Impedance of new ALICE beam pipe

Benoit Salvant, Rainer Wanzenberg and Olga Zagorodnova

Acknowledgments:
Elias Metral, Nicolas Mounet, Mark Gallilee, Arturo Tauro

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Main points

- The impact of the proposed change of ALICE beam pipe on effective impedances is rather small.
- A single bellow impedance contribution is significant and should be avoided if possible (we understand that it is not possible here).
- The heating on the smaller diameter pipe will increase and could reach 5 to 6 W/m for HL-LHC parameters. Is that acceptable?
- The stainless steel (resp. Aluminium) at 20.1 mm radius should cope with 20 W/m (resp. 4 W/m) with HL-LHC beam. Is that acceptable?
- If both of these points are acceptable, then there is no reason for the impedance team to reject the request.
- This is not linked to the upgrade, but due to the large diameter of the cone, many modes are present and could lead to large heat load in case they are excited by the post-LS1 beam or HL-LHC beam.

    → should be monitored closely.

    → was there any temperature observation to see if something was already going on before LS1?

    → is there a way to increase the monitoring at the occasion of the upgrade?

Agenda

- Context
- Impedance computations for the updated version of the ALICE beam pipe
- Conclusions

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**

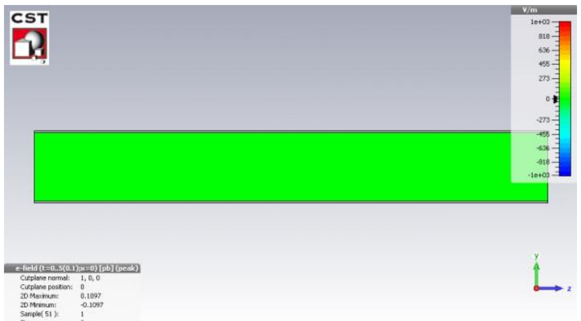
Context: impact of beam impedance on performance

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

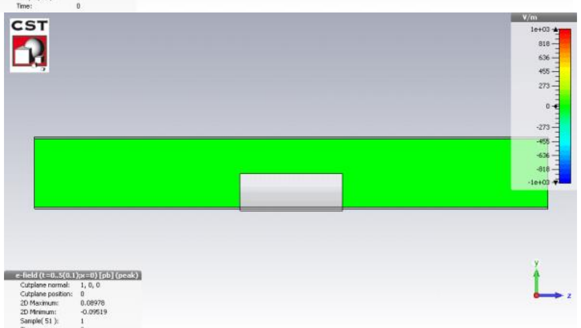
  it will produce wakefields that will perturb the following particles

  → 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

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New geometry ALICE (1.2 m at 18.2 mm radius)

