Update on impedance studies of the new RF finger design for the HL-LHC triplet fingers

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Acknowledgments:
Cedric Garion, Jaime Perez Espinos, E. Metral,
TE-VSC and WP2 members

15th HL-LHC TCC

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Questions to be answered

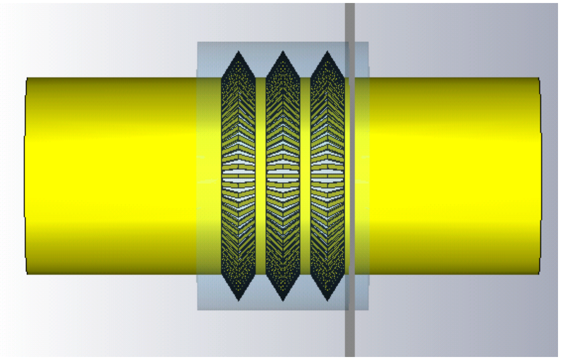
- Does the concept of deformable RF fingers show any showstopper for an application in the HL-LHC triplet area?

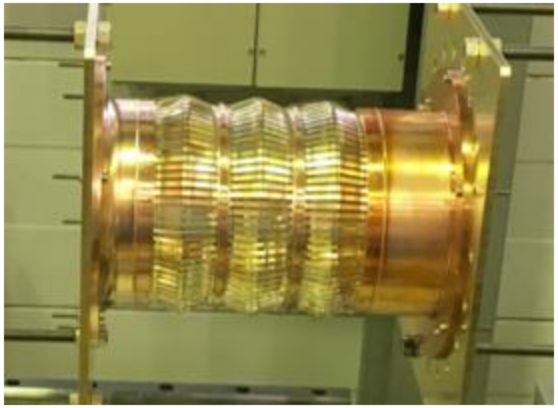
- What is the maximum acceptable angle of the fingers? (Could the baseline of 15° be relaxed?)

- Does the second wall bring any significant improvement?

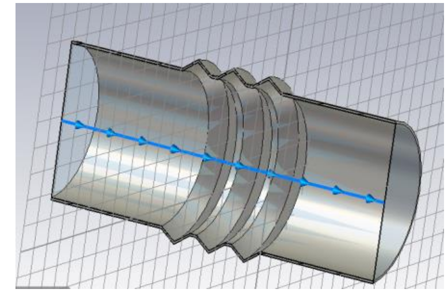
Impedance studies

- Context
- Simulation work
- Measurement work





Beam coupling impedance



- When the LHC beam traverses a device which
  - is not smooth
  - or is not a perfect conductor,

  it will produce wakefields that will perturb the following particles

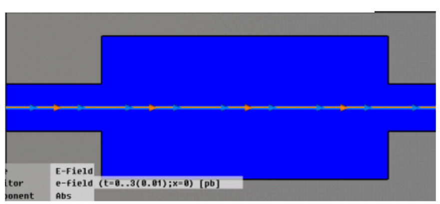
  → resistive or geometric wakefields (in time domain) and impedance (in frequency domain).

- 3D simulation of electromagnetic perturbation caused by an obstacle or a dispersive beam pipe:

Smooth perfect conducting pipe

→ No additional perturbation due to the device

Cavity



→ Perturbation of electromagnetic fields
→ Unwanted resonant kicks
→ Loss of energy

→ EM fields are perturbed during and after the passage of the bunch
→ Beam loses energy → beam induced heating
→ Beam gets unwanted kicks → beam instability (longitudinal or transverse)

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 global LHC impedance allowed maximization of luminosity to the experiments

There are still instabilities in the LHC today

→ longitudinal instabilities below bunch length of ~0.85 ns

→ transverse instabilities along the cycle

→ in view of the increase of intensity for HiLumi, we need to keep impedance low and reduce it whenever possible

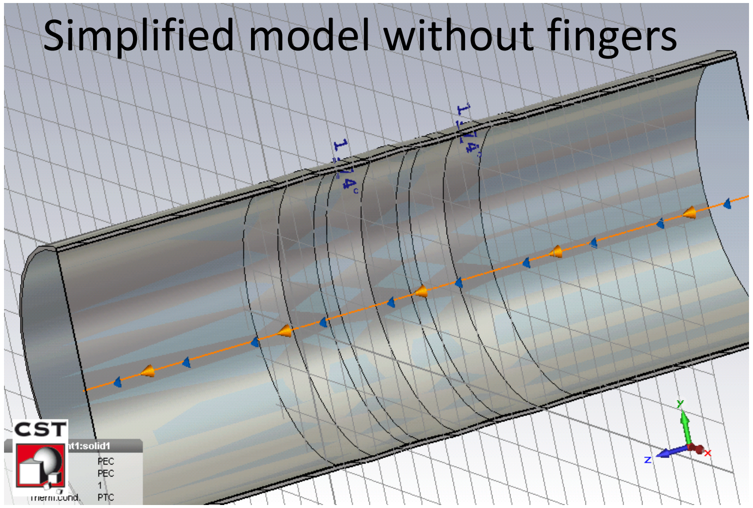
Impedance studies

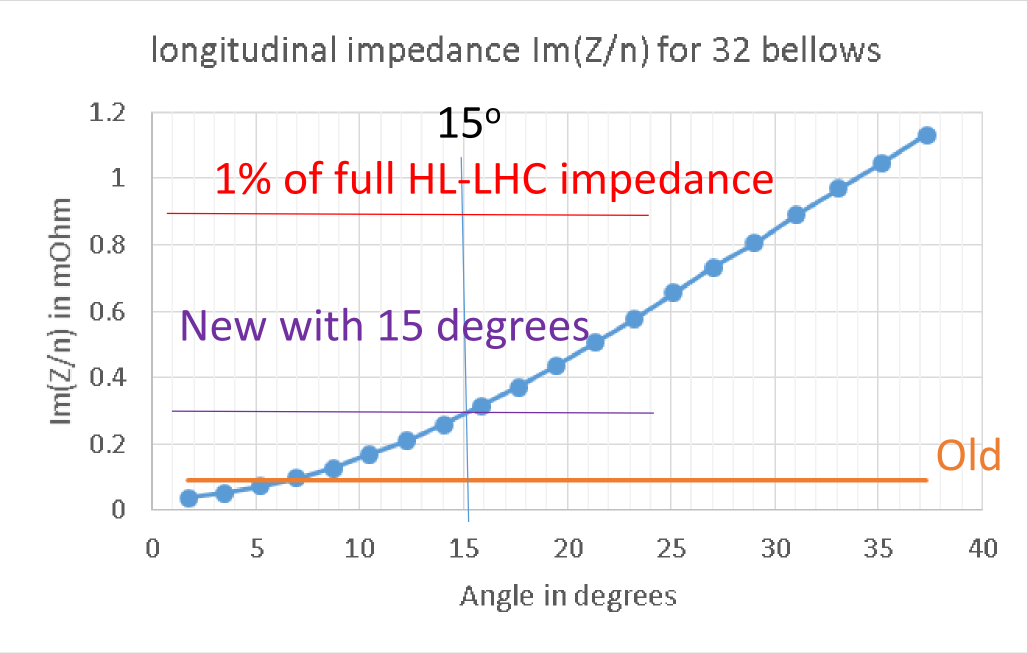
- Context

- Simulation work
  - Simplified model for assessment of low frequency impedance
  - More detailed model for assessment of resonant modes
  - R&D with ACE3P to account for
    - Coupling with outside cavity for low frequency impedance
    - Lateral offset

