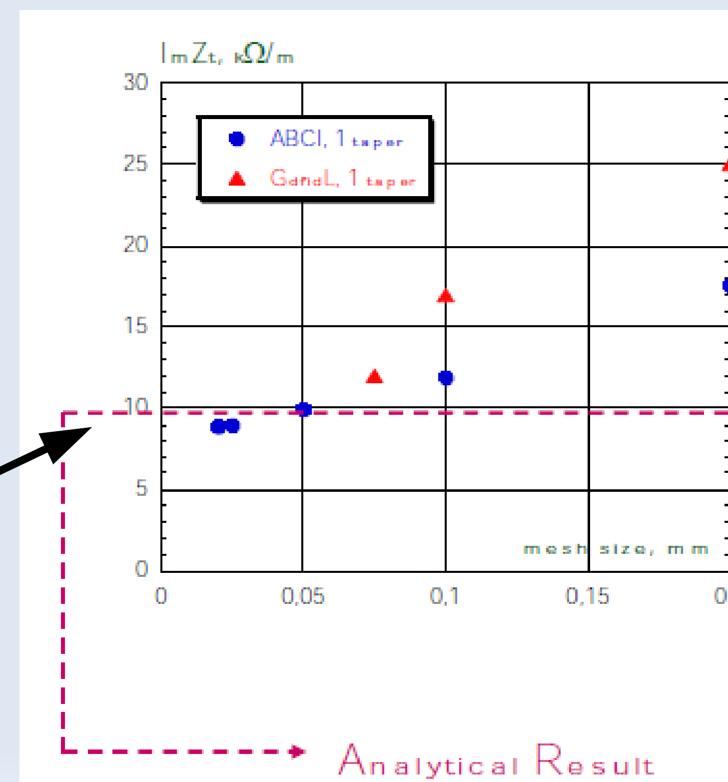
Very small mesh size needed (due to taper): < 0.2mm

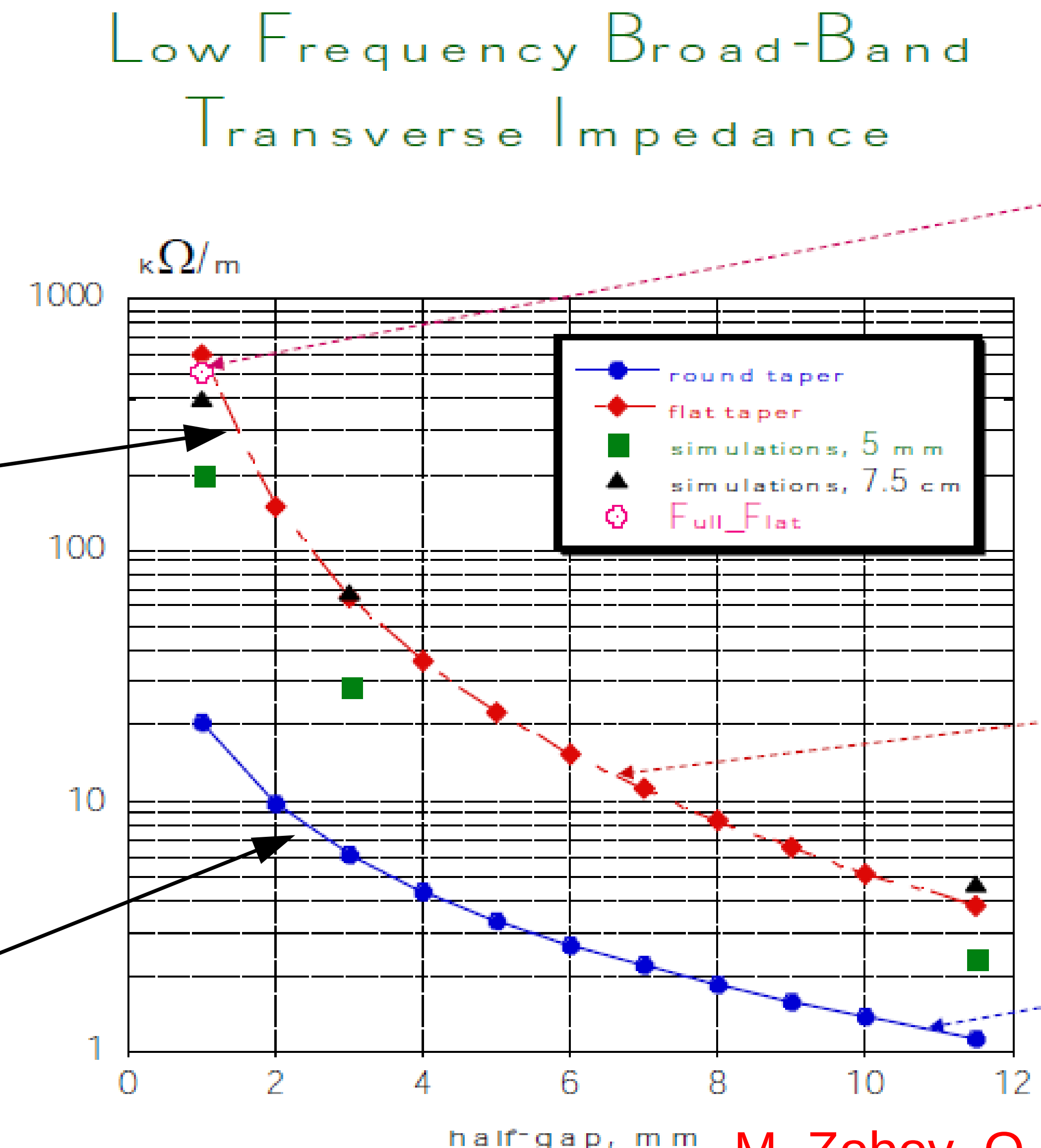


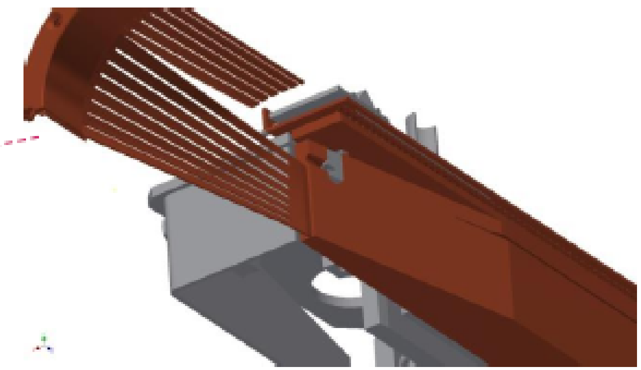
Example of convergence study (for round taper here)

Geometric impedance of current collimators

New geometric model

Previous geometric model





$$Z_T = j\frac{Z_0 w}{4}\int dz \frac{(g')^2}{g^3}$$

$$Z_T = j\frac{Z_0}{2\pi}\int dz \left(\frac{b'}{b}\right)^2$$

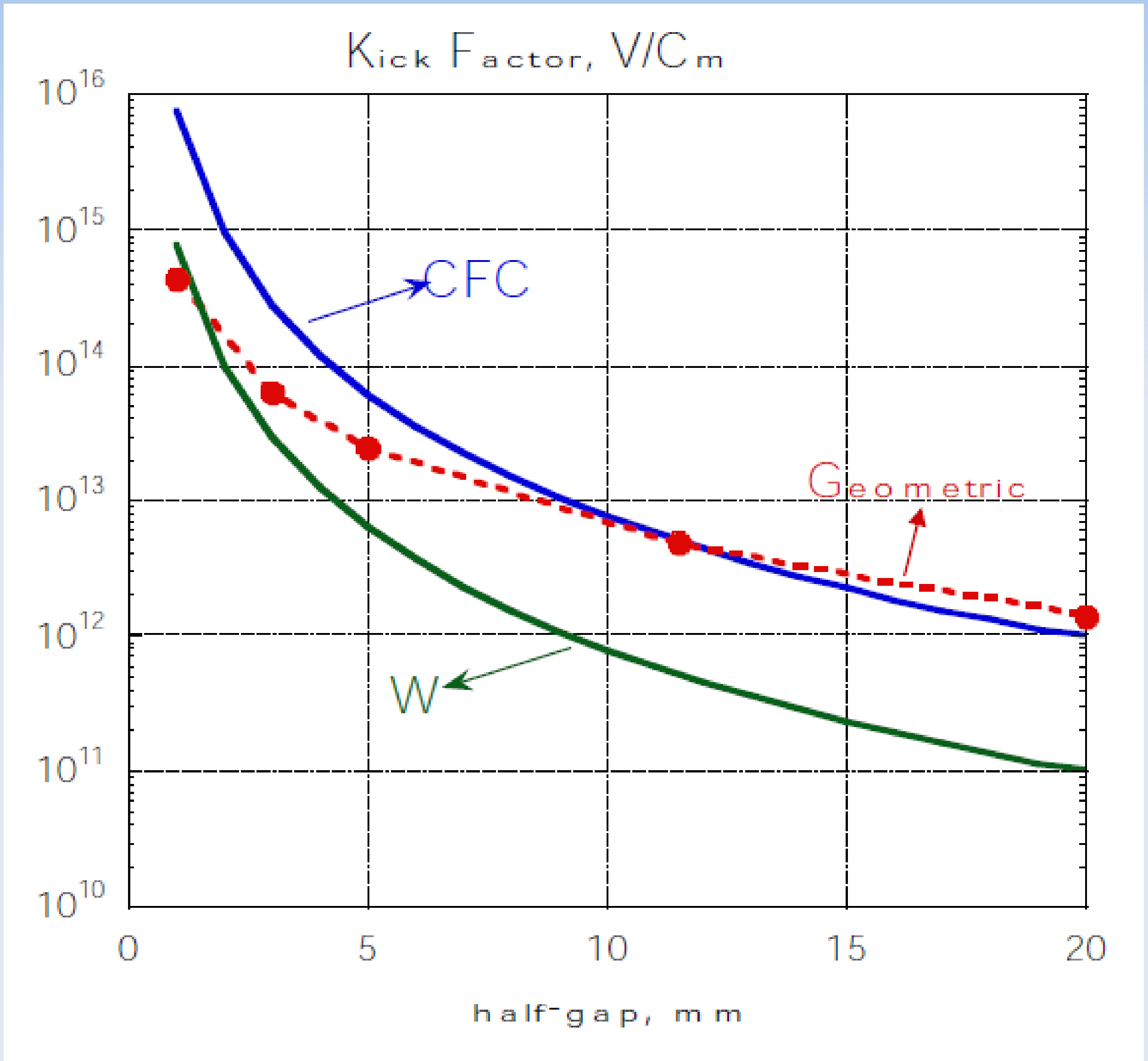
M. Zobov, O. Frasciello, S. Tomassini (INFN)

Geometric impedance of current collimators

From a simple "kick factor" analysis (~single-bunch tune shifts):

→ Geometric impedance dominates tungsten collimators,

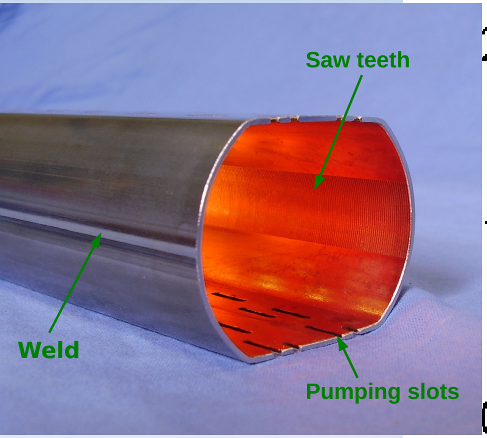
→ geom. imp not negligible w.r.t RW imp. of (relatively opened) CFC collimators (IR6, or TCP/TCS at injection).