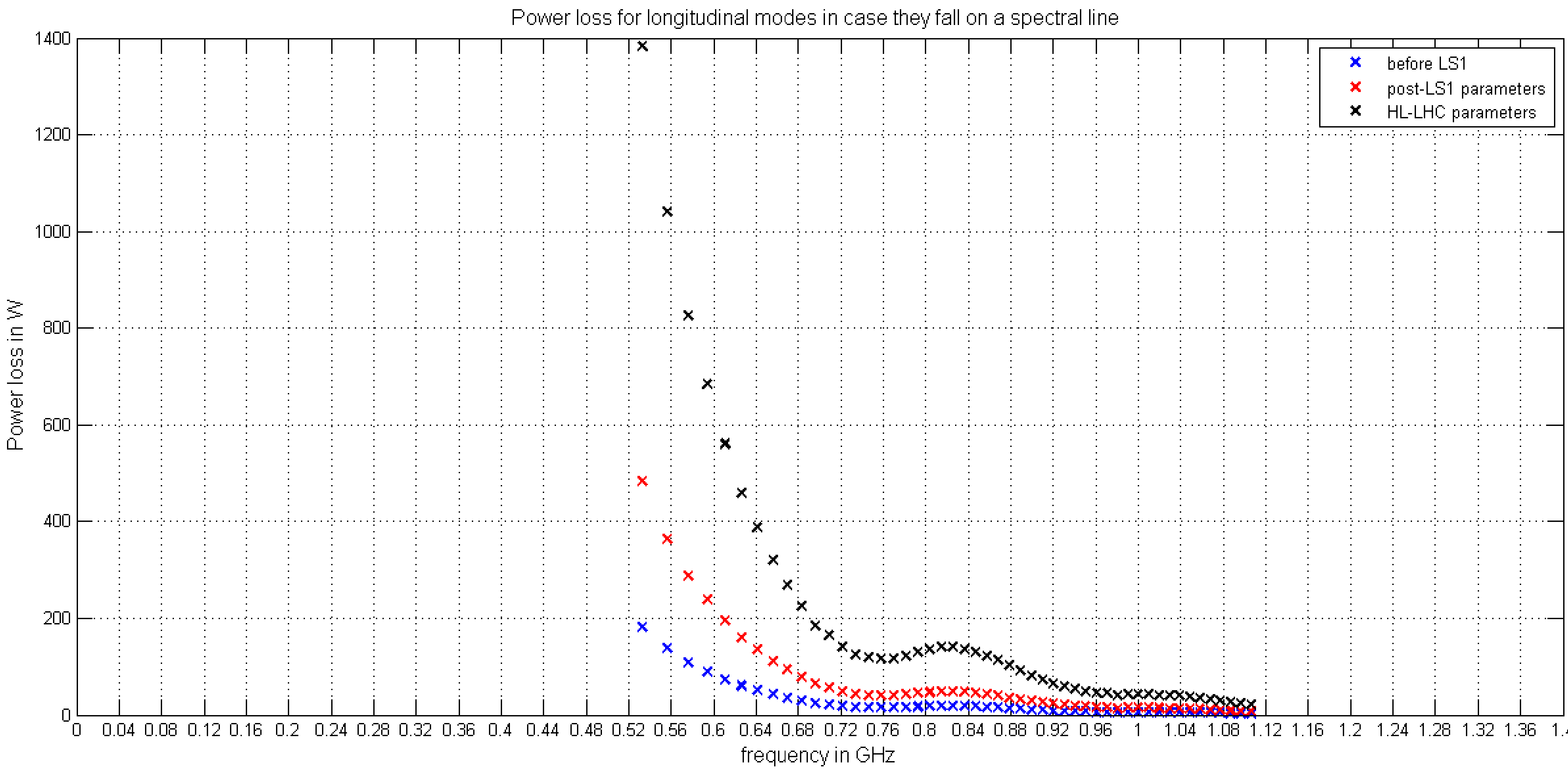
	resistive wall: 1.2 m length at 18.2 mm radius	geometric	2 bellows (20.7 to 28.5 mm, 65 mm length)
Effective longitudinal impedance $Im(Z/n)^{eff}$	1.7 μΩ	1.2 mΩ	0.56 mΩ
Effective transverse impedance $Im(Z^{eff})$	96 Ω/m	3 kΩ/m	8.6kΩ/m
Power loss before LS1	1 W/m	~ 400 W (for 1.25 ns)	0
Power loss for post-LS1	2 W/m	~ 1 kW (for 1.25 ns)	0
Power loss for HL-LHC beam	5.4 W/m	~ 3 kW (for 1.25 ns)	0

→ Are these values an issue?

Before LS1: 2*1374 bunches at 1.6e11 p/b (1 ns bunch length)
Post-LS1 beam: 2*2748 bunches at 1.3e11p/b (1 ns bunch length)
HL-LHC beam: 2*2748 bunches at 2.2e11p/b (1 ns bunch length)

Power from resonant modes

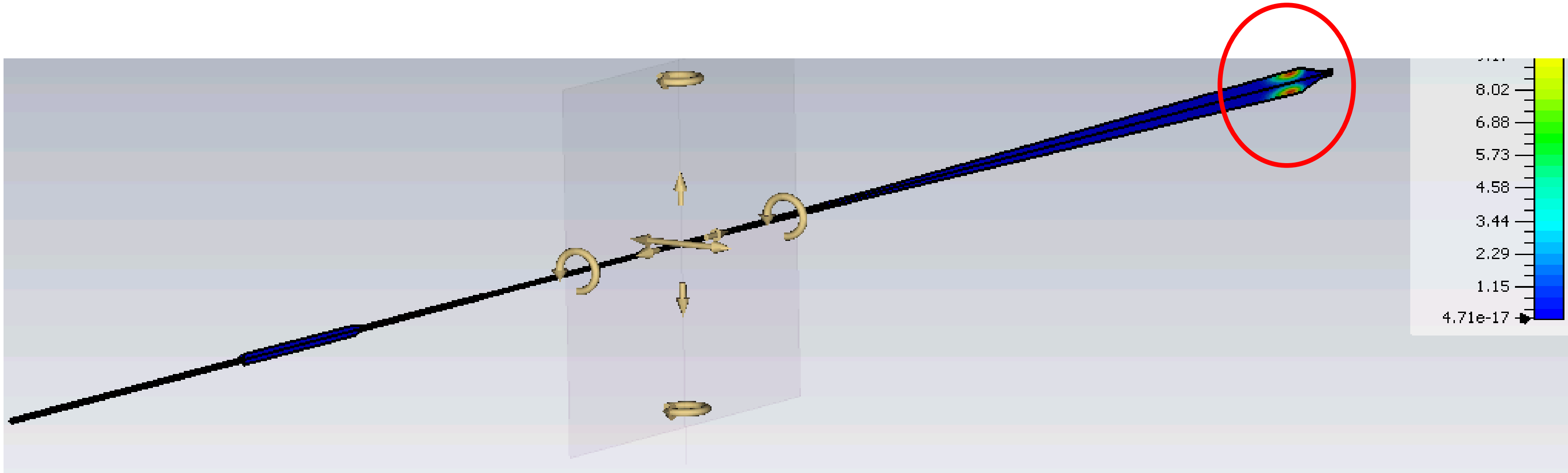
Modes from R. Wanzenberg and O. Zagorodnova



