# Impedance aspects of Crab cavities

R. Calaga, N. Mounet, B. Salvant, E. Shaposhnikova

Many thanks to
F. Galleazzi, E. Metral, A. Mc Pherson, C. Zannini

# Summary

- It would be useful to collect all updates on geometries and resonant parameters of all crab cavities.
- Impact on SPS beam seems limited.
- Impact on LHC beam seems significant (16 cavities + very large beta functions).
- We need to converge on the acceptable limits for resonant modes, but the parameters and options are changing very fast.
- Current longitudinal limit for all new LHC hardware is 200 kOhm (conservative). Relaxing this limit would mean freezing some parameters. Are we in a position to do this now?

# Agenda

- SPS crab cavity tests
  - Impedance of the new Y chamber
  - Impedance of the crab cavities during SPS operation
  - Impedance of the crab cavities during dedicated MDs
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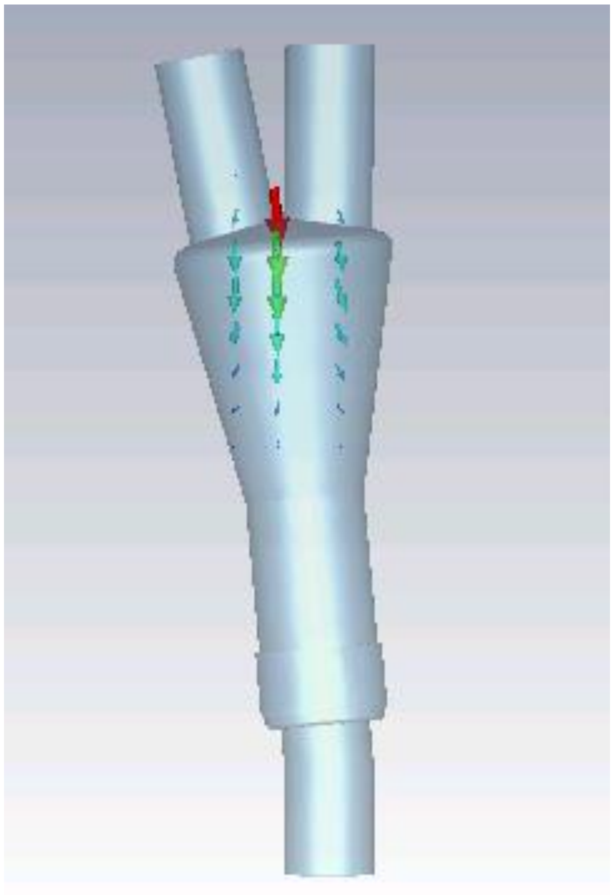
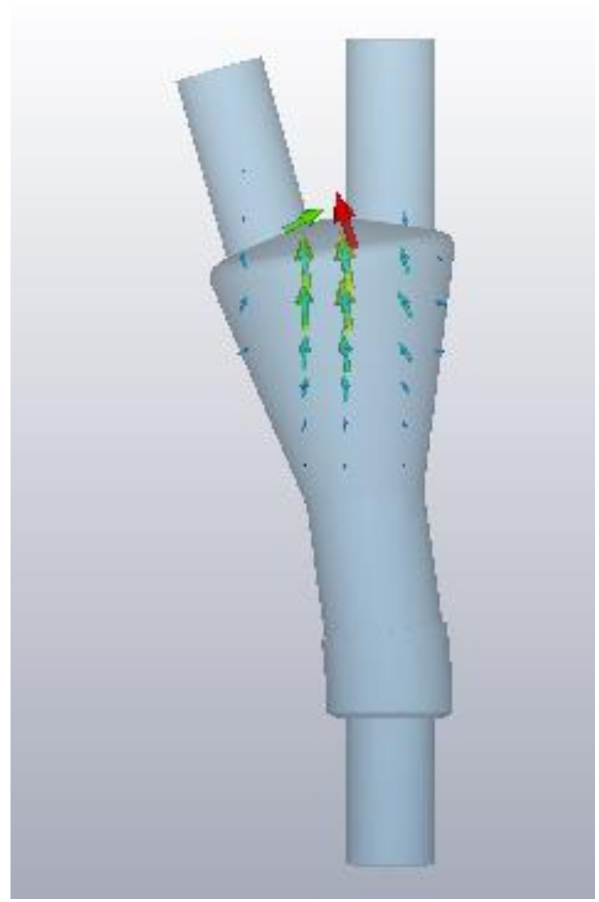
# Impedance of the new Y chambers

Current chamber (12 degrees)



New chamber (16 degrees)



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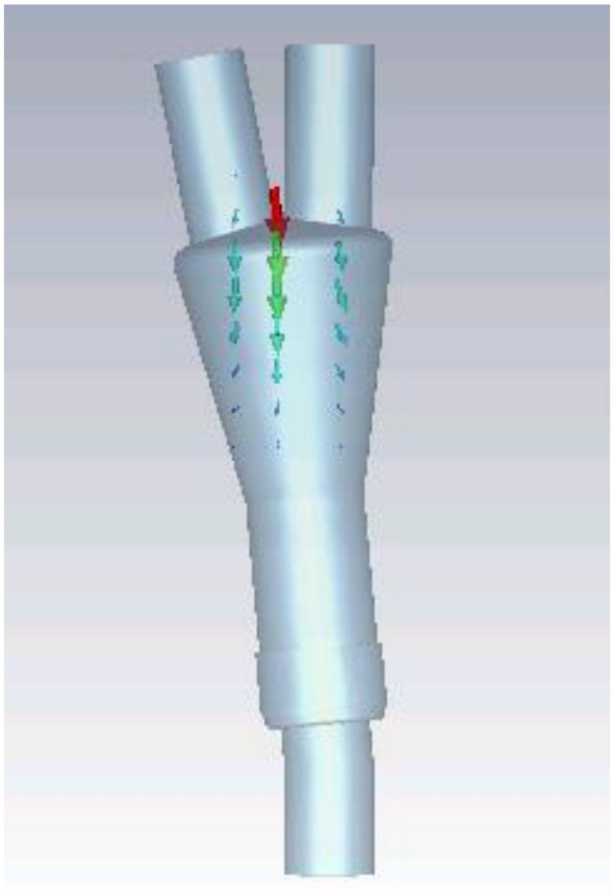

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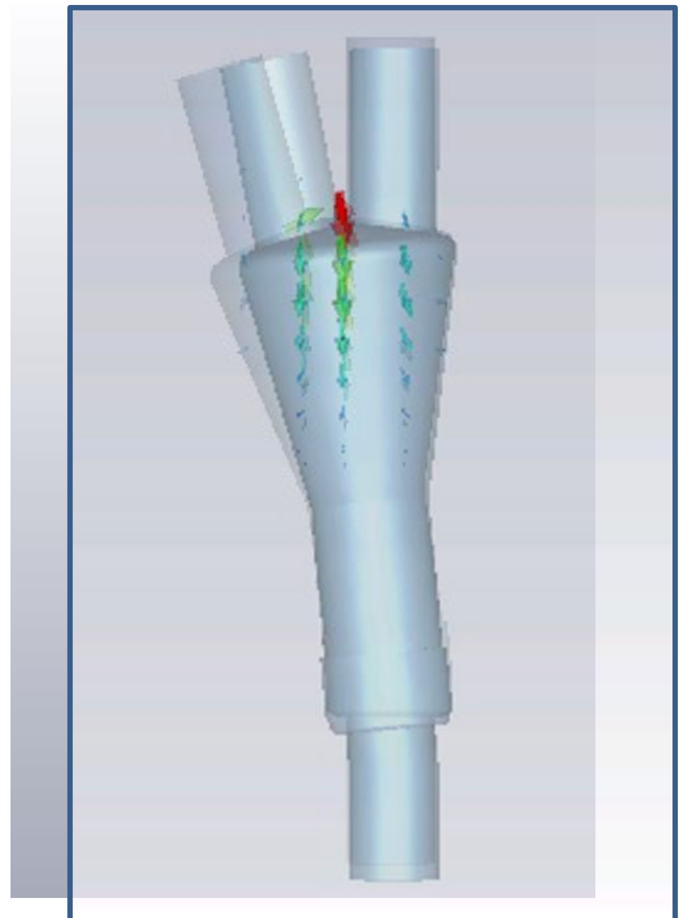
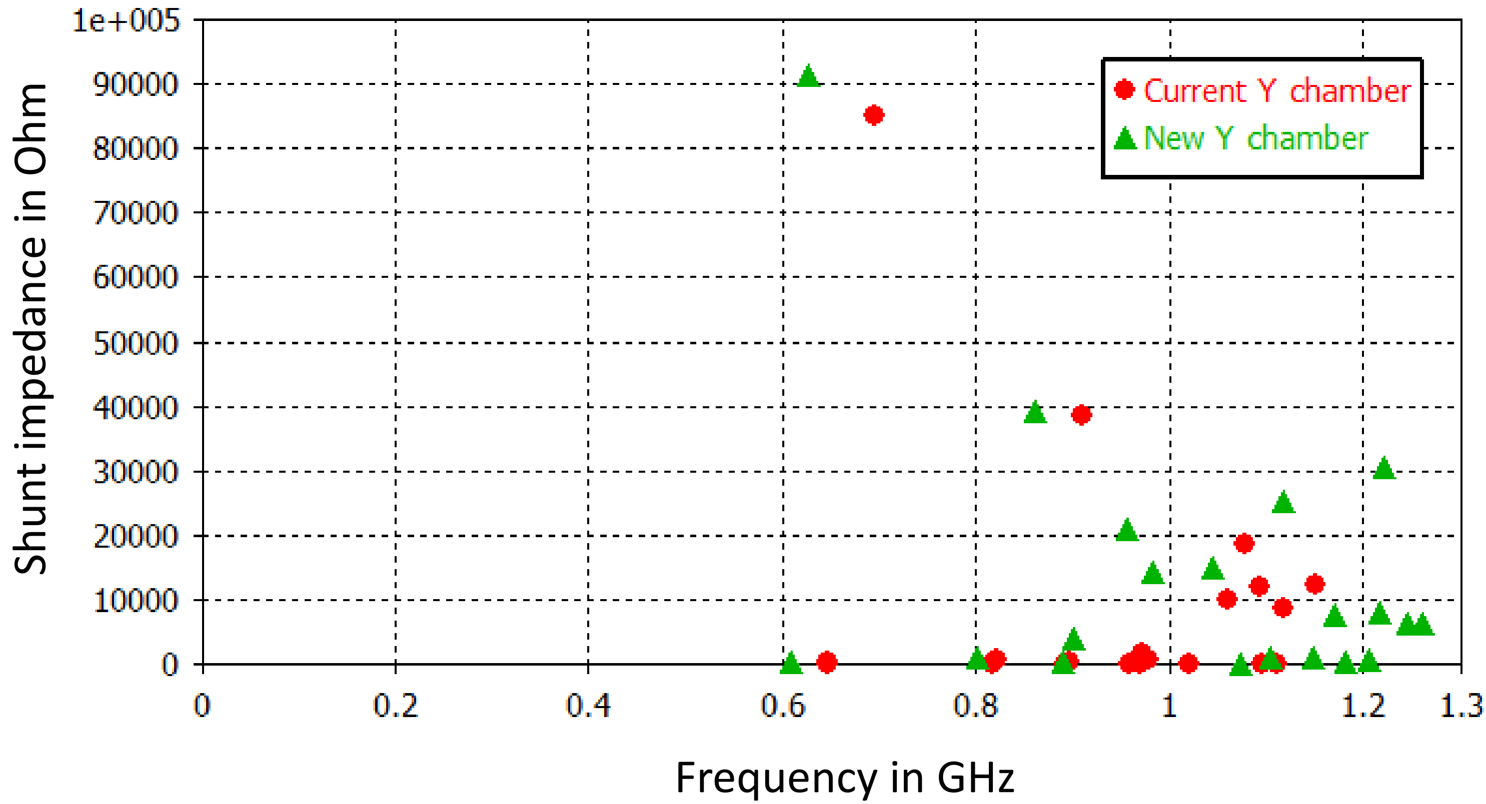


→ Slight increase of volume to accommodate for the angle

→ Real geometry also has a bellow on the taper (currently studied by Phoevos and Alick)

# Impedance of the new Y chambers

Comparison of modes between new Y chamber (16 deg) and current Y chamber (12 deg)




→ 3D Model by F. Galleazzi does not contain the bellow
→ New Y chamber would be slightly worse than the current chamber for longitudinal modes
→ It would make sense to profit from the change of Y chamber to reduce its impedance

# Impedance of the new Y chambers

- Transverse effective impedance at low frequency:

| | **Current Y chamber** | **New Y chamber** |
|---|---|---|
| Zx (total) | Ongoing | 21 kOhm/m |
| Zy (total) | Ongoing | 5 kOhm/m |
| Zlong | 2.4 mOhm | 3.5 mOhm |

→ Impact of two new Y chambers expected to be small compared to SPS impedance (~10 Ohm and 20 MOhm/m)

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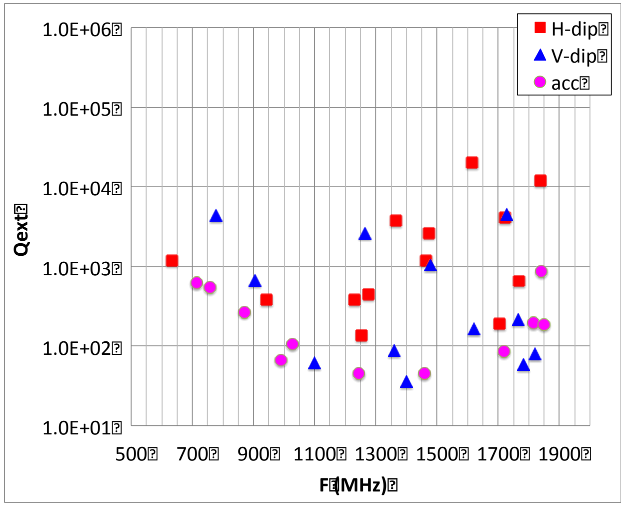
# Impedance of the crab cavities during operation

