# First results of calculation of wakefields for the LHCb experimental chamber.

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- Description of the geometrical model.
- Description of accuracy tests for 2D and 3D models.
- 2D calculations for the approximate geometry
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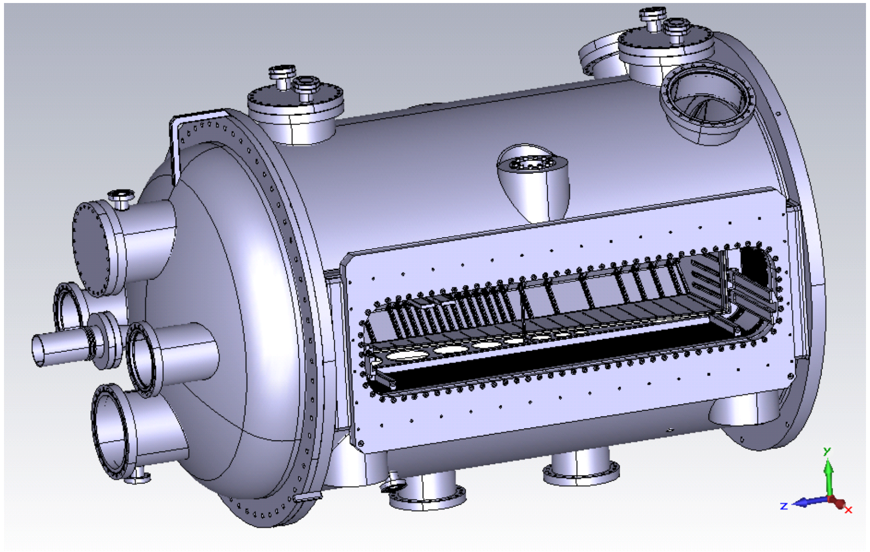
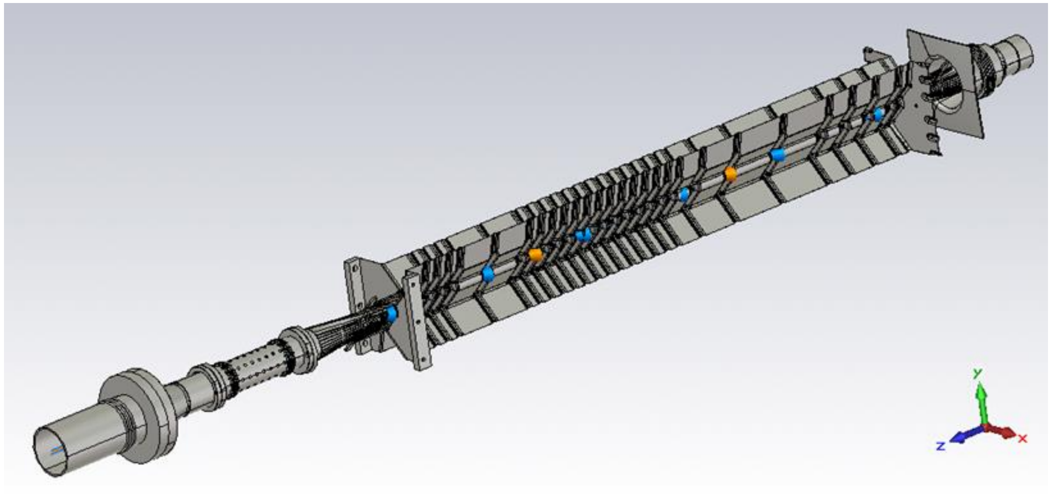
# Description of the geometrical model.



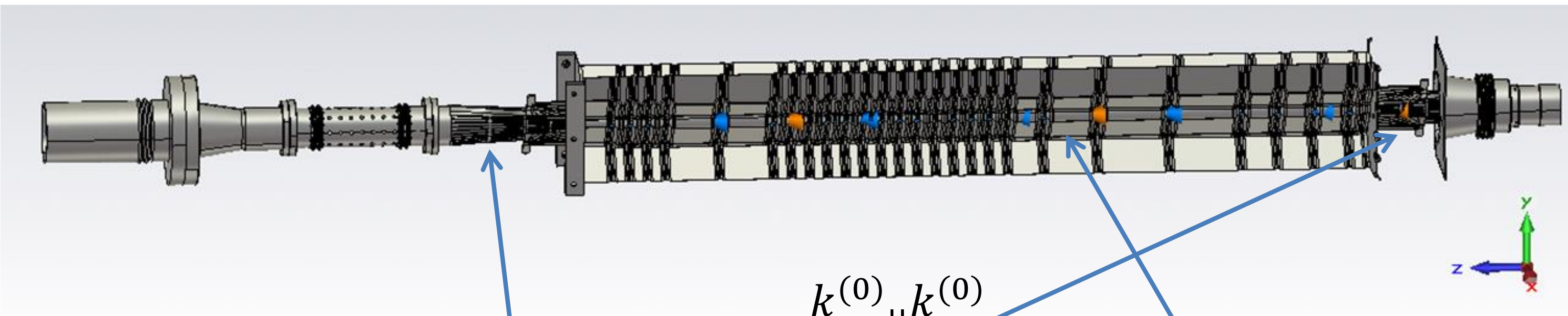

Original structure of experimental chamber was developed in CATIA system.
The structure was exported to CST MW Studio 2015 (B. Salvant)



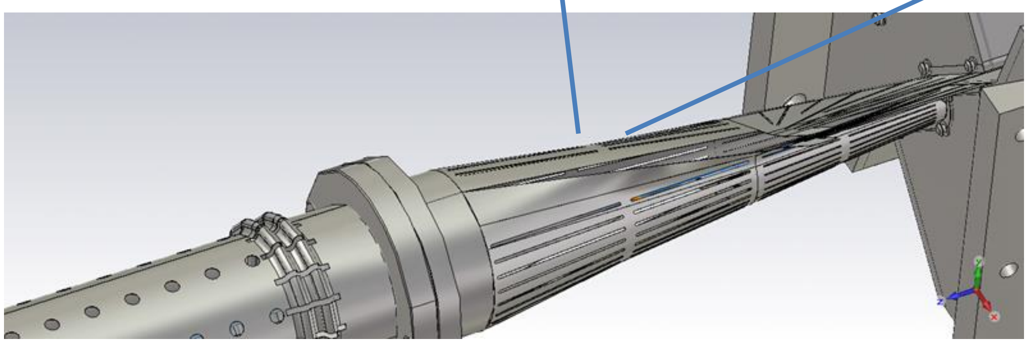

3D structure for calculations with help of the CST MW Studio 2015

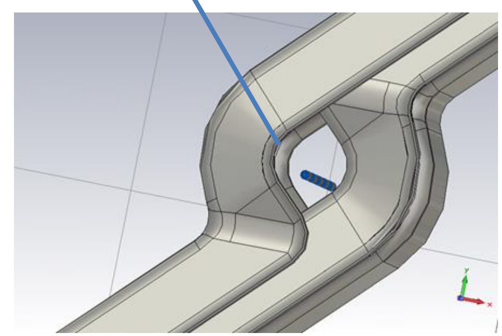
# Description of the geometrical model.

Beam pipe of the LHCb chamber in CST MW Studio.



$k^{(0)}{}_{||}k^{(0)}$



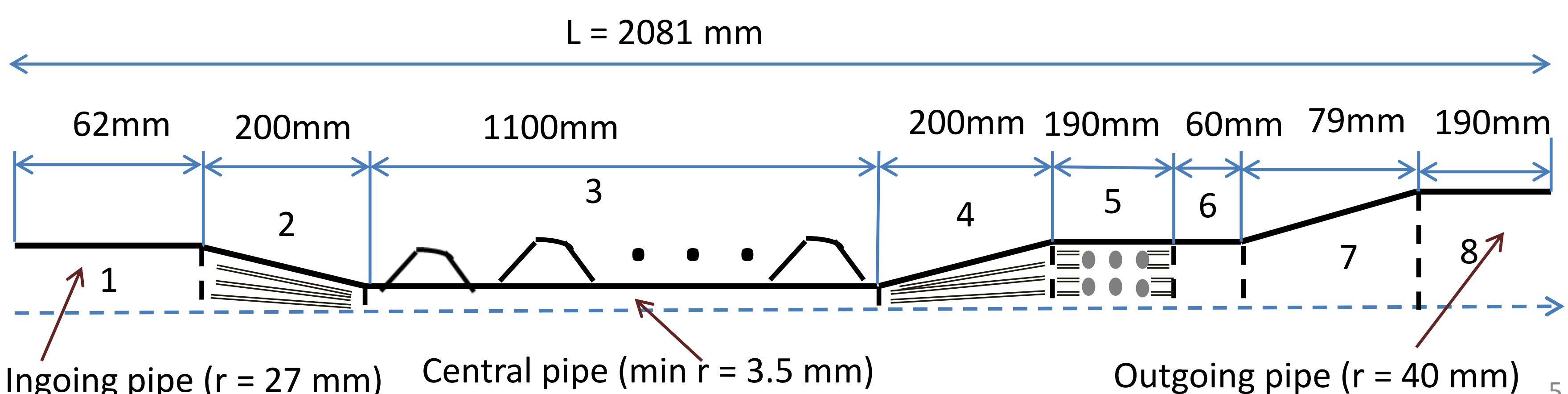


Tapering with slots
(max radius= 27mm, min radius=3.5mm)

Aperture of the middle part of the beam pipe.(min radius= 3.5mm)

# Description of the geometrical model.

| Number of elements | Length of the element (z) | Radius of elements (r) | Comments |
|---|---|---|---|
| 1 | 62 mm | 27 mm | Round pipe (ingoing) |
| 2 | 200 mm | 27 mm - 3.5 mm | Taper wit slots |
| 3 | 1100 mm | 3.5mm | Middle part of the beam pipe |
| 4 | 200 mm | 3.5 mm – 27 mm | Taper with slots |
| 5 | 190 mm | 27 mm | Round pipe with slots |
| 6 | 60 mm | 27 mm | Round pipe |
| 7 | 79 mm | 27 mm – 40 mm | Taper |
| 8 | 190 mm | 40 mm | Round pipe (outgoing) |



# Description of accuracy tests for 2D and 3D models.

- The original geometry of the LHCb experimental chamber is about 2 meter long.
  The maximal radius of the chamber is 40 mm, and minimal radius is about 3.5mm.
  We need a lot of mesh points for 3D calculations with help of the CST Microwave Studio.

- In order to estimate accuracy of calculations, short part of the chamber was considered –
- the pipe with taper from one side of the chamber.
  This part of the chamber is rotationally symmetric structure.