Significant increase of power loss with HL-LHC parameters

→ even the modes at higher frequencies are significant (of the order of 20 to 50 W)

Location of modes?



Linked to the large diameter of the cone → localized there
No changes foreseen in this area, so these modes are not affected by the upgrade

New geometry ALICE (1.2 m at 18.2 mm radius)

	resistive wall: 1.2 m length Be at 18.2 mm radius	geometric	2 bellows (20.7 to 28.5 mm, 65 mm length)	Full LHC	% of full LHC	(%increase)
Effective longitudinal impedance $Im(Z/n)^{eff}$	1.7 μΩ	1.2 mΩ	0.56 mΩ	90 mΩ	RW << 0.1% Bellows~0.6% Geometric~1.3%	(+60%) (+34%) (+5%)
Effective transverse impedance $Im(Z^{eff})$	96 Ω/m	3 kΩ/m	8.6kΩ/m	2 MΩ/m	RW << 0.1% Bellows~0.4% Geometric~0.1%	(+300%) (+45%) (+50%)
Power loss for nominal beam	1.5 W/m	~400 W (for 1.25 ns)	0	-	RW ~ 1.5 W/m Modes ~ 200 W	+60% same
Power loss for post-LS1 beam	2 W/m	~1 kW (for 1.25 ns)	0	-	RW ~ 2 W/m Modes ~ 500 W	+60% same
Power loss for HL-LHC beam	5.4 W/m	~3 kW (for 1.25 ns)	0	-	RW ~ 5.4 W/m Modes ~ 1.5 kW	+60% same

→ Small impact on effective impedances (i.e. on single bunch stability)

→ Larger heating due to smaller aperture: can the beam pipe sustain 5 to 6 W/m in HL-LHC?

→ No link to the change of geometry, but potentially high heat loads due to modes could be obtained with HL-LHC beams in case the mode frequencies fall on beam spectral lines (already pointed out to LEB and HL-LHC management in 2013)

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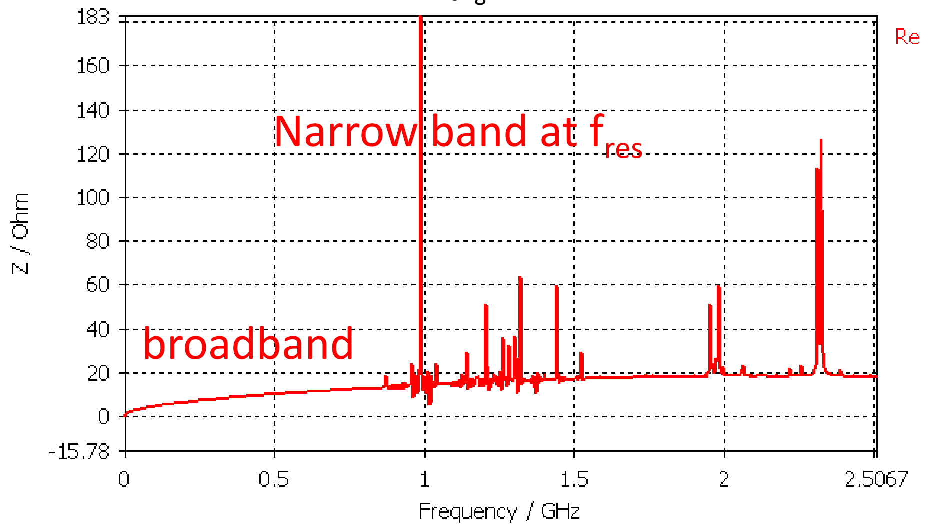
Computing power loss

- Power lost by the beam in a device of impedance Z_{long} (see E. Métral at Chamonix 2012):