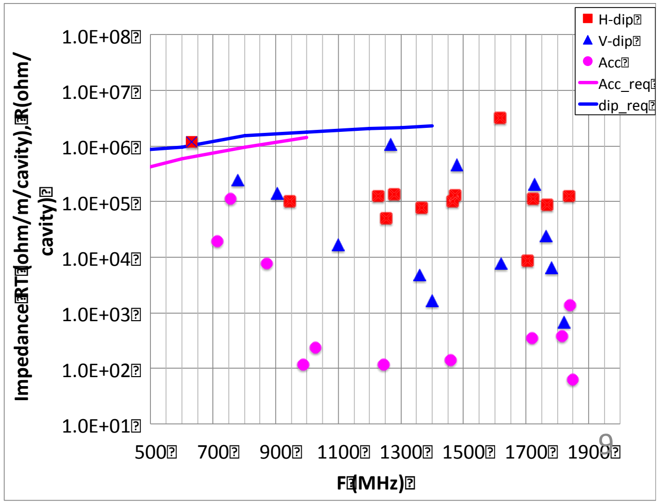
- Unlikely that any SPS operation occurs with crab cavities IN (information: Alick and Karel). However, let's check:
- Assumes symmetric contribution from Y chamber
- Damped longitudinal modes of ~100 kOhm between 700 and 900 MHz would be similar to the modes of the Y chamber
- Other transverse modes at very high frequency for the SPS, and still small compared to the SPS effective impedance (20 MOhm/m - broad due to kickers).
- Transverse effective impedance of one crab cavity is small (~3 kOhm/m)

→ Impact of two crab cavities not expected to be a critical issue for SPS operation with LHC beam

→ therefore, crab cavities not expected to limit significantly the dedicated MD beams (if modes well damped)

HOM Coupler Optimization & RF Modeling, Zenghai Li, LHC-CC13



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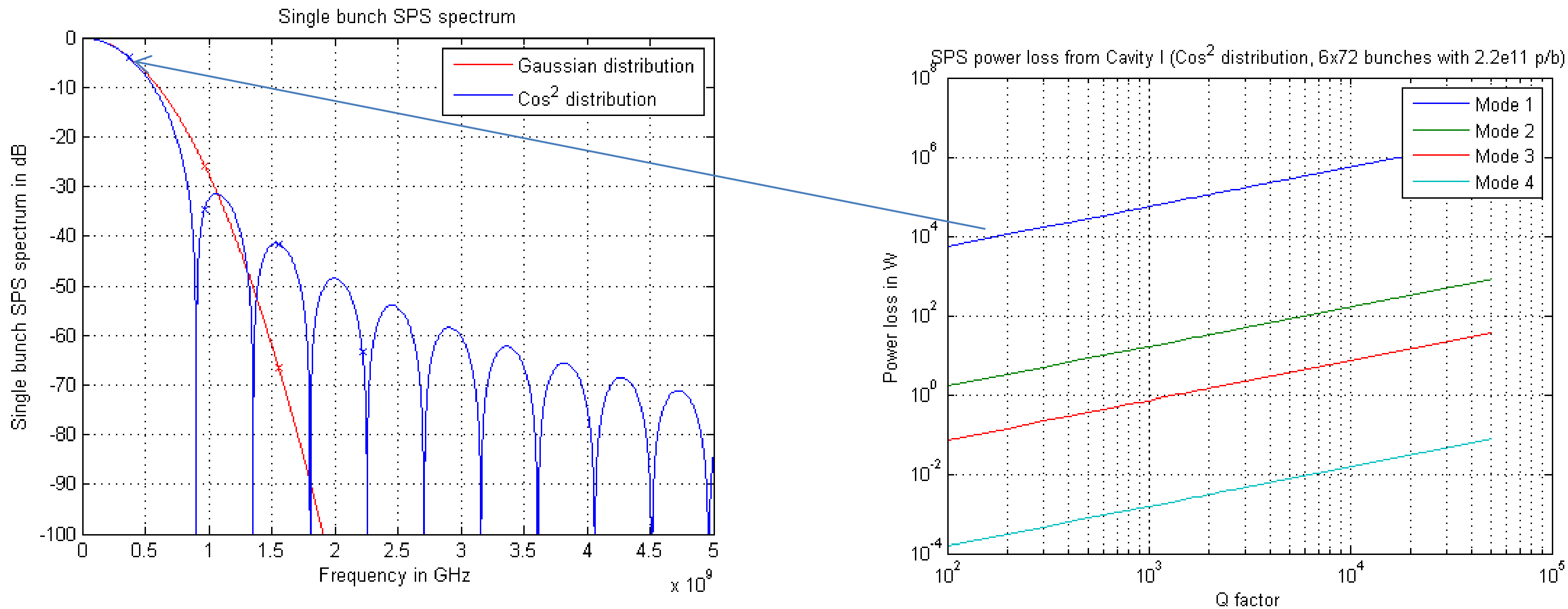
# Power from SPS beam: cavity I (Lancaster)

1.6 ns bunch length, 6x72 bunches with 2.2e11 p/b
→ Quite optimistic before LS2
→ worst case scenario (also on beam spectrum line)




→ With Q=1000, power loss for the worst mode (375 MHz) is ~50 kW

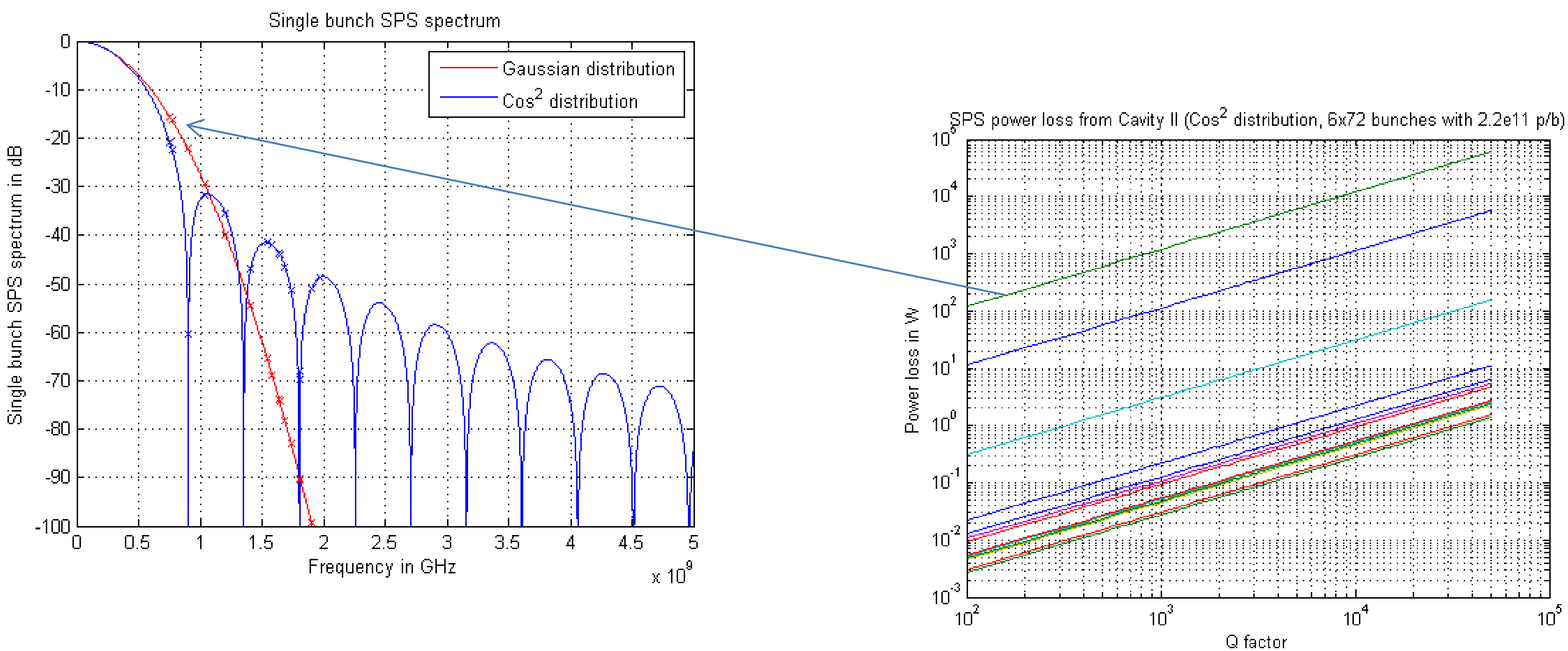
Using Ploss=(2*(M*Nb*e*frev)^2*h(f)^2*R/Q*Q;

# Power from SPS beam: cavity II (ODU)

1.6 ns bunch length, 6x72 bunches with 2.2e11 p/b

→ Quite optimistic before LS2

→ worst case scenario (also on beam spectrum line)



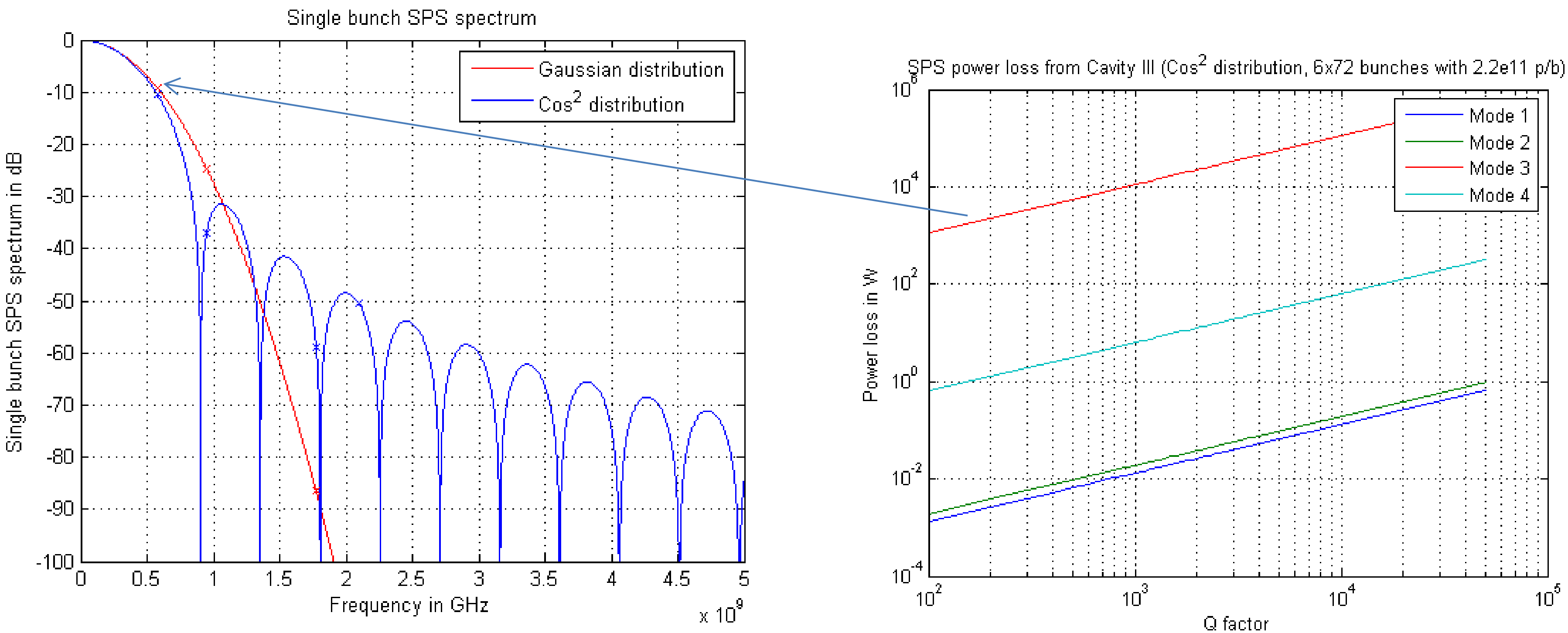

→ With Q=1000, power loss for the worst mode (772 MHz) is ~1 kW

# Power from SPS beam: cavity III (BNL)

1.6 ns bunch length, 6x72 bunches with 2.2e11 p/b

→ Quite optimistic before LS2

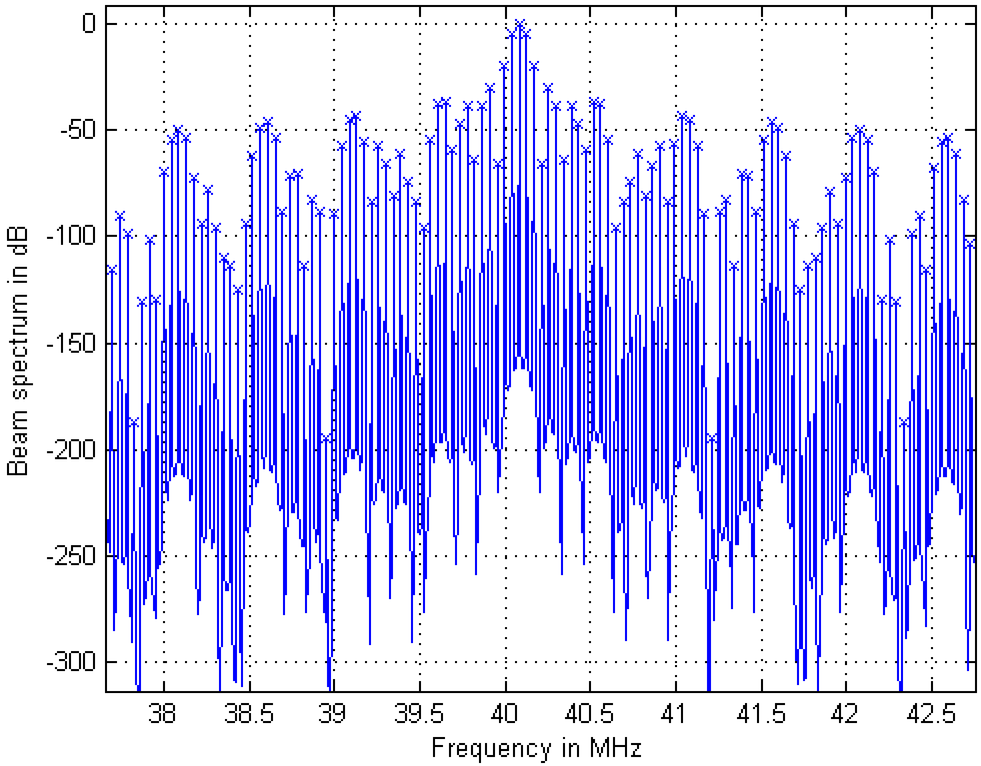
→ worst case scenario (also on beam spectrum line)




→ With Q=1000, power loss for the worst mode (577 MHz) is ~10 kW (worst case)

# Off resonance effect

Normalized SPS beam spectrum for 25 ns beam (288 bunches)




→ Very strong reduction in beam spectrum if 0.5 MHz away from resonance

→ Also developed by E. Metral at IBIC 2013 and R. Calaga et al in a note

→ Are these worst case power values still reasonable?
→ In summary for SPS, impact on beam is expected to be limited

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# Requests for shunt impedance of resonant modes

- History of requests for maximum longitudinal shunt impedance added to LHC at a given frequency:
  - E. Shaposhnikova (CC10 workshop)
    → 200 kOhm limit for ultimate intensity, 1 ns, 2.5eVs at 7 TeV relaxed beyond 600 MHz as $(\tau f_r)^{5/3}$
  - A. Burov (CC11 workshop)
    → 2.4 MOhm limit for ultimate intensity, 1.1 ns at 7 TeV
  - B. Salvant based on A. Burov's model (HiLumi 2012 workshop)
    → 1.7 MOhm limit for 2.2e11 p/b, 1 ns at 7 TeV

→ Need convergence of theoretical models and guidance of macroparticle simulations

→ Ongoing heavy work (N. Mounet):
- Impedance model with and without additional resonant modes
- DELPHI and HEADTAIL simulations to assess intensity limits

→ Current limit for current installation into LHC set to max Rs~200 kOhm per resonant mode up to 1.5 GHz (agreed with BE/RF-BR).