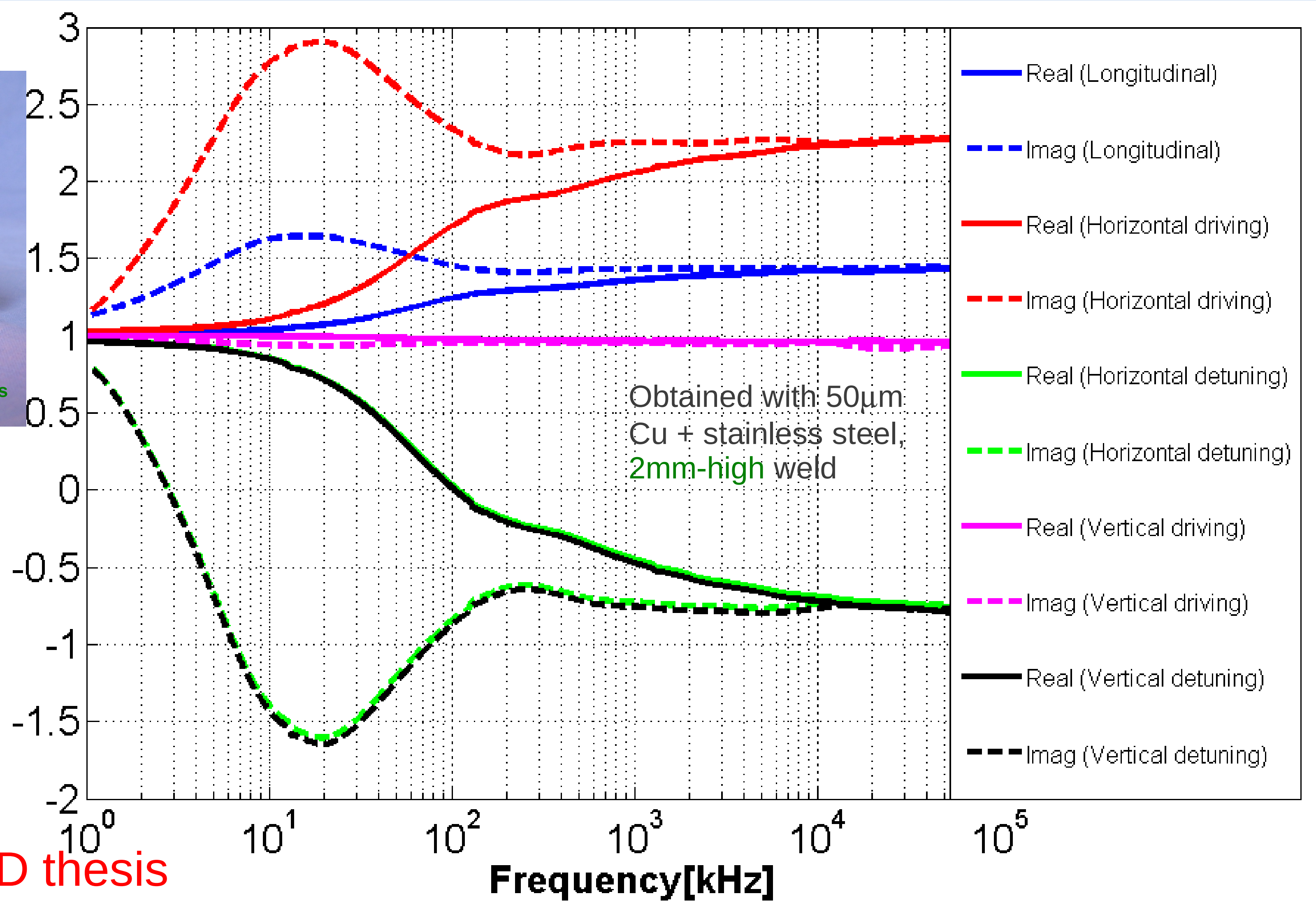
M. Zobov, O. Frasciello, S. Tomassini (INFN)

Resistive-wall impedance of beam screens: impact of the weld

- Current beam screens: weld modelized by a frequency dependent factor which can be more than 2 (dipolar horizontal): from 3D CST simulations



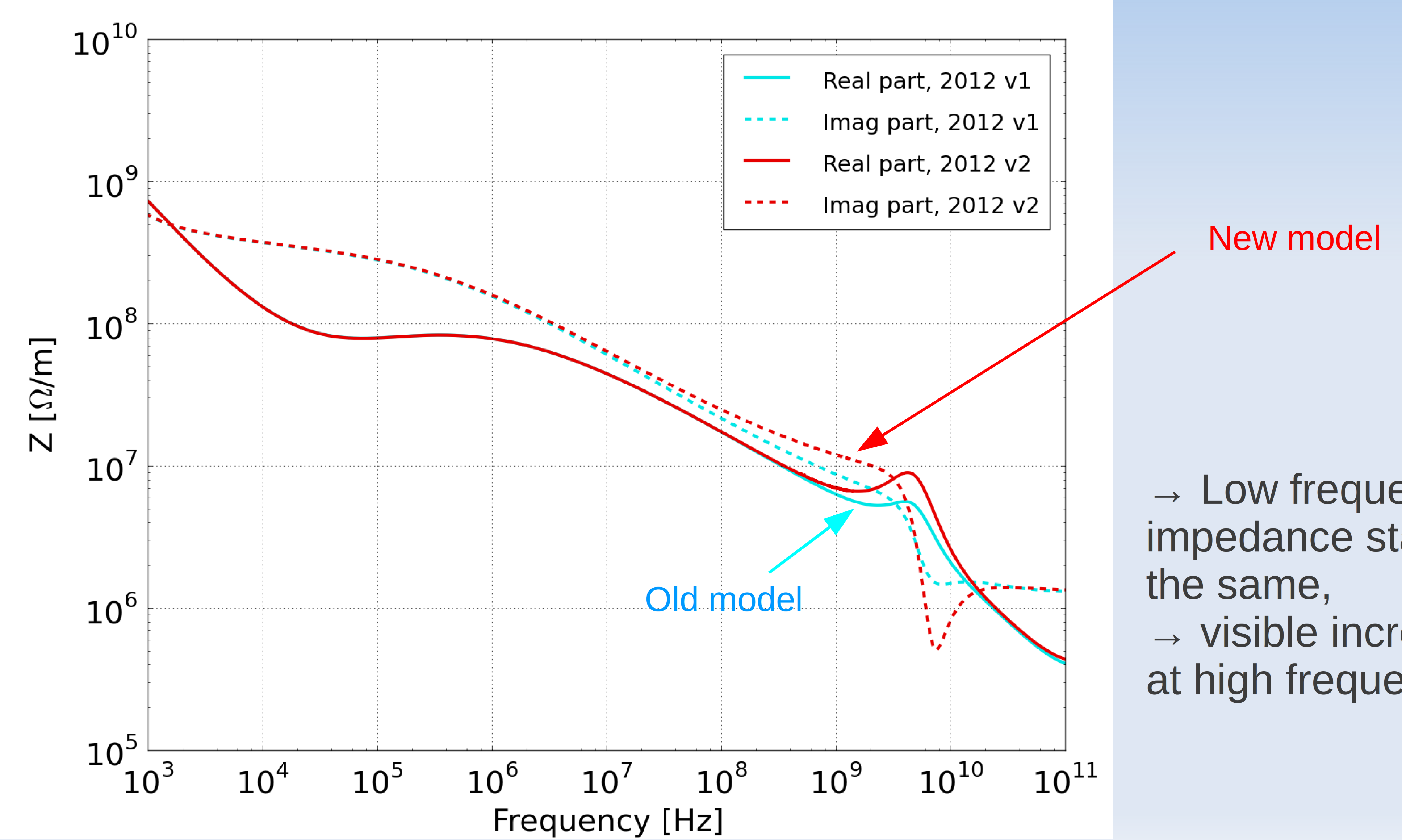
Very weakly dependent on beam screen size



C. Zannini – PhD thesis

Comparison between "old" and "new" model

- With typical 2012 (4TeV) physics settings: vertical dipolar impedance



→ Low frequency impedance stays the same,
→ visible increase at high frequency.

Comparison between ”old” and ”new” model

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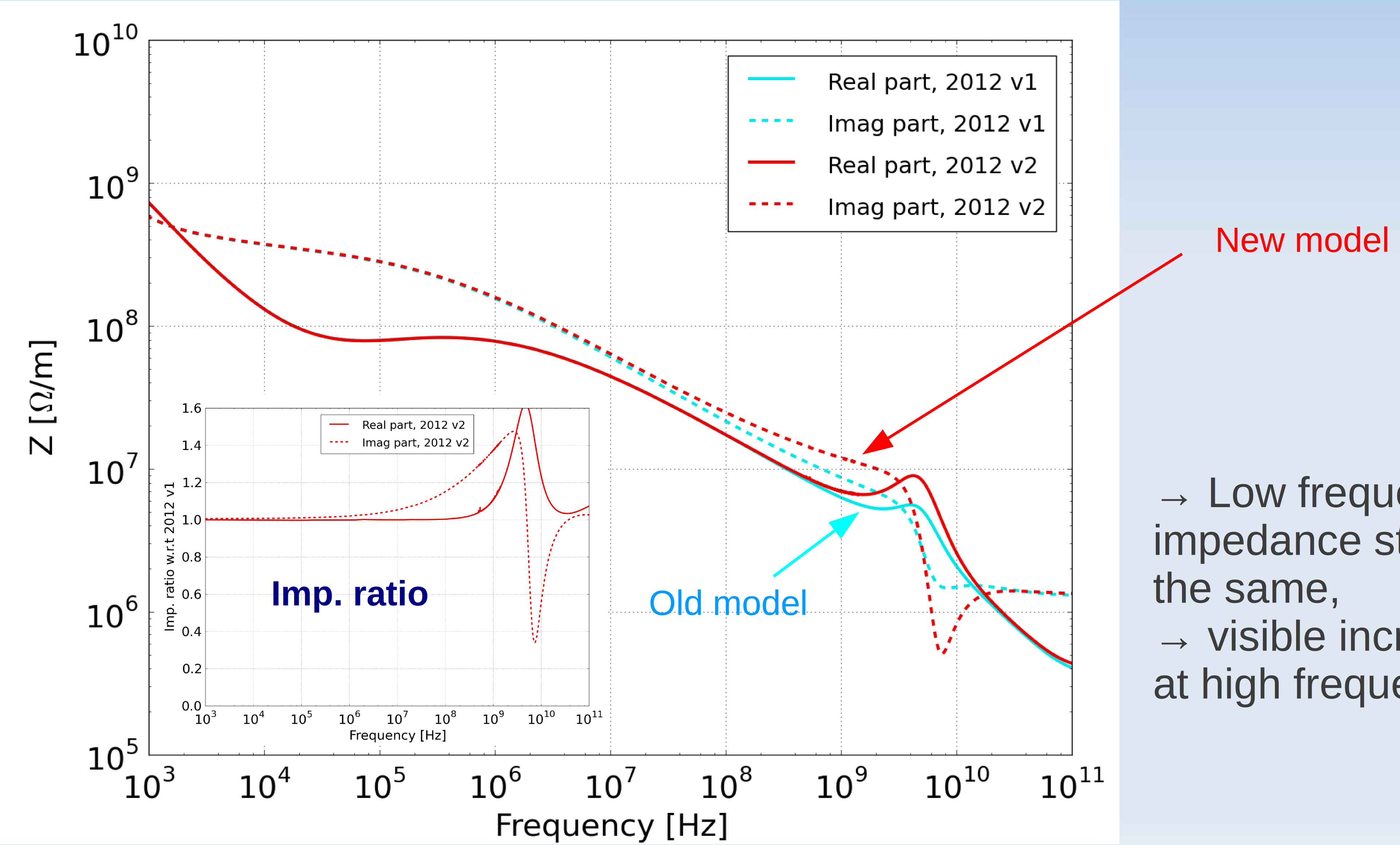
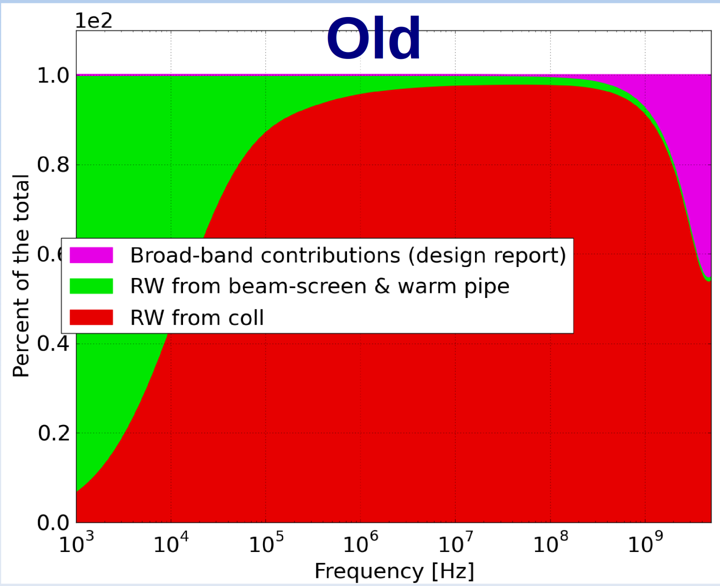


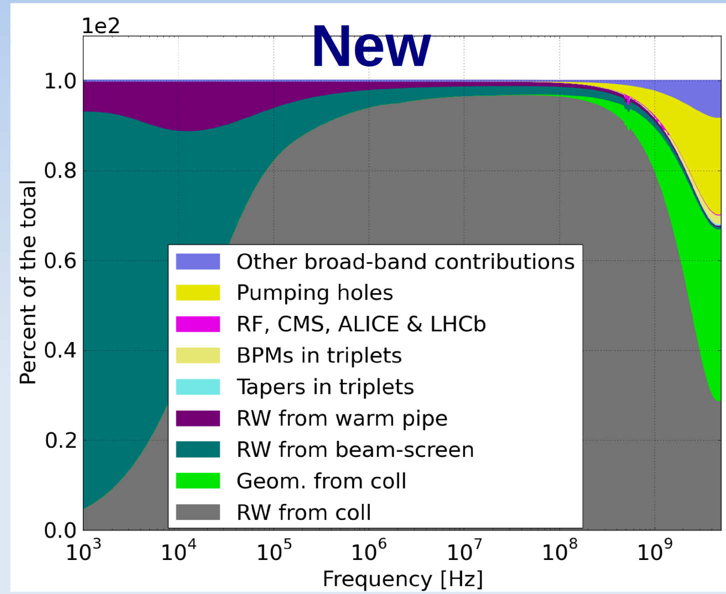
→ Low frequency impedance stays the same,
→ visible increase at high frequency.