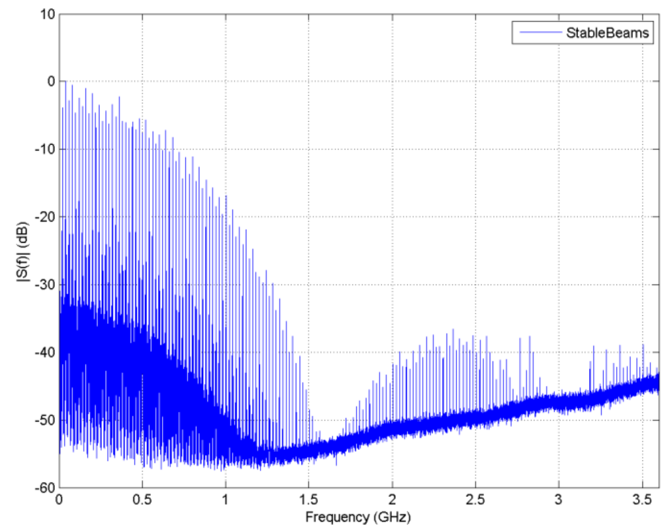
$$P_{loss} = 2\left(eMN_b f_{rev}\right)^2 \left(\sum_{p=1}^{\infty} \mathrm{Re}\left[Z_{long}(2\pi p M f_{rev})\right] \times Powerspectrum(2\pi p M f_{rev}) \right)$$

M=2808 bunches
N_b=1.15 10^{11} p/b

Impedance Re(Z_{long}) of TCP in physics



Power spectrum measured on 50 ns
by P. Baudrenghien and T. Mastoridis



Effect of **25 ns** on RF heating?

- Power lost by the beam in a device of impedance Z_{long} (see E. Metral at Chamonix 2012):

$$P_{loss} = 2(eMN_b f_{rev})^2 \left(\sum_{p=1}^{\infty} \mathrm{Re}\left[Z_{long}(2\pi p M f_{rev})\right] \times \mathrm{Powerspectrum}(2\pi p M f_{rev}) \right)$$

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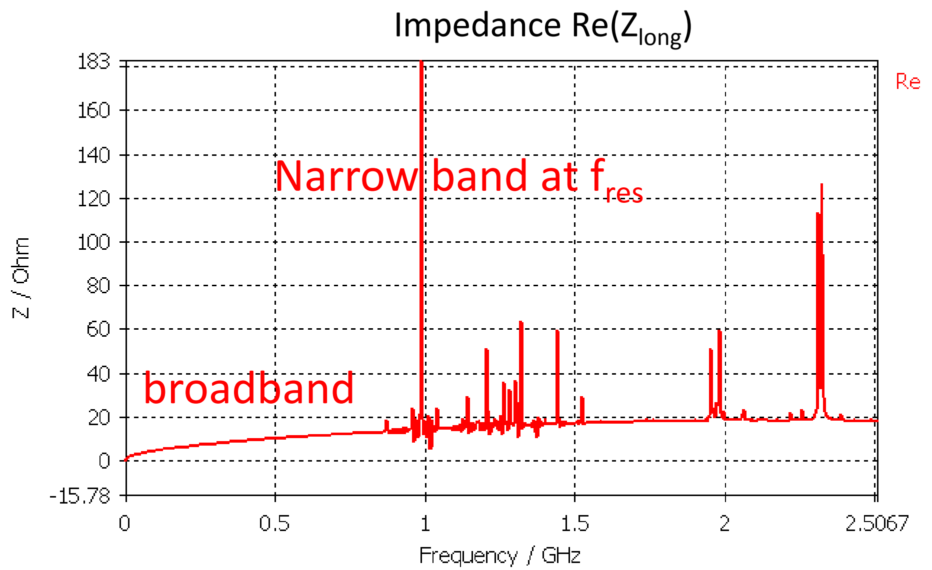
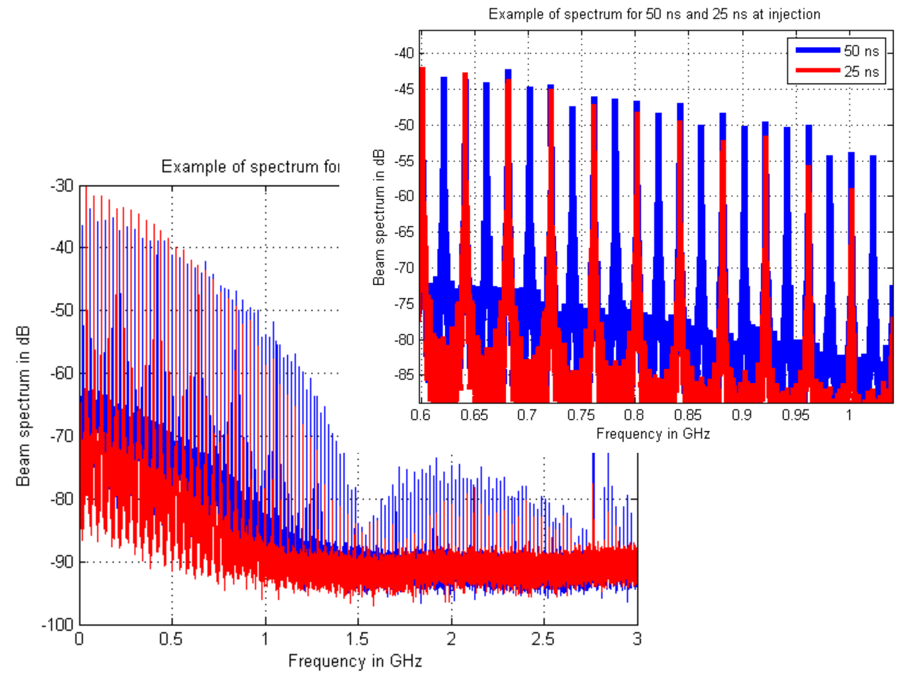