- Measurement work
  - Wire and probe measurements to identify resonant modes

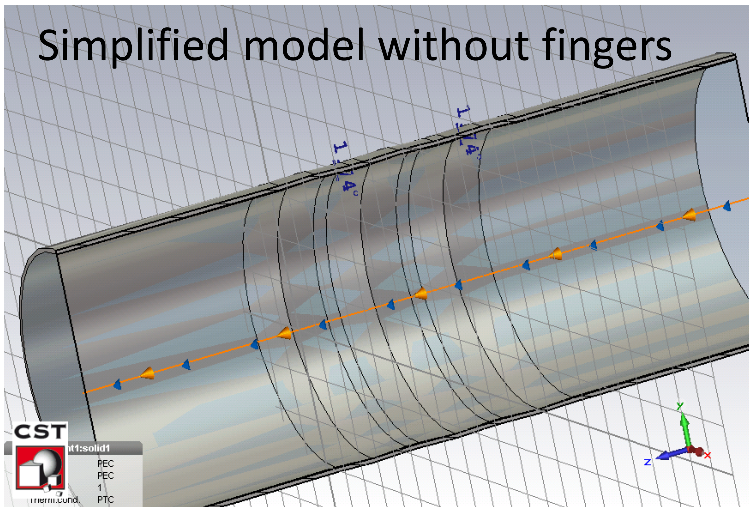
Longitudinal low frequency impedance

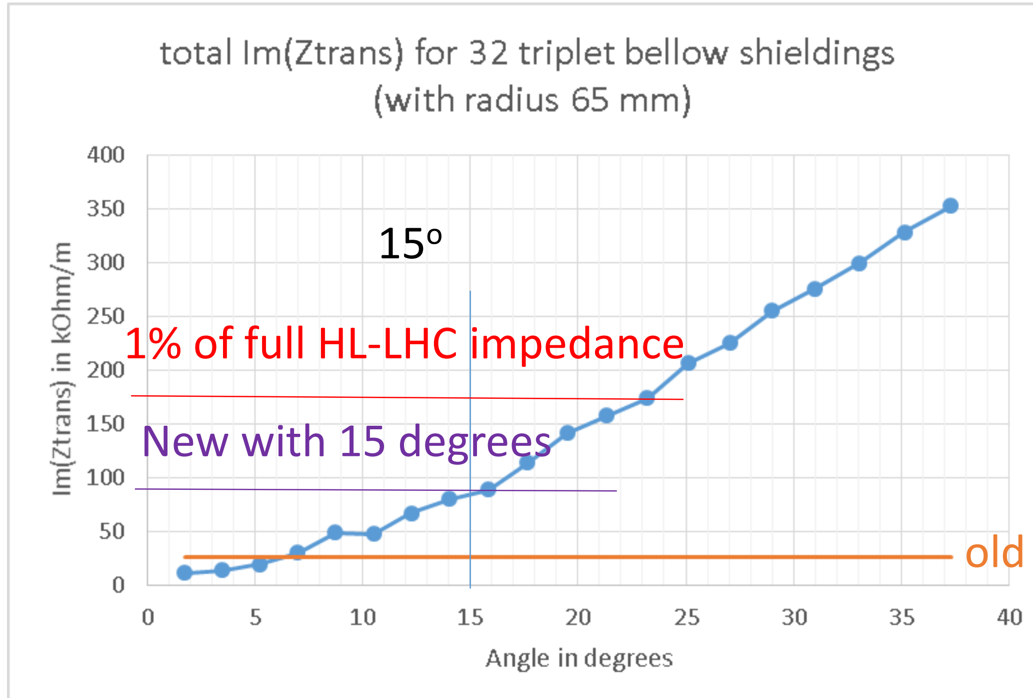




→ Assuming 32 shieldings with 65 mm radius
→ Large contribution compared to current shielding type (estimated a factor 3.5 increase)
→ Would amount to 0.3% of total impedance
→ Going to 30 degrees for all shieldings would reach 1% of full HL-LHC impedance

Transverse low frequency impedance





- → Assuming 32 shieldings with 65 mm radius at 12 km beta function
- → Large contribution compared to current shielding type (estimated a factor 3.5 increase)
- → Would amount to 0.5% of the total LHC impedance
- → Increase to 30 degrees reaches 1.5 % of the full HL-LHC impedance
- → Risk to increase beyond 15 degrees, in fact we already said it should be reduced.

Any showstopper?

- Simulation work
  - Simplified model for assessment of low frequency impedance
  - More detailed model for assessment of resonant modes
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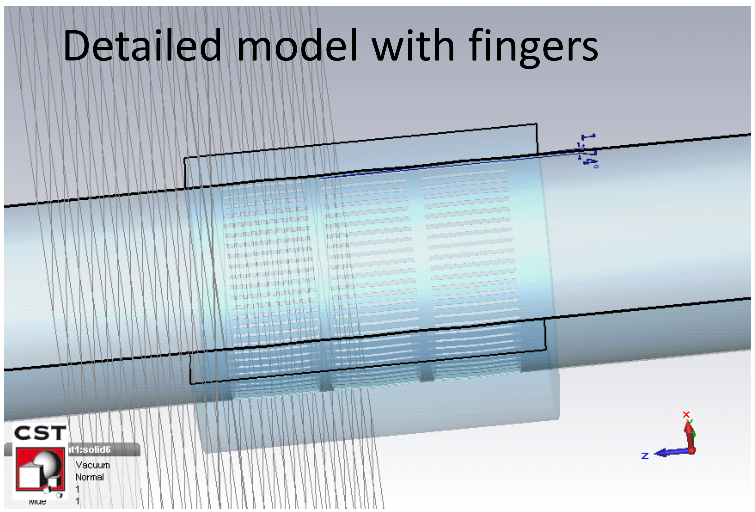
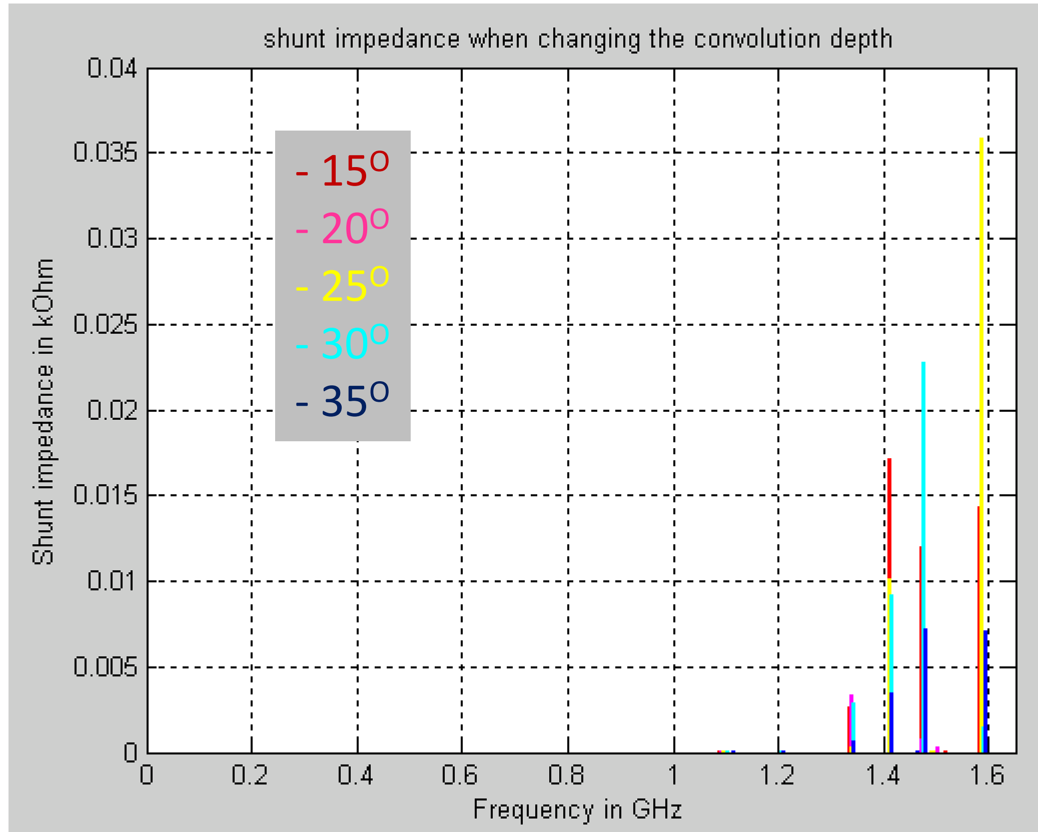
- Measurement work
  - Wire and probe measurements to identify resonant modes

Longitudinal modes

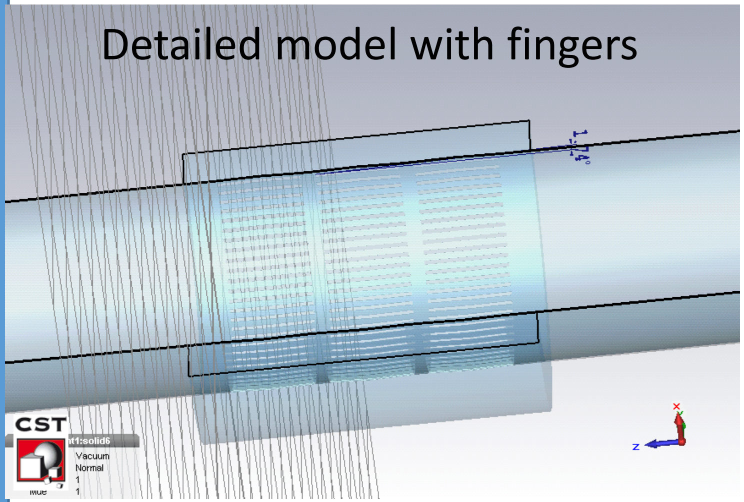
→ RRR of copper beryllium CuBe C17410 is 2.3 and conductivity is 50% of copper, so resistivity of copper is used as first assumption (fingers should be at 50 to 70 K).