→ This limit is known to be conservative (in particular since the bunch length is longer than the design bunch length) and could be revised following the results of the study.

# Longitudinal impedance limit for coupled bunch instabilities

- Many parameters can/will change for the chosen options of HL-LHC:
  - Higher bunch and beam intensity (2748 bunches with 2.2e11 p/b)
  - 200 MHz or 800 MHz ? Longitudinal emittance? Bunch length?
- Until the parameters are clearer, this limit shall continue to be enforced.

With 16 (or 12) identical cavities per beam, this would mean a limit of 12 kΩ (or 16 kΩ) per cavity

→ Possibility to use two sets of different cavities to increase the threshold by a factor 2.

→ Interesting suggestion by E. Shaposhnikova to detune and spread all longitudinal modes of the cavities on purpose

→ Limit would then be back to 200 kΩ per cavity.

| Worst longitudinal mode | Cavity I (Lancaster) | Cavity II (ODU) | Cavity III (BNL) |
|---|---|---|---|
| Frequency (MHz) | 375 | 772 | 577 |
| R/Q (Ω) | 125 | 180 | 108 |
| **Min Q to reach 12 kOhm/cavity** | **100** | **70** | **110** |
| **Min Q to reach 200 kOhm/cavity** | **1600** | **1100** | **1850** |
| Required separation Δf>f/Q (MHz) | 0.2 | 0.7 | 0.3 |

→ Would this detuning be feasible for many cavities?

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# Crab cavity simulations and importing into LHC impedance model

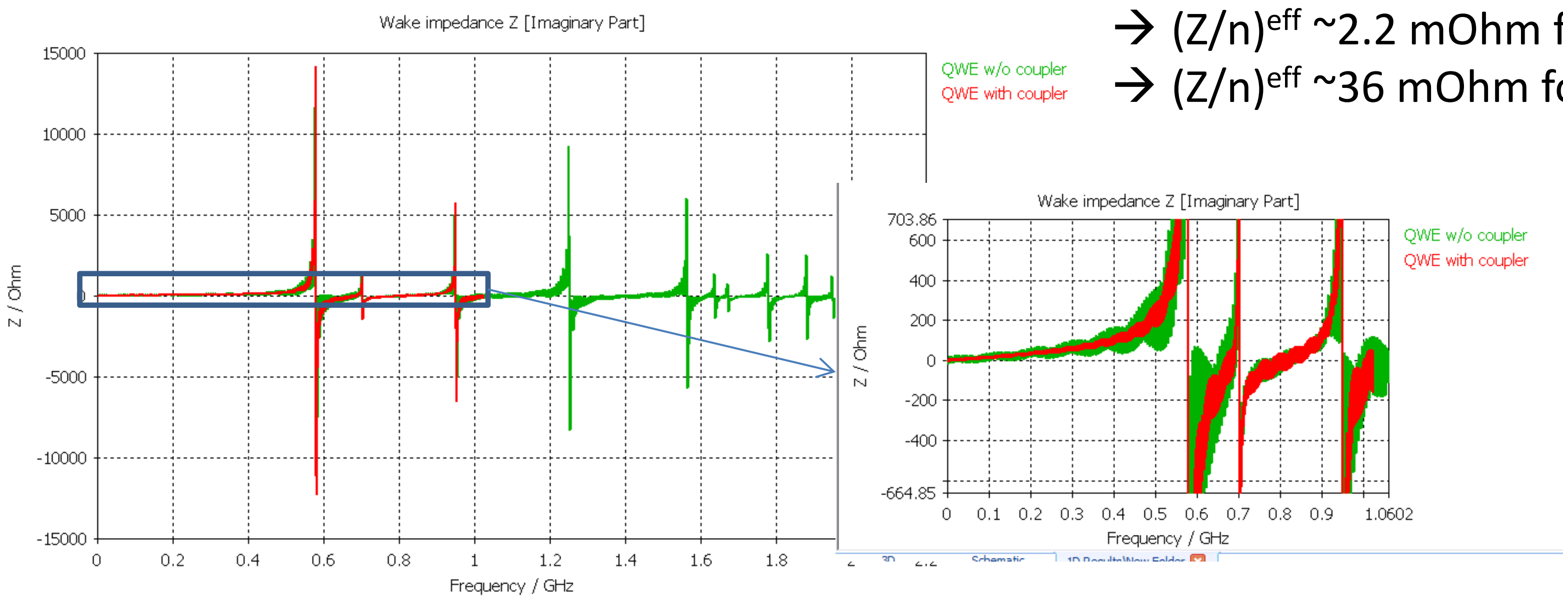
- Crab cavities have very large resonances
  - simulated through eigenmode solver

    → f, R, Q

- Is there anything besides the resonances?
  - Effect on synchrotron and betatron tune shift would come from effective longitudinal and transverse impedances
  - Simulated through wakefield solver → ex: QWE cavity

→ $(Z/n)^{eff}$ ~2.2 mOhm for 1 cavity

→ $(Z/n)^{eff}$ ~36 mOhm for 16 cavity



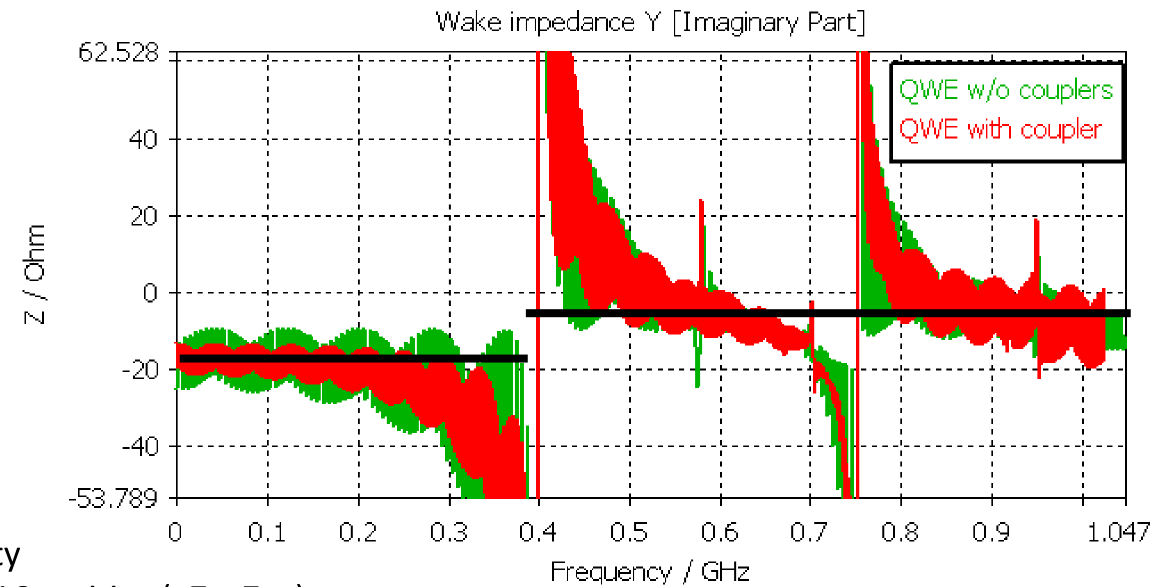

→ 16 crab cavities per beam would add 40 % of the total LHC impedance (below 500 MHz).

→ Is that acceptable for LHC beam stability?

→ How to account for both correct resonance parameters and correct effective impedance?

# Crab cavity simulations and importing into LHC impedance model

- Transverse case




Beam displacement= 5 mm

→ $Z^{eff}$ ~ 20 Ohm/5 mm=4 kOhm/m for 1 cavity

→ $Z^{eff}$ ~ 30 Ohm/5mm*16=100 kOhm/m for 16 cavities (<Zx+Zy>)

→ Which is 5% compared to the total LHC impedance at injection (~2 MOhm/m)

→ However, beta in collisions can be of the order of 4 km → $Z^{eff}$ ~ 100e3 *4000/70= 5 MOhm/m for 16 cavities

→ 16 crab cavities per beam would add 25 % of the total LHC impedance (below 400 MHz).

→ Is that acceptable for LHC beam stability?

→ How to account for both correct resonance parameters and correct effective impedance?

First idea: We chose to add constant impedance contributions to resonator models

→ Problem: are we not counting the same contribution twice ?

→ At low frequency, Zresonator → j*R/Q *f/fr in longitudinal and j*R/Q in transverse.

For the specific QWE case:

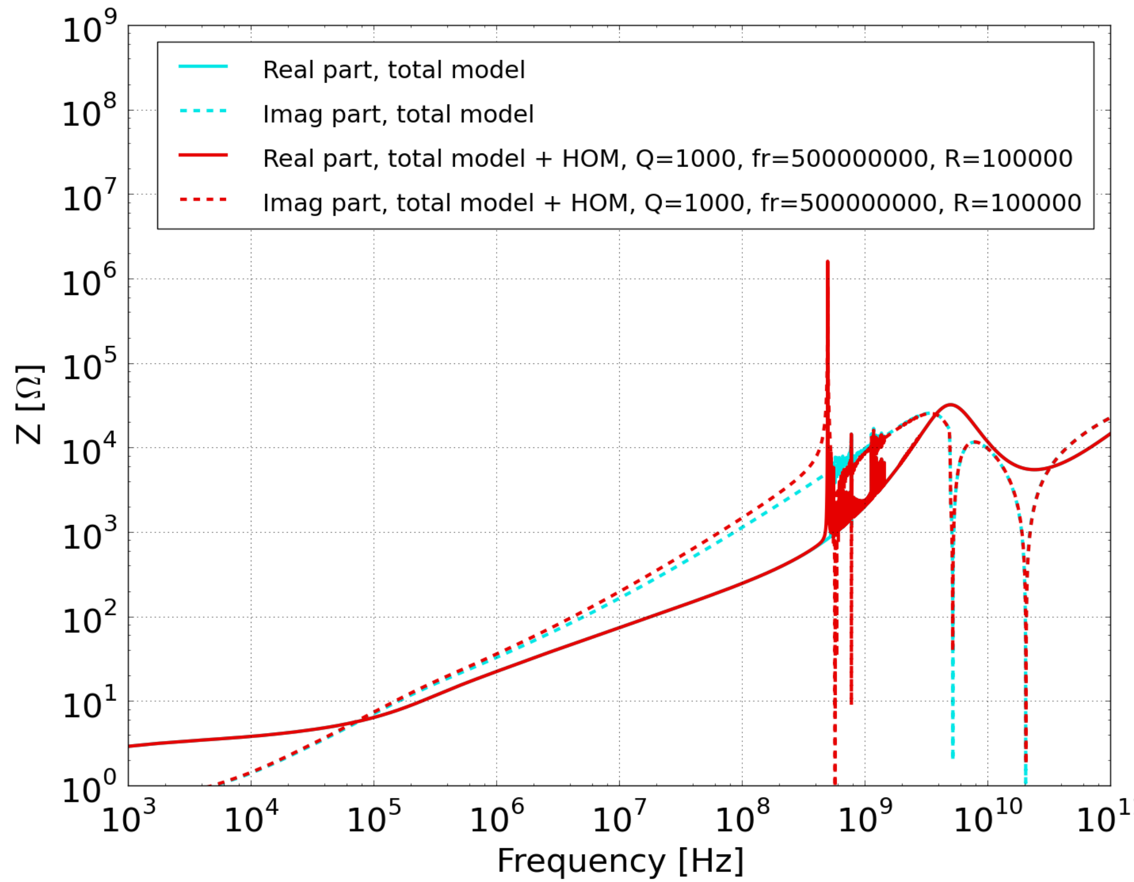
- Im(Zlong/n)~ R/Q/fres*frev~108/577e6*11e3=2 mOhm (2.2 mOhm computed) → the longitudinal mode could be enough

- Im(Ztrans)~R/Q=400 Ohm (convention: Zt[Ohm/m]=R[Ohm]*ω/c=3.3 kOhm/m) → the transverse mode could be enough

→ most likely no need to add constant values, as we thought we should do.