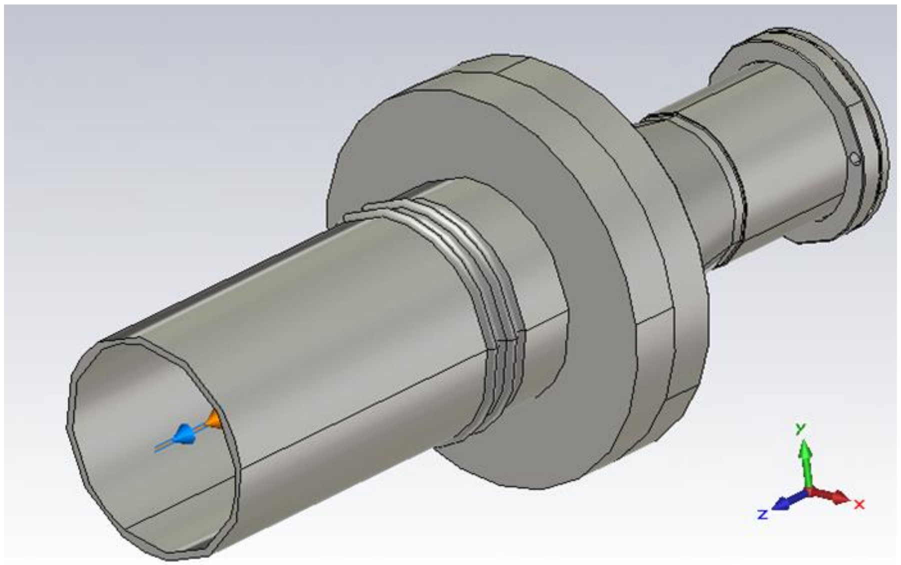
- The calculations of the longitudinal wake potential have been done for three different cases (see picture on the next slide):

1. for the original 3D-structure (import from CATIA system),
2. For 3D geometry with same dimensions , modelled in CST MW Studio.
3. For 2D geometry with same dimensions.

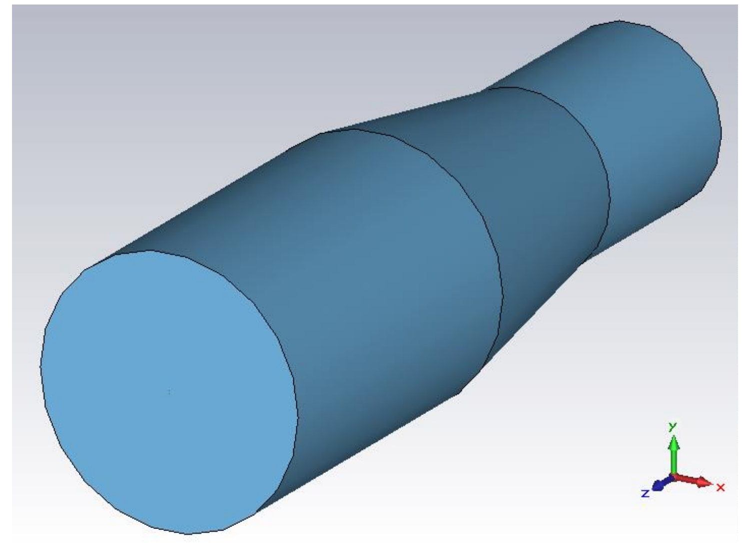
- The calculations have been done with help of CST MW Studio for the 3D-structures, and with help of the program ECHO-2D for the 2D-structure.

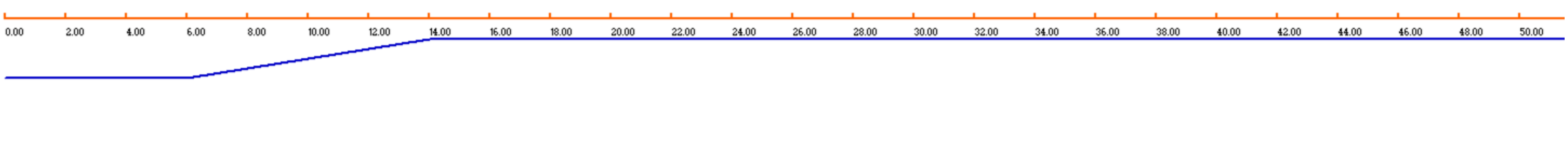
# Description of accuracy tests for 2D and 3D models.

Rotationally symmetric pipe with taper (Import from CATIA system).



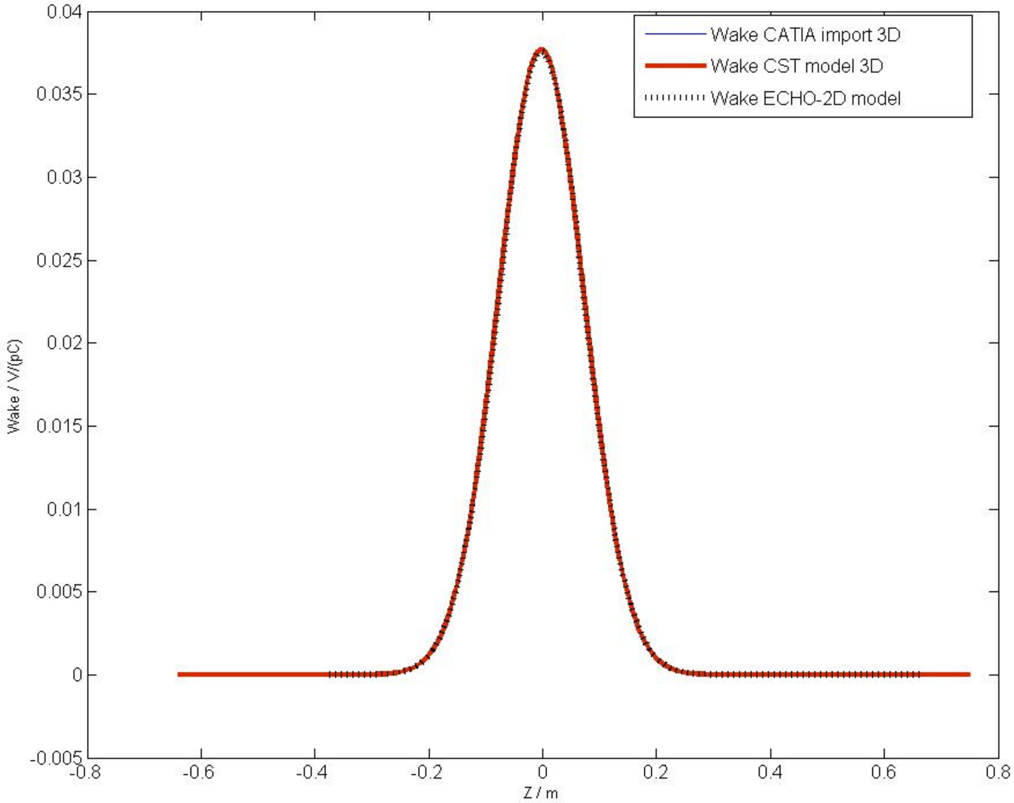

Rotationally symmetric pipe with taper (CST model).




2D-model for the program ECHO-2D.

# Description of accuracy tests for 2D and 3D models.




$$W_{\|}(x_1, y_1, x_2, y_2, s) \approx W_{\|}^{(0)}(s) + (x_2\, x_1 + y_2\, y_1)\, W_{\|}^{(1)}(s),$$

$$W_{\|}^{(m)}(s) = -L^{(m)}\, c^2 \frac{d}{ds} g(s)$$

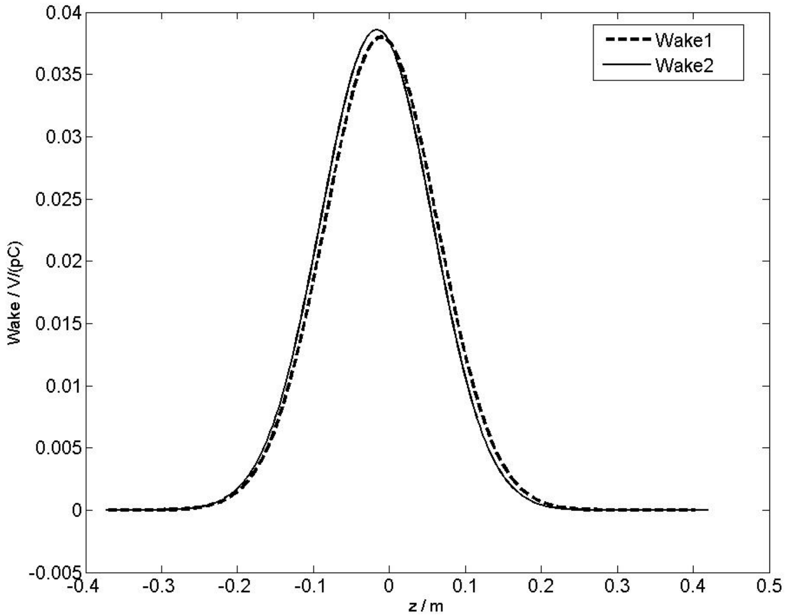
$$k_{\|\mathrm{tot}}^{(0)} = \int ds\, W_{\|}^{(0)}(s)\, g(s)$$

$k_{\|}$=0.0267 V/pC

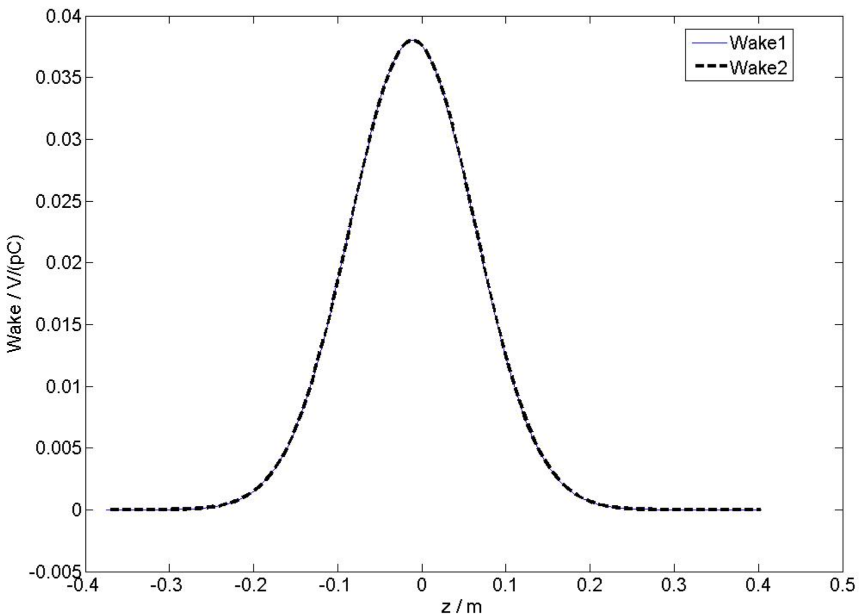
Comparison of longitudinal wake potentials of pipe with taper for three different cases.
All wake potentials have been calculated for Gaussian bunch with rms bunch length of 7.5 cm.
For the 2D-calculation a step size of Δz = 2mm in the longitudinal and of Δr = 2mm in the radial have been used.
For the 3D-calculation a step sizes of Δz = 2mm, Δx = 2mm, Δy = 2mm have been used.

