Where are we on the impedance model of HL-LHC?

Alexey Burov, Mike Barnes, Philippe Baudrenghien, Rama Calaga, Hugo Day, Wolfgang Hofle, Juan Esteban Mueller, Themis Mastoridis, Elias Métral, Nicolas Mounet, Stefano Redaelli, Benoit Salvant, Elena Shaposhnikova, Laurent Tavian, Rainer Wanzenberg, Olga Zagorodnova, M. Zobov et al.

Many thanks to Stephane Fartoukh, Riccardo de Maria, Simon White.

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Agenda

- Context
- Current impedance model and related limitations
  - Beam instabilities
  - Beam induced heating
- What is planned to change
- On-going impedance computations for HL-LHC
  - Collimators
  - Experimental pipes and forward detectors
  - Crab cavities
  - Hollow electron lens
  - High bandwidth feedback
- Perspectives

High Luminosity LHC

Context

- HL-LHC baseline parameters :
  - Significant increase of bunch intensity
    from currently ~1.6 10^{11} p/b to 2.2 10^{11} p/b (25 ns) or 3.5 10^{11} p/b (50 ns)
  - decrease to nominal bunch length
    from currently ~1.25 ns to 1 ns
    → **Would the current LHC impedance be able to cope with these parameters?**
    → **Much smaller bunch length seems excluded from heating point of view.**
- Additional sources of impedance are planned to be installed
  - Experimental beam pipes (LHCb, ALICE, ATLAS, CMS)
  - Forward detectors (planned to be removed in LS3)
  - Collimators with BPMs and new collimators
- Additional sources of impedance related to HL-LHC:
  - Crab cavities
  - Electron lens
  - High bandwidth damper kicker
- Reduction of impedance planned:
  - Replace current collimator material by a better conductor
    → **Still under study by the collimation team as many implications? Will it be enough?**
    → **Will there be a need for an impedance reduction campaign to reach HL-LHC parameters**

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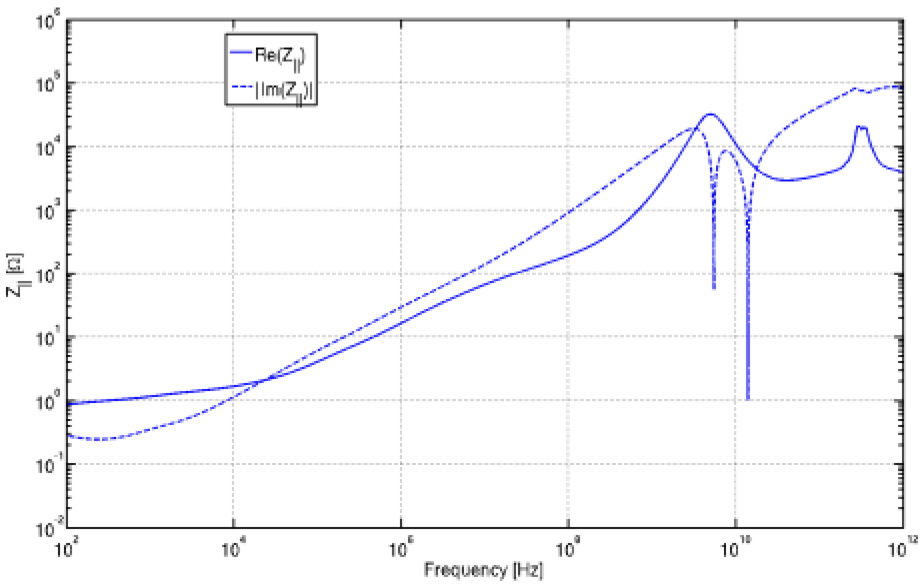
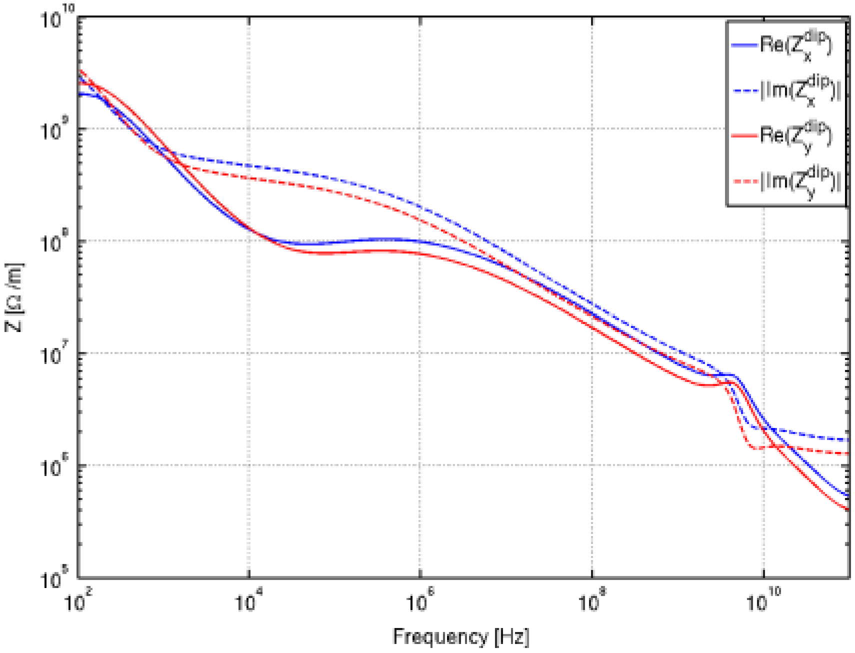
Current LHC impedance model