Comparison between ”old” and ”new” model

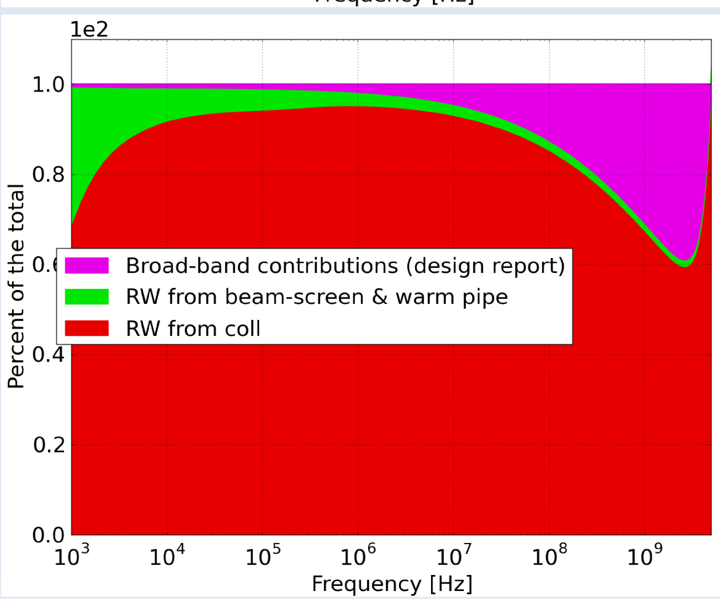
- Details of the various contributions in each model (vertical dip.), in percent:

Real part

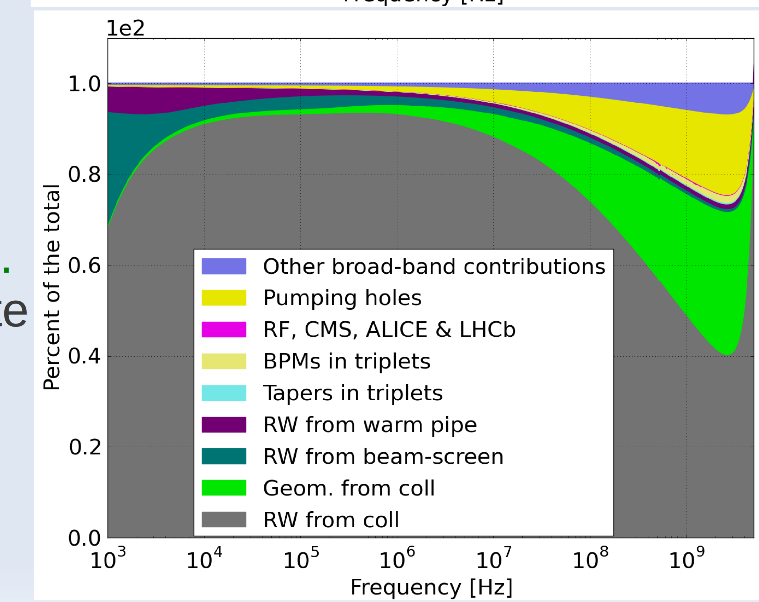




Imag. part

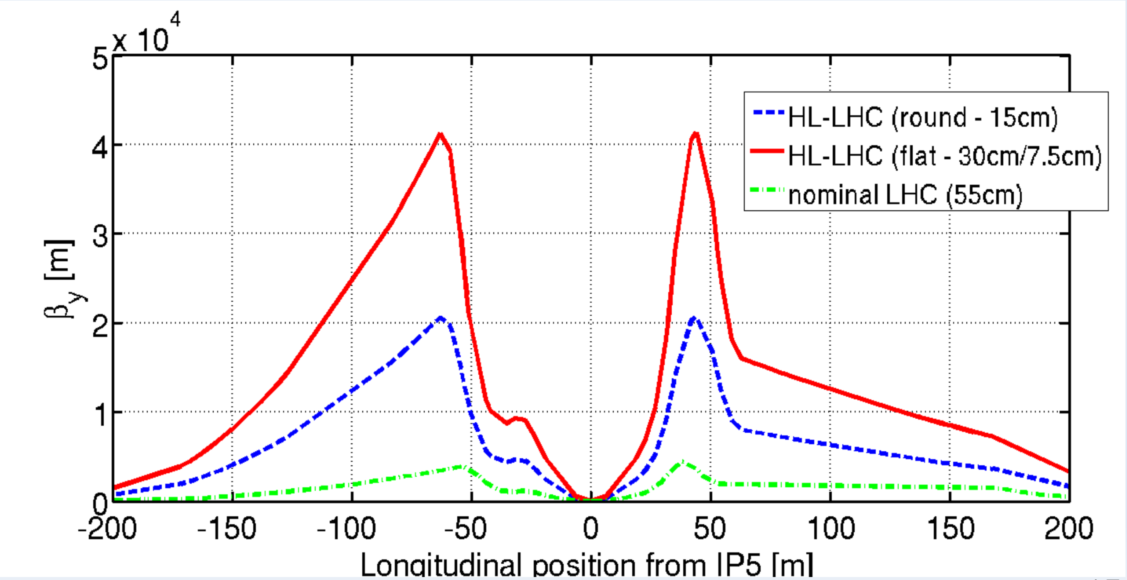


Impact of geom. imp. of coll. quite visible (also pumping slots)



What will change in HL-LHC ?

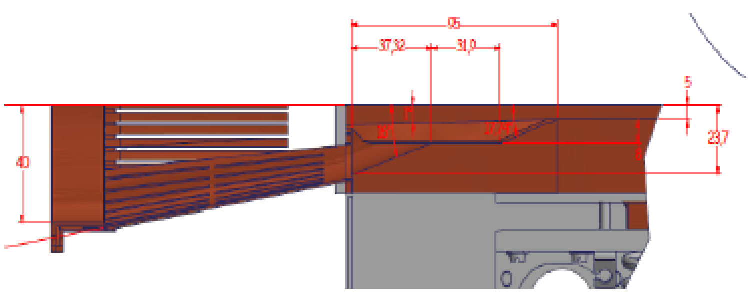
- Changes:
  - Molybdenum (or Mo-coated) secondary collimators under study,
  - geometric impedance of collimators: double taper due to BPM button (already after LS1) – M. Zobov & O. Frasciello (INFN),
  - triplet region: new apertures, tapers and BPMs (B. Salvant),
  - New broad-band and high order modes of CMS and ATLAS (R. Wanzenberg and O. Zagorodnova - DESY),
  - crab cavities (B. Salvant),
  - beam-beam wire compensation.
  - Higher beta functions (in IR1 & 5 but also in the arcs – ATS optics):

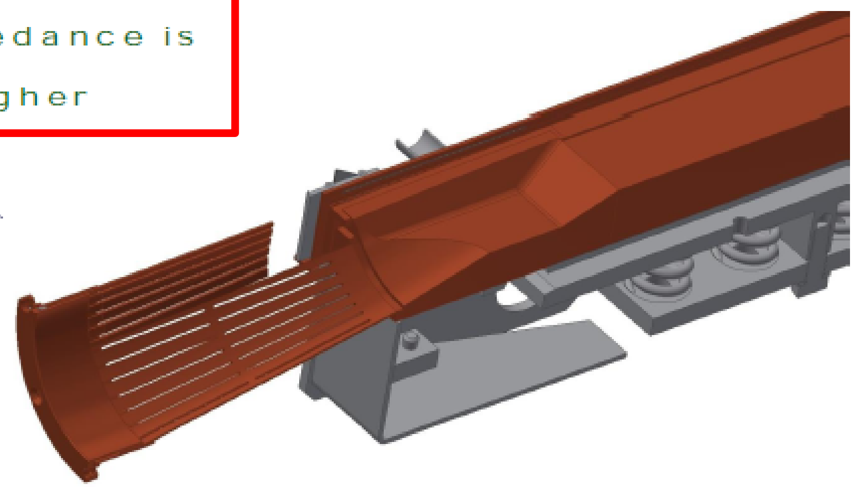


Geometric impedance of collimators with BPM

Impedance Increase due to BPM Cavity

The transverse effective impedance is estimated to be about 20% higher

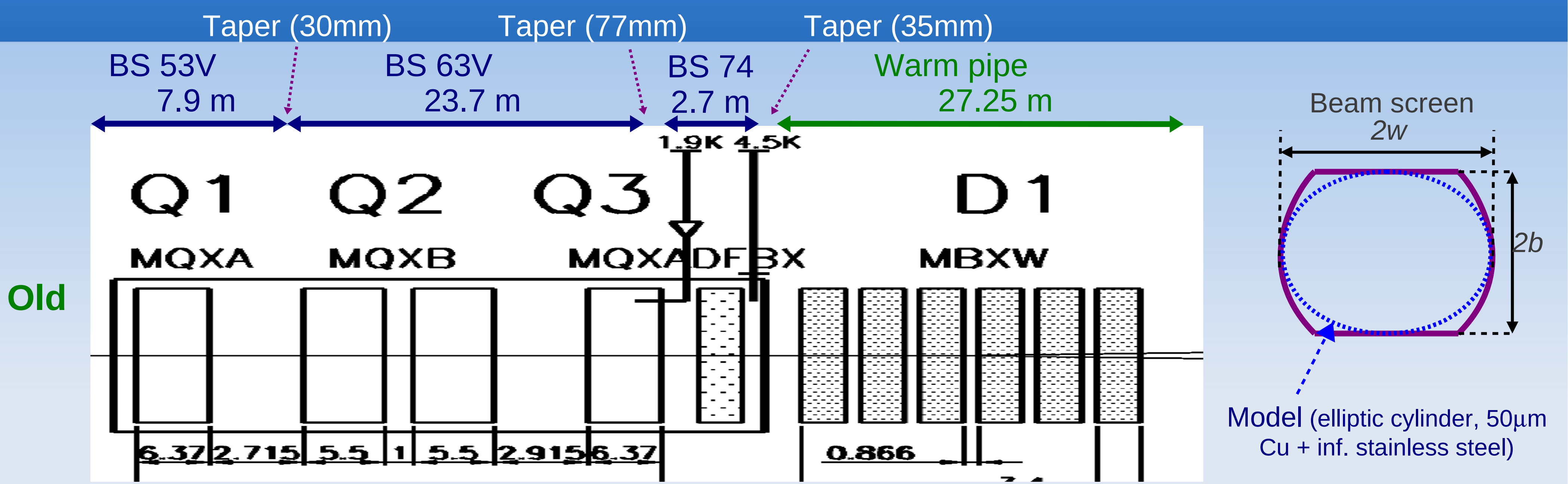




	With BPM cavity	Without BPM cavity
Half gaps (mm)	k_T(V/Cm)	k_T(V/Cm)
1	$3.921 \cdot 10^{14}$	$3.340 \cdot 10^{14}$
3	$6.271 \cdot 10^{13}$	$5.322 \cdot 10^{13}$
5	$2.457 \cdot 10^{13}$	$2.124 \cdot 10^{13}$

M. Zobov, O. Frasciello, S. Tomassini (INFN)

HL LHC triplet layout (IR1 & 5)