# 2D calculations for the approximate geometry.

Longitudinal monopole wake potential for rotationally symmetric approximate model (with round pipe in center) of the full LHCb experimental chamber has been calculated with ECHO-2D program.
Dimensions of the approximate model are presented on the Slide 5.
The calculations have been done for Gaussian bunch with rms bunch length of 7.5 cm.
Different mesh was used for the calculations.



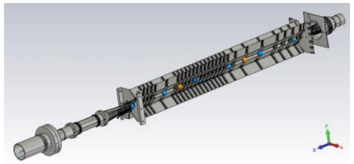

Longitudinal monopole wake potentials:
Wake 1 - Δz = 2mm, Δr = 0.5mm
Wake 2 - Δz = 4mm, Δr = 1mm
$k_{\parallel}$=0.0266 V/pC

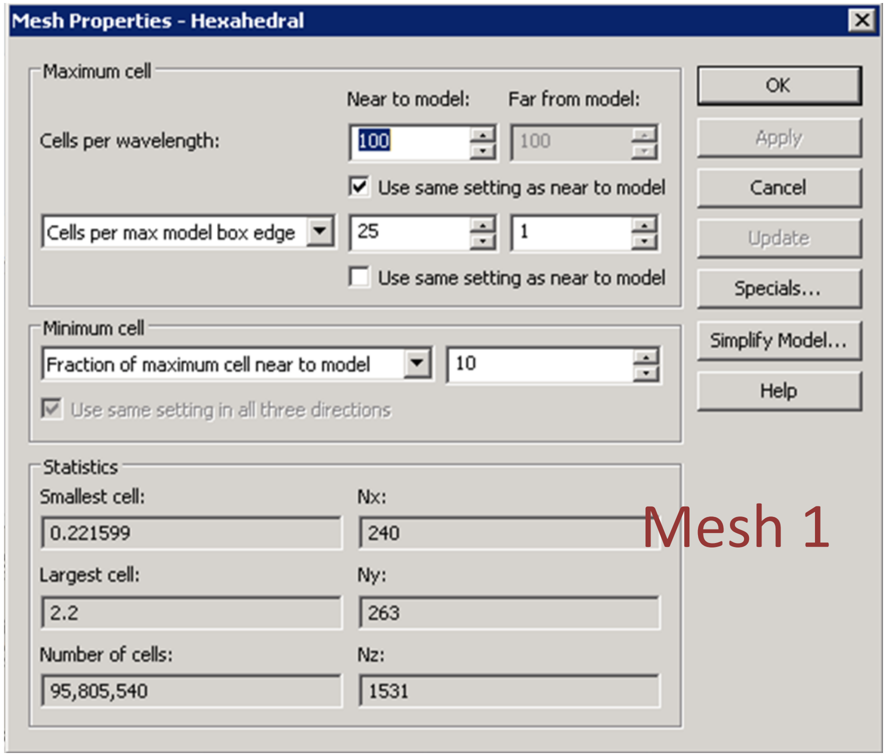


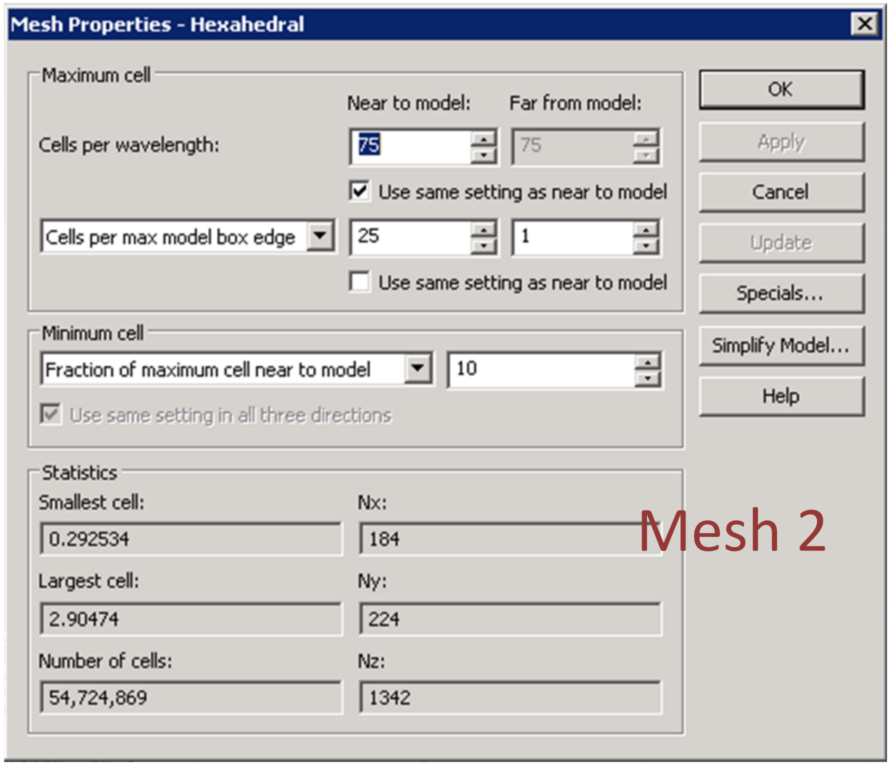

Longitudinal monopole wake potentials:
Wake 1 - Δz = 1mm, Δr = 0.1mm
Wake 2 - Δz = 2mm, Δr = 0.5mm
$k_{\parallel}$=0.0266 V/pC

# 3D calculations with CST Microwave Studio 2015

Longitudinal component (z - component) and transverse components (x, y - components) of wake potential were calculated for the original geometry of the LHCb experimental chamber.
Wakefields solver of the CST Particle Studio was used for the calculations.
The calculations have been done for Gaussian bunch with rms bunch length of 7.5 cm.
Beam location - on the axis (x=0,y=0).
Different hexahedral mesh sets were used for the calculations.
Mesh1 is mesh with maximal possible number of mesh cells for this structure.

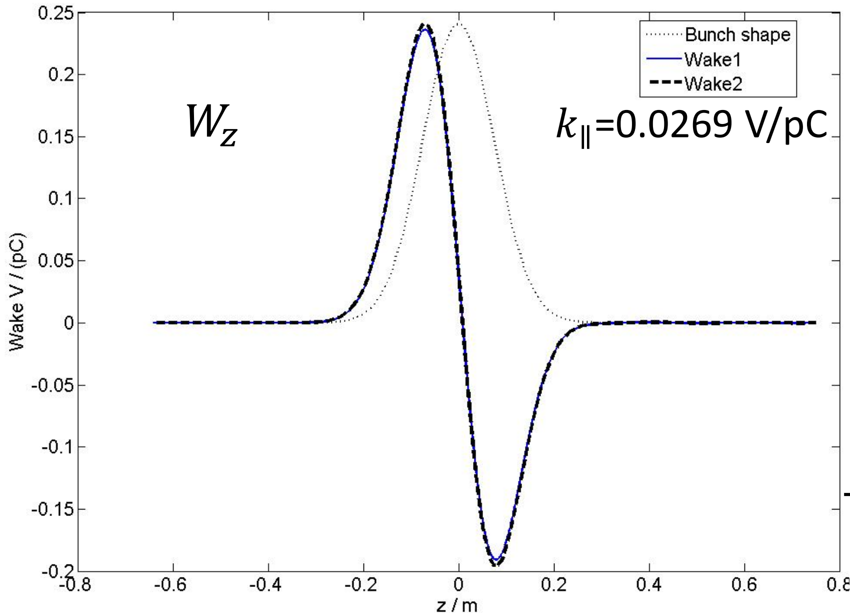




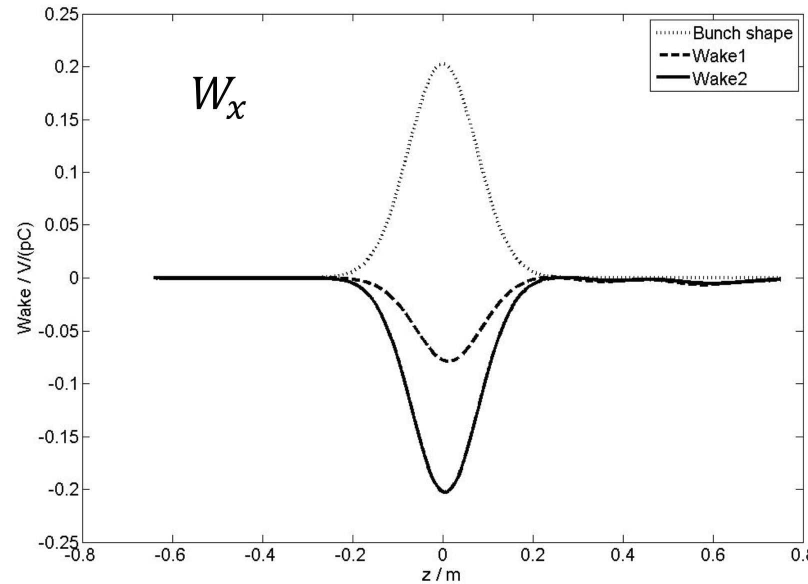
# 3D calculations with CST Microwave Studio 2015

z-component of the wake potential




⊥

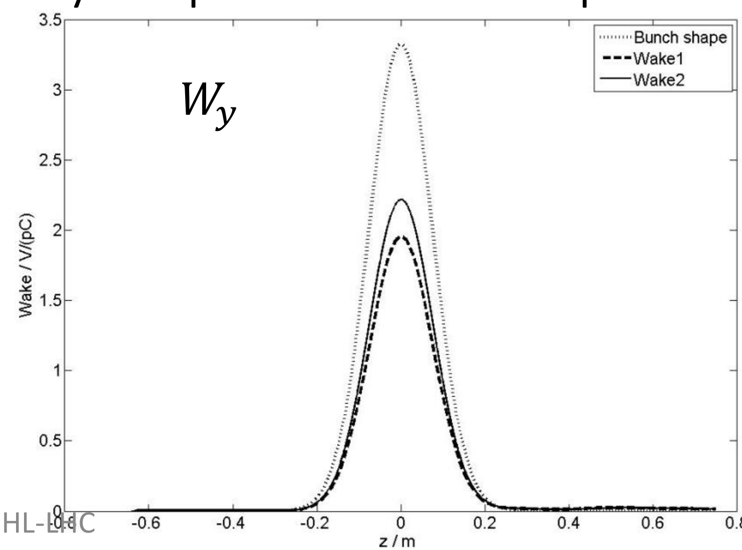
x-component of the wake potential




Wake 1 - for Mesh1 (95 805 540 cells)
Wake 2 - for Mesh2 (54 724 869 cells)

| | Mesh1 | Mesh2 |
|---|---|---|
| $k_{||}$(V/pC) | 0.0269 | 0.0269 |
| $k_{\perp x}$ (V/pC) | 0.0547 | 0.1430 |
| $k_{\perp y}$ (V/pC) | 1.3807 | 1.5682 |

y-component of the wake potential



# Conclusion.

- The accuracy of the calculations of the wake potentials for the original 3D-model of the LHCb experimental chamber is not sufficient.
  Dependence of the results on the mesh is very high.
  To solve this problem with sufficient accuracy, we need a more powerful computer or another program.
  Also we can perform the calculations for a smaller segments of geometry.