The impedance model contains contributions from collimators, beam screens, warm beam pipe and a broadband impedance model (from design report).

Longitudinal impedance model at 450 GeV



Transverse impedance model at 4 TeV



Other impedance contributions will be added (in particular from 3D simulations).

High Luminosity LHC

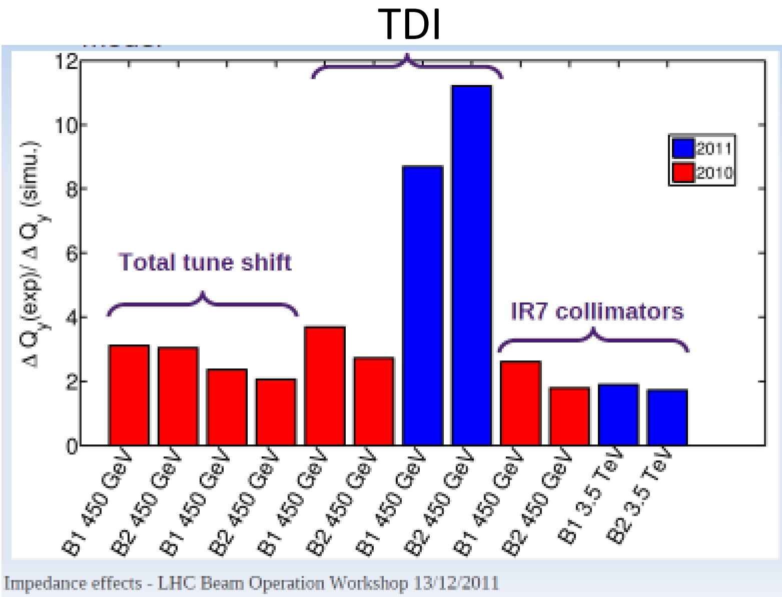
PhD thesis N. Mounet, EPFL 2012

Comparison between current impedance model and beam measurements

- Transverse impedance

There is still a discrepancy of a factor 2 at top energy between the tune shift measurements and the impedance model predictions.

N. Mounet et al, Evian LHC beam operation workshop, Dec. 2011

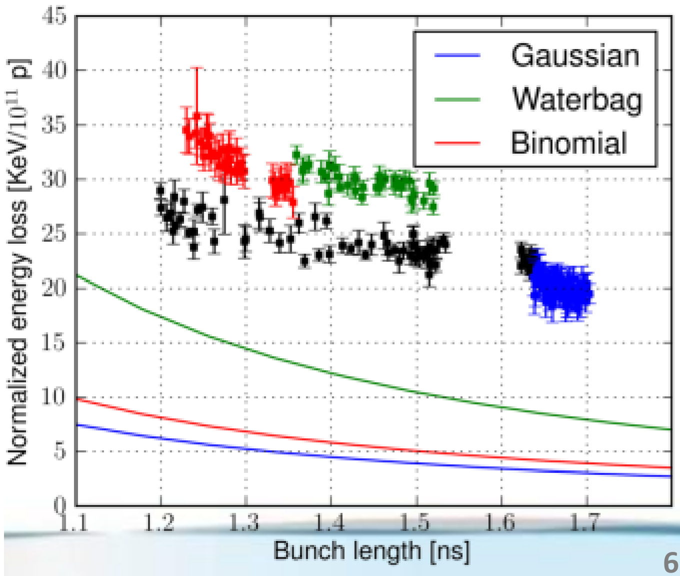


- Longitudinal impedance

Significant discrepancy (factor 2 to 6) observed between model and synchrotron phase shift measurements