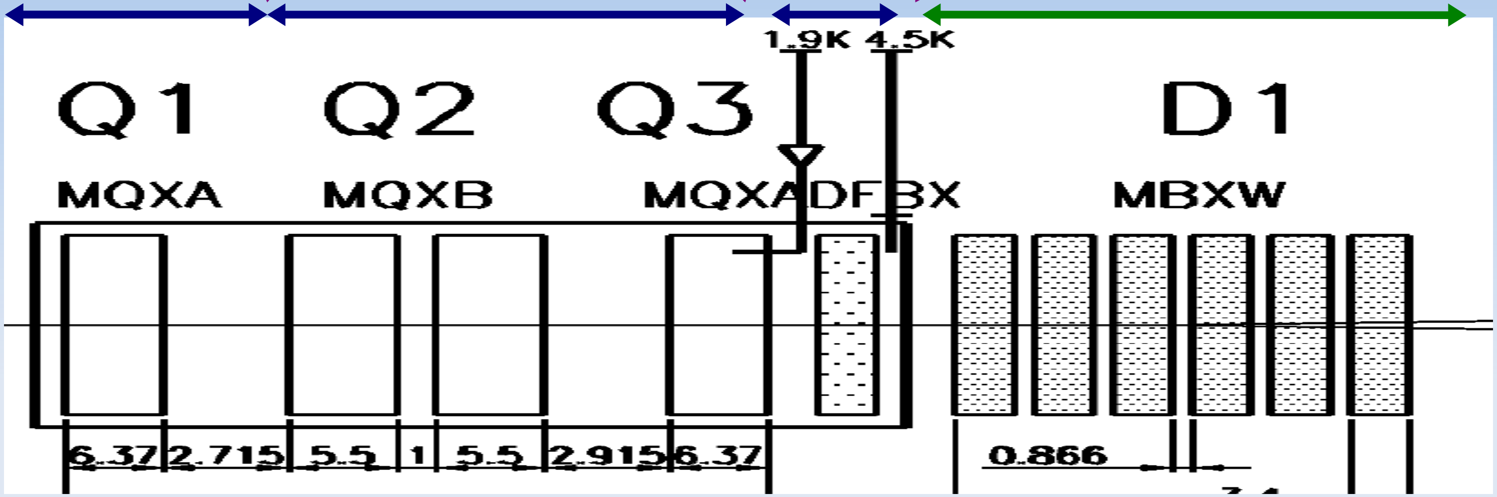


HL LHC triplet layout (IR1 & 5)

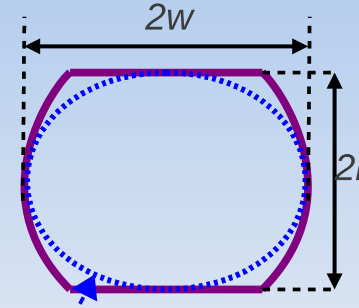
Taper (30mm) Taper (77mm) Taper (35mm)

BS 53V 7.9 m | BS 63V 23.7 m | BS 74 2.7 m | Warm pipe 27.25 m

Old

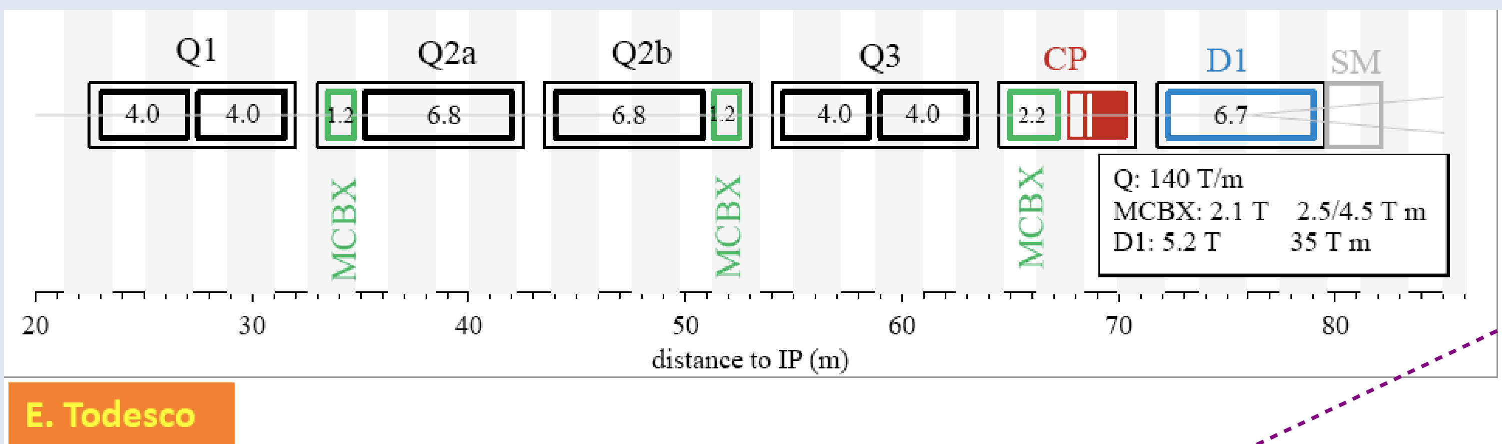


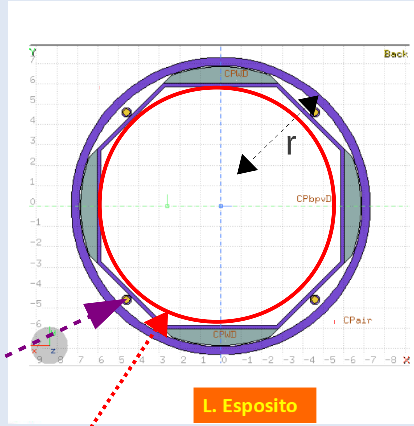
Beam screen



Model (elliptic cylinder, 50µm Cu + inf. stainless steel)

New





New BS, 9.5m, r =50.5mm

Taper

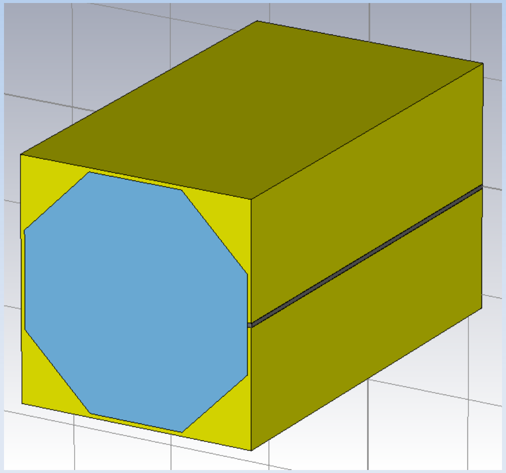
New BS, r =60.5mm

Model: s. steel cylinder
- with 0.5µm amorphous carbon "aC" (ρ=10^{-2} Ω.m – M. Taborelli) and 50µm Cu.

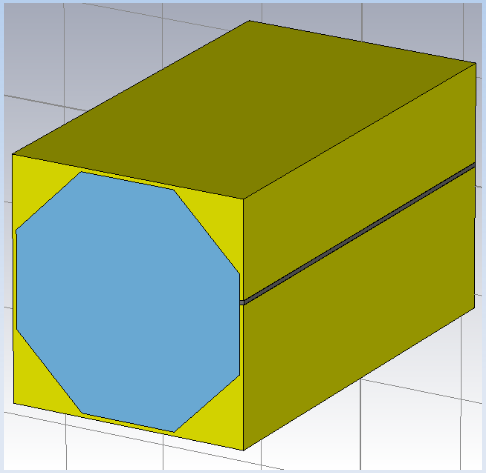
Resistive-wall impedance of new beam screens: impact of the weld

- 3 different positions tested, with either 1mm or 2mm height (CST):

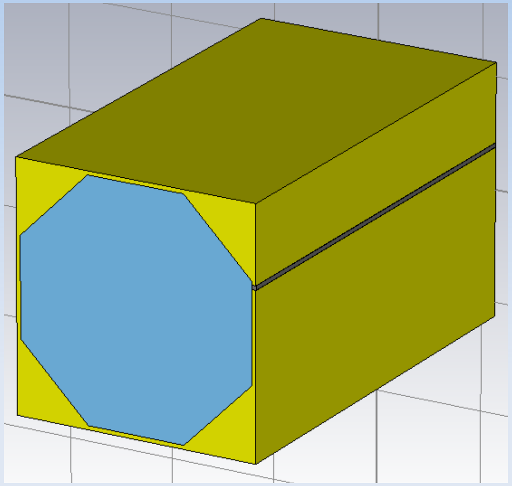
Pos. 1

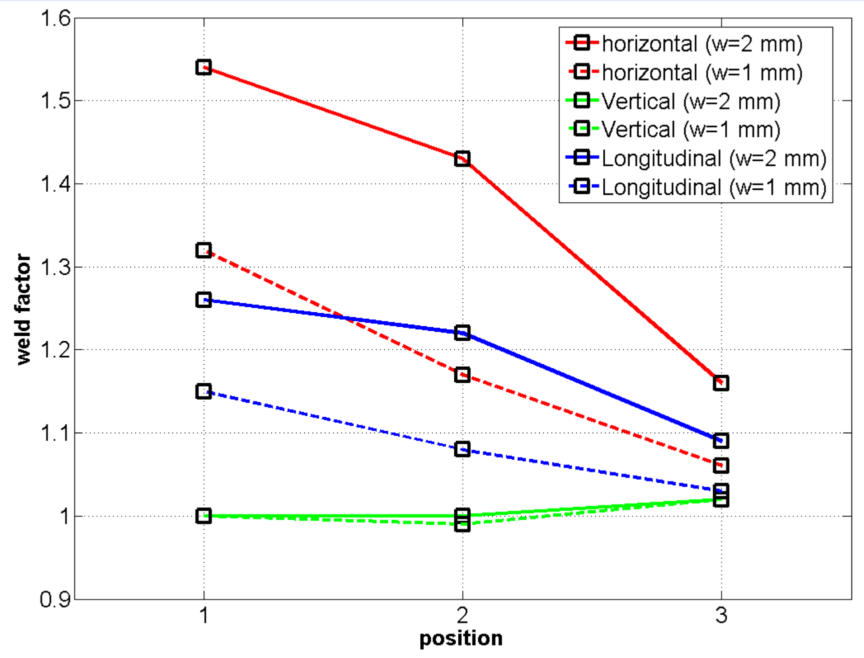


Pos. 2



Pos. 3





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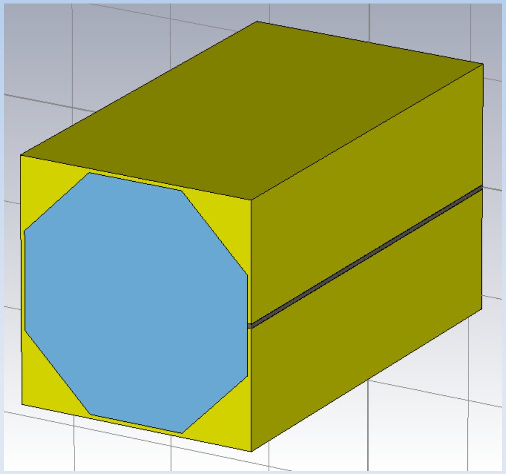
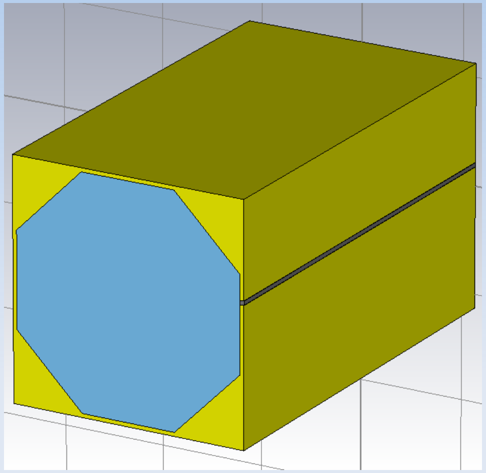
Resistive-wall impedance of new beam screens: impact of the weld

- 3 different positions tested, with either 1mm or 2mm height (CST):