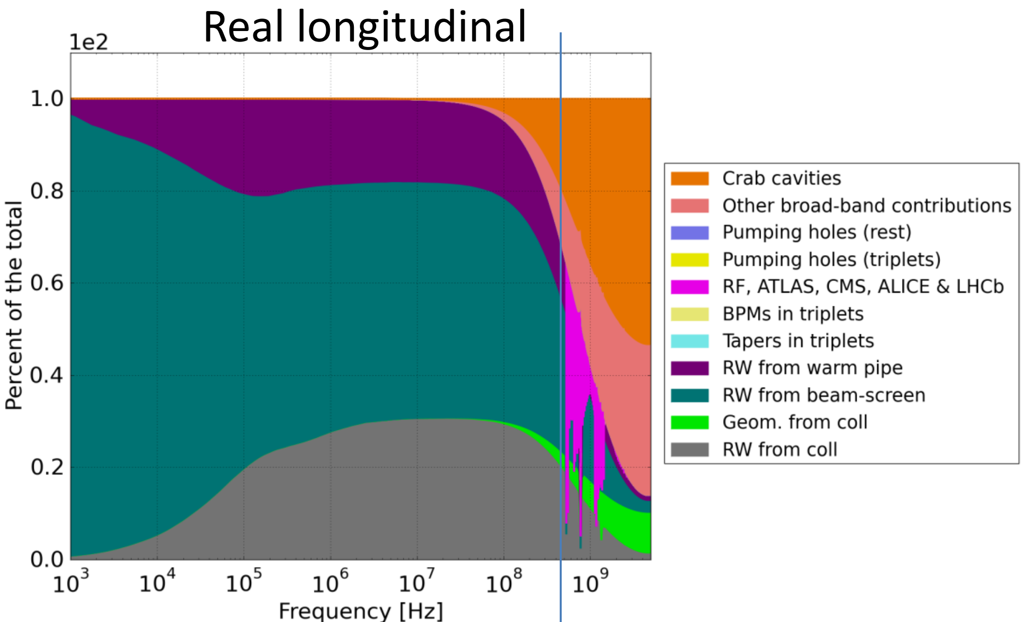
# Contribution of longitudinal crab cavity to LHC impedance model

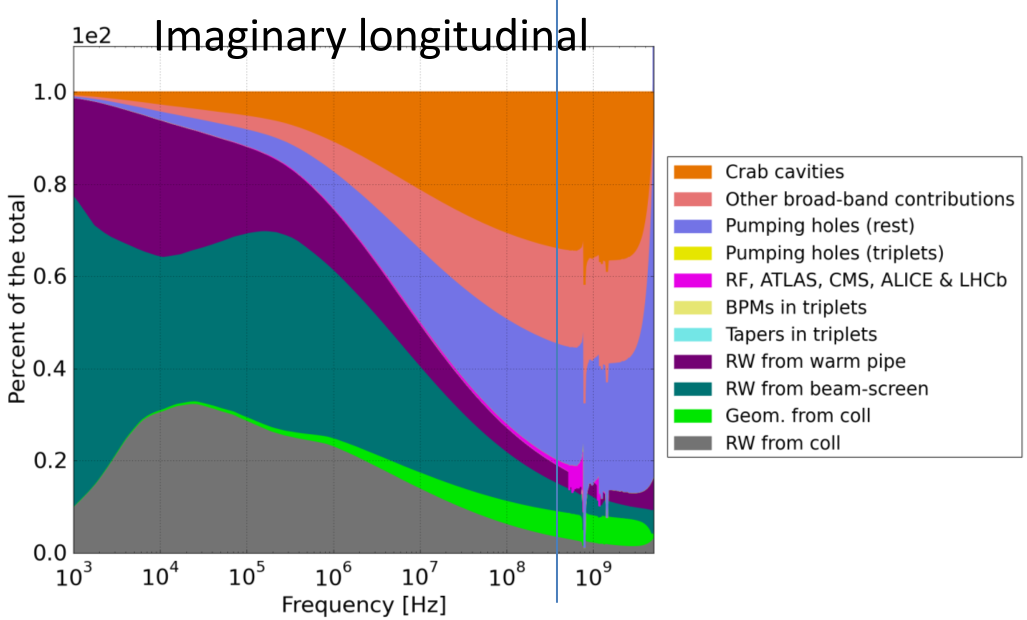
Impact of longitudinal mode of 16 cavities at 500 MHz (R=100 kOhm, Q=1000)




→ Quite noticeable on the current LHC model (on both real and imaginary part)

# Contribution of the low frequency part to the longitudinal impedance model



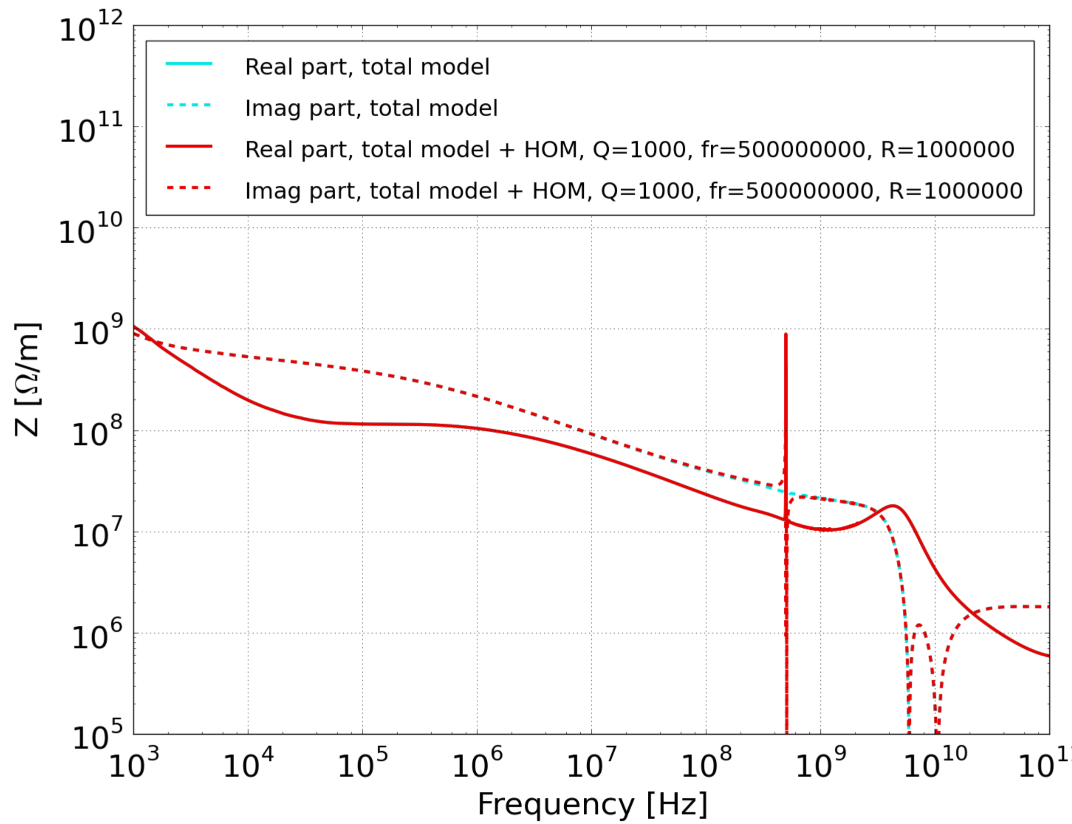




Important question as the impedance contribution of the crab cavities is not negligible!

Here only the effective part of the crab cavity is shown (valid up to 400 MHz only)

# Contribution of crab cavity to impedance model

- Example of Rt=1 MOhm/m and Q=1000

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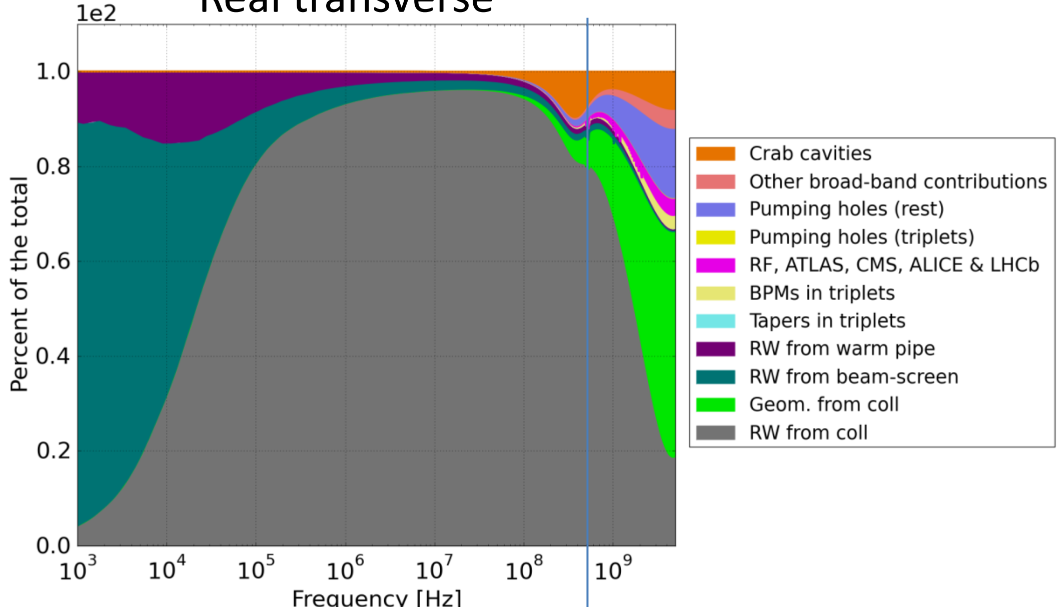
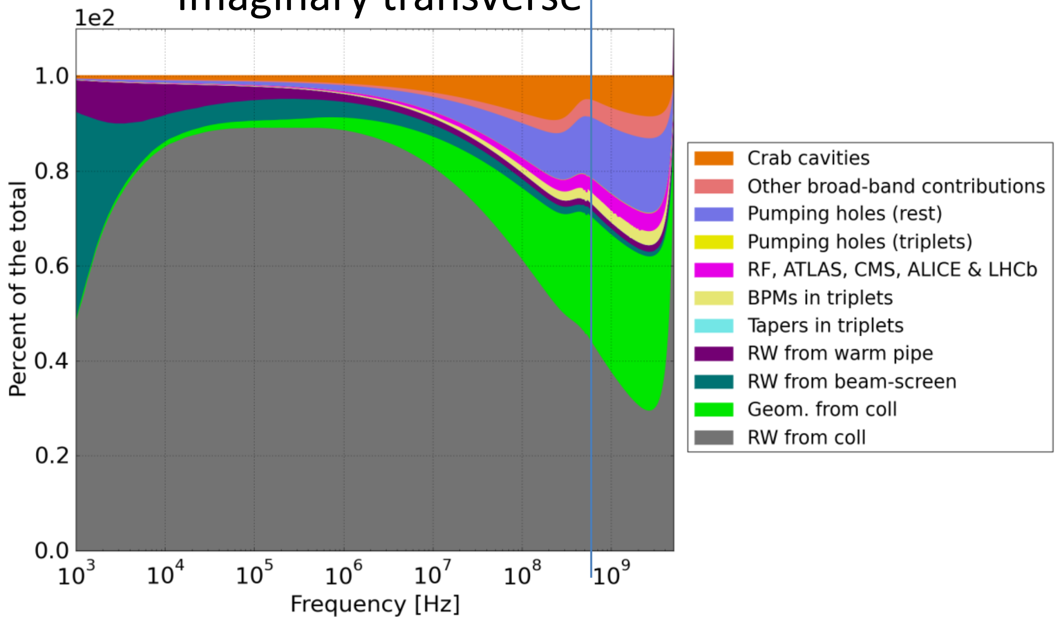
# Contribution of the low frequency part to the longitudinal impedance model

Real transverse




Imaginary transverse

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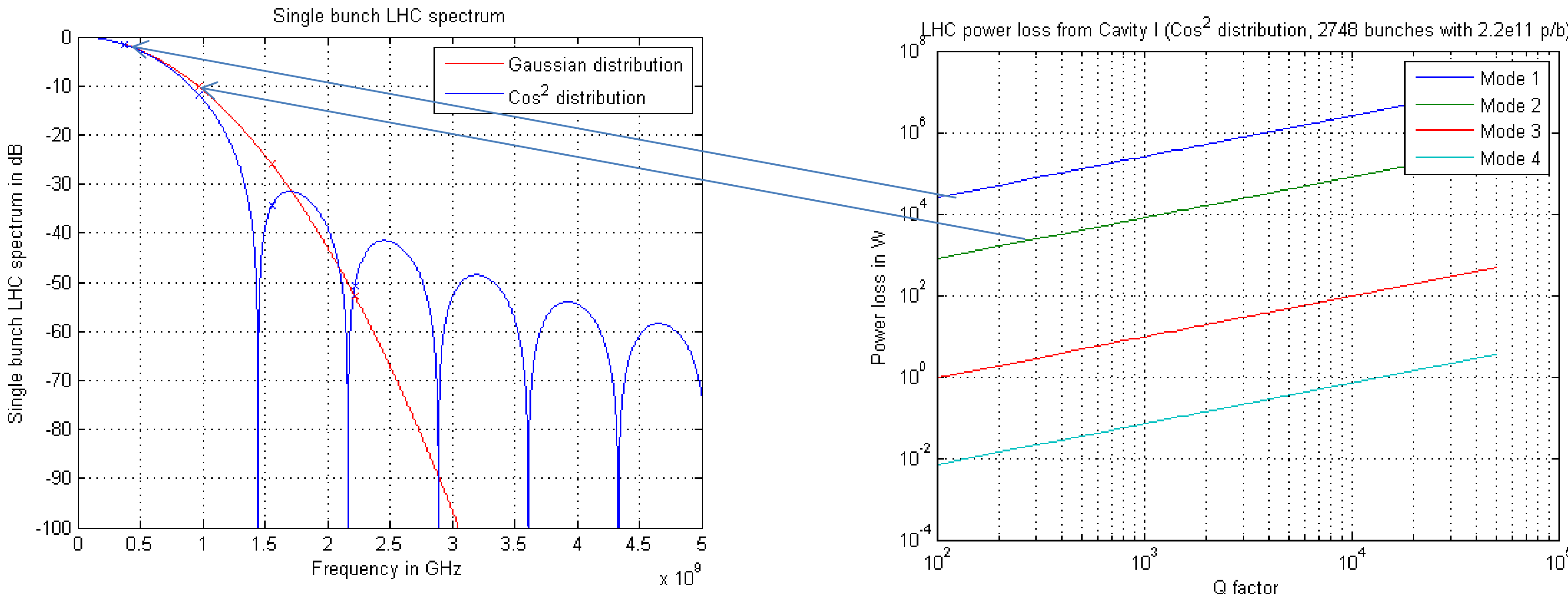
# Power from LHC beam (cavity I, Lancaster)