- Assumptions: same bunch length and same bunch distribution for 50 and 25 ns spacing

→ **same beam spectrum but with half of the peaks**

→ switching to 25 ns for broadband:

increase by factor $\frac{M^{25} * (Nb^{25})^{\wedge}2}{M^{50} * (Nb^{50})^{\wedge}2} = 1.05$

→ switching to 25 ns for narrow band falling on a beam harmonic line (f_{res}= k*20 MHz):

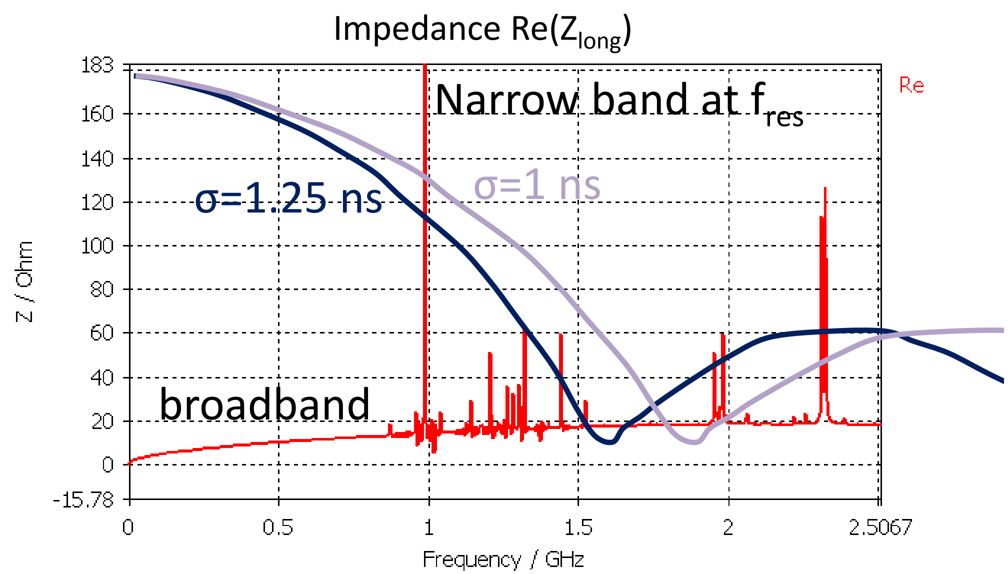
increase by factor $\frac{(M^{25} * Nb^{25})^{\wedge}2}{(M^{50} * Nb^{50})^{\wedge}2} = 2$ (if f_{res}=2*k*20 MHz) or 0 (if f_{res}=(2*k+1)*20 MHz)