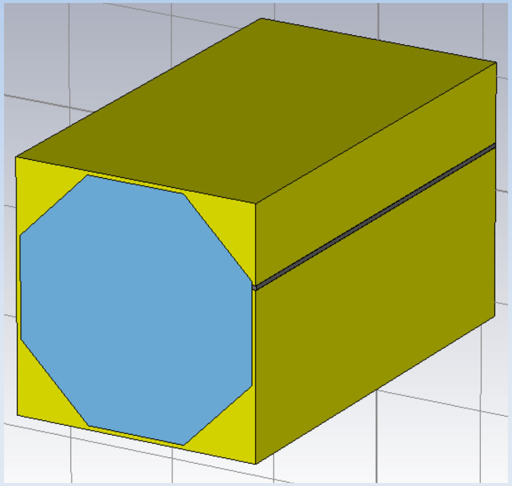
Pos. 1

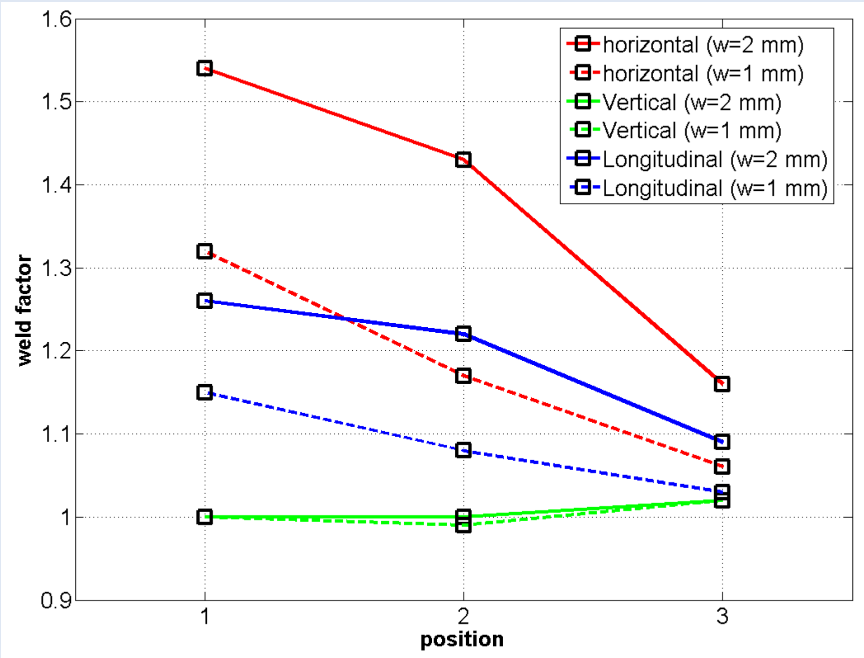


Pos. 2



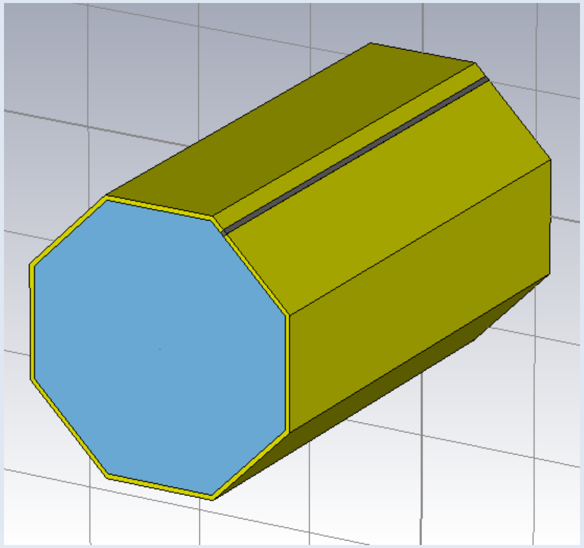
Pos. 3





Finally, baseline close to pos. 3 (2mm) (but in another corner):

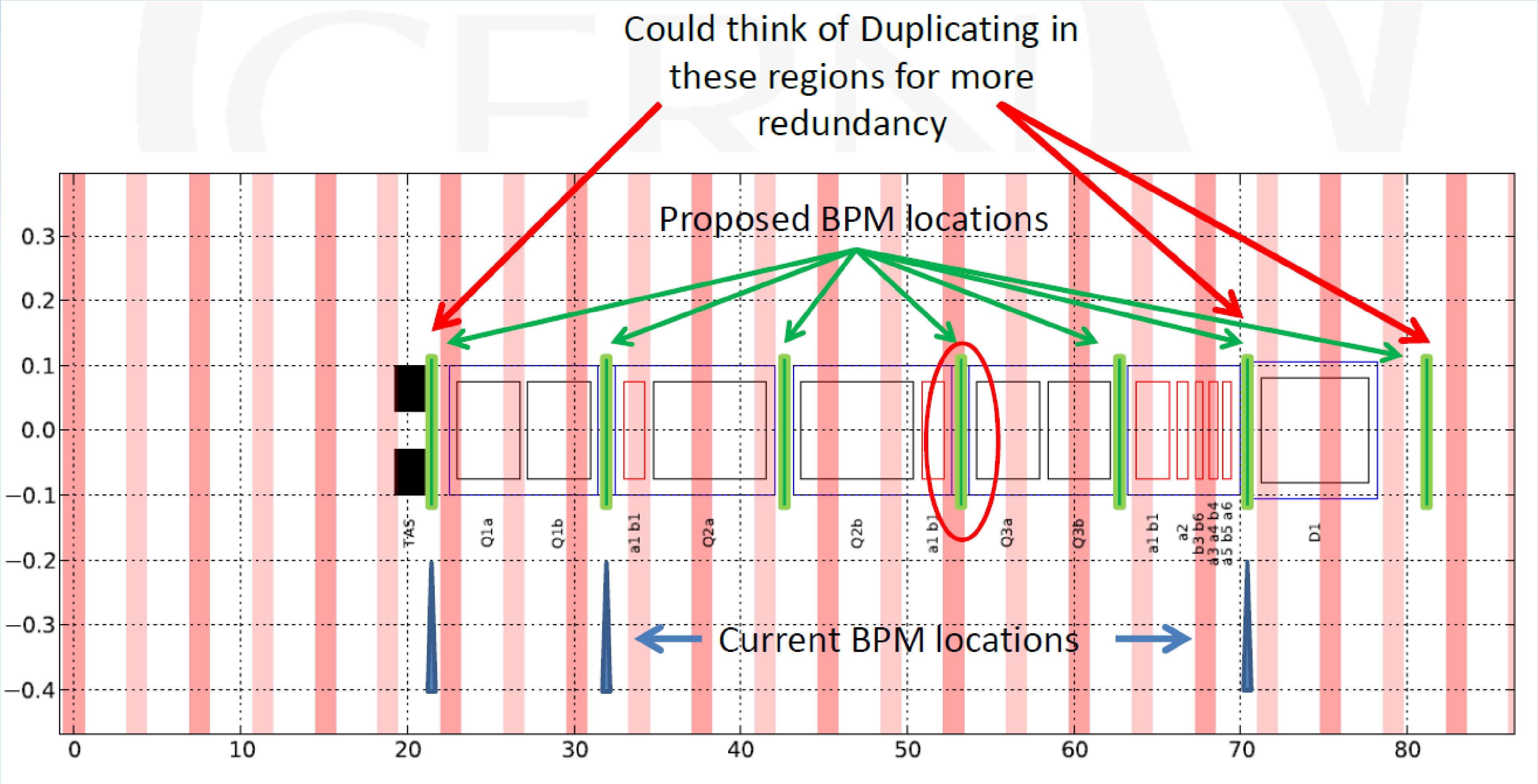
⇒ Much smaller impact of the weld than in current beam screen.



C. Zannini

BPMs in triplets

- From R. Jones, HL-LHC PLC meeting (18/01/2013):



BPMs in triplets

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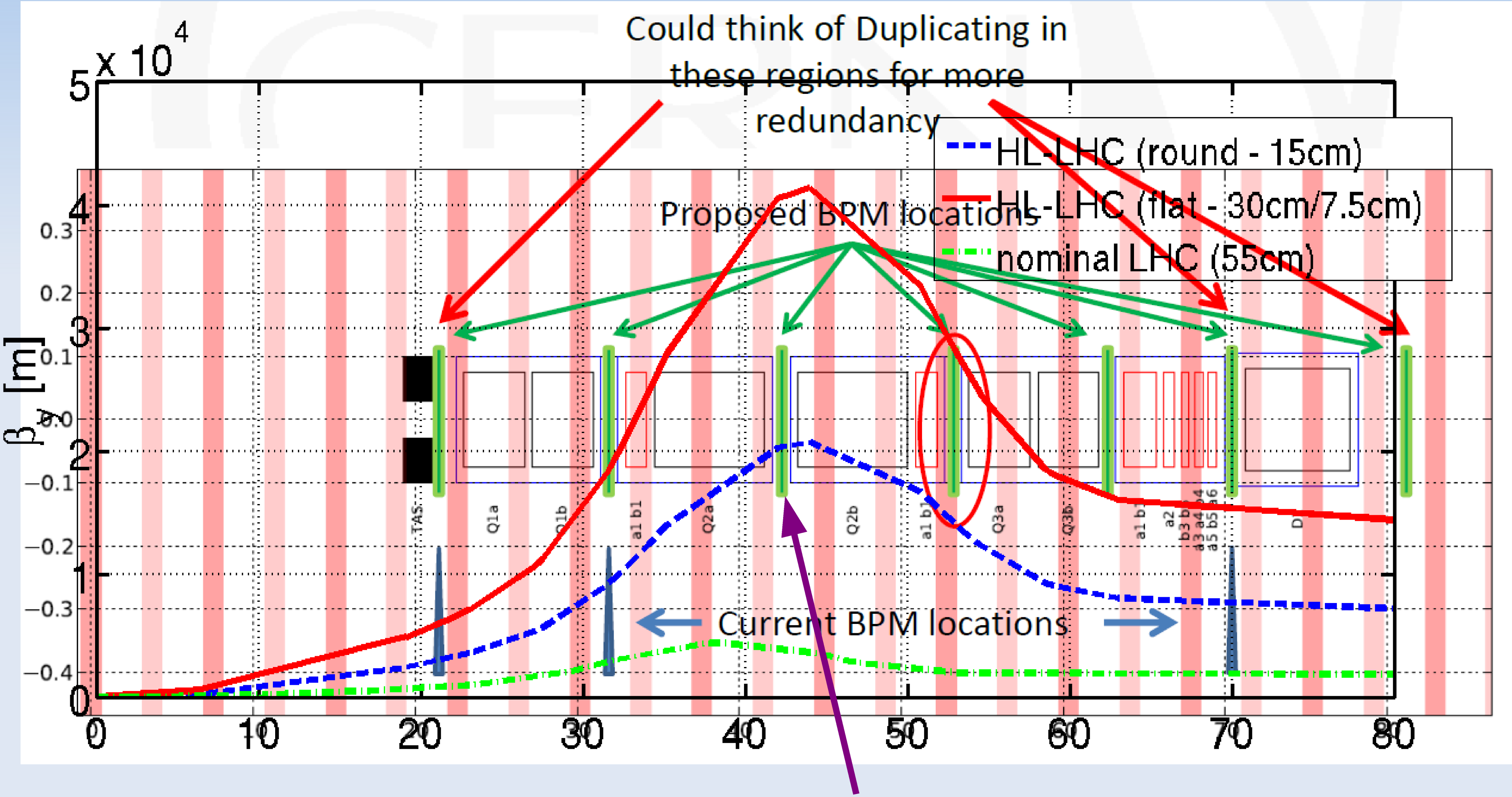

This one has the same effect as hundreds of BPMs with average beta functions.