- Next steps of the calculations:
  1. Calculations of the wake potentials on-axis for 3D original model with sufficient accuracy .
  2. Calculations of the wake potentials of-axis for approximate models and for original model for different mesh sets.

# Putting this in the LHC context

Benoit Salvant and Olga Zagorodnova
for the impedance team

# Context: minimizing the beam impedance of the LHC

- LHC optimized for low impedance and high intensity beams

  From the design phase, the LHC has been optimized to cope with high intensity beams and significant effort and budget were allocated to minimize the impedance of many devices and mitigate its effects

- Some examples:
  - **Tapers** (11 degrees) and RF fingers for all collimators
  - **Conducting strips** for injection kickers MKI
  - Dump kickers MKD **outside of the vacuum pipe**
  - **RF fingers** to shield thousands of bellows
  - **Wakefield suppressor** in LHCb
  - **Avoid sharp steps** between chambers and limit tapers to 15 degrees
  - **ferrites and cooling** in all kinds of devices (ALFA, TOTEM, TDI, BSRT, etc.)

- Consequence: small LHC impedance allowed maximization of luminosity to the experiments before LS1

- For comparison:

| Orders of magnitude | SPS | LHC (injection) | improvement |
|---|---|---|---|
| Length | 7 km | 27 km | [/m length] |
| Effective longitudinal impedance | 10 Ohm | 0.1 Ohm | **by a factor ~400** |
| Effective transverse impedance | 20 MOhm/m | 2 to 4 MOhm/m | **by a factor ~40** |

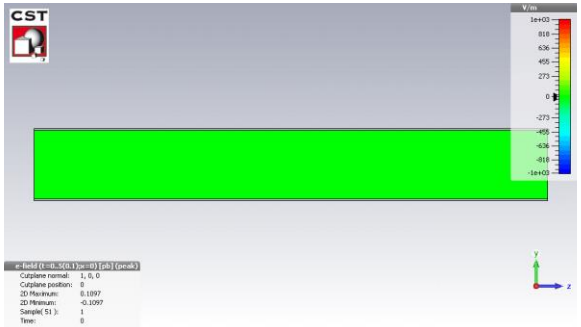
# Context: impact of beam impedance on performance

- When a beam of particles traverses a device which
  - is not smooth
  - or is not a perfect conductor,

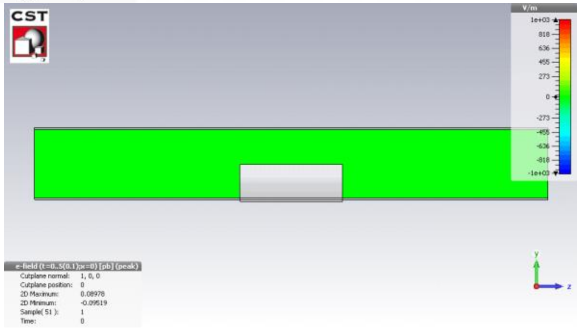
  it will produce wakefields that will perturb the following particles

  → resistive or geometric wakefields (in time domain) and impedance (in frequency domain).

- These wakefields are perturbations to the guiding EM fields to keep the beam stable and circulating.




Round beam pipe
(radius 40 mm)




Round beam pipe
with Roman pot
(at 1 mm from the beam)

→ Strong perturbation of the electromagnetic fields by the Roman pots during (short range wake fields) and after (long range wakefields) the passage of the bunch

# Context: impact of beam impedance on performance

- These perturbations are usually decomposed into longitudinal and transverse wakefields

  - **longitudinal wakefields** lead to energy lost from the particle and dissipated in the walls of the neighbouring devices

    → **heating** of beam surrounding

    → temperature interlocks or degradation of machine devices

    → ***limits the LHC intensity and luminosity***

  - **longitudinal wakefields** lead to perturbation of the synchrotron oscillations

    → can excite **longitudinal instabilities**

    →degrades longitudinal emittance

    → ***limits the LHC intensity and luminosity***

  - **Transverse wakefields** lead to perturbation of the betatron oscillations

    → can excite **transverse instabilities**

    → degrades transverse emittance

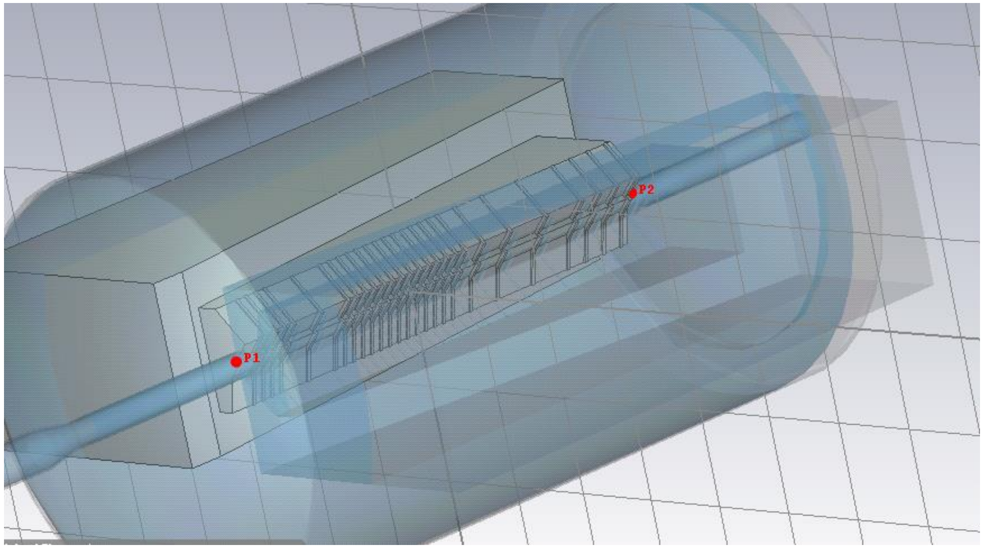
    → ***limits the LHC intensity and luminosity***

→ Need to study in detail the 3 components of the wakefields (real and imaginary parts) as a function of frequency (short range and long range) to identify threats to LHC operation

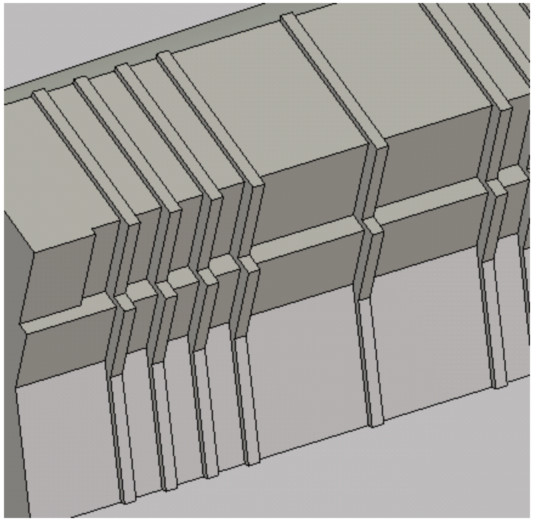
# Simplifying the geometry further, to be able to keep the surrounding tank

- Simulation with full structure was crashing all the time
- We decided to redraw the full structure inside CST to avoid meshing issues (not a funny task!)
- Very coarse simplifications were therefore applied as a first step (to wakefield suppressor and blending of edges of the RF box)