→ Not surprising as we focused on the main contributors to the transverse impedance (beam screens and collimators)

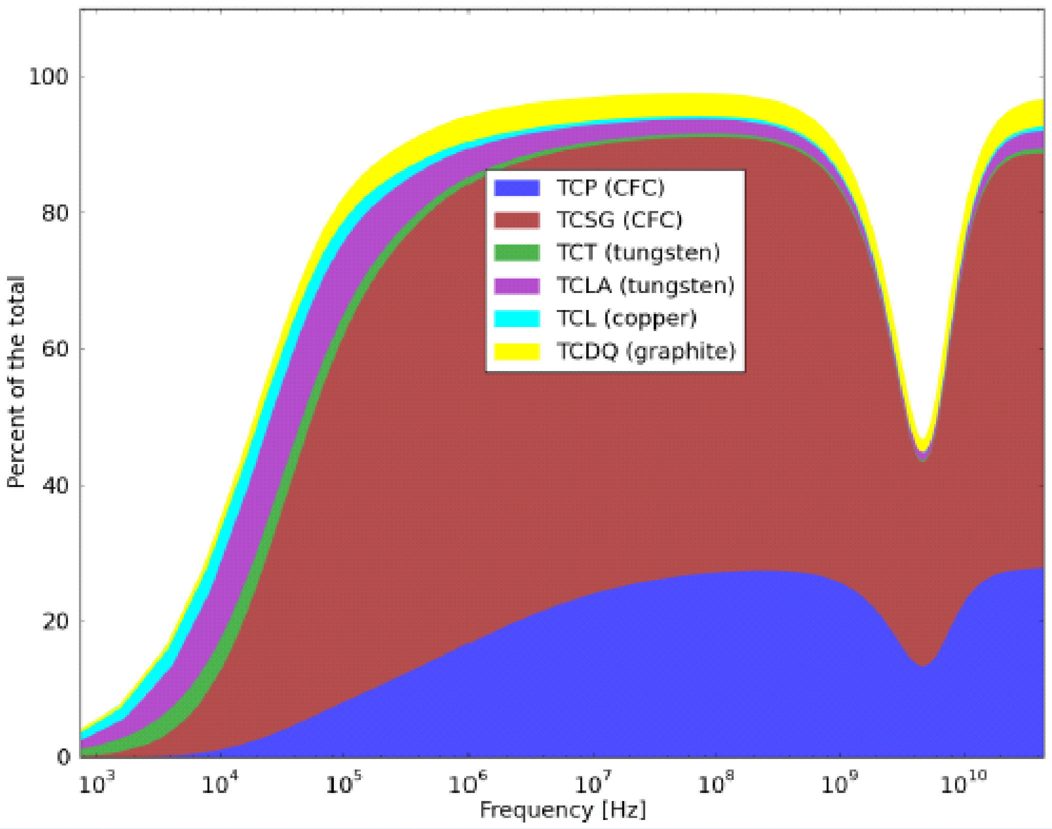
J. Esteban Mueller et al, [MOP252]



Need to improve the current impedance model, and understand the difference with available measurements

Contribution of various collimator families to total impedance (1/2)

- Real part of the impedance: relative contribution of collimator families to total impedance model (vertical dipolar, 4 TeV, 2012 settings):



⇒ TCSG and TCP are largely dominant.

Note: this is similar in horizontal.