BPMs in triplets

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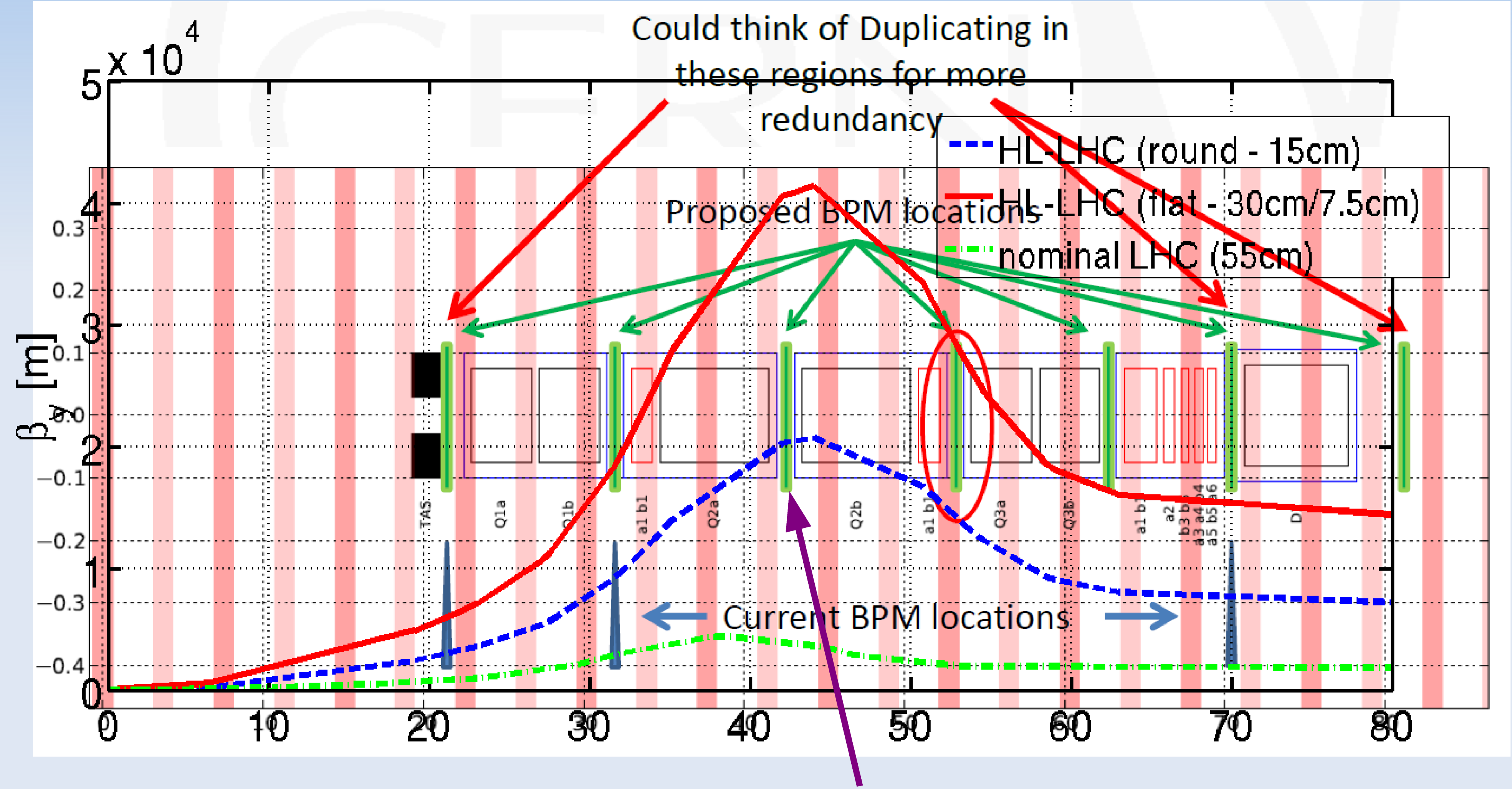
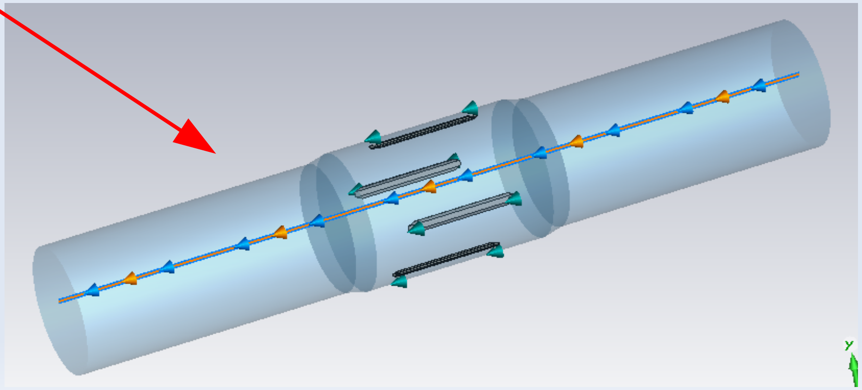


This one has the same effect as hundreds of BPMs with average beta functions.

BPMs in triplets: geometric impedance

- Many BPMs and huge beta functions !
- All stripline BPMs (*l=0.12*m for the strip length), except one combined BPM (buttons / stripline) in front of Q1.
- Larger aperture for HL-LHC BPMs in triplets (diameter D=140mm vs 60 or 80mm for the current ones) (impedance in ~$1/D^2$).
- Two approaches to compute impedance:
  - analytic formula for stripline BPM by K. Y. Ng [Handbook of Acc. Phys. & Eng., Sec. 3.2] + values obtained for button BPM by B. Spataro [LHC Project Note 284],
  - CST simulations made by B. Salvant

→ agreement within a factor ~2.



Crab cavities

- From B. Salvant (2nd HiLumi annual meeting): broad-band model

Transverse

	1 cavity Zx in Ω	1 cavity Zy in Ω	1 cavity <Z>= (Zx+Zy)/(2*d) in Ω/m
LHCRF	6	2	800
BNL	18	10	2800
ODU	10	19	2900
UK	25	4	2900

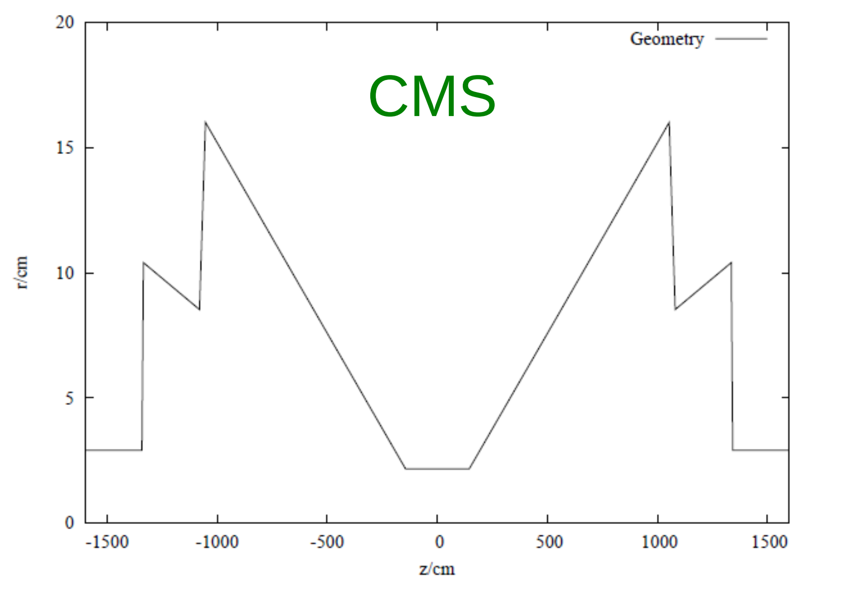
Longitudinal

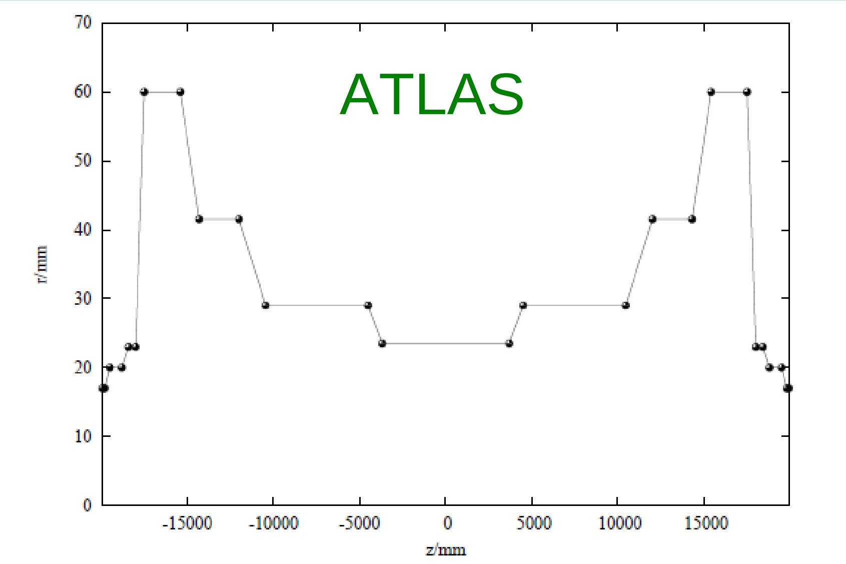
	For 1 cavity Z/n (mOhm)	for 12 cavities Z/n (mOhm)
LHCRF	1.7	14 (8 cavities)
BNL	1.8	22
ODU	2.2	26
UK	2.4	29

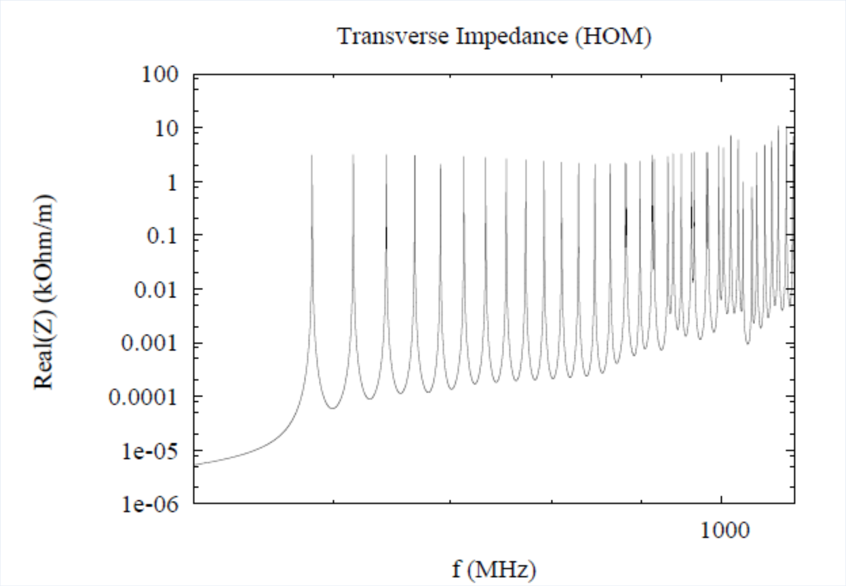
  - 16 cavities considered (between D2 and Q4).
  - Model still quite pessimistic (constant impedance up to ~5GHz).

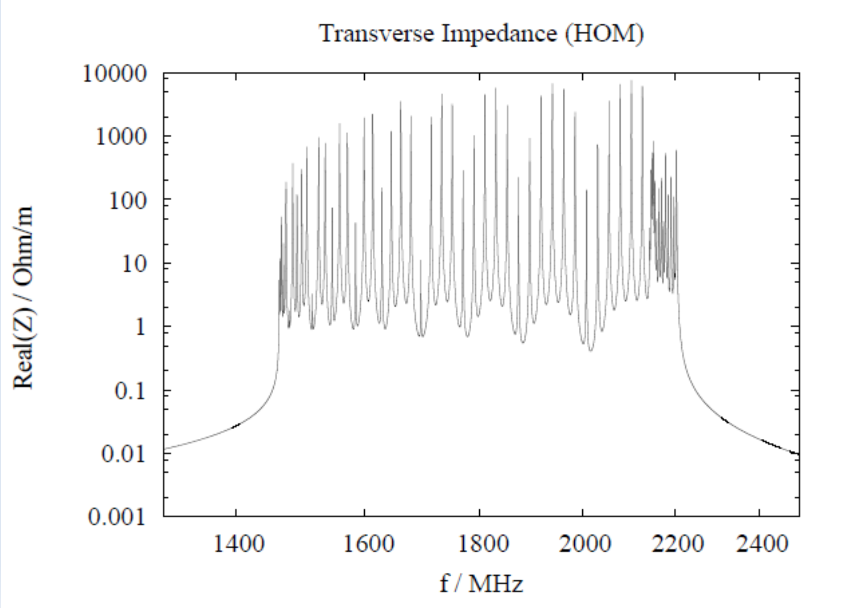
New experimental chambers: HOMs

R. Wanzenberg, O. Zagorodnova (DESY)









New experimental chambers: low frequency broad band impedance

R. Wanzenberg, O. Zagorodnova (DESY)

CMS

Parameter	New chamber	Present chamber	Δz/cm	Δr/cm
$k_{\|\|tot}^{(0)}$ (V/nC)	2.36	2.36	0.2	0.1
$k_{\perp}^{(1)}$ (V/pCm)	2.38	2.36	0.2	0.1

ATLAS

Vacuum chamber	Kick parameter $k_{\perp}^{(1)}$ (V/pCm)	Impedance $Z_{\perp}^{(1)}(\omega)$ (kΩ/m)
ATLAS w/o bellows	1.72	$-i\,1.52$
one bellow	1.99	$-i\,1.76$
ATLAS w. two bellows	4.11	$-i\,3.64$
Sum ATLAS + 10 bellows	21.6	$-i\,19.2$