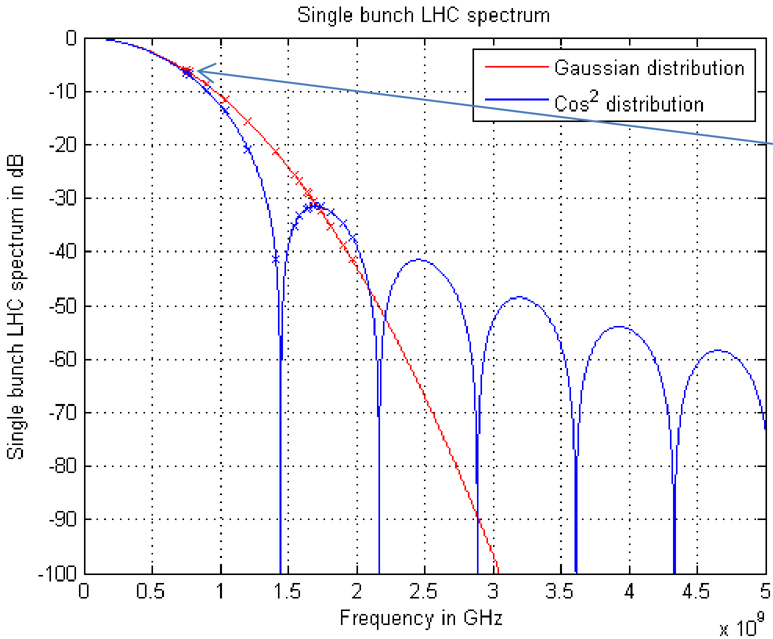
1 ns bunch length, 2748 bunches with 2.2e11 p/b
→ worst case scenario (on beam spectrum line)

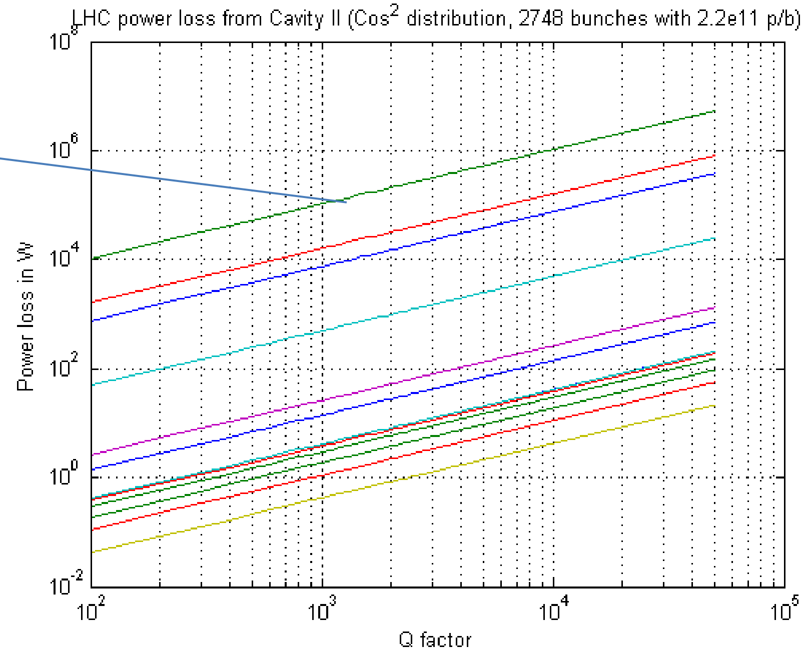



→ With Q=1000, power loss for the worst mode (375MHz) is ~200 kW

# Power from LHC beam (cavity II, ODU)

1 ns bunch length, 2748 bunches with 2.2e11 p/b
→ worst case scenario (on beam spectrum line)

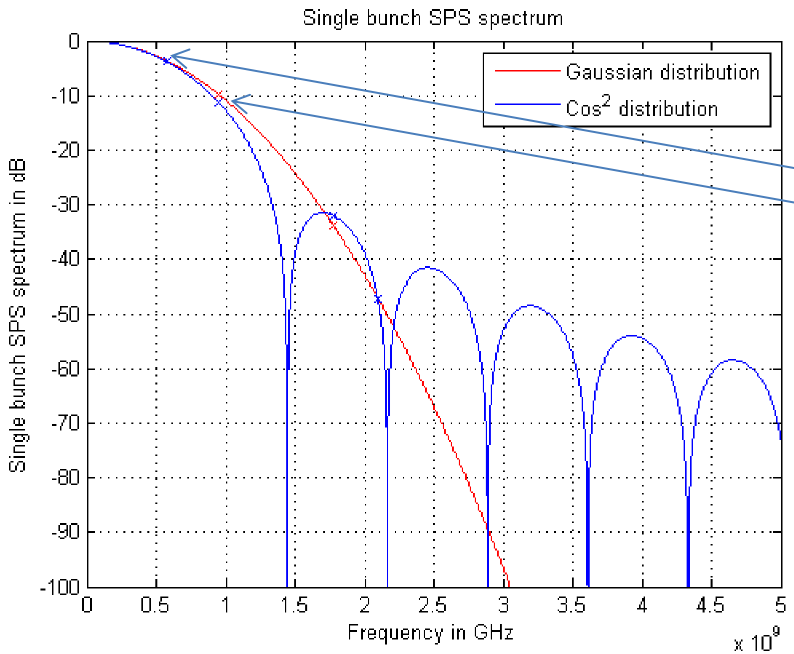


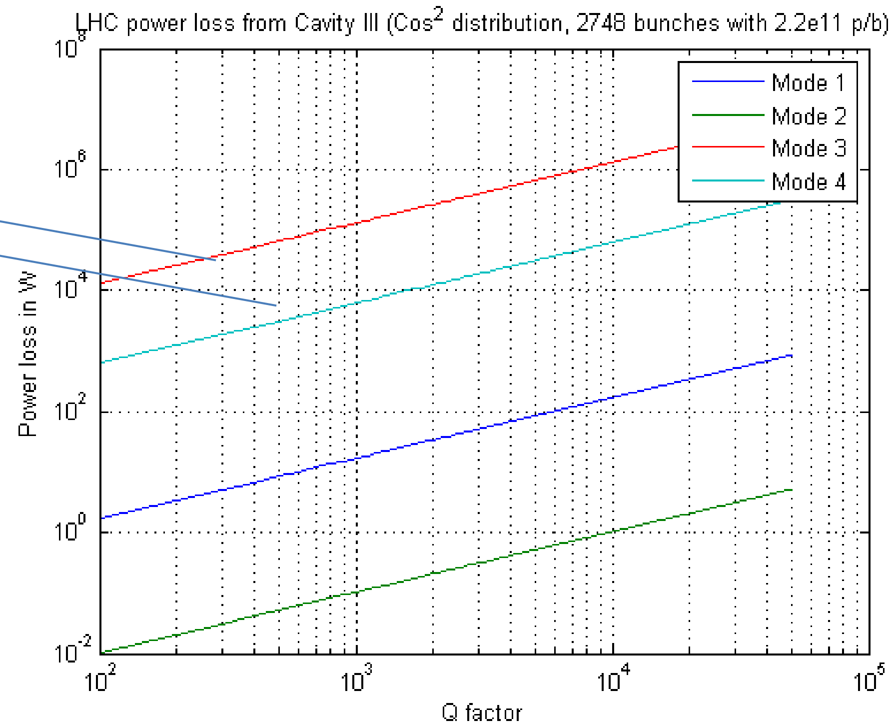




→ With Q=1000, power loss for the worst mode (772MHz) is ~100 kW

# Power from LHC beam (cavity III, BNL)

1 ns bunch length, 2748 bunches with 2.2e11 p/b
→ worst case scenario (on beam spectrum line)




→ With Q=1000, power loss for the worst mode (570MHz) is ~100 kW

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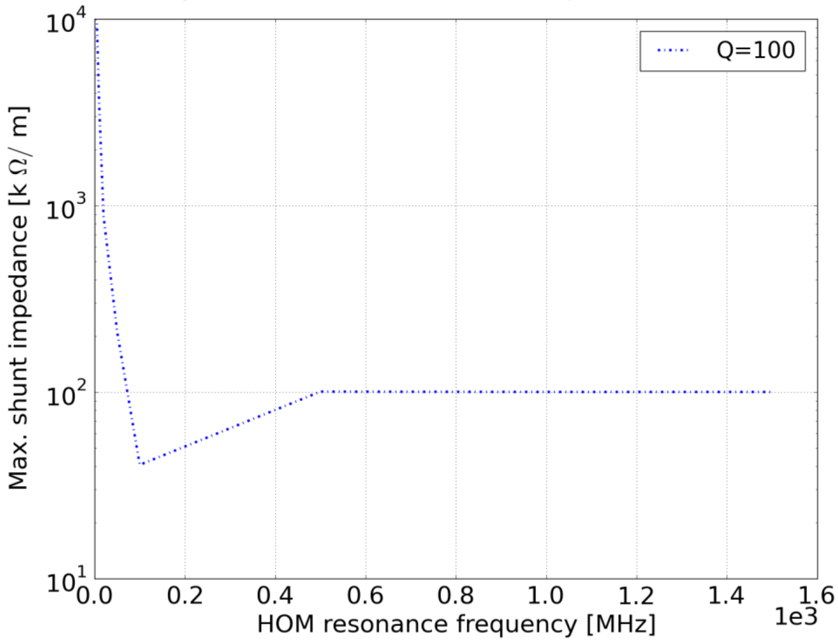
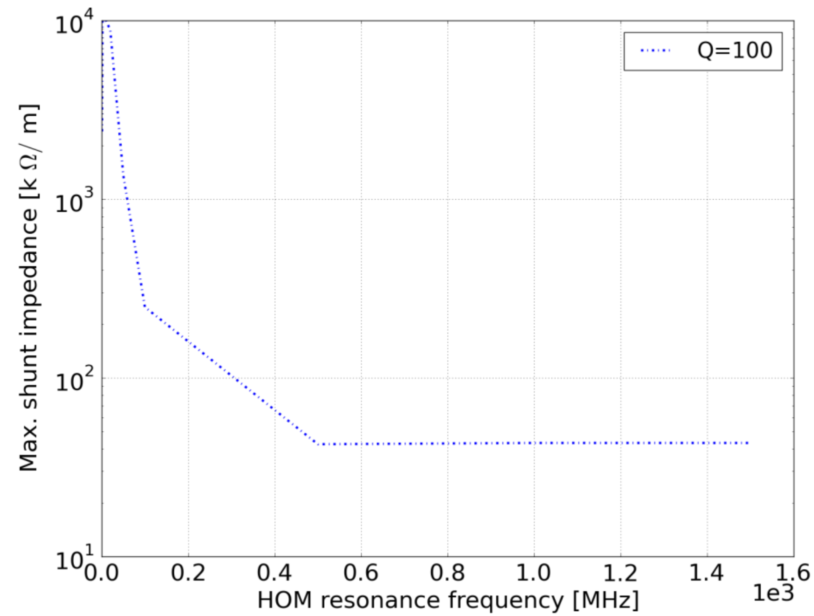
# Impact on transverse stability

- Ongoing studies with DELPHI: example of max shunt impedance of transverse mode vs frequency to increase the TMCI threshold by less than 1% (with Q=100)