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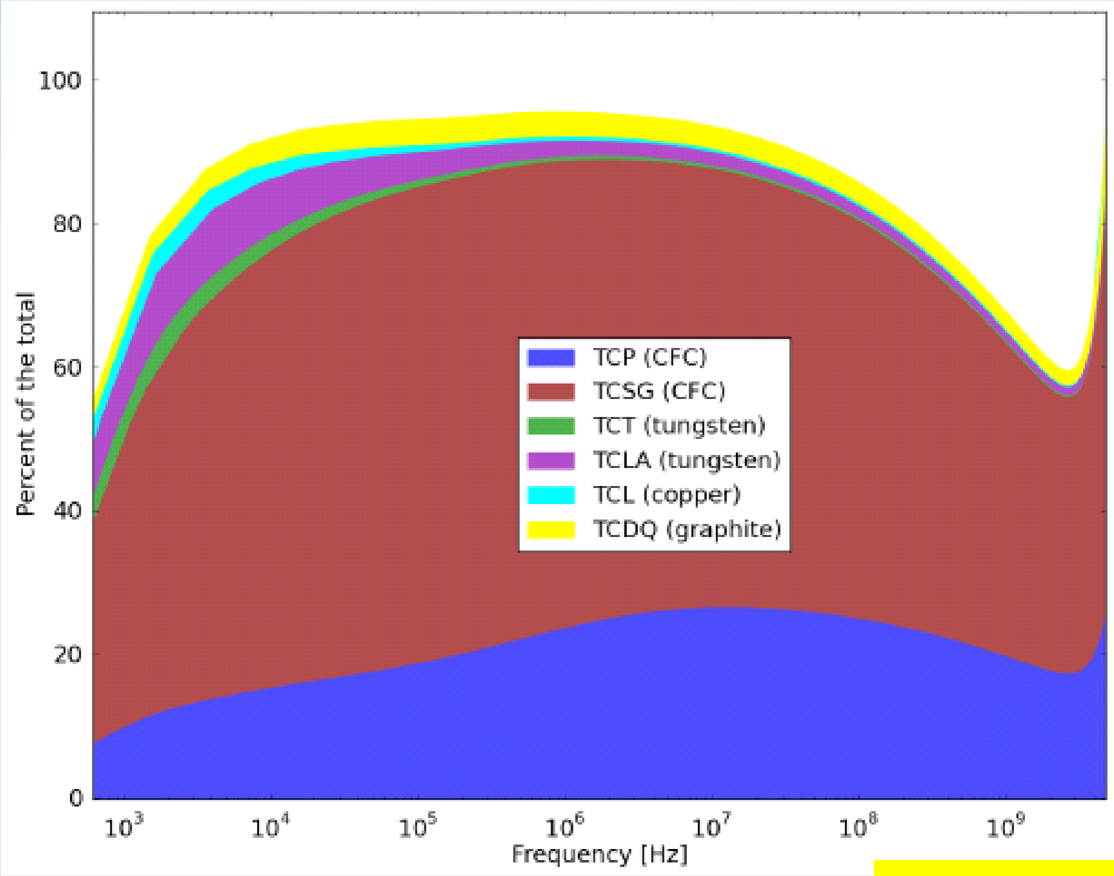
N. Mounet et al, ColUSM meeting, Oct. 2012

Contribution of various collimator families to total impedance (2/2)

- Imag. part of the impedance: relative contribution of collimator families to total impedance model (vertical dipolar, 4 TeV, 2012 settings):



⇒ TCSG and TCP are largely dominant.

Note: this is similar in horizontal.

N. Mounet et al, ColUSM meeting, Oct. 2012

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Beam instabilities

- Mainly transverse instabilities have been experienced in 2012
- They are believed to be caused by the complex interplay of transverse impedance and its damping mechanisms (e.g. octupoles, chromaticity, damper settings, beam-beam effects, non-linearities). See for instance the talk of Elias Metral and Simon White for the status of ongoing studies.

  → current limitation is at flat top during the squeeze and collision beam process, but not in stable beams

  → where does the limit lie in stable beam?

  Hint
  → high pile up MD by the beam-beam team showed that single bunch with ~3e11 p/b could be accelerated to 4 TeV, stored and collided.

- Will we need an impedance reduction campaign?

  Need to see the results of the ongoing studies on coupled bunch instabilities, and continue our simulation effort to assess intensity limits (N. Mounet et al). Also we should not forget that the efficiency of several damping mechanisms decreases with energy.