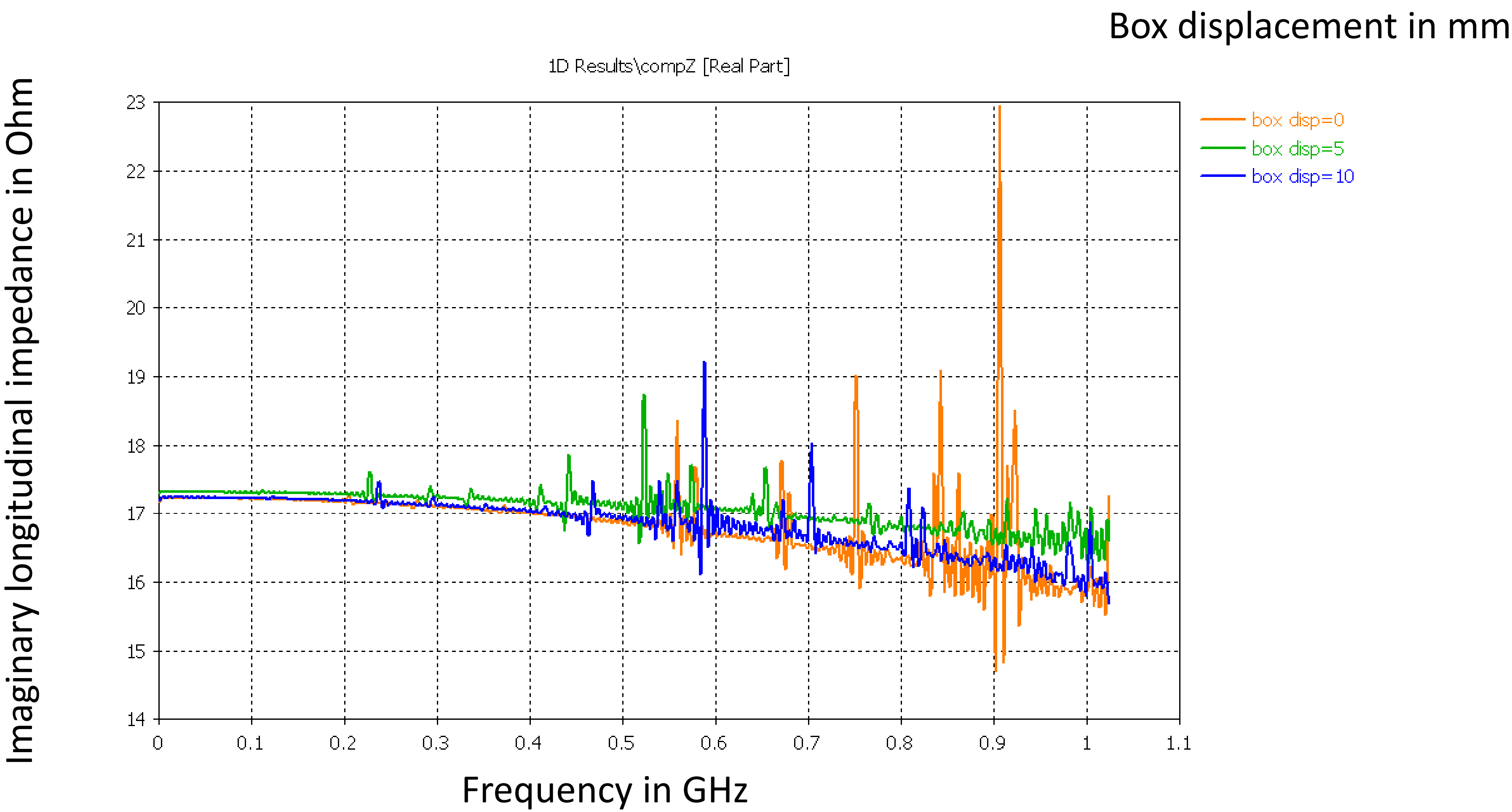
Simplified structure




Detail of the RF box

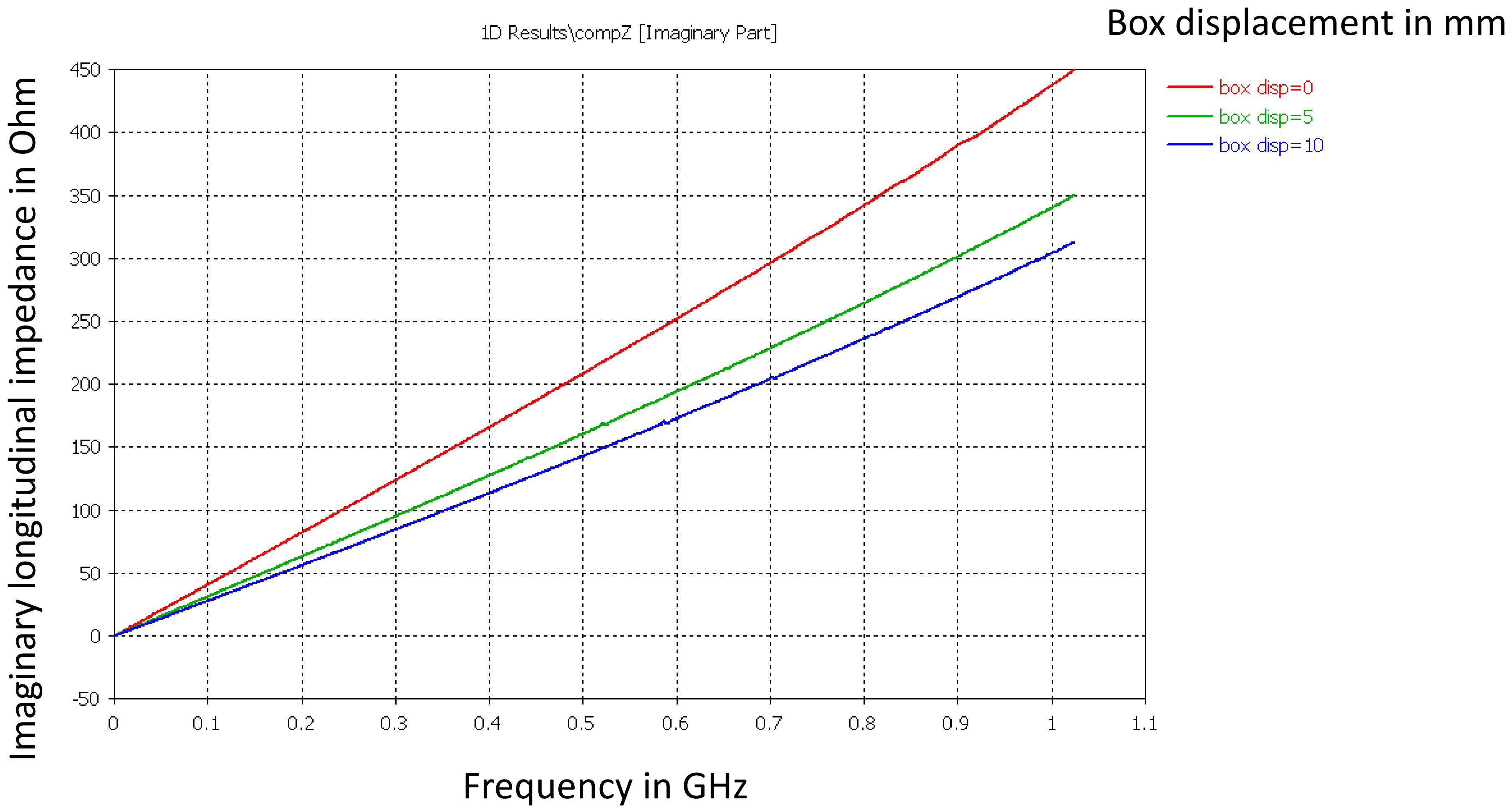


# Longitudinal impedance (real)




→ Non zero real longitudinal impedance at low frequency due to “global step out”
→ Clear presence of longitudinal modes above 400 MHz (impact to be assessed)

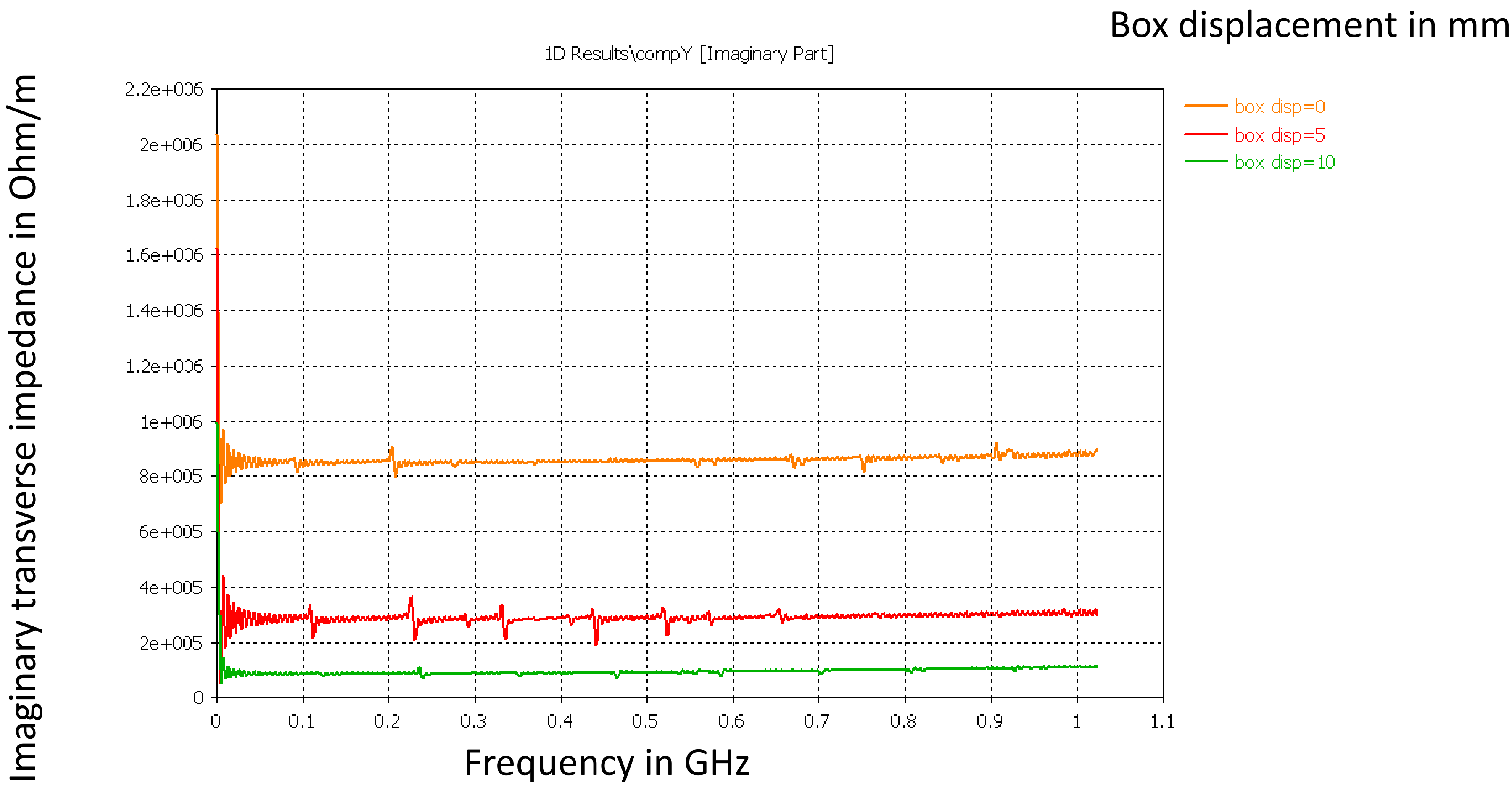
# Longitudinal impedance (imaginary)




→ Rather reasonable behaviour

→ Large low frequency imaginary impedance, most likely due to the bellow-like structure of the box Im(Zeff/n)~4.7 mOhm (full LHC is 90 mOhm). → to be investigated.