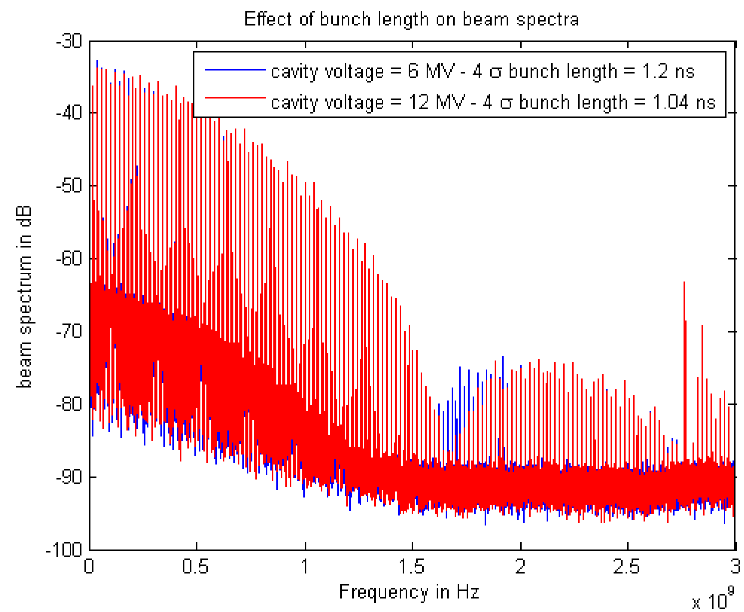
Effect of **bunch length** on RF heating?

- Power lost by the beam in a device of impedance Z_{long} (see E. Metral at Chamonix 2012):

$$P_{loss} = 2(eMN_b f_{rev})^2 \left(\sum_{p=1}^{\infty} \mathrm{Re}[Z_{long}(2\pi pMf_{rev})] \times Powerspectrum(2\pi pMf_{rev}) \right)$$

M=2808 bunches
N_b=1.15 10^{11} p/b





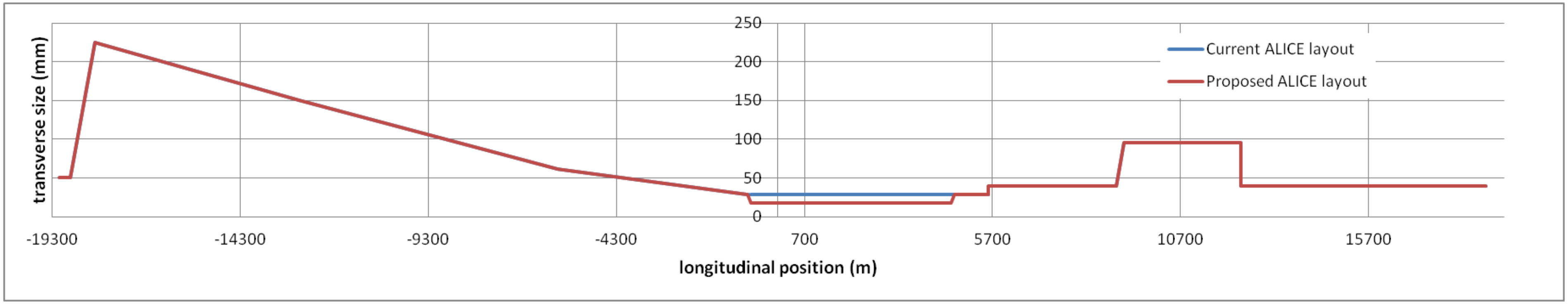
- Assumption: same bunch distribution for 25 ns and 50 ns
  → **beam spectrum is extended to higher frequencies with an "homothetic" envelope**

→ switching to lower bunch length for broadband:
in general regularly increases (depends on broadband resonant frequency)

→ switching to lower bunch length for narrow band:
enhances some resonances , damps others, excites higher frequency resonances

From the heating point of view, the longer the bunch the better in most cases.

ALICE aperture change request



Nota: the new tapering angle is 7 degrees.

ALICE (Beryllium - length 5.317 m)

Transverse

Energy	Inner radius	Bunch length ($4\sigma_t$)	$Im(Z_t^{eff})$ [Ω/m] resistive part	$Im(Z_t^{eff})$ [Ω/m] geom. part	$Im(Z_t^{eff})$ [MΩ/m] total (LHC ring)
450 GeV	29 mm	1.3 ns	120		~2.4
450 GeV	17.5 mm	1.3 ns	550	~350	
7 TeV	29 mm	1 ns (nominal)	105		~25
7 TeV	17.5 mm	1 ns (nominal)	480	~350	