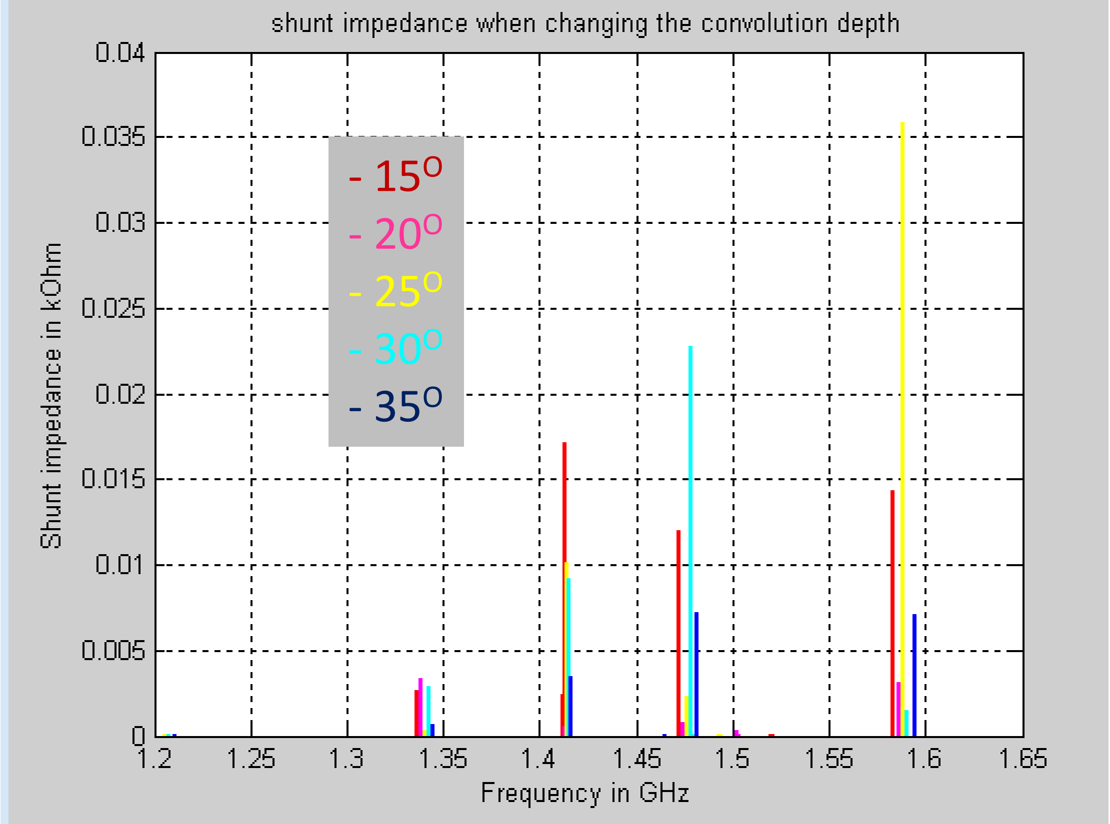




→ Low shunt impedance, even when multiplying by 32 modules (which would be extremely pessimistic, since all modules should have slightly different geometries)

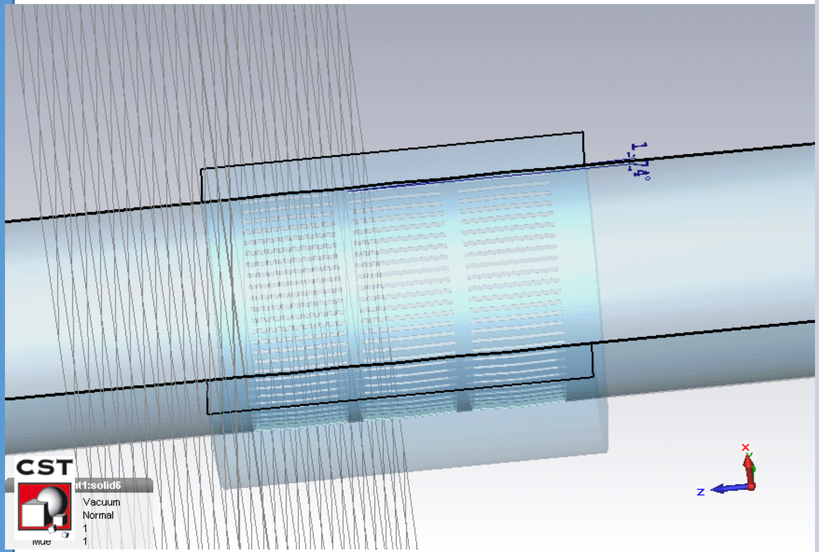
Longitudinal modes

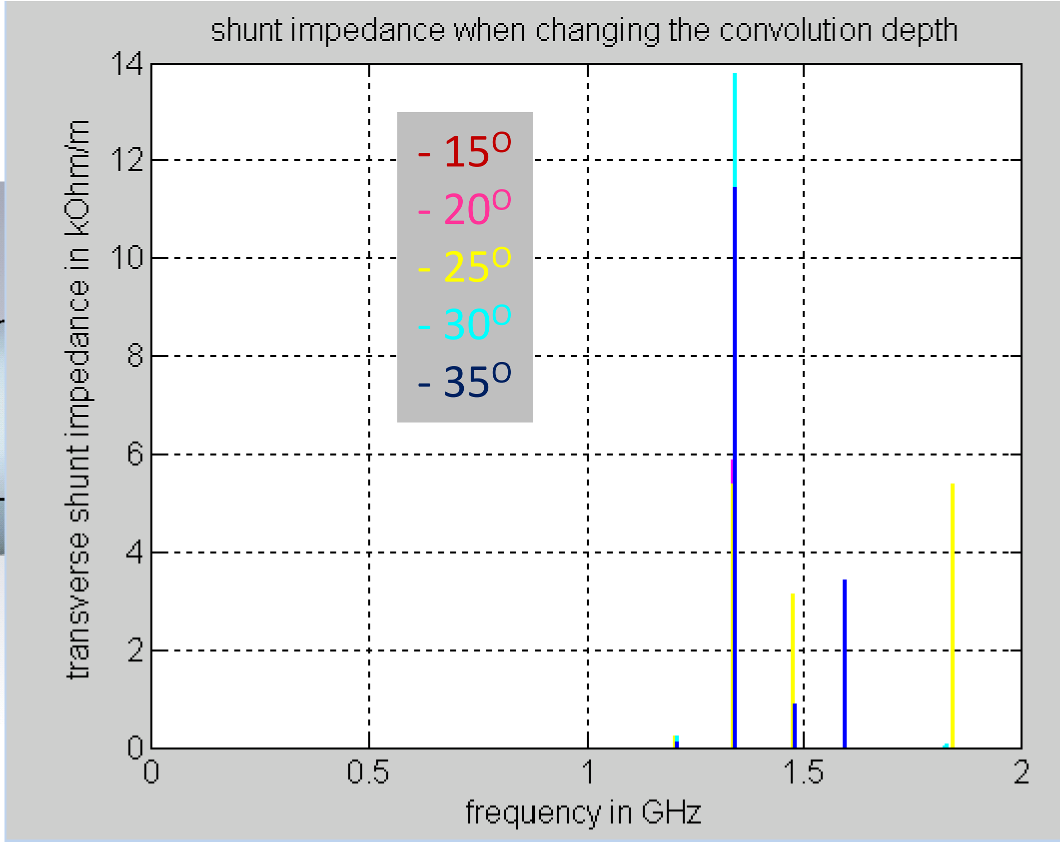




→ No clear dependence on the angle for this new larger radius, to be studied further
→ With this larger radius, some modes are entering the beam spectrum zone for very low bunch length
→ Power loss from these modes estimated of the order of 0.1 W in the worst case (with 0.9 ns bunch length)
→ Have to be careful that small power loss on thin fingers could have consequences

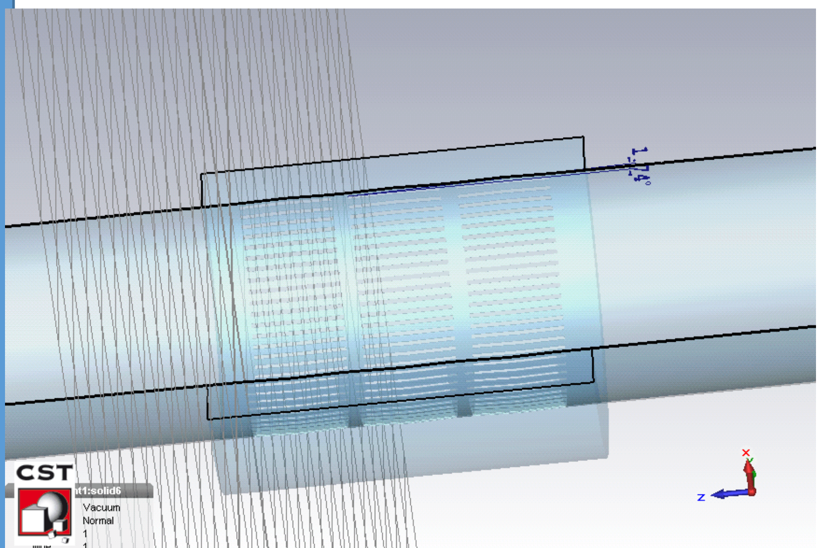
Transverse modes

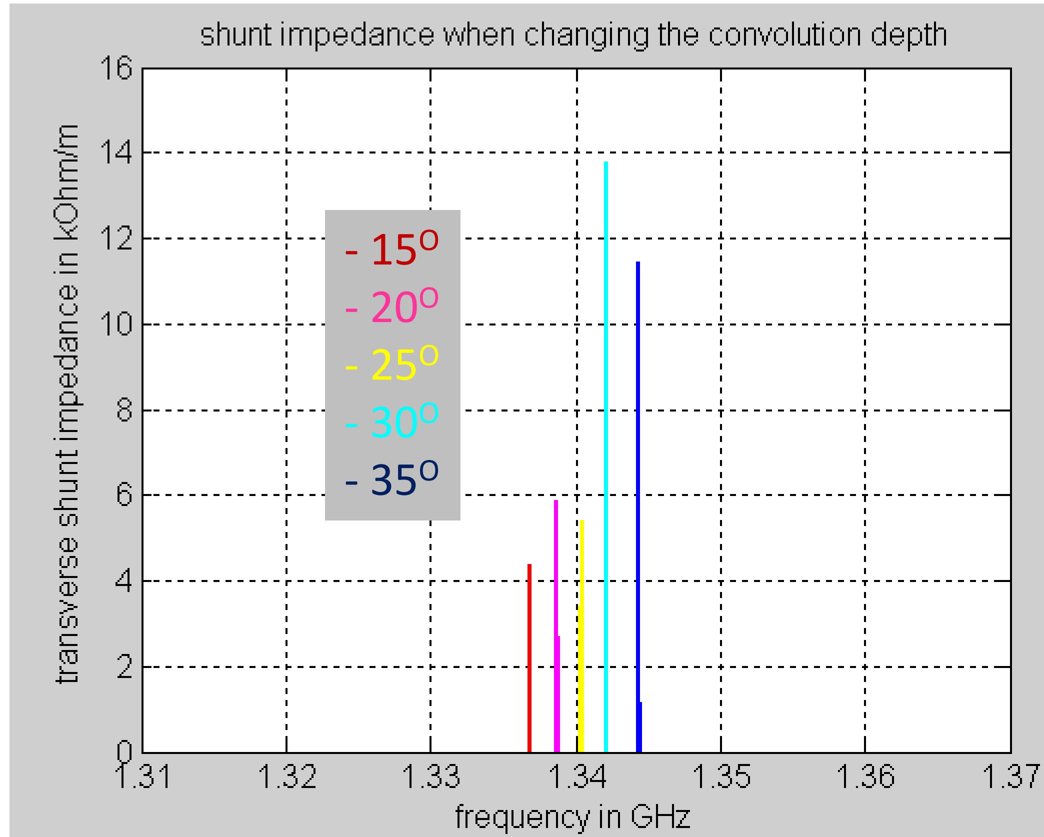




→ Quite a few transverse modes.