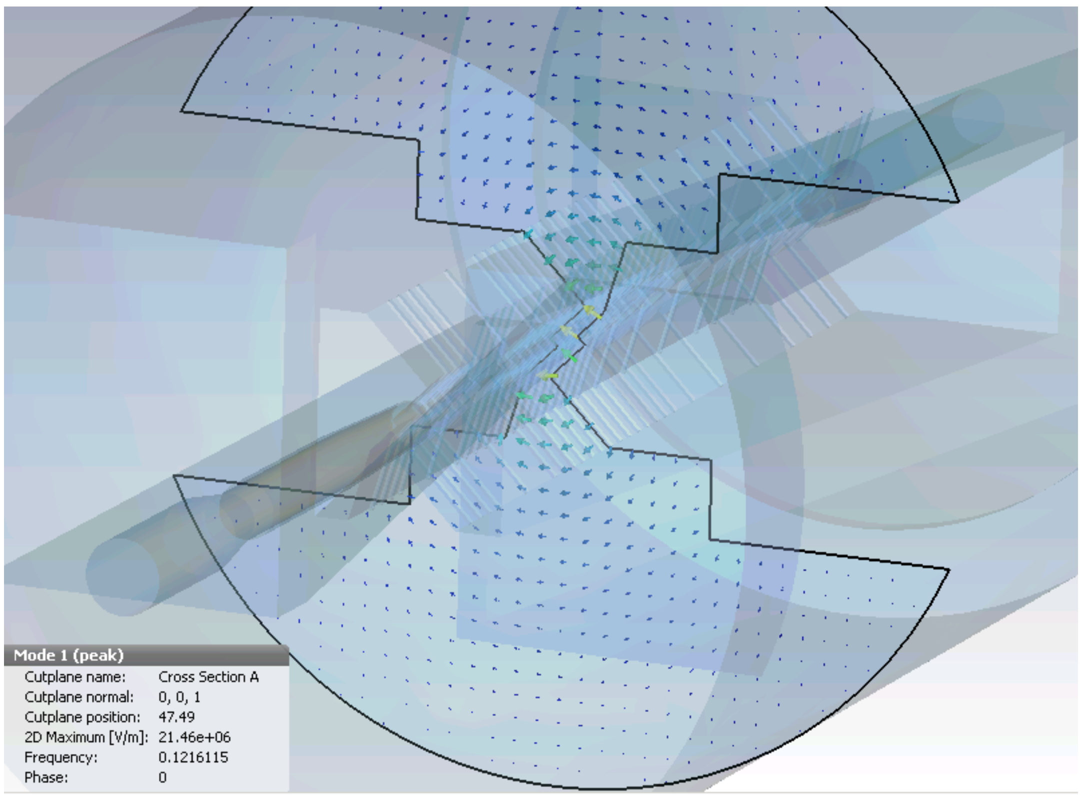
# transverse impedance




→ Rather reasonable behaviour
→ ~1 MOhm/m when closed (to be confirmed of course)
→ Clear presence of low frequency transverse modes from 100 MHz onwards (similar to modes in collimator structure)

# Looking at resonant modes

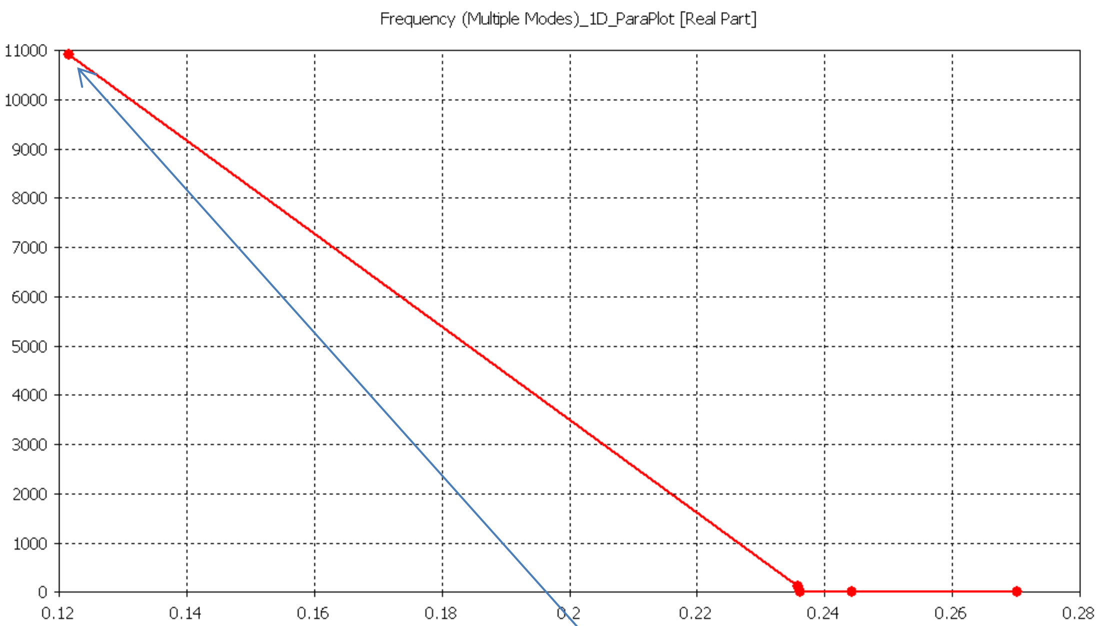
- Need to use another solver (eigenmode) and different mesh type (tetrahedrons)
- Simulation with full structure was crashing all the time

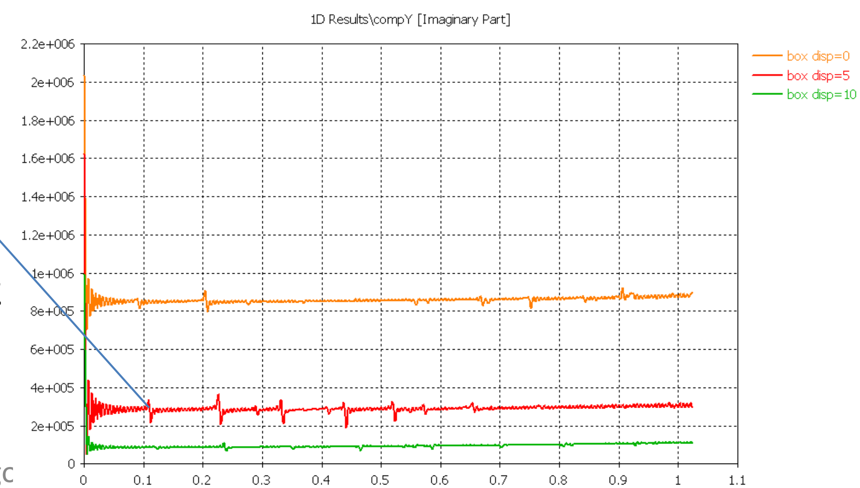



First mode at 120 MHz
(for disp=10 mm):

→ Looks like a transverse mode

# Results from eigenmode

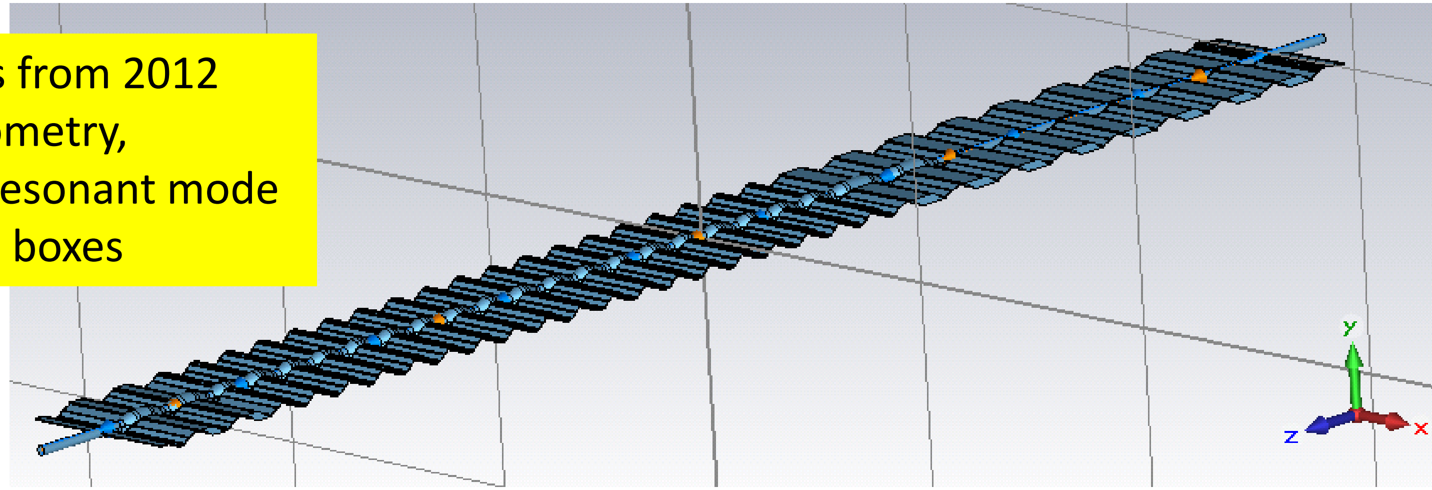



First estimate: transverse mode at 120 MHz
Impedance would be in the 1 MOhm/m
(not accounting for beta function)

# Preliminary results for the LHCb VELO radius reduction (5.5 mm to 3.5 mm)

Preliminary results from 2012
With non final geometry,
and assuming no resonant mode escapes out of the boxes



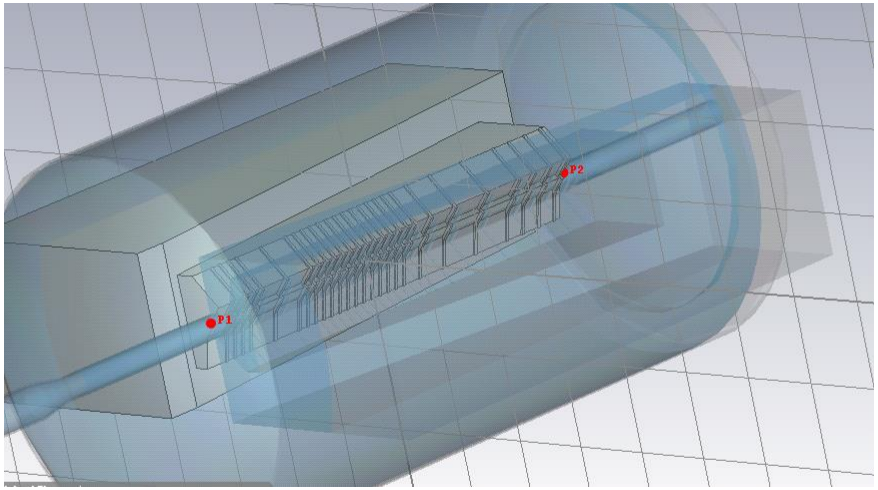

Final geometry not known → current geometry roughly scaled by 2/3 in both transverse directions.
Very twisted shape → difficult to import 3D model, low accuracy of simulations, convergence issues, far from analytical models

| | Im(Zlong/n) | Im(Zvertical) | Im(Zhorizontal) |
|---|---|---|---|
| Current RF box | ~ 1 mΩ | ~0.4 MΩ/m | ~0.3 MΩ/m |
| "New" RF box | ~ 1 mΩ | ~1.3 MΩ/m | ~1.1 MΩ/m |
| **Total LHC (in stable beams)** | **90 mΩ** | **25 MΩ/m** | **25 MΩ/m** |

The radius decrease leads to an increase of longitudinal (resp. transverse) impedance estimated to be up to 1% (resp. 0.5%, thanks to the low beta function at the VELO location) of the total LHC impedance . Actual impedance and power loss with HL-LHC parameters need to be checked and optimized when final geometry is known.