High chroma and damper at 50 turns




Chroma=0 and no damper



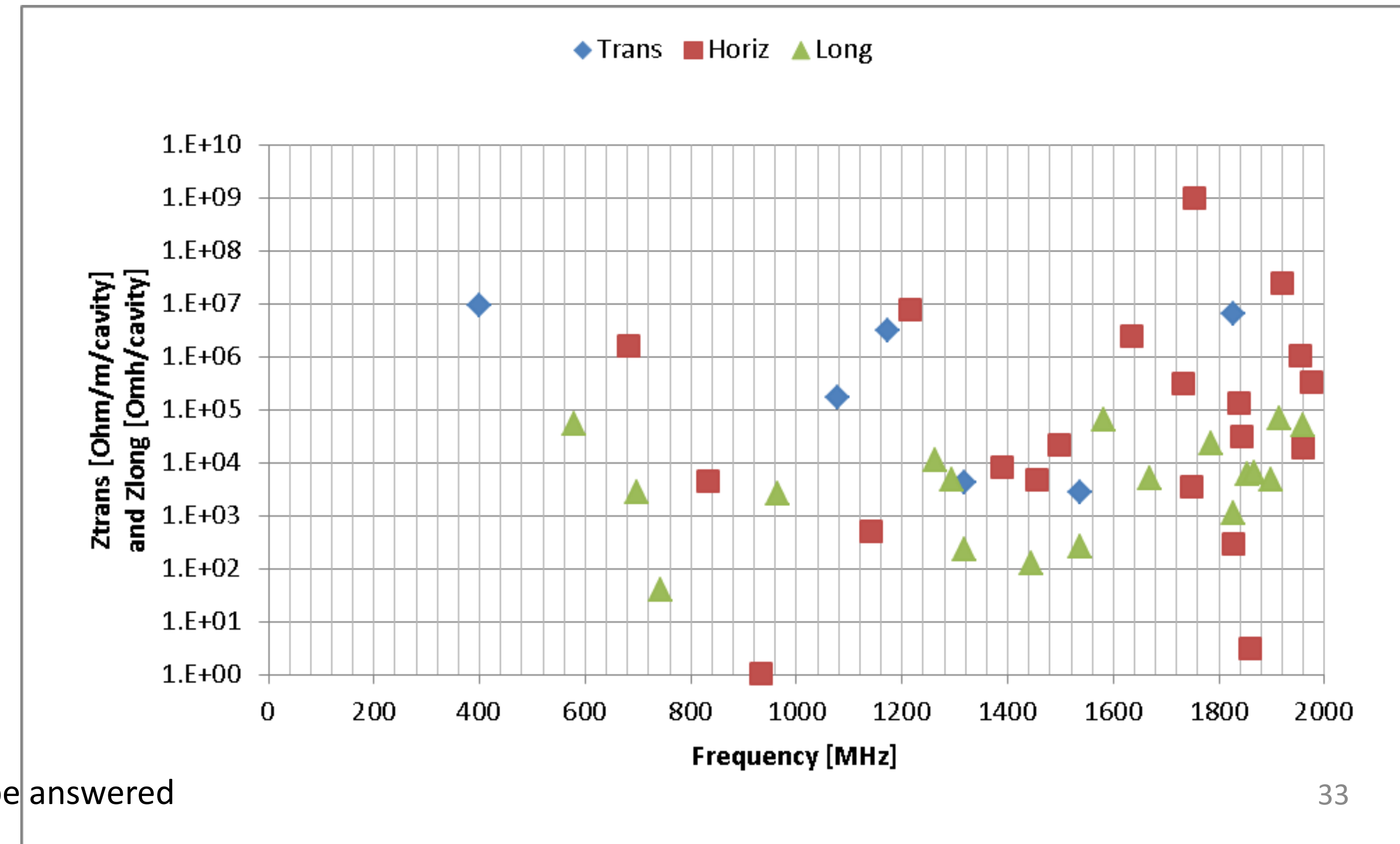

→ 50 to 100 kOhm/m would not affect too much the TMCI threshold

# Summary

- It would be useful to collect all updates on geometries and resonant parameters of all crab cavities.
- Impact on SPS beam seems limited.
- Impact on LHC beam seems significant (16 cavities+ very large beta functions).
- We need to converge on the acceptable limits for resonant modes, but the parameters and options are changing very fast.
- Current limit for all new LHC hardware is 200 kOhm (conservative). Relaxing this limit would mean freezing some parameters. Are we in a position to do this now?

# News since December

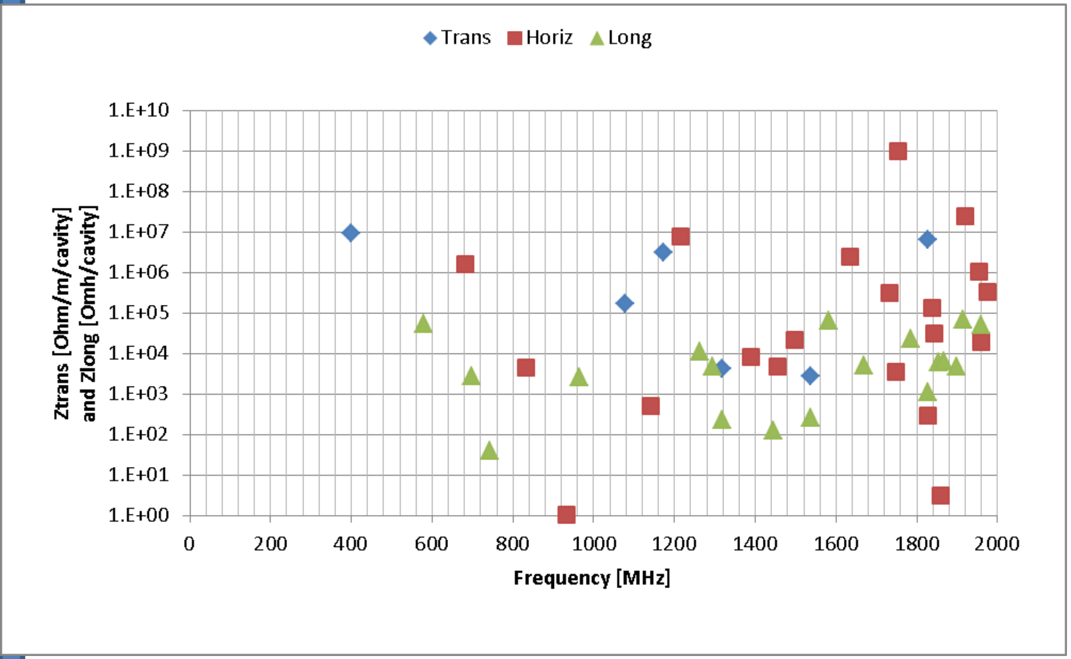
- Table of HOMs provided for QWE (Silvia from BNL)
- Table of HOMs provided for DQWCC (but main transverse deflecting mode missing)
- What about the third option?

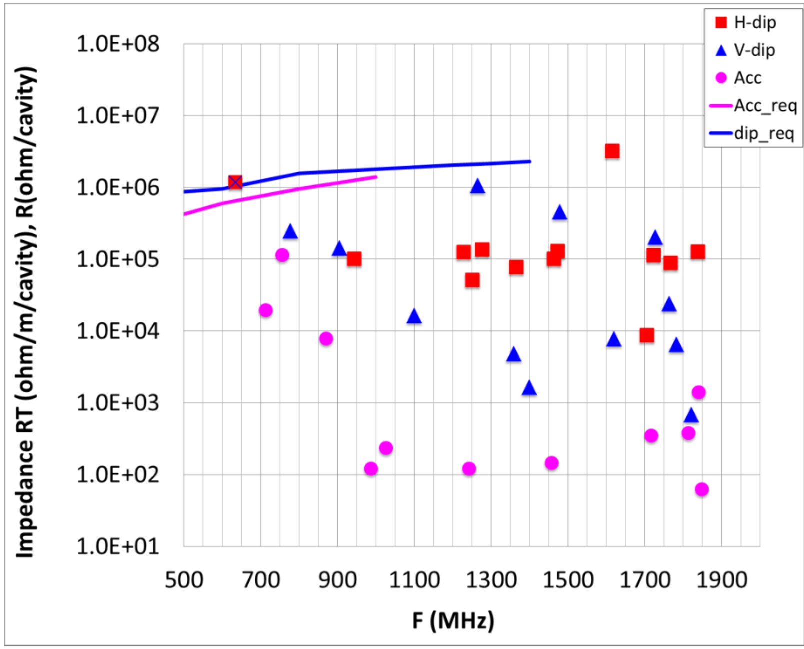



QWE cavity

Still some questions to be answered

# Shunt impedances: QWE vs RF dipole

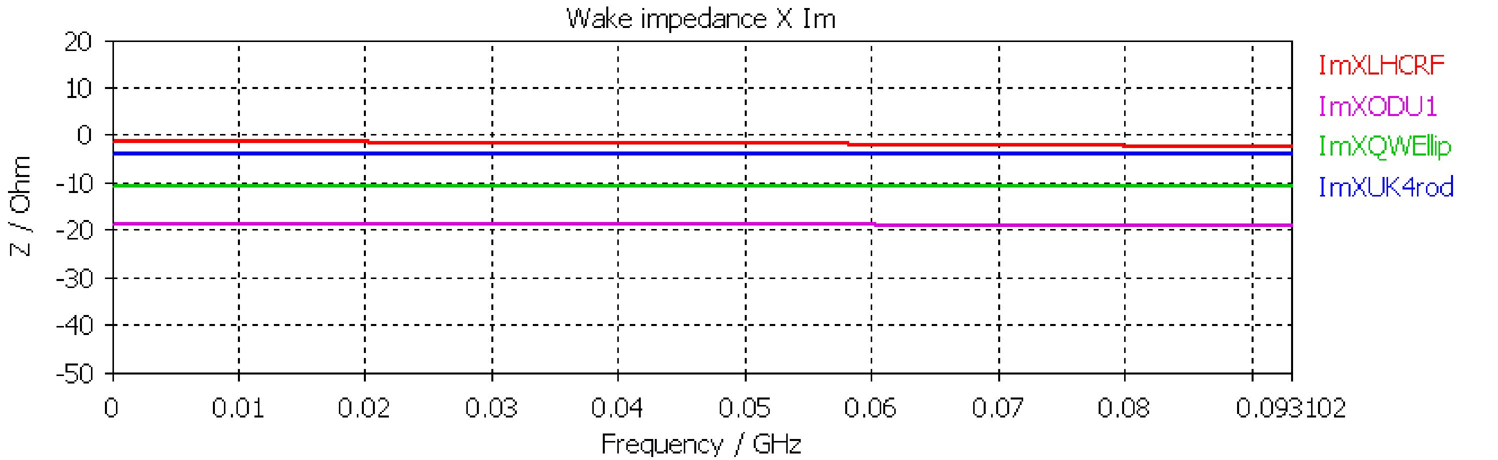



→ Longitudinal modes all below 100 kOhm

→ Some transverse modes of the order of 10 MOHm/m (per cavity), impact to be checked by DELPHI

# Low frequency transverse impedance of crab cavities (16 per beam)




| | 1 cavity<br>Zx<br>in Ω | 1 cavity<br>Zy<br>in Ω | 1 cavity<br><Z>= (Zx+Zy)/(2*d)<br>in Ω/m | 1 cavity<br>Zeff=<Z>*β/<β><br>in Ω/m | 16 cavity<br>Zeff=<Z>*β/<β><br>in Ω/m |
|---|---|---|---|---|---|
| LHCRF | 6 | 2 | 800 | 800 | 6.4E+03 (8 cav) |
| BNL | 18 | 10 | 2800 | 93E03 | 1.5E+06 |
| ODU | 10 | 19 | 2900 | 97E03 | 1.6E+06 |
| UK | 25 | 4 | 2900 | 97E03 | 1.6E+06 |

In collisions, β =4km and <β> =120 m is the average beta at the collimators, main impedance source which is not changing with the new optics.

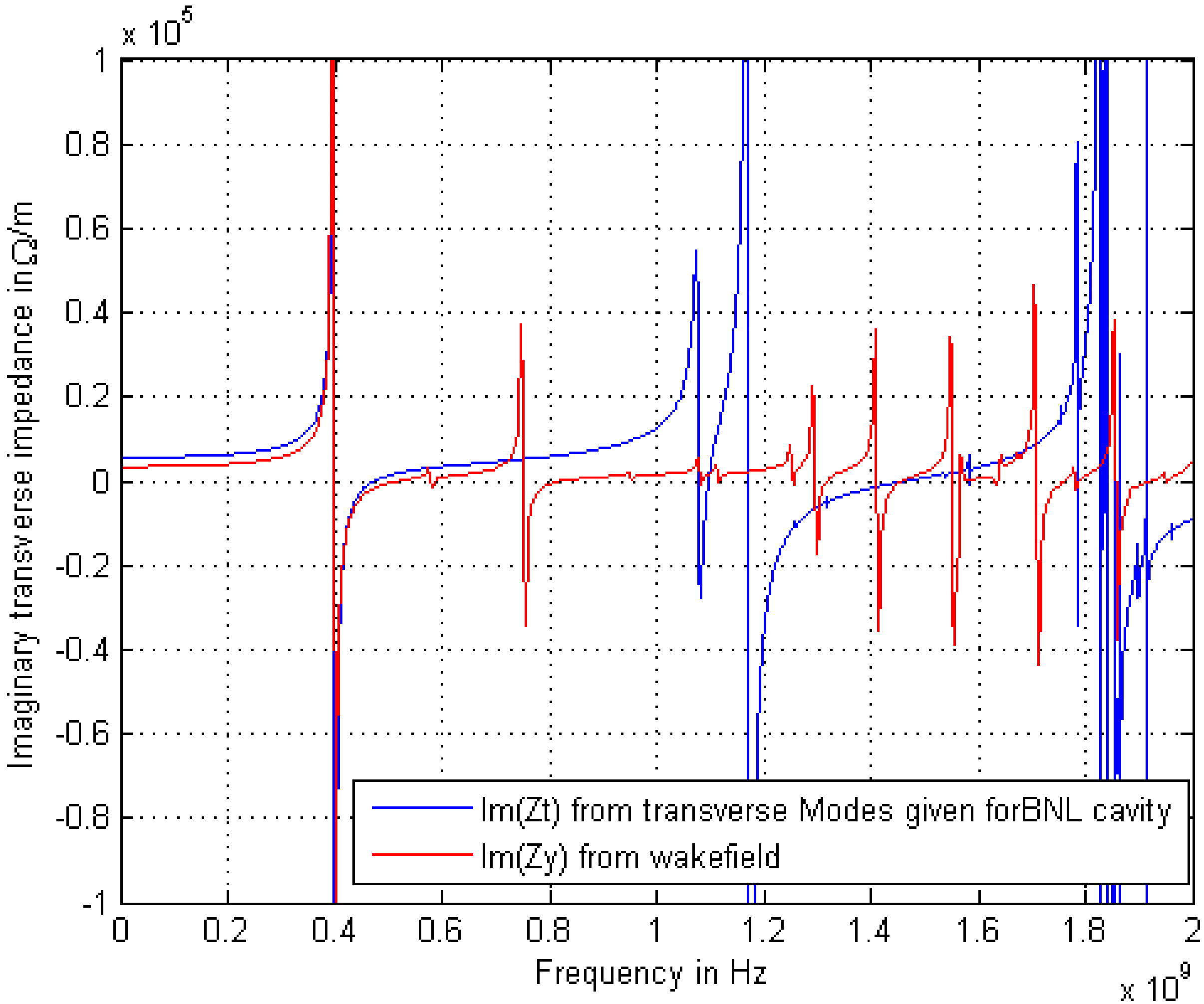
**At injection, 16 cavities represent 2.5% of the full LHC impedance, in collisions 6%**