Transverse modes





→ Increasing the angle makes modes generally worse (by a factor 3 to 4).

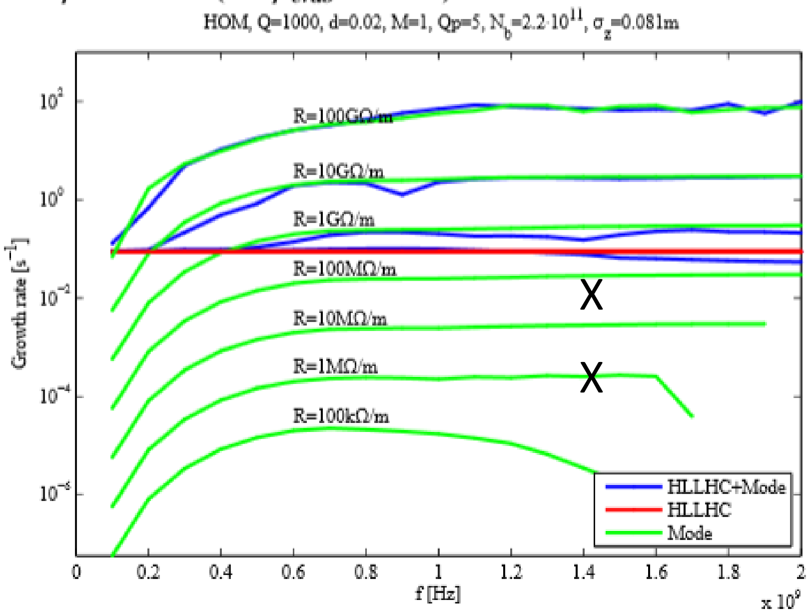
We systematically studied the effect of a HOM added to the HL-LHC baseline:

- $R_s \in (100\ k\Omega/m, ..., 100\ G\Omega/m)$
- $f_{res} \in (100\ MHz, ..., 2\ GHz)$
- $Q = 1000$ to ensure $\Delta f = f_{res}/Q > f_{rev}$.

Scenario: Single bunch, 50 turns damper, $Q' = 5$, $N_b = 2.2 \cdot 10^{11}$ ppb, $\sigma_z = 8.1$ cm.

HL-LHC impedance baseline: Low impedance collimators (MoC+5μm Mo on IP7).

HL-LHC optics: V1.1 with $\beta^* = 15cm$ (i.e. $\beta_{crab} \simeq 3600$) .



→ From $R_s \simeq 1\ G\Omega/m$ we exceed the baseline impedance model.

→ Worst case scenario (very pessimistic):5 kOhm/m*13km/70m*32= 32 MOhm/m for 15 degrees

→ Worst case scenario (very pessimistic):14 kOhm/m*13km/70m*32= 83 MOhm/m for 30 degrees

Conclusions from simulations with simple models so far

- Models are very simplified (in particular for the low frequency impedance) and results should be taken with care.

- The impedance contributions are significant, in particular in the transverse plane due to the large beta functions.

- These shielded bellows are representing ~ 5 m, i.e. ~0.02% of the full machine length

  → would represent ~1% of the full impedance of LHC.

  → not a great achievement for a device designed for impedance shielding!

- Increasing the angle makes impedance contributions worse and increase the risk of being wrong with the simplified simulations.

- Impact of transverse offset is not accounted for here.

- No identified showstopper so far.

Impedance studies

- Simulation work
  - Simplified model for assessment of low frequency impedance
  - More detailed model for assessment of resonant modes
  - R&D with ACE3P to account for
    - Coupling with outside cavity for low frequency impedance
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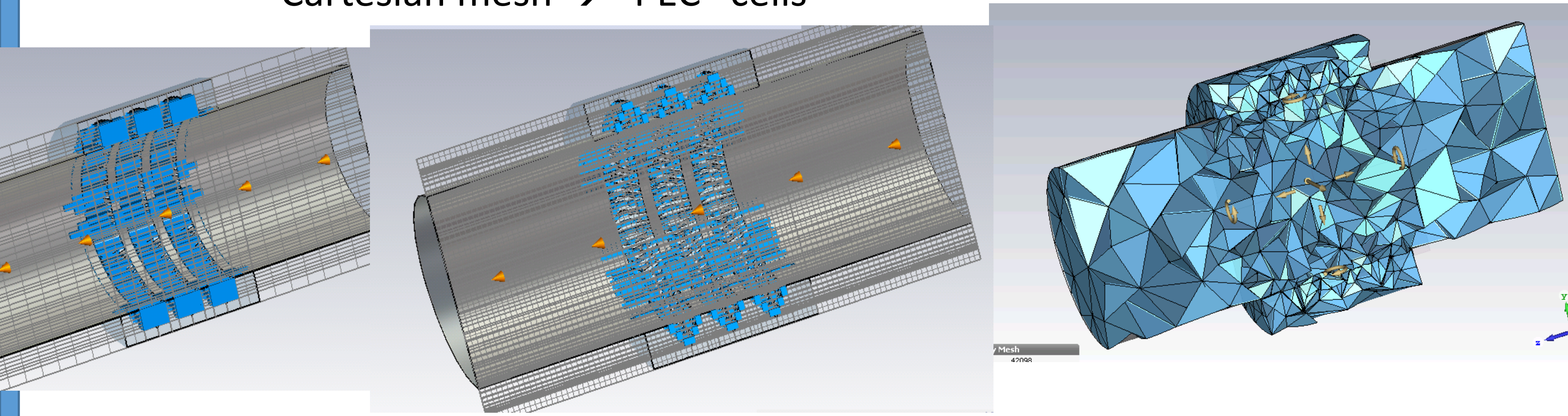
- Measurement work
  - Wire and probe measurements to identify resonant modes

Simulation effort

- Difficult geometry to simulate with Cartesian mesh:

  → small impedance, thin fingers that are not parallel to the Cartesian mesh → “PEC” cells



- Tests started with ACE3P (with Kyrre Sjobaek).

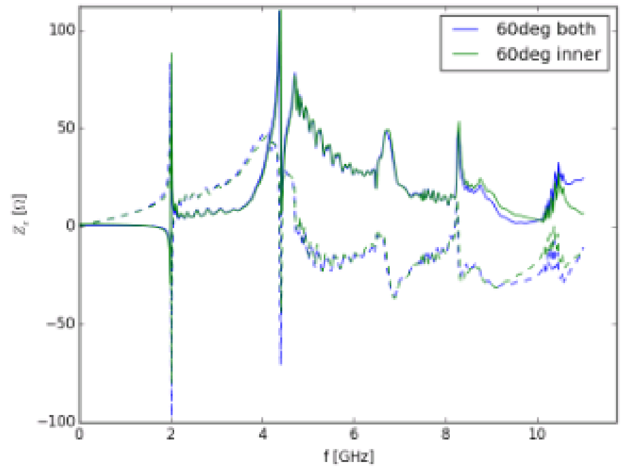
Longitudinal wake

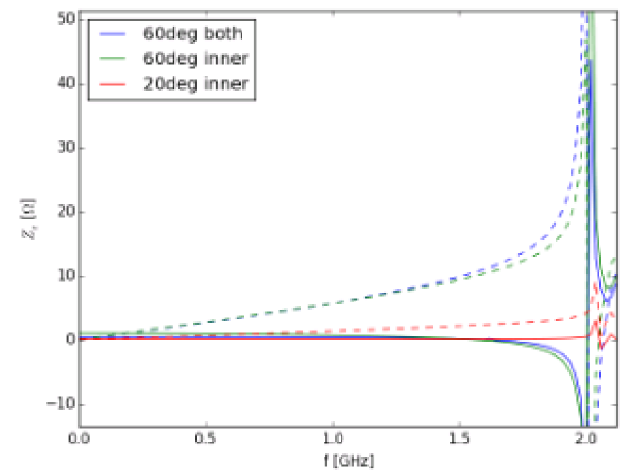
- Longitudinal wake
  - Complete structure vs. only inner part: Very similar
  - TM_{010}-like mode found at expected frequency
  - Stretching out $\Rightarrow$ amplitude drops
  - Analytical model ($\lim \beta\gamma^2 \to 1$):

$$Z_L \propto \mathrm{i} * f * L * \ln\left(\frac{b'}{b}\right)$$

From "Selection of formulae concerning proton storage rings" by Guignard, Gilbert (1977)

- Transverse wake: Some technical difficulties, next time. . .