# Preliminary results for the LHCb VELO radius reduction (5.5 mm to 3.5 mm)

New 2014 geometry




Preliminary results! Requires more crosschecks

| Effective impedances | Im(Zlong/n) | Im(Zvertical) | Im(Zhorizontal) |
|---|---|---|---|
| Current RF box | ~ 1 mΩ | ~0.4 MΩ/m | ~0.3 MΩ/m |
| Full VELO structure | ~ 4.7 mΩ | ~1 MΩ/m | ~1 MΩ/m |
| **Total LHC (in stable beams)** | **90 mΩ** | **25 MΩ/m** | **25 MΩ/m** |

First simulations indicate a rather large effective longitudinal impedance. We have to understand whether this is true (needs convergence studies!) and if true where this is coming from.
Also, we should keep in mind that we compare the full structure to the box.

# Conclusion

- We have just started
- Preliminary tests were done
- Structure is very difficult to handle
  - Coarse simplifications
  - Large amount of work for us to redraw and simplify
- Impedance of the new LHCb VELO is not small with respect to the full LHC impedance and should be carefully checked in the next few weeks
- Mitigation measures may be needed, to be confirmed

# What's next?

- Get more confident with our simulations:
  - Benchmarks between simple and complicated models
  - More convergence studies to be more confident for the transverse plane
- Computation with the final foil thickness (100 microns)
- Computations for injection geometry (should be similar to the old box)
  - Plan to get also the CATIA structure in open position in the future?
- Beam induced heating computations (for LHC and HL-LHC)
- Requests to the design team:
  - Possibility to simplify further the structure already in CATIA?
  - Also get shorter test models?
- Need to perform measurements on mockup and final device
- Find possible mitigations if needed.

Thank you very much for your attention!

# Backup (talk from 2012)

# First ideas on the impact of the reduction of the aperture of the LHCb VELO on its impedance

B. Salvant, M. Ferro-Luzzi, A. Grudiev. O. Kononenko, C. Zannini for the impedance team

LEB meeting 26 October 2012

# Agenda

- Proposal to reduce inner diameter of LHCb VELO from 5.5 mm to 3.5 mm
- Context of the impedance study
- Preliminary impedance results
- Power loss results
- outlook

# Proposal to reduce LHCb inner diameter

- The precise geometry of the new VELO is not yet known

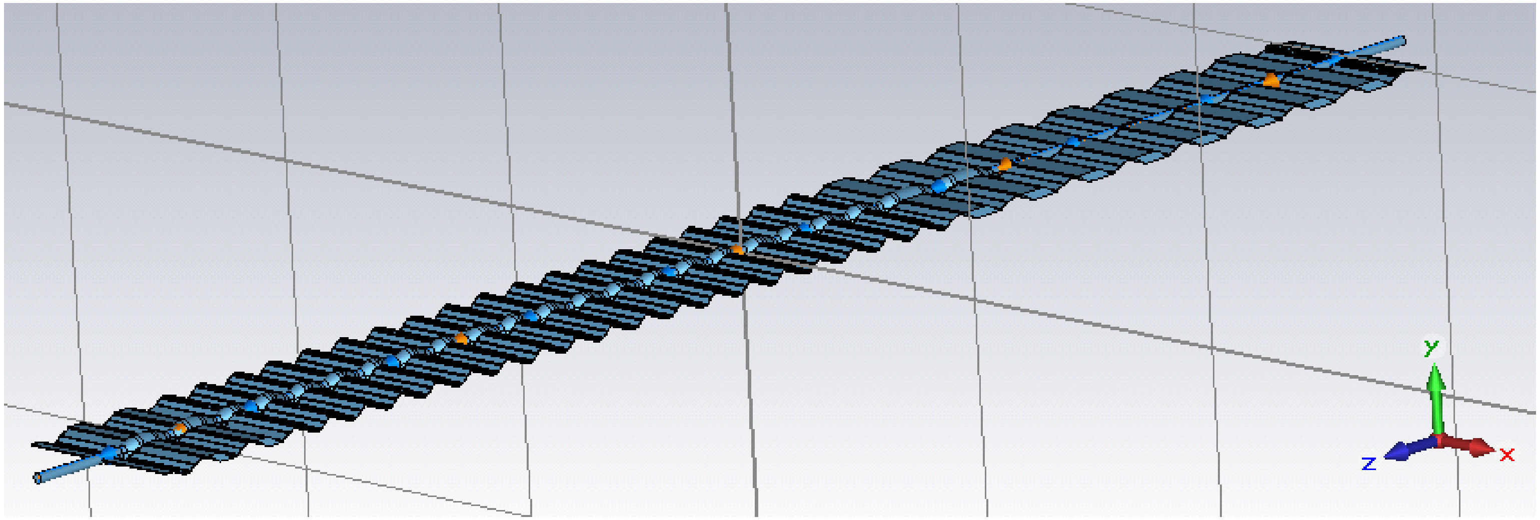
  → difficult to estimate the impact of the final geometry

  → proposal of Massimiliano: scale the current geometry by 2/3 to give orders of magnitude.

- The new inner radius should be 3.5 mm instead of 5 mm, with possibly a reduction of the thickness of the Aluminum from 300 microns to 200 microns

# Context of the impedance studies

- Impedance  simulations with MAFIA on a simplified geometry were performed in 1999-2001 leading to the installation of a wakefield suppressor (NIKHEF)
- Getting a clean working 3D model for this very twisted geometry has been very difficult
- the whole geometry had to be regenerated and its very special non regular shape made things very tricky. The model currently used is still not satisfactory from the mesh point of view.
- The wakefield suppressor was not studied yet.



# Impedance results:

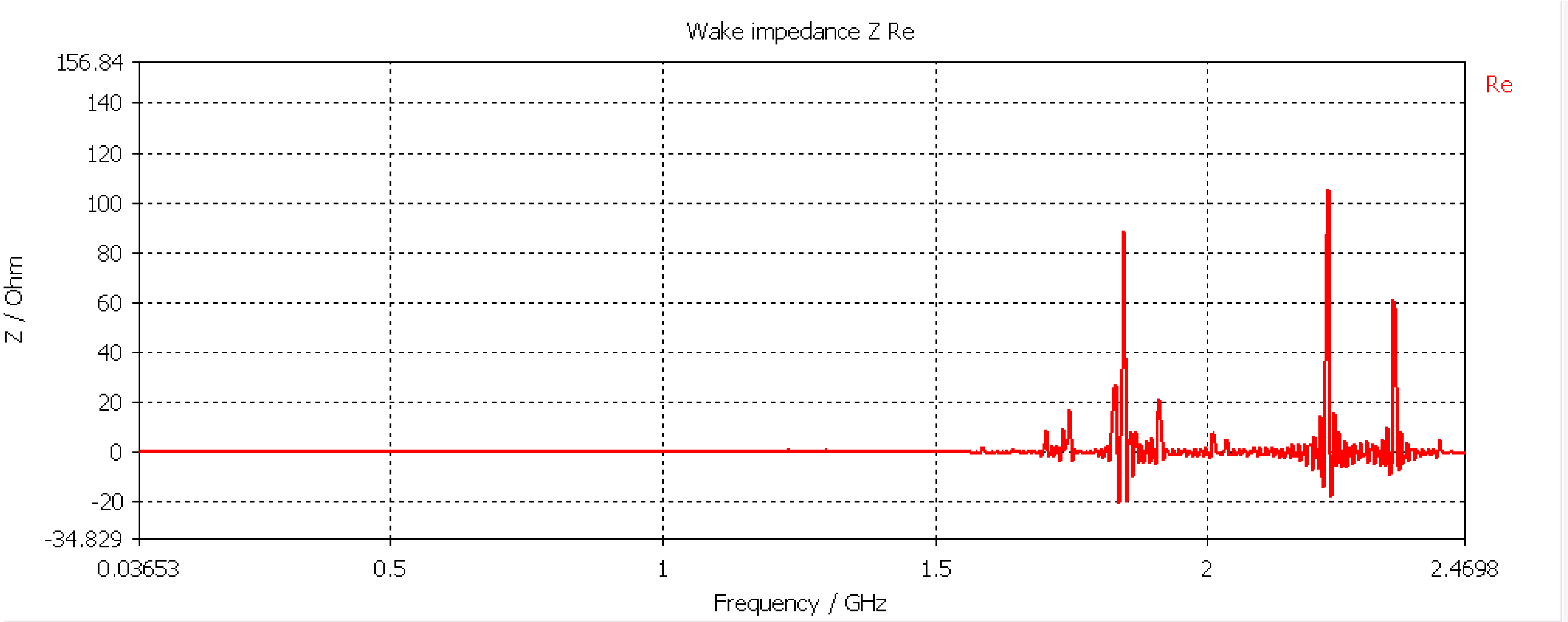
- Still serious issues with the model
- Final geometry not known

  → Results to be taken only as orders of magnitude to give a hint on expected trends

- Impedance contributions:
  - Resistive contribution (due to the material)
  - Geometric contribution (due to the geometry)

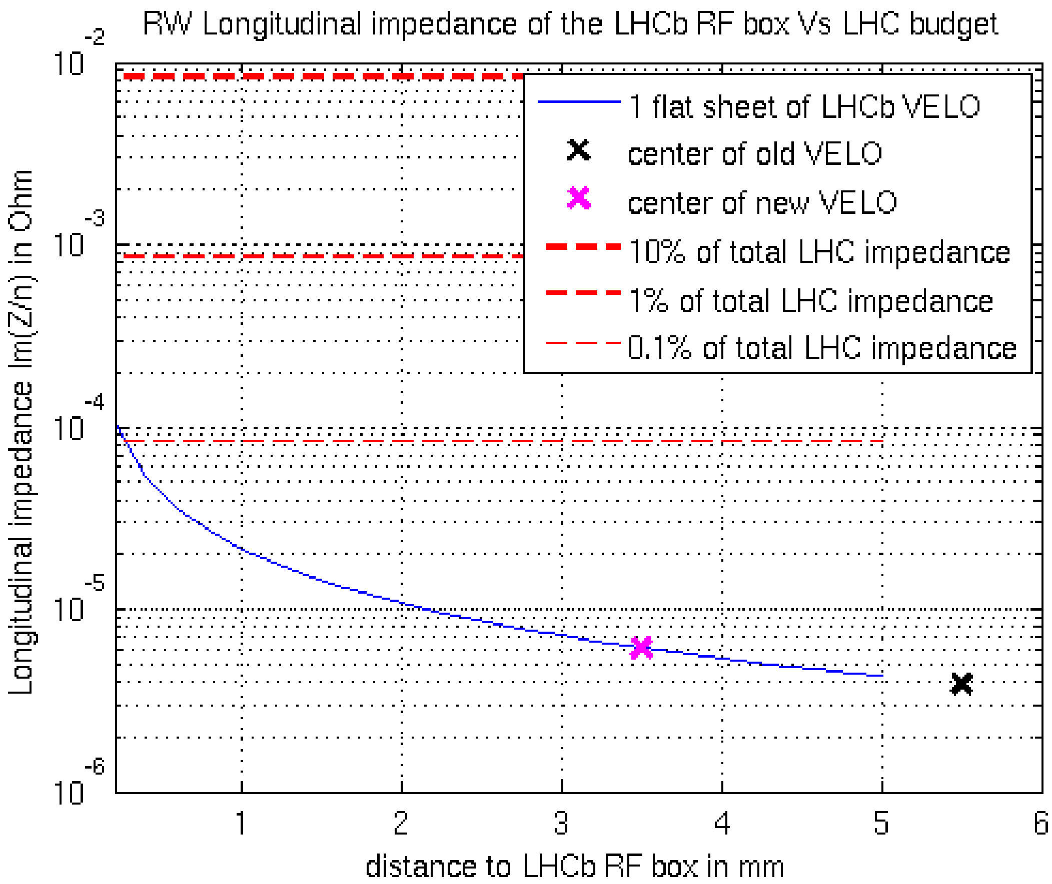
  - “Low” frequency broadband contribution (Ztrans, Z/n for stability and power loss)
  - Resonant modes (longitudinal and transverse for stability, longitudinal for power loss)