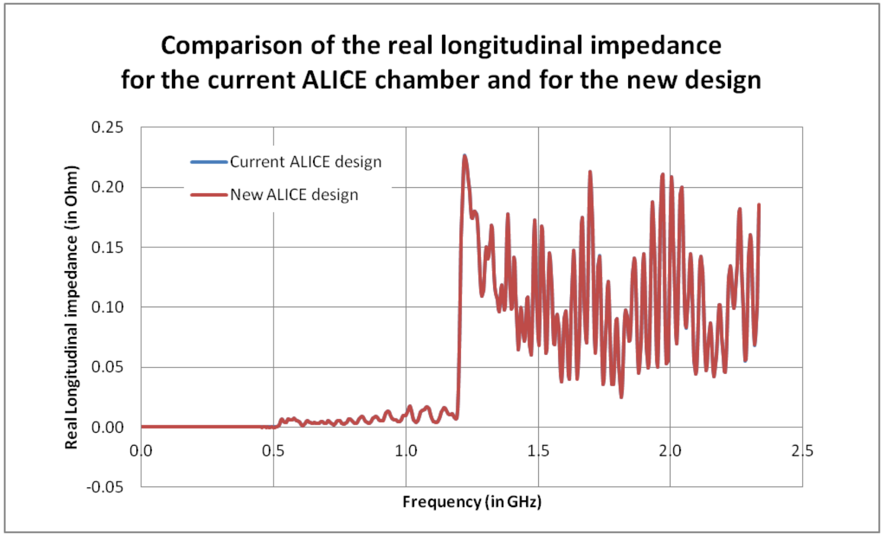
Longitudinal

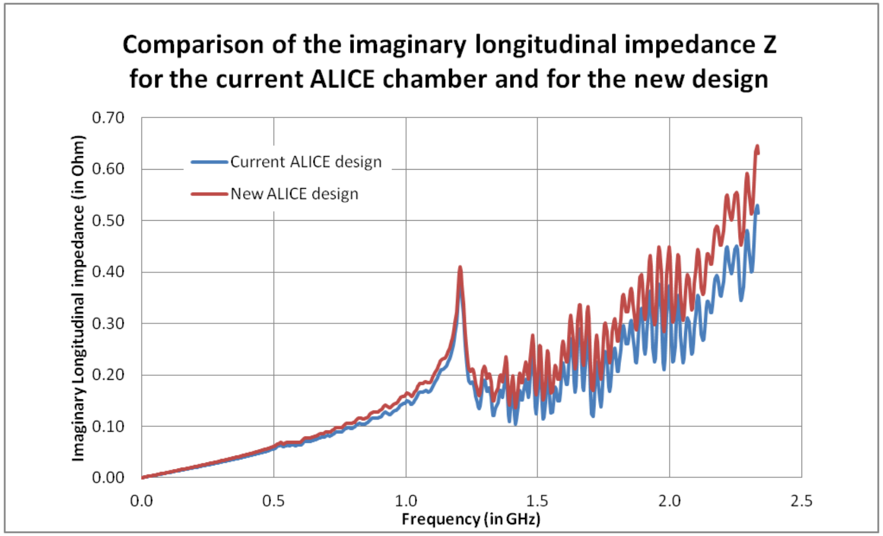
Energy	Inner radius	Bunch length ($4\sigma_t$)	$(Z_{\|\|}/n)^{eff}$ [Ω] resistive part	$(Z_{\|\|}/n)^{eff}$ [Ω] total (LHC ring)	Power loss in W (2 beams)
450 GeV	29 mm	1.4 ns (MD)	$j\,0.8\ 10^{-5}$	$j\,0.09$	1
450 GeV	17.5 mm	1.4 ns (MD)	$j\,1.2\ 10^{-5}$		1.7
7 TeV	29 mm	1 ns (nominal)	$j\,0.5\ 10^{-5}$	$j\,0.085$	0.9
7 TeV	17.5 mm	1 ns (nominal)	$j\,0.8\ 10^{-5}$		1.6

→ significant increase of impedance with the new geometry. However, it remains very small compared to the total LHC impedance. Is a 70% increase in power loss ok?

Also: geometric $Im(Z/n)=1\ 10^{-7}$ Ohm

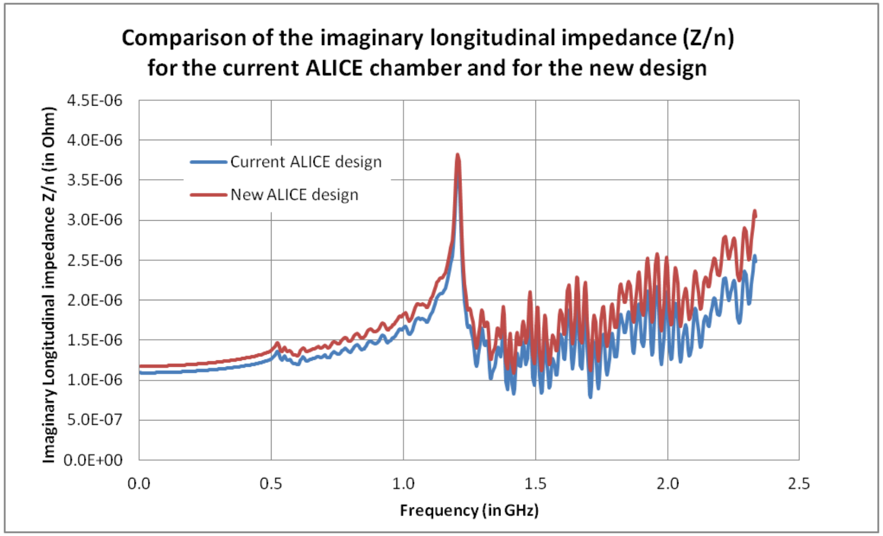
Longitudinal impedance
(broadband computed from ABCI, all materials PEC)