High Luminosity LHC

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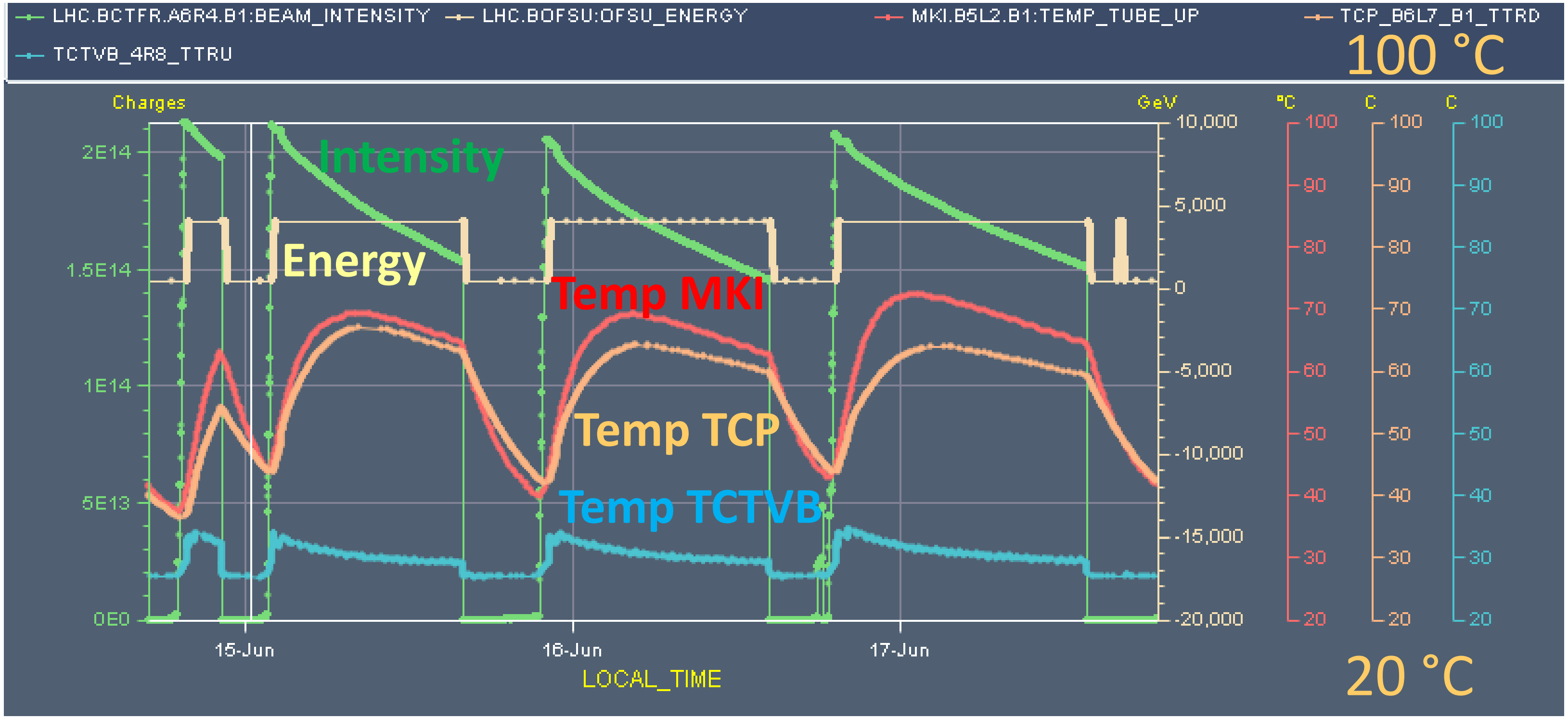
Beam induced heating?



→ Example of temperature of certain LHC devices during physics fills
- → MKI: injection kicker (interlock for injection at ~61 degrees C)
- → TCP: primary collimator
- → TCTVB: 2-beam tertiary collimator

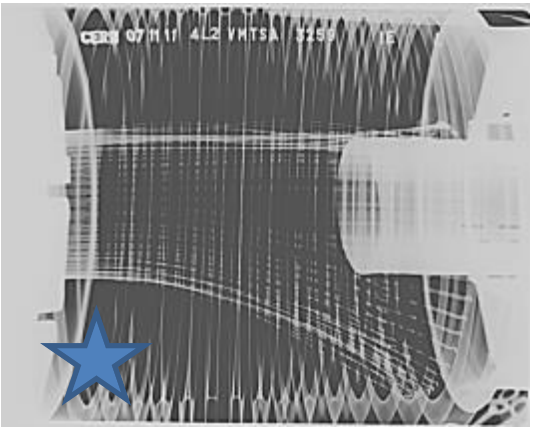
→ Temperature increase due to the interaction of beam induced wake fields with the surrounding