# Preliminary impedance results: resonant modes

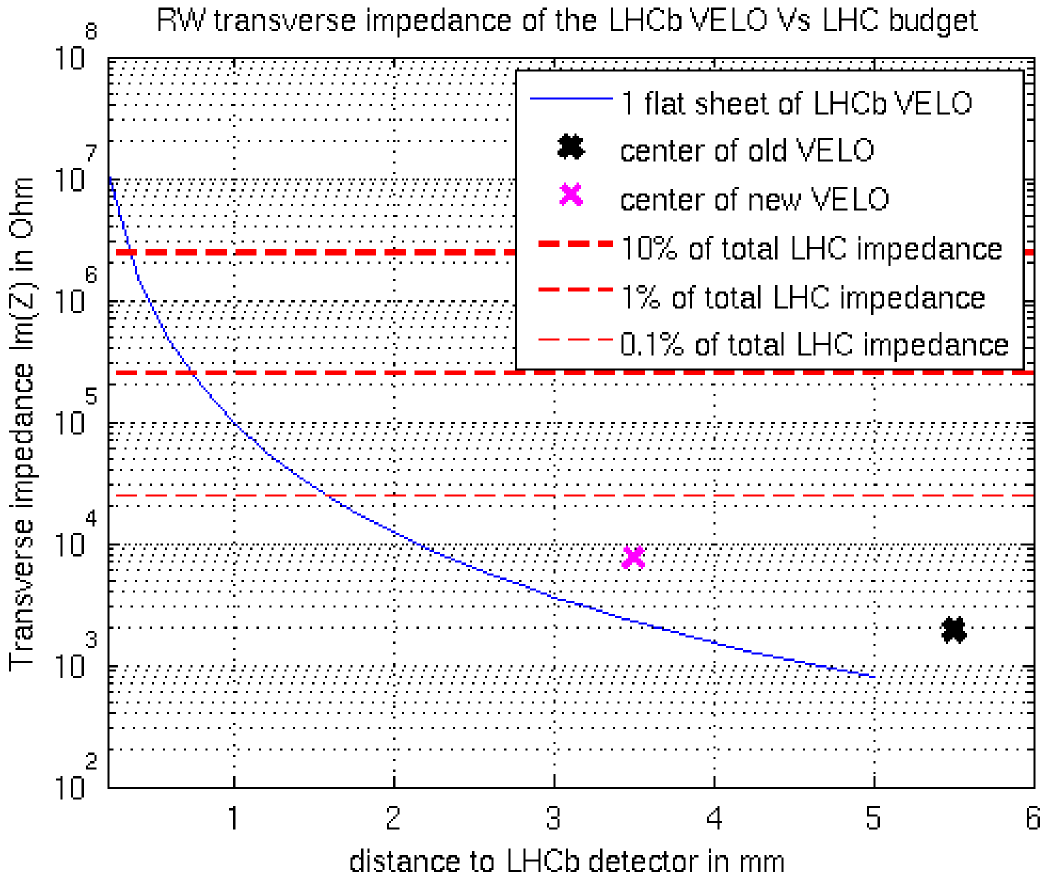



Significant modes beyond 6 GHz but not many modes below 2 GHz

# Preliminary impedance results: longitudinal resistive contribution



# Preliminary impedance results: transverse resistive contribution

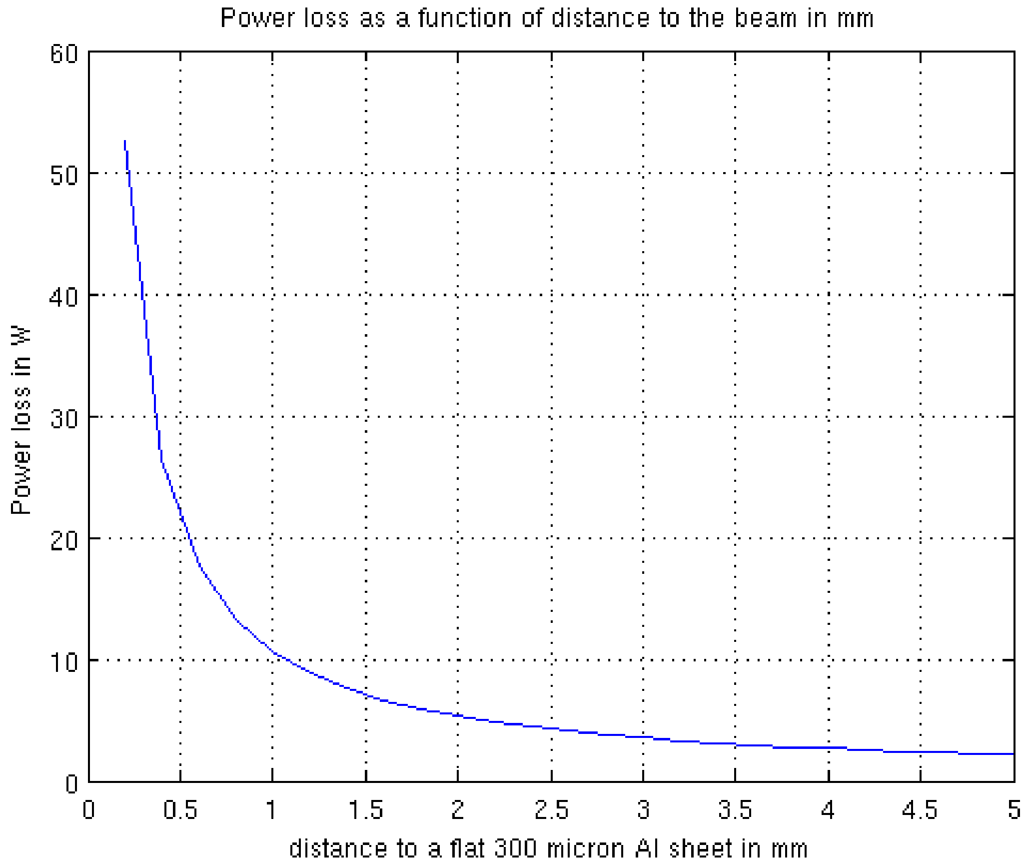


# Preliminary impedance results: geometric contributions

| | Im(Zlong/n) | Im(Zvertical) | Im(Zvertical) |
|---|---|---|---|
| Current RF box | ~ 1 mOhm | 0.4 MOhm/m | |
| "New" RF box | ~ 1 mOhm | 1.3 MOhm/m | |
| | | | |
| Total LHC (collisions) | 90 mOhm | 25 MOhm/m | 25 MOhm/m |

The vertical geometric impedance at low frequency increases significantly (factor 3) and reaches 5% of the total transverse impedance. To be checked.

# Preliminary impedance results: power loss

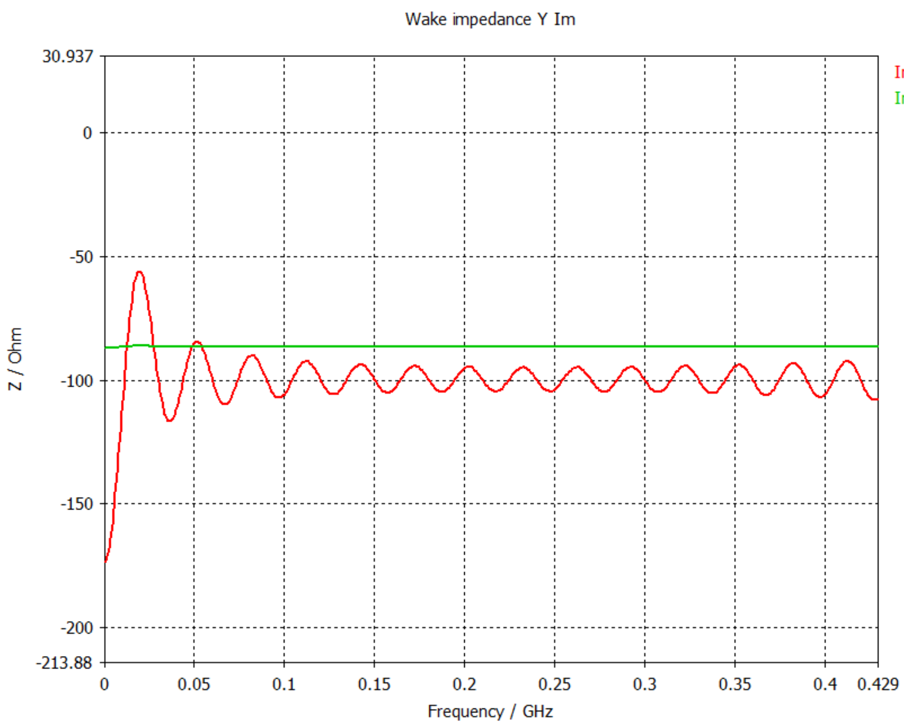


# Outlook

- The reduction in diameter should increase the impedance (not a surprise)
- The vertical geometric impedance at low frequency increases significantly (factor 3) and reaches 5% of the total transverse impedance. To be checked.

# More checks on transverse impedance

- Formula for bellow by K. Ng does not work as the period of the convolutions is much larger than the inner radius (hopefully as it predicts a factor 10 more than CST simulations)
- 3D simulations of 3.2 mm and 5.5 mm radius bellows (~1 m length):




- 3.2 mm: $Im(Z_y)$= 200 kOhm/m
- 5.5 mm: $Im(Z_y)$= 170 kOhm/m
- LHCb VELO at 3.2 mm: (200/0.2e-3)=1 MOhr
- LHCb VELO at 5 mm: (80/0.5e-3)=200 kOhm/