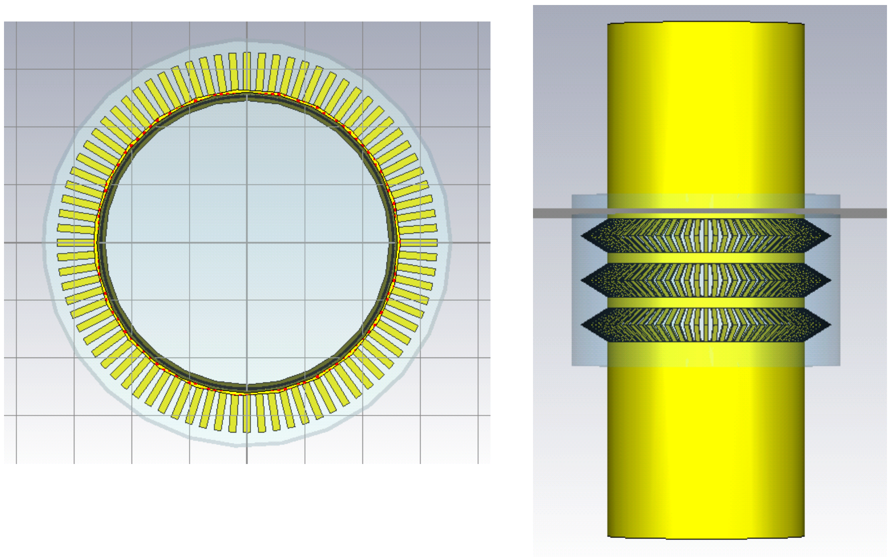
Important outcome of these first tests:

→ Very similar longitudinal impedance at low frequency for simplified model and full model

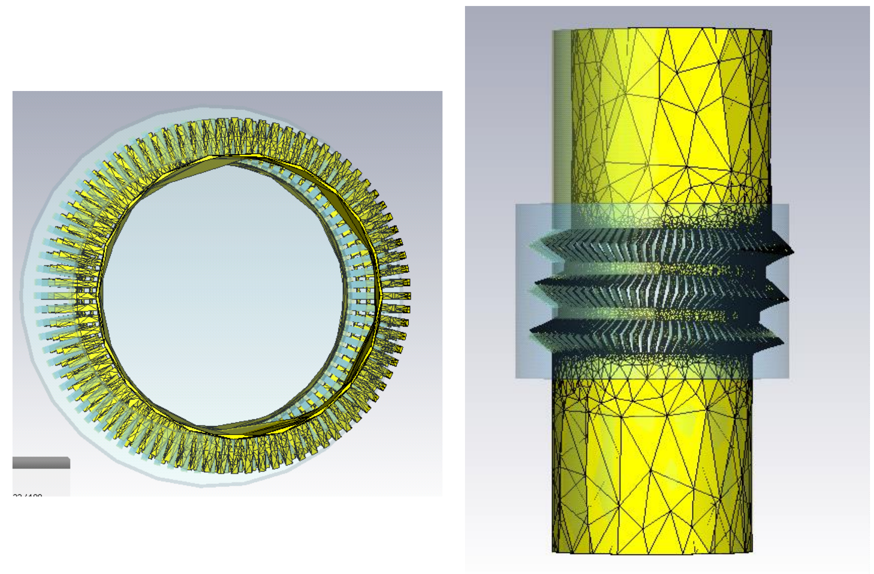
→ Simulations of the closed structure are not fundamentally irrelevant.

Simulation effort

- Work on trying to assess the impact of lateral offset in ACE3P and CST



Starting structure



Structure after applying lateral offset

→ Ongoing work
→ Problem that existing coupled simulation schemes allow only mesh "perturbation"
→ Incompatibility issues between requirements for EM and mechanical simulations, (thickness of materials)

Any showstopper?

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    - Coupling with outside cavity for low frequency impedance
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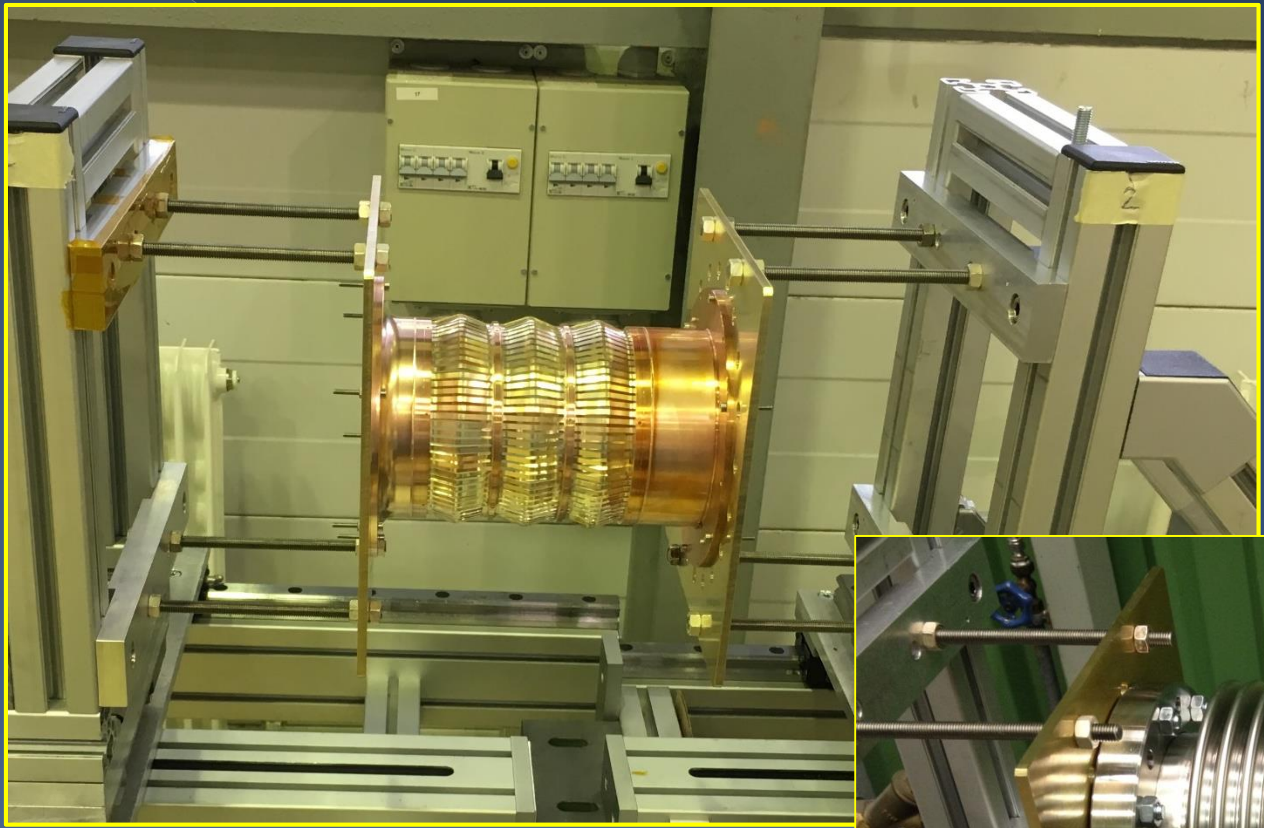
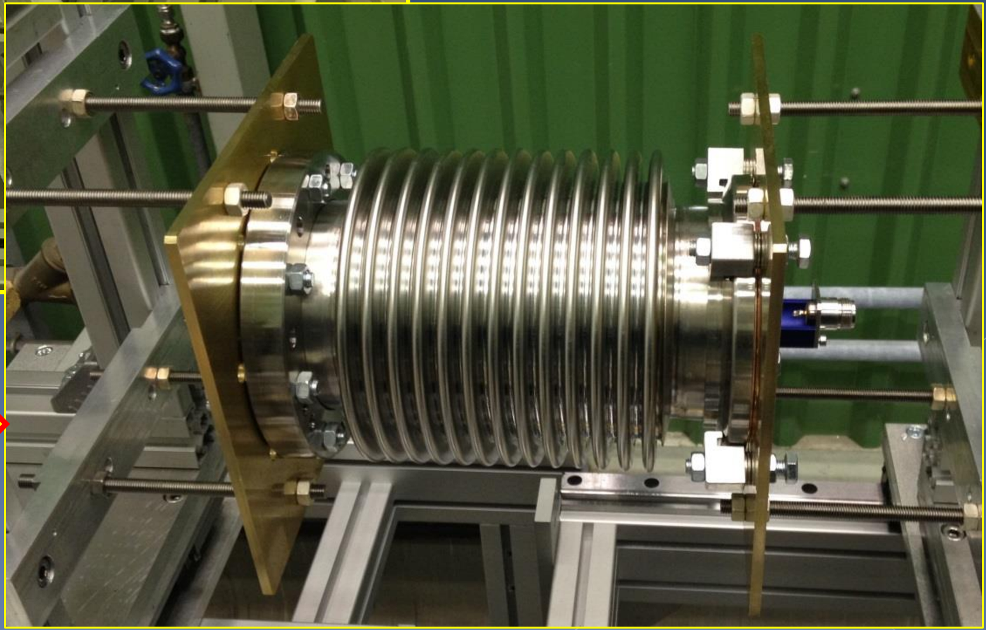
- Measurement work
  - Wire and probe measurements to identify resonant modes

Measurements of 3-convolution RF-finger (ID=111mm)



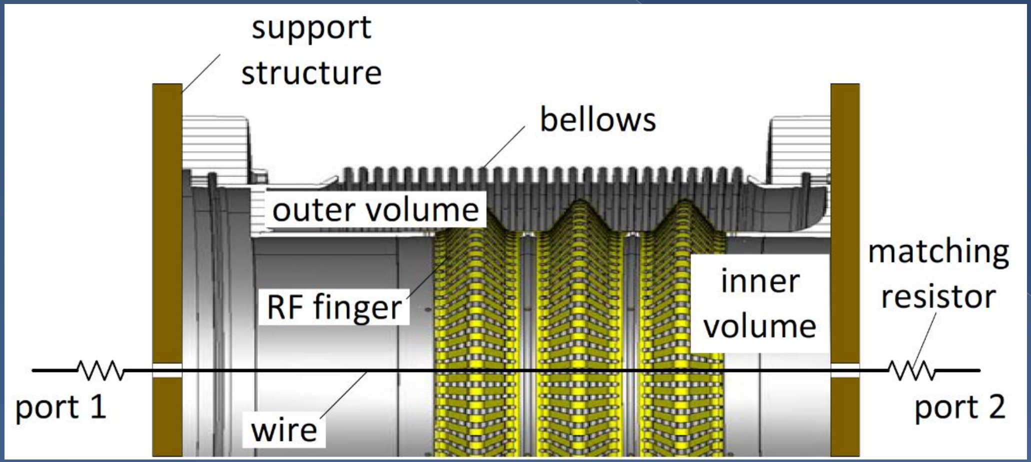
For a correct evaluation, the outer bellows have to be mounted (in both cases) to catch the radiated fields.