# Impedance model (from Nicolas)

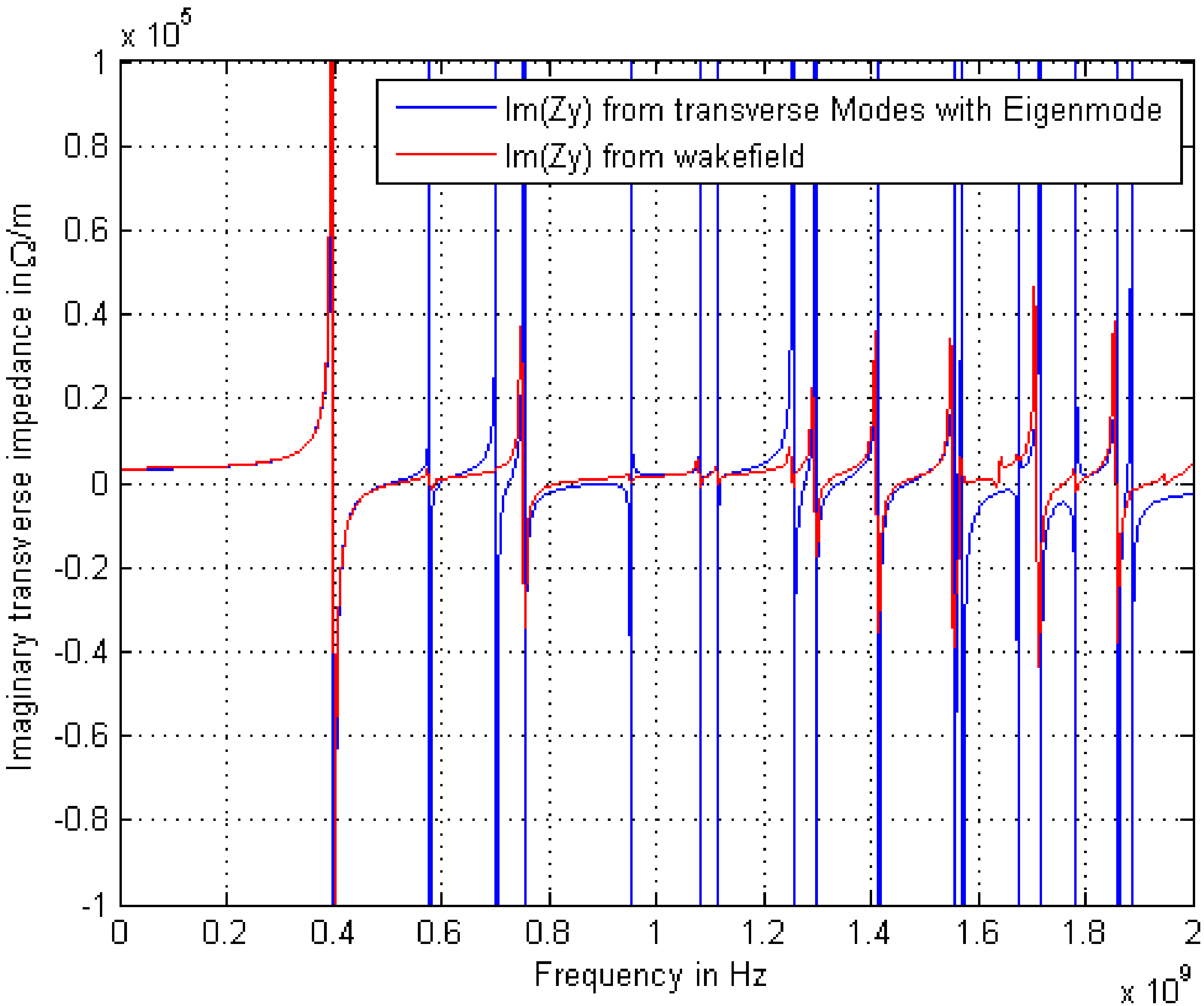
- Added the QWE transverse modes (no additional broadband contribution added)
- Crosschecks ongoing to confirm that we can use the transverse R/Qs directly.

  → issue of the

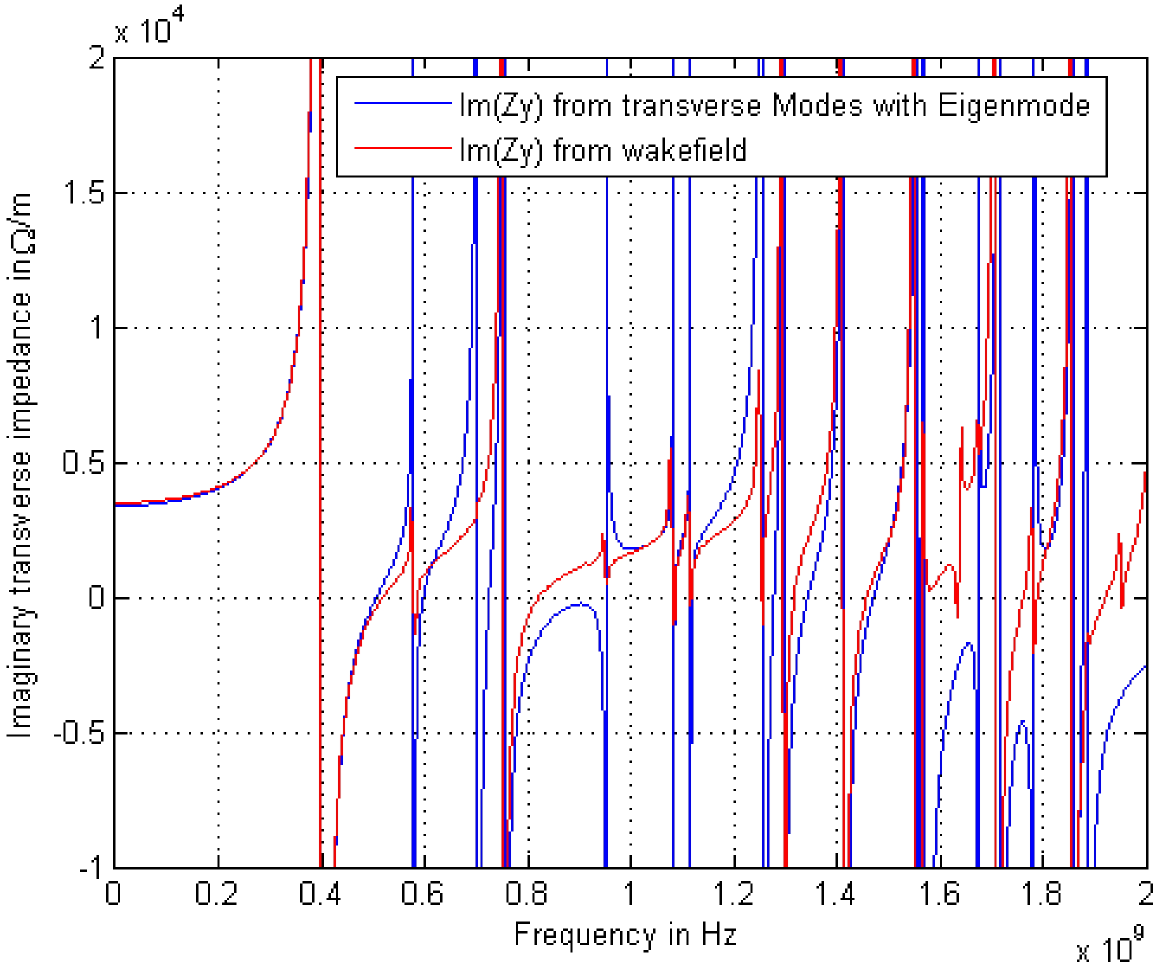
# Comparison between list of modes and wakefield



# Comparison between eigenmode and wakefields

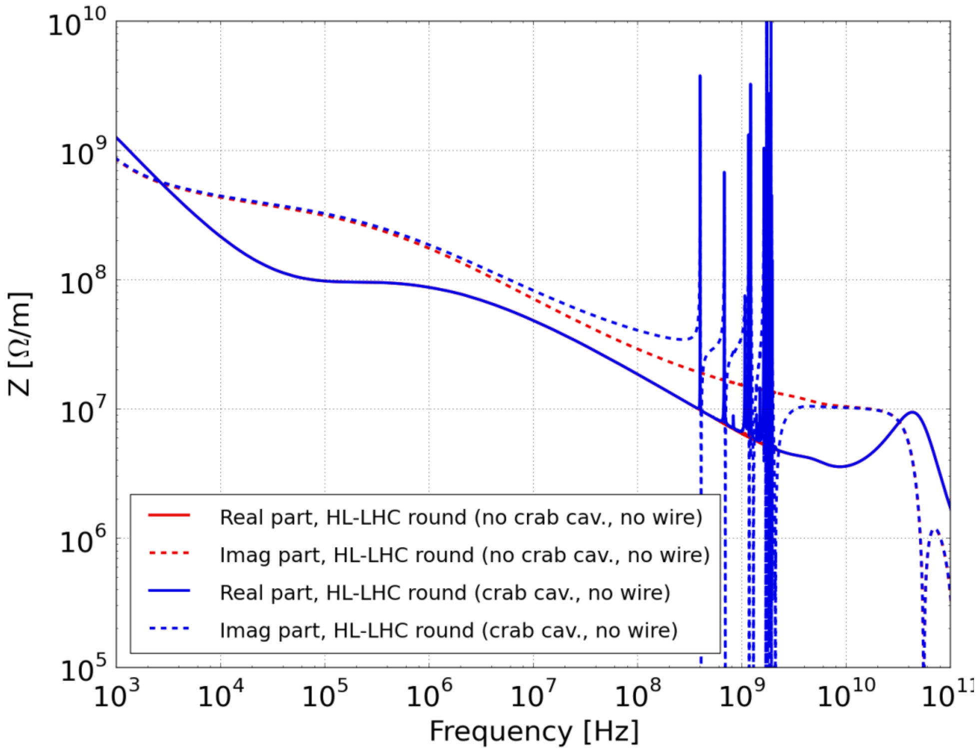


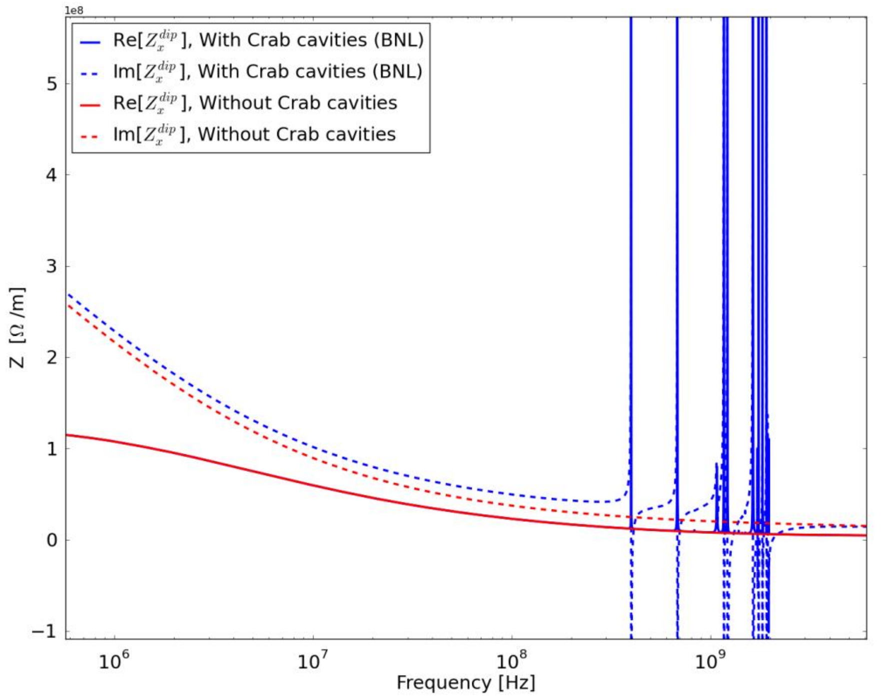
# Comparison between Eigenmode and Wakefields




→ Good agreement for low frequency.
→ Could be reasonable to sum all the resonator modes also for low frequency

# Effect of vertical impedance

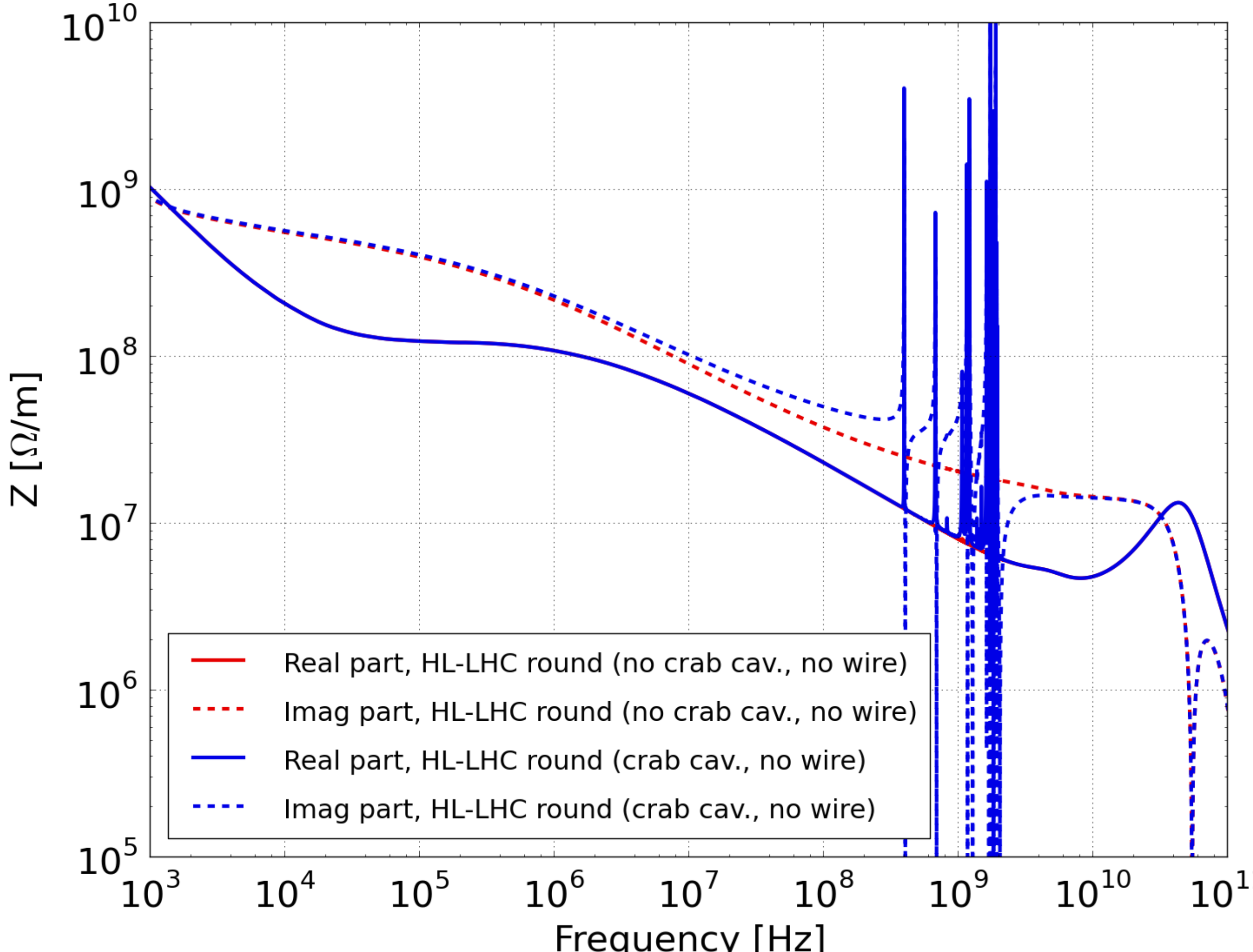



Current issue: we model the modes as resonators and the sum of R/Qs from the table do not match the low frequency imaginary impedance from wakefield.