Unshielded bellows are strong contributors

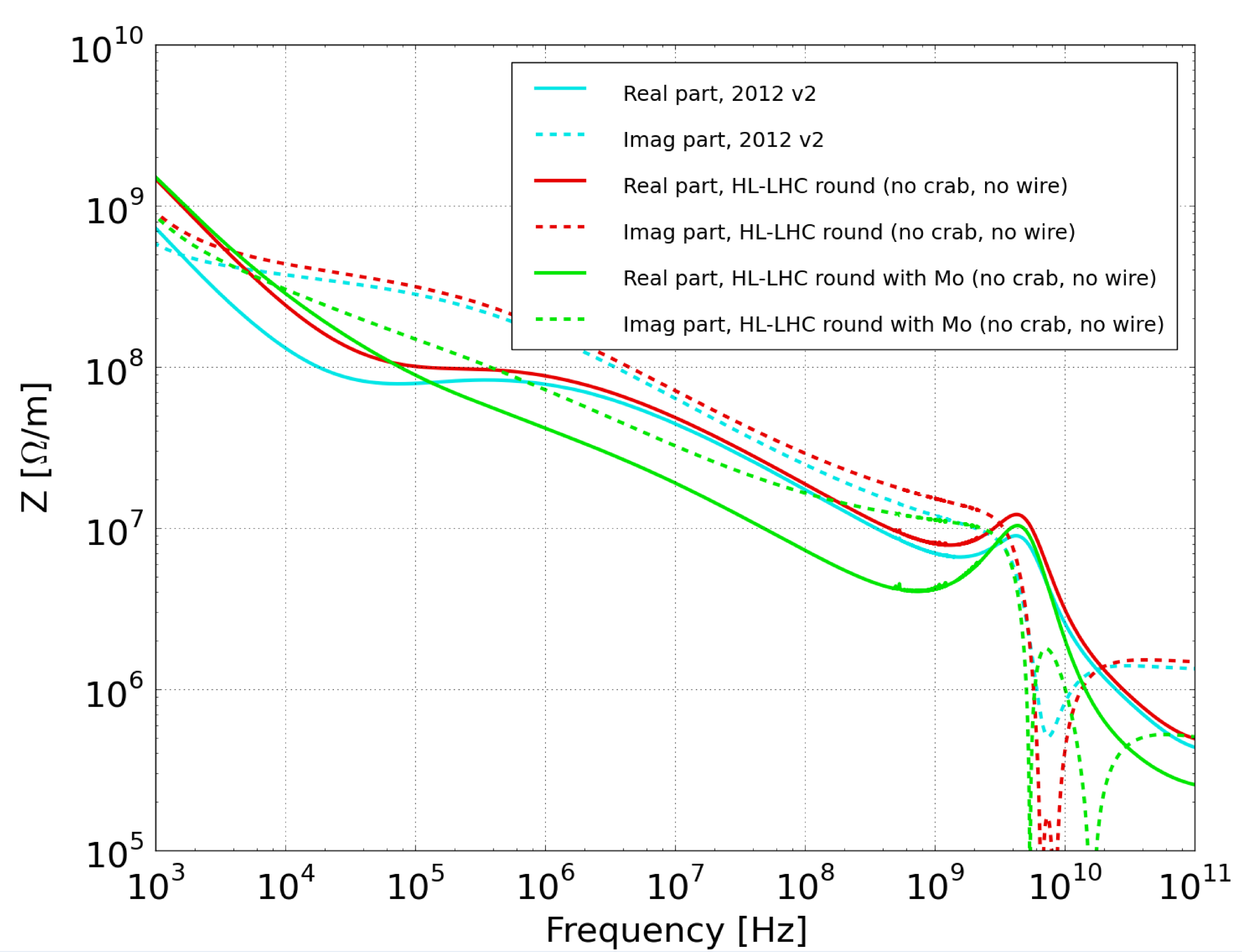
Beam-beam wire compensators

- See also next talk by R. Steinhagen.
- 2 options studied:
  - Stand-alone wire, modelled (very simply) as a stripline kicker (1m long, 1mm radius),
  - Wire embedded in an (additional) 1m-long tungsten collimator

    → essentially, impedance = collimator impedance (RW + geometric).
- In all cases, assumed 4 wires (~150m from IP1 & 5, each side), at 9.5σ (pessimistic).

Final comparison LHC vs HL-LHC

- Dipolar vertical impedance without crab cavities nor wire, testing also the possibility to have Mo collimators for the TCS in IR3 & 7:



⇒ HL-LHC increases by at max. ~20% the total impedance,
⇒ Mo is very efficient to decrease the total impedance.

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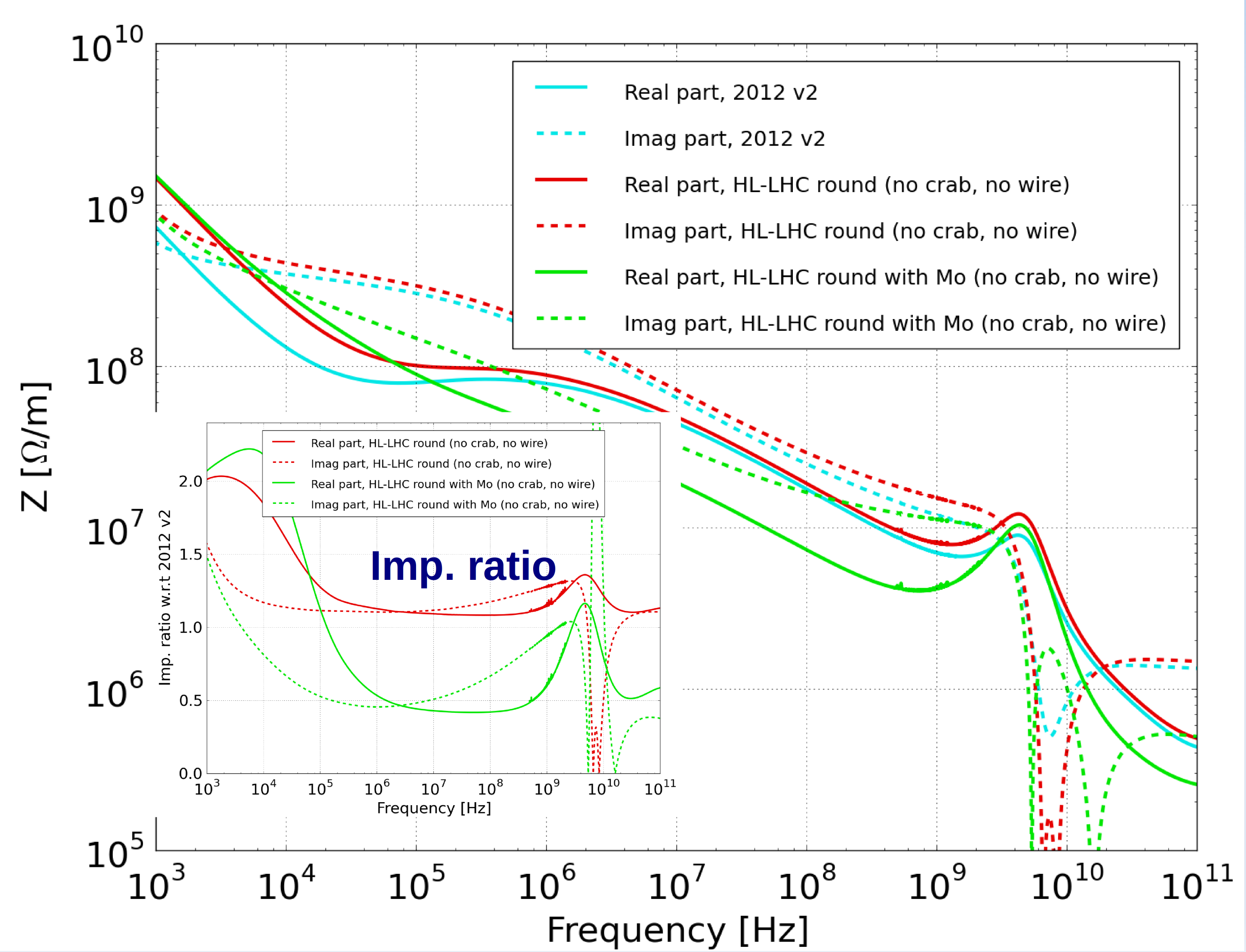
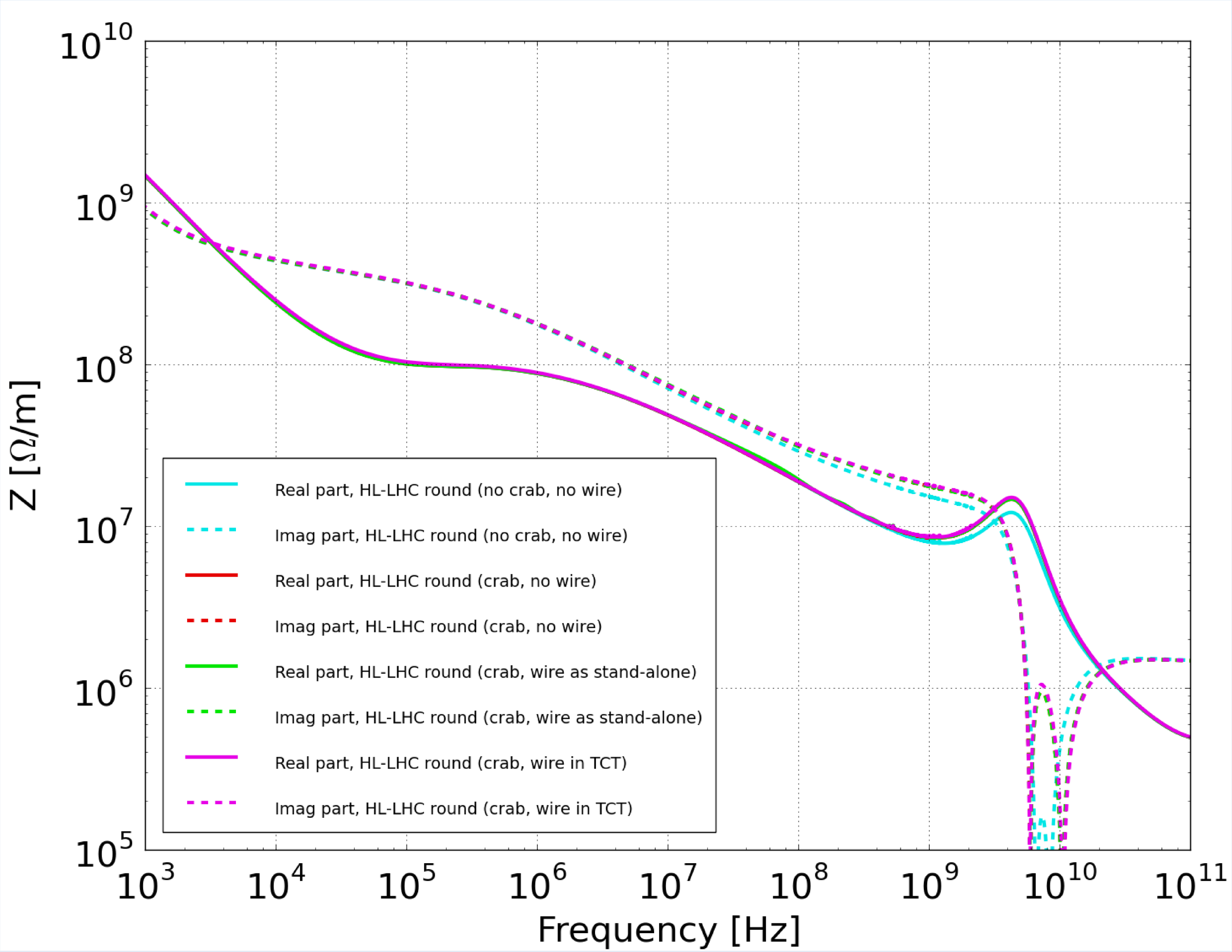


⇒ HL-LHC increases by at max. ~20% the total impedance,

⇒ Mo is very efficient to decrease the total impedance.

Impact of crab cavities and wire compensator

- HL-LHC dipolar vertical impedance:

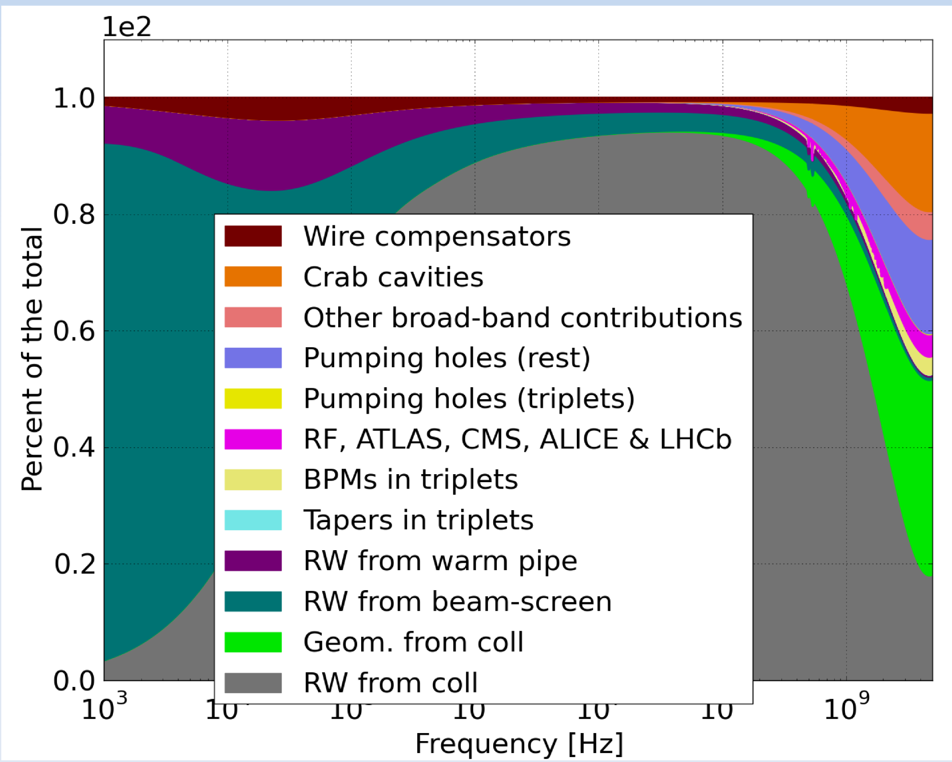


⇒ Only crab cavities have a significant impact.