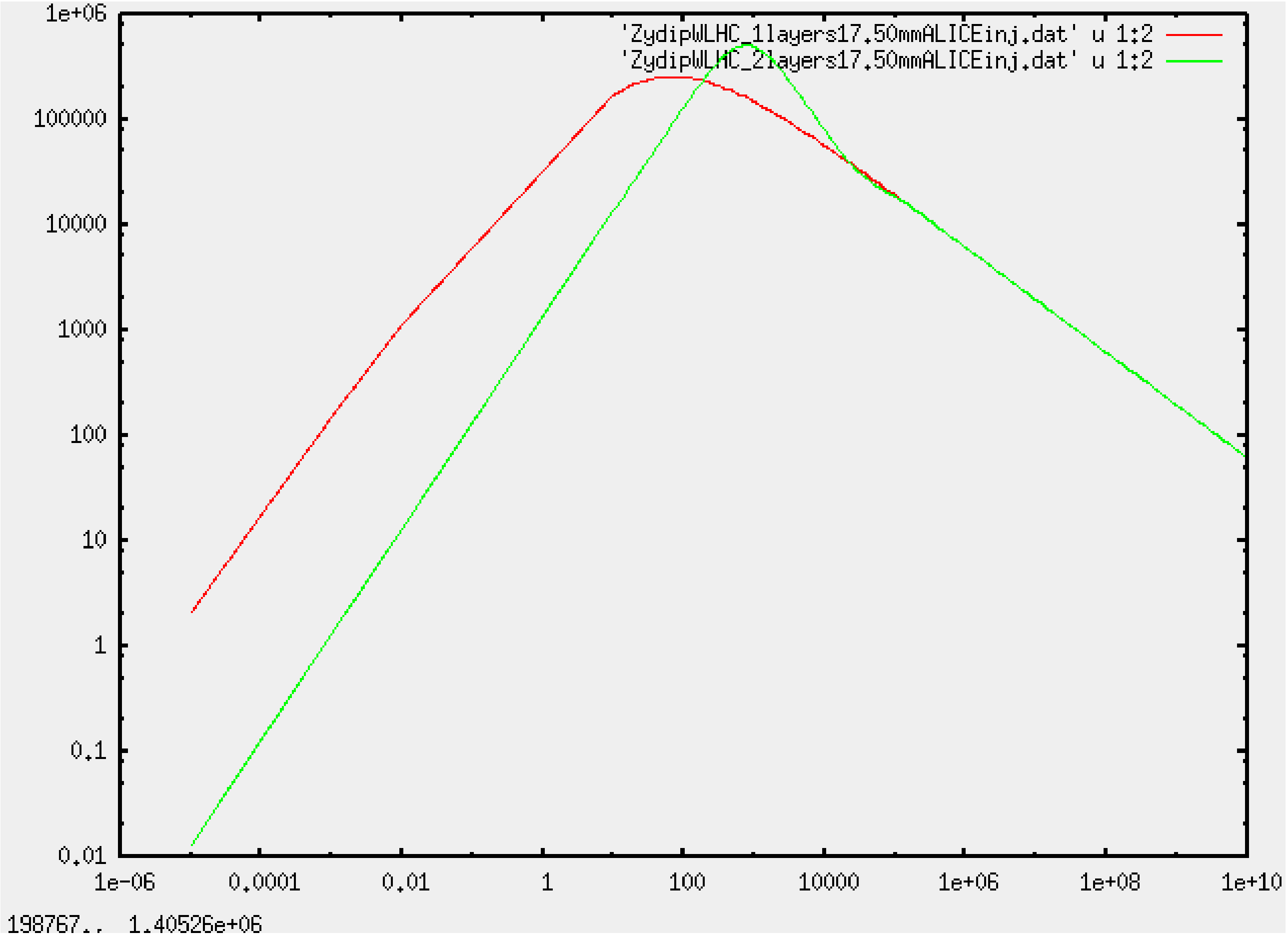


- No measurable difference in the real part of the impedance

- There is an increase of 7% of the imaginary part of the impedance



1 vs 2 layers



Difference visible below 100 kHz