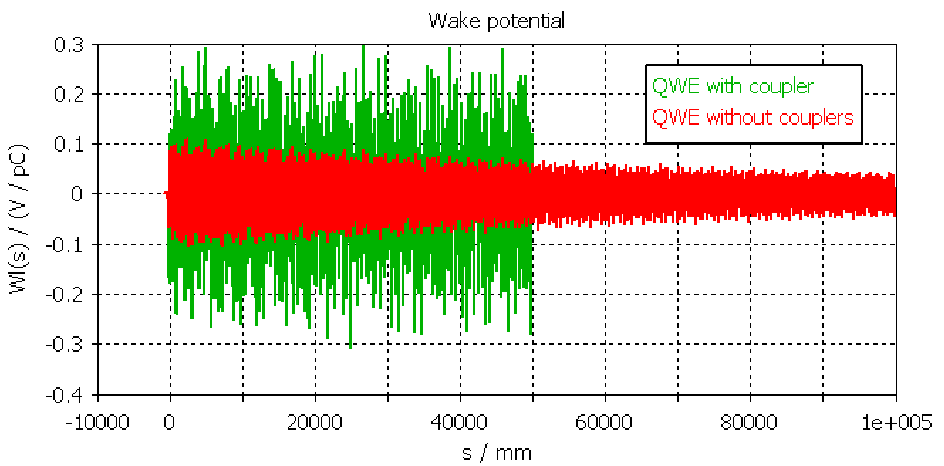
Also: modes beyond the deflecting modes are very different. To be understood.

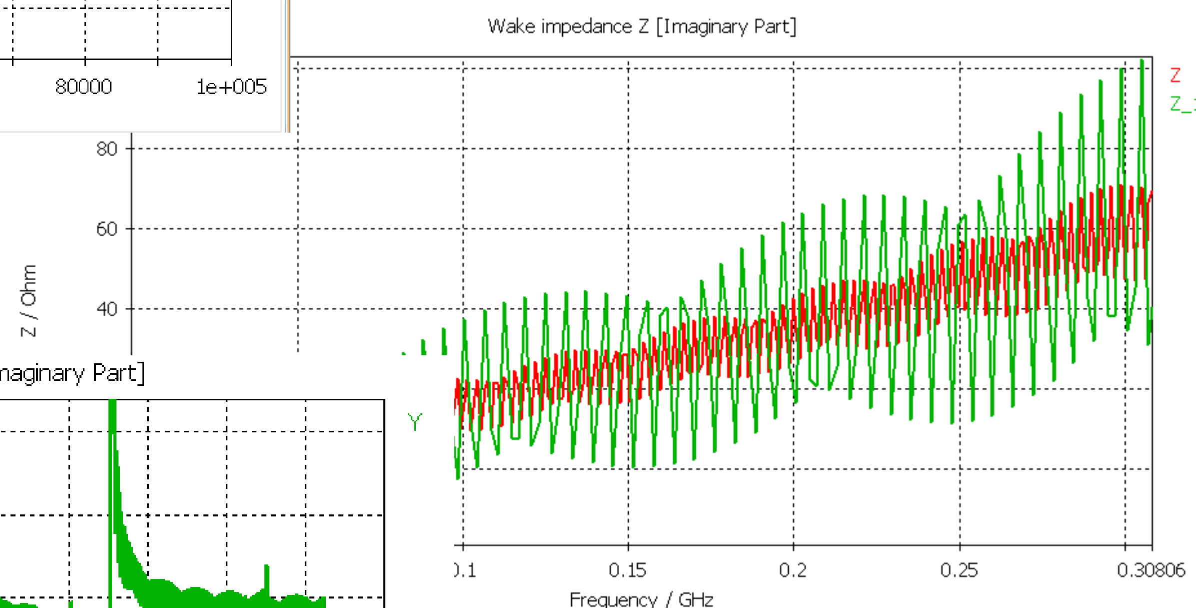
# Effect of horizontal impedance

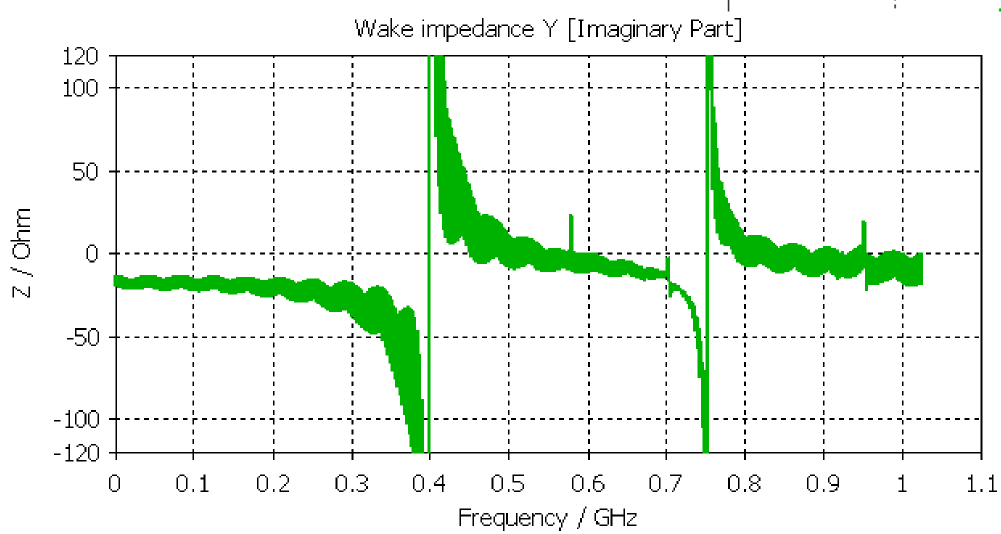


# Conclusions

- Adding resonators in the model could be consistent for transverse plane
- Need for more crosschecks before the review

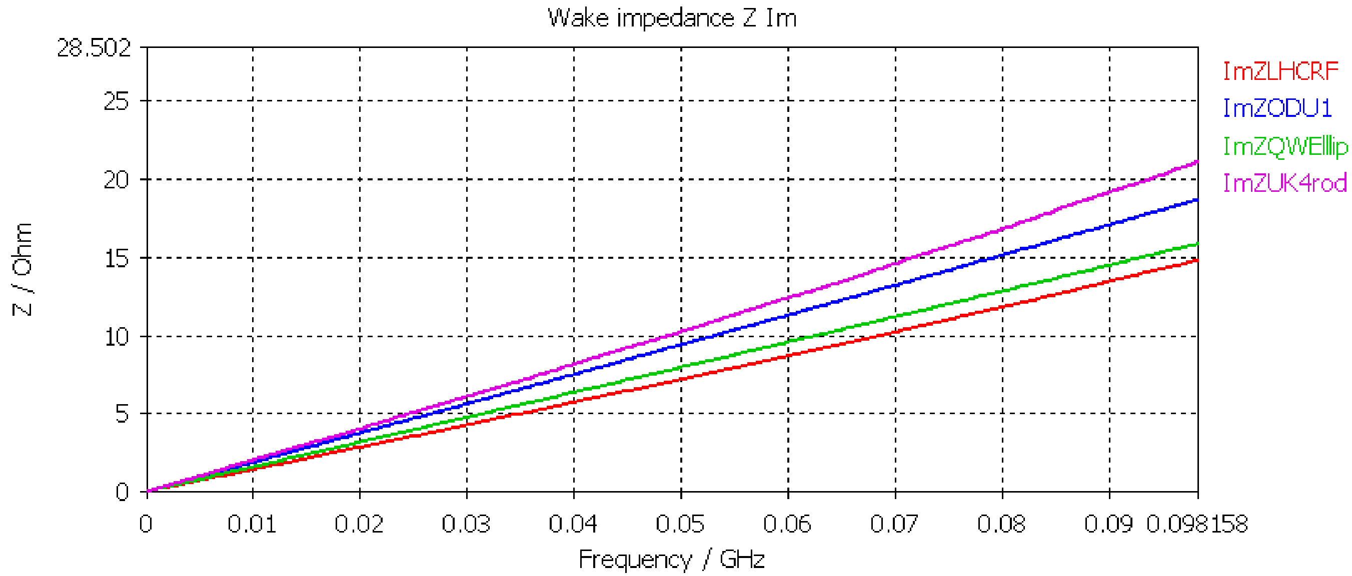

Wake potential
QWE with coupler
QWE without couplers
W(s) / (V / pC)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-10000
0
20000
40000
60000
80000
1e+005
s / mm


Wake impedance Z [Imaginary Part]
Z
Z_1
Y
Z / Ohm
80
60
40
0.15
0.2
0.25
0.30806
Frequency / GHz


Wake impedance Y [Imaginary Part]
Z / Ohm
120
100
50
0
-50
-100
-120
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
Frequency / GHz

# Low frequency longitudinal impedance of crab cavities (8 or 12 per beam) - preliminary

3D models from
R. Calaga
Q. Wong
B. Hall
S. De Silva

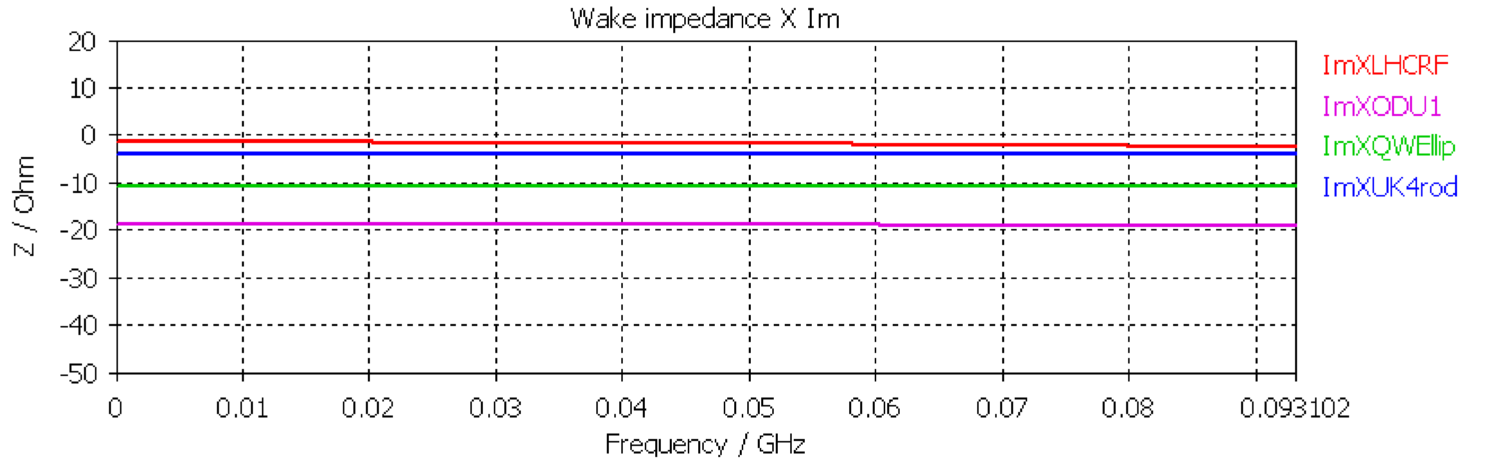



| | For 1 cavity Z/n (mOhm) | for 12 cavities Z/n (mOhm) |
|---|---|---|
| LHCRF | 1.7 | 14 (8 cavities) |
| BNL | 1.8 | 22 |
| ODU | 2.2 | 26 |
| UK | 2.4 | 29 |

To be compared to the current LHC budget of 90 mOhm

Very large contribution (20% to 30%) to be followed up with BE/RF-BR

# Low frequency transverse impedance of crab cavities (8 or 12 per beam) - preliminary




| | 1 cavity<br>Zx<br>in Ω | 1 cavity<br>Zy<br>in Ω | 1 cavity<br><Z>= (Zx+Zy)/(2*d)<br>in Ω/m | 1 cavity<br>Zeff=<Z>*β/<β><br>in Ω/m | 12 cavity<br>Zeff=<Z>*β/<β><br>in Ω/m |
|---|---|---|---|---|---|
| LHCRF | 6 | 2 | 800 | 800 | 6.4E+03 (8 cav) |
| BNL | 18 | 10 | 2800 | 93E03 | 1.1E+06 |
| ODU | 10 | 19 | 2900 | 97E03 | 1.2E+06 |
| UK | 25 | 4 | 2900 | 97E03 | 1.2E+06 |

In collisions, β =4km and <β> =120 m is the average beta at the collimators, main impedance source which is not changing with the new optics.

**At injection, 12 cavities represent 2% of the full LHC impedance, in collisions 4%**