→ Has strongly affected operation since intensity ramp up started in mid-2011

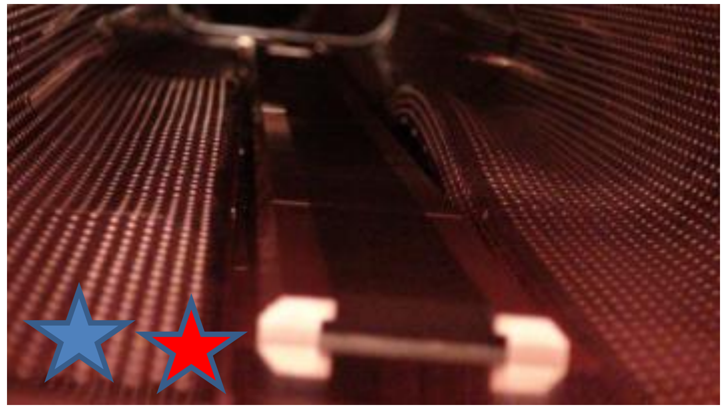
High Luminosity LHC

Heating issues

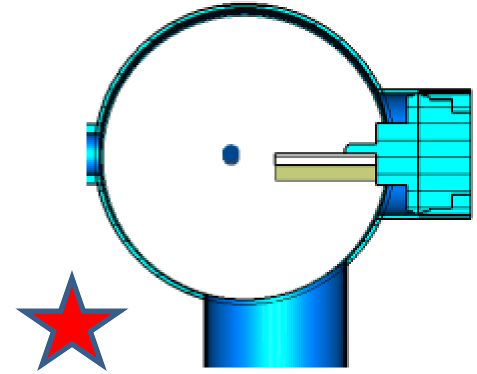
Damaged vacuum module in 2011
→ Repaired and reinforced



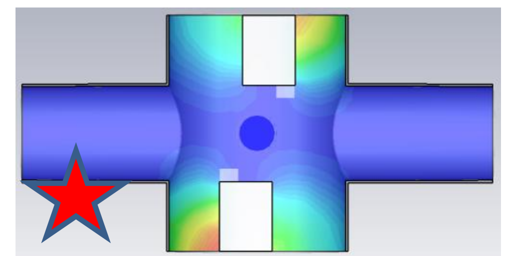
Damaged injection collimator
→ will be be reinforced
→ New design underway