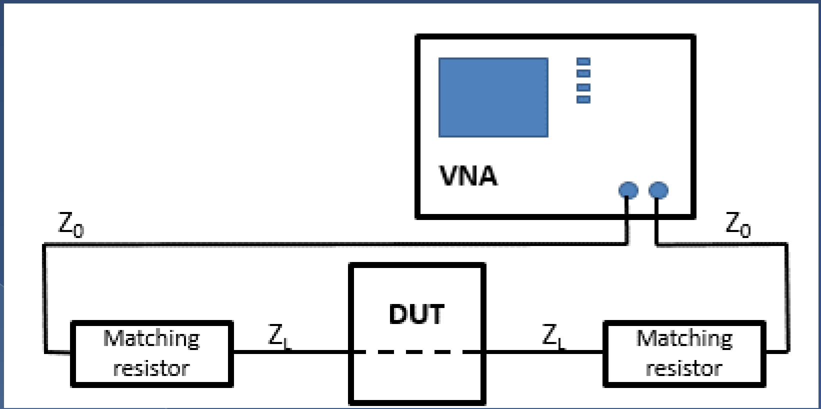


Measurement Method and the "Object"

The structure WITH the outer bellow becomes "nested coaxial line" with two nested coaxial volumes (inner and outer).

Coupling via RF-finger slits.



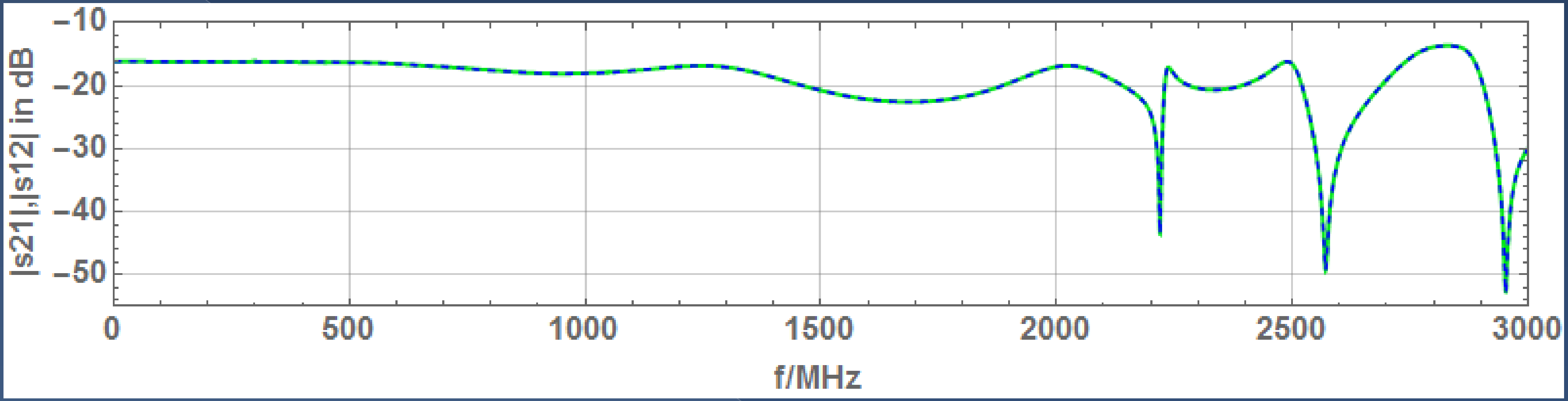


Standard measurement methods are:

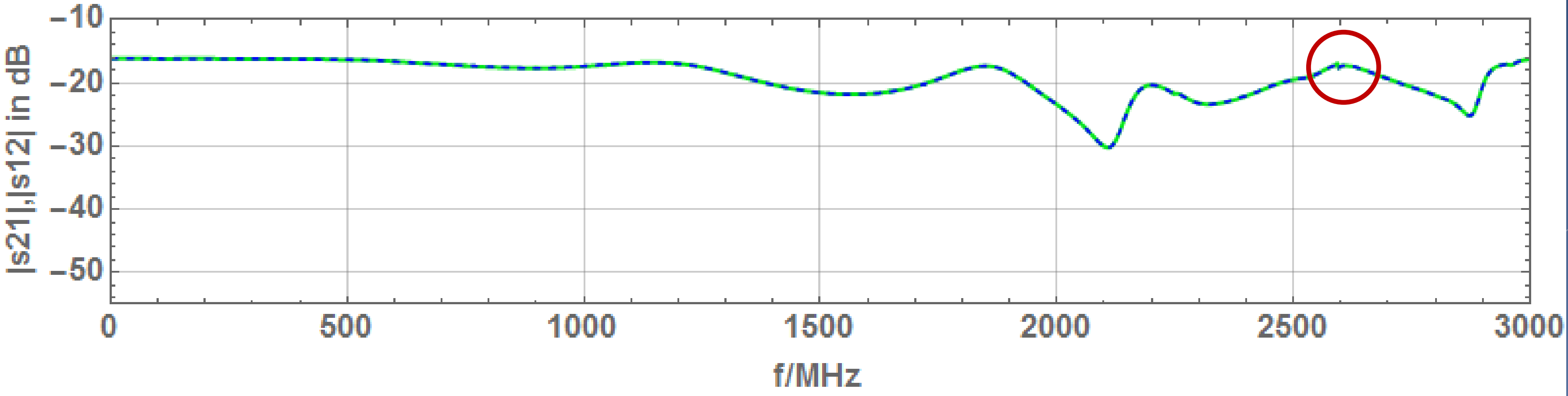
- *(Beam-simulating) wire method, and*
- *Probe measurements.*

3-Convolution Shielding

Measurements without bellows mounted



Measurements **with** bellows mounted



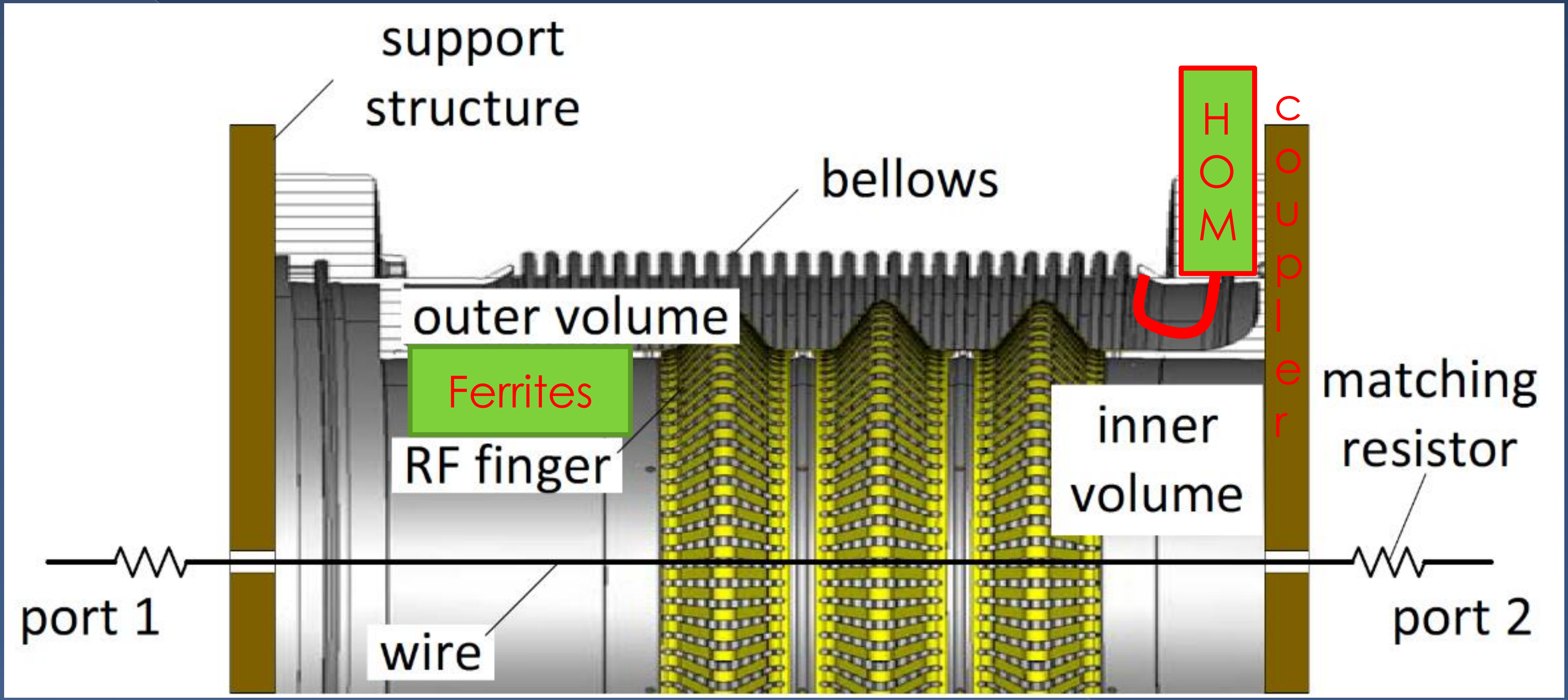
→ No obvious resonance observed with the design provided

Outcome of measurements

- Tedious non-trivial measurements;
- Measurements do not show large resonances with bellow mounted on 3-convolution shielding;
  - First resonance around 2 GHz
- However, several aspects are still not understood:
  - Difference in observed resonances for 2-convolution bellows (many resonances) and 3 convolution bellows (small number of resonances) is not yet explained!
  - Thus, we cannot interpolate to different radii -> each of them needs either explicit measurement or simulation.
  - Impact of the transverse offset needs to be better understood.