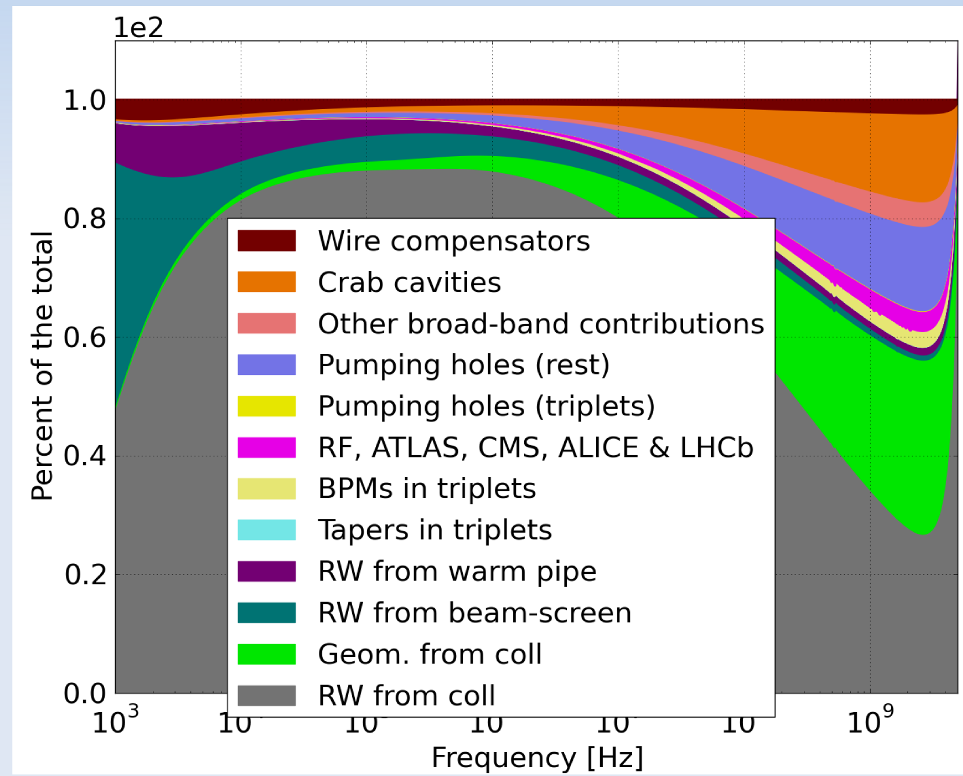
Contributions to the HL-LHC impedance

- Vertical dipolar impedance:

Real part



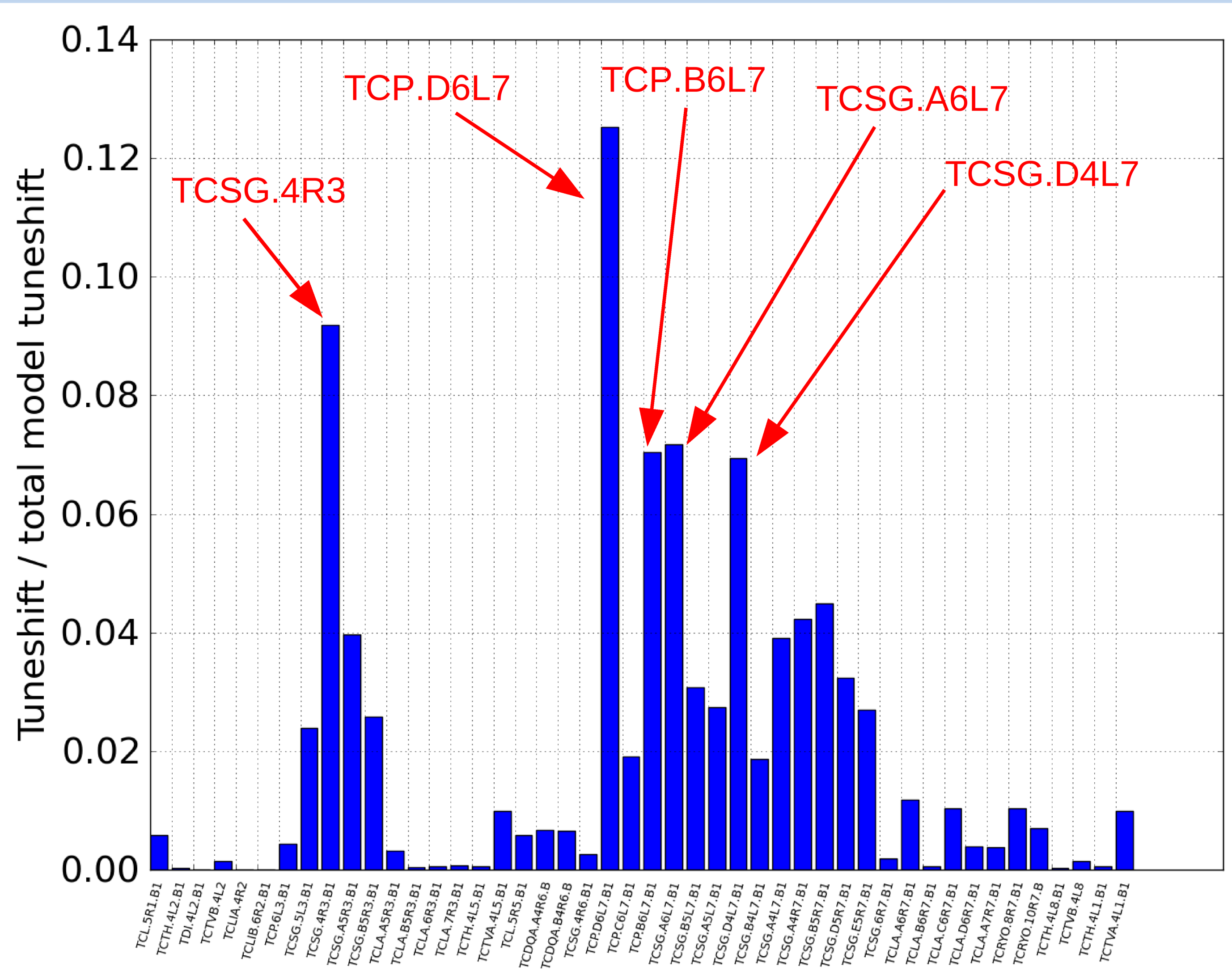
Imag. part



⇒ HL-LHC main contributions are collimators (RW & geometric), pumping holes and crab cavities.

Highest impedance contributors among collimators (LHC model)

- In terms of tuneshift (single-bunch) with *Q'=0* & 1.7 10^{11} p+/bunch: ratio between tuneshift from each collimator vs. total impedance tuneshift (vertical)



Highest impedance contributors among collimators (HL-LHC model)

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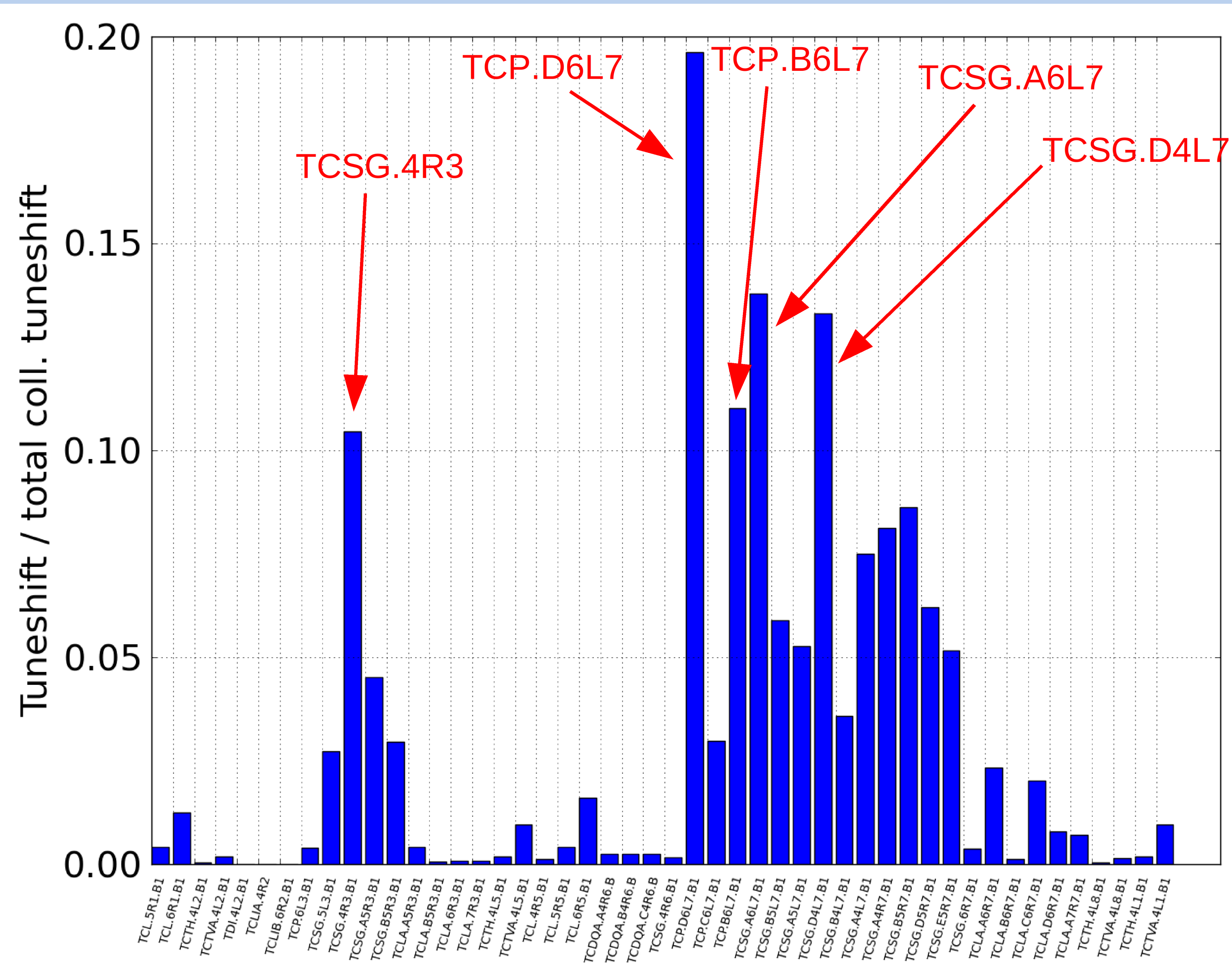

Same collimators dominate impedance as for LHC → resistive-wall (CFC)

Conclusions

- *Still work in progress...*
- LHC impedance model refined to better take into account several geometric contributions (coll. taper impedance, pumping holes, tapers and BPMs in triplets, HOMs in RF cavity and experimental pipes)

  → model same as previous model at low frequency, signficantly higher (40%) around 1 GHz.
- First HL-LHC model built, taking into account the same contributors are for the LHC, plus some additions (additional BPMs in triplets, crab cavities, wire compensator, HOMs in experimental pipe).
- HL-LHC impedance not dramatically higher than LHC one. Crab cavities could be a worry (but still quite pessimistic broad band model).
- Mo coated secondary collimators could decrease total impedance very significantly.
- Special caution should be given to devices in high beta regions, as well as unshielded elements.

Appendix: HL-LHC collimator settings

- Collimator settings used for HL-LHC, in number of σ (with ε=3.5 mm.mrad and E=6.5 TeV) (R. Bruce):

Collimator family	# σ
TCP IR3	15
TCS IR3	18
TCLA IR3	19.9
TCP IR7	5.7
TCS IR7	7.7
TCLA IR7	10
TCRYO IR7	10
TCT IR 1 & 5	10.5
TCL IR 1 & 5	10
TCT IR 2 & 8	29.9
TCDQ IR6	9
TCS IR6	8.5
TDI & TCLI	retracted