→ No clear showstopper so far, but some questions and worries
→ It is clear that the proposed shielding geometry needs to be measured as soon as available

Next Steps – Mitigation (if required)



If the high-Q resonances from the outer volume pose a problem, we propose to consider damping in-situ with absorbers or with a small HOM coupler.

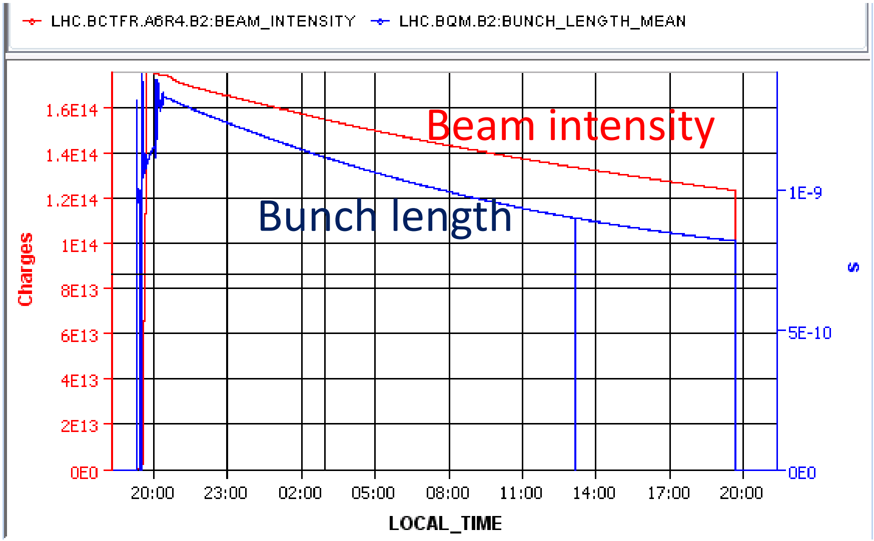
Questions to be answered

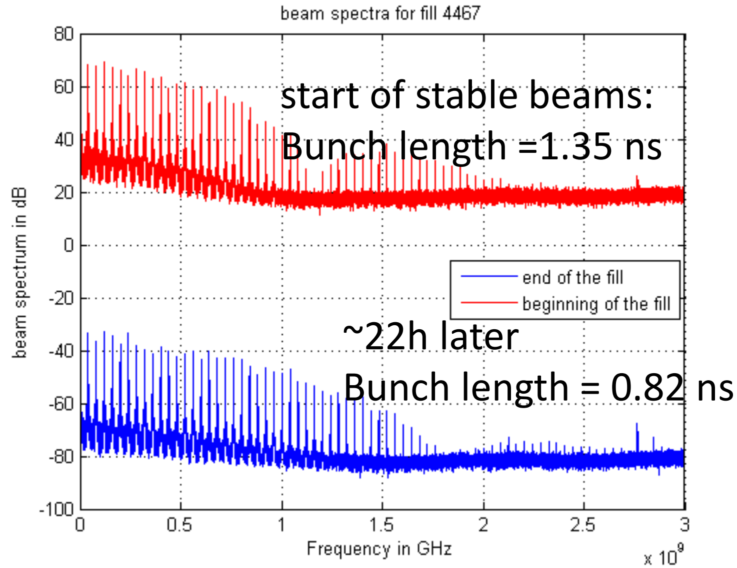
- Does the concept of deformable RF fingers show any showstopper for an application in the HL-LHC triplet area?
  → Contrary to the first bellow shielding proposed for collimators, no showstopper seen so far with this new design, but some questions and worries.
  → Further validation requires measurements with the updated design.

- What is the maximum acceptable angle of the fingers? (Could the baseline of 15° be relaxed?)
  → With increasing angle, gradual increase of:
    - impedance contributions
    - uncertainty of simulations, especially in case of transverse offset.
  → The operating angle should be kept as low as possible to minimize impedance contributions and risk of unwanted coupling with the external volume as well as unexpected EM-behaviour.
  → 15 degrees sounds reasonable (even though the contribution is much larger than the existing design).

- Does the second wall bring any significant improvement?
  → There does not seem to be much to gain with the double wall.
  → Could a feedthrough be foreseen, in case it is needed? It would be important to help measurements on the prototype in any case

Impact of bunch length reduction during the fill:

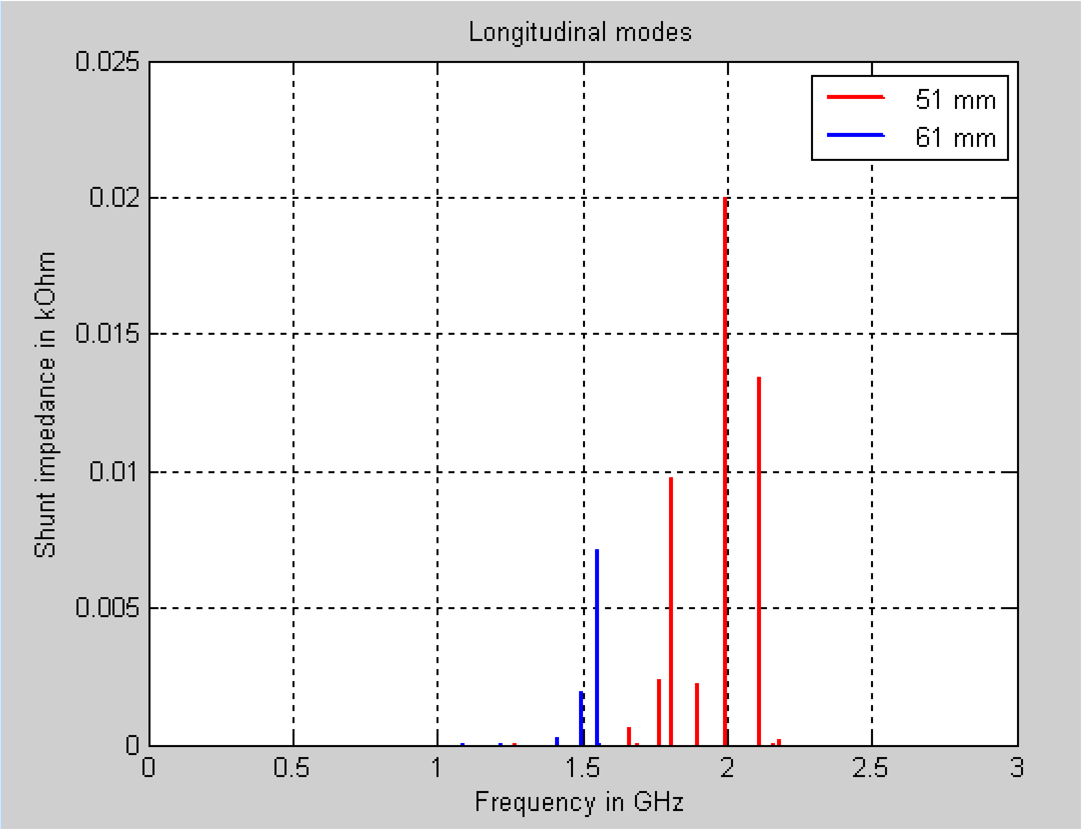


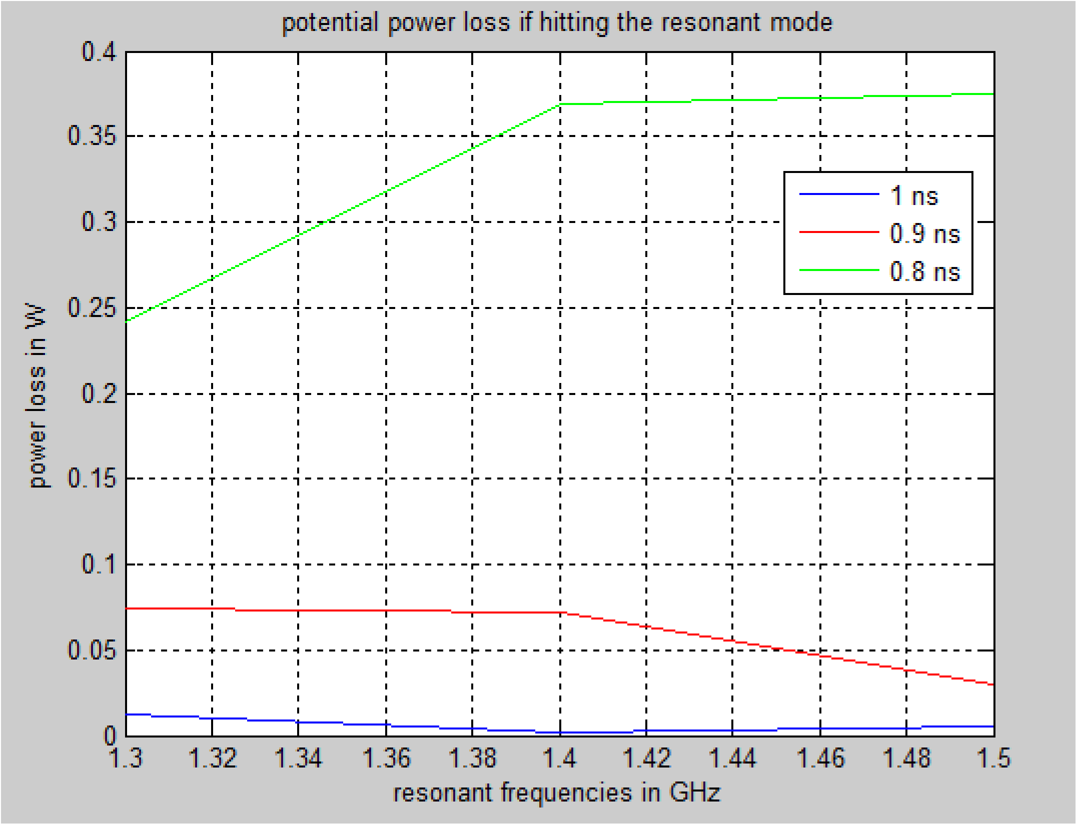


- **Power spectrum extends to higher frequency → more beam induced heating**
  → not a showstopper so far as intensity also decreases.
- **More luminosity**
  → not a showstopper either (!): expected gain with 2016 parameters ~2 % (from Fanouria's model).
- **Reducing luminous region** *(input from Jamie)*
  → request of LHCb/ALICE to keep the luminous region more constant.
  → ATLAS and CMS do not mind too much as long as there is a gain in luminosity.
- **Longitudinal instabilities at very low bunch length**
  → not an apparent issue in 2015 from bunch by bunch luminosity

→ It would be useful to be ready to control bunch length by bunch flattening

Longitudinal modes



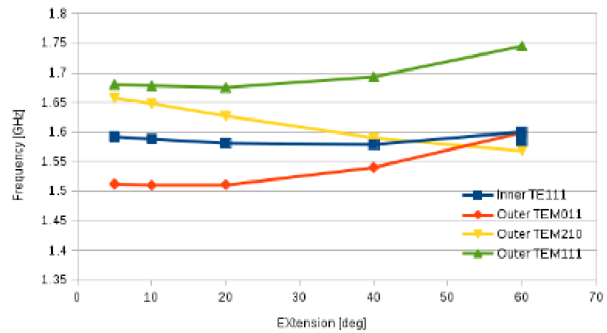


potential power loss if hitting the resonant mode
power loss in W
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1.3
1.32
1.34
1.36
1.38
1.4
1.42
1.44
1.46
1.48
1.5
resonant frequencies in GHz
1 ns
0.9 ns
0.8 ns

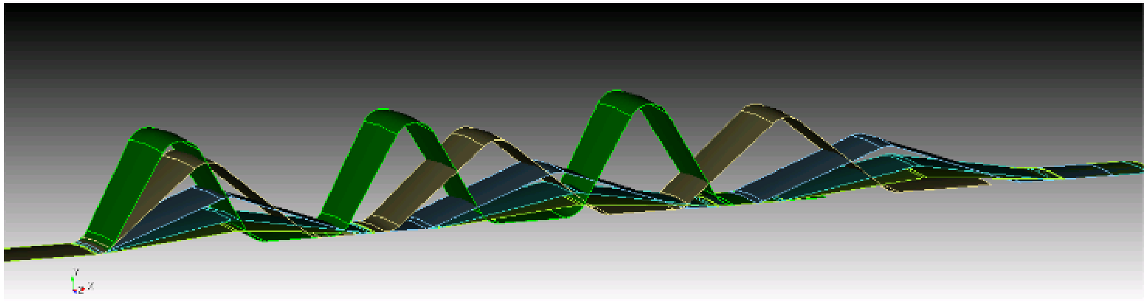
Kyrre's simulations with ACE3P

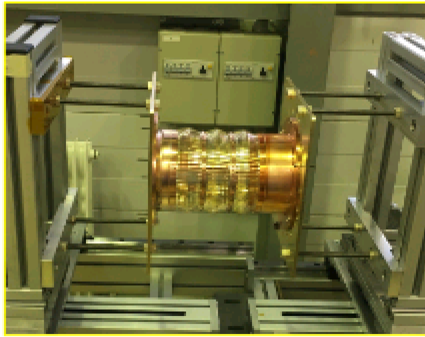
Effect of stretching the structure

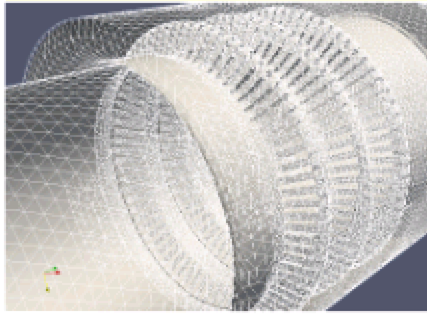
- Use geometry parametrization
- Would expect more coupling if inner- and outer resonances cross
- They do for large angles; but mode symmetry is different
- Dependency on vacuum bellow radius and corrugations not studied



deg	5	10	20	40	60
mm	39.3	38.3	34.1	19.6	0.0







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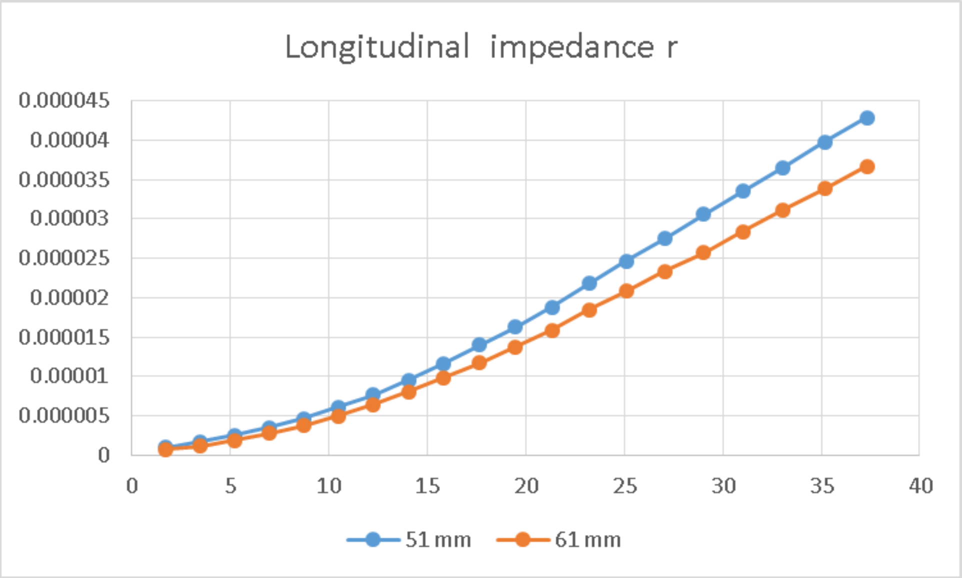
ted as 0 mm, no outer corrugations

→ Should stay clear of possible resonance coupling
→ The lower the angle the better


Longitudinal impedance r
0.000045
0.00004
0.000035
0.00003
0.000025
0.00002
0.000015
0.00001
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30
35
40
51 mm
61 mm

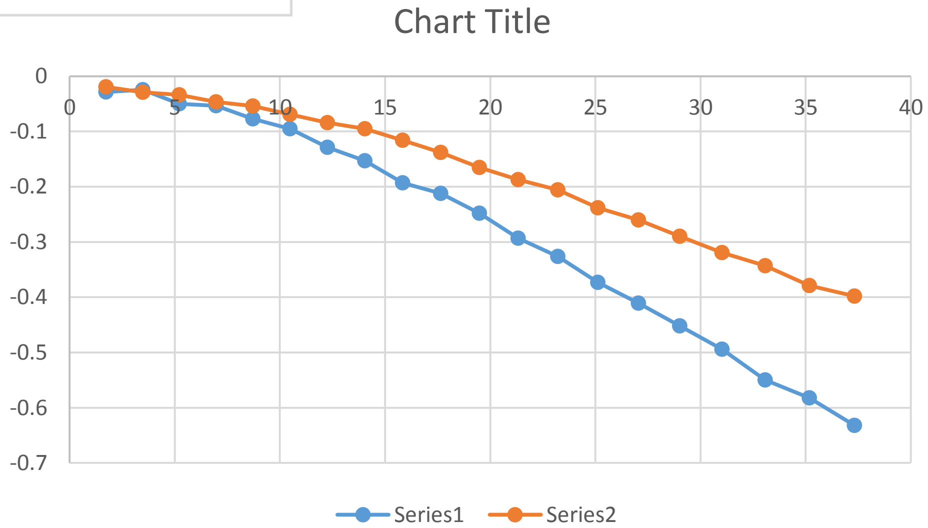
Chart Title
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-0.1
-0.2
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Series1
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