Damaged synchrotron light monitor
→ Temporary replacement
→ New design



ALFA detector could be damaged
→ Cooling will be added



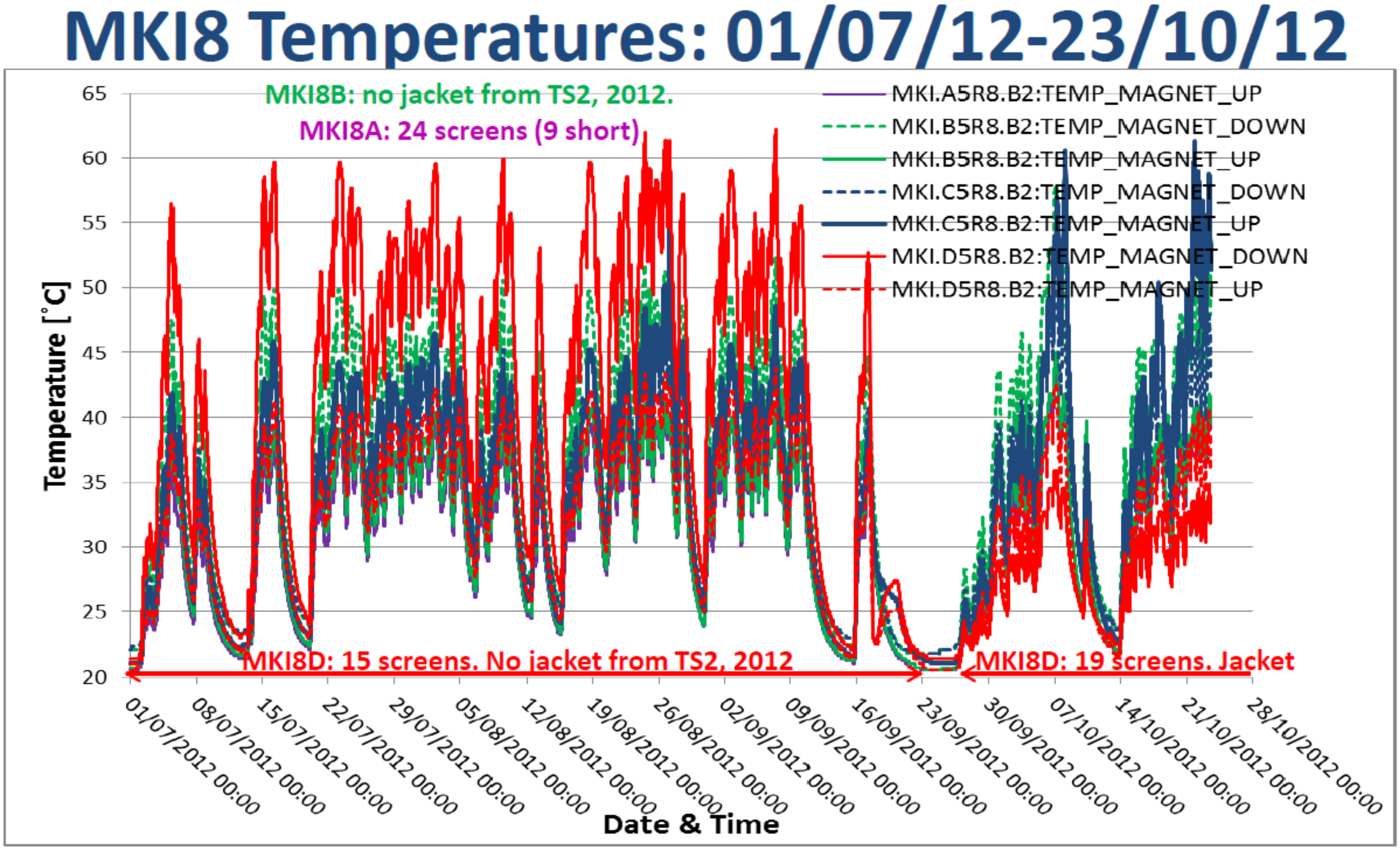
Injection kicker delays injection
→ Bakeout jackets removed
→ screen conductors optimized

Primary collimator is heating (1/6)
→ Cooling will be fully checked

one single cryogenic module (Q6R5) has no margin for cooling.

Broadband   Narrow band   (supposed)

Example of successful impedance reduction leading to heating reduction after technical stop 3 in September 2012 (courtesy M. Barnes, H. Day et al)



Heating in HL-LHC era?

- It is expected that many devices should be modified to survive in the HL-LHC era, and particular attention should be put before LS3 on monitoring:
  - Injection kickers (MKI)
  - Injection protection collimator (TDI)
  - beam screens (standalones and arcs)
    → current cooling system should be sufficient
    (more in Laurent Tavian's talk on Friday)
  - More monitoring is needed to detect abnormal temperature increase and prevent damage to equipment, as it happened to RF fingers, TDI and BSRT.
- **Nominal bunch length (1ns)**
  - Not a strong request from experiments (so far) to reach 1 ns at all costs
  - Currently BSRT and ALFA roman pots prevent decreasing the bunch length
  - Tests in the end of 2012 at injection energy will give more information on additional potential limitations to reaching 1 ns
  - important to control and shape the longitudinal distribution to minimize heating
  - The 4 cm bunch length option seems very unfavourable from the heating point of view

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What is planned to change during LS1?

- New collimators with BPMs (all TCTs and TCSG6)
  - Significant increase of impedance due to the new design approved by the CERN management
- Additional collimators?
- Diameter decrease was requested by all experiments
  - ATLAS, CMS, ALICE, LHCb
  - Impedance checked with the help of DESY collaborators
    (R. Wanzenberg and O. Zagorodnova)
- Request for new forward detectors (should be removed before LS3)
- Some non-conformities will be studied (TCP, standalone)
- Improvements foreseen for:
  - Injection kickers MKI (improve shielding)
  - Synchrotron Light Monitor BSRT
  - ALFA roman pots (cooling urgently needed)
  - RF fingers (following recommendations of the RF finger working group)
  - 2-beam-TCTVB collimators are planned to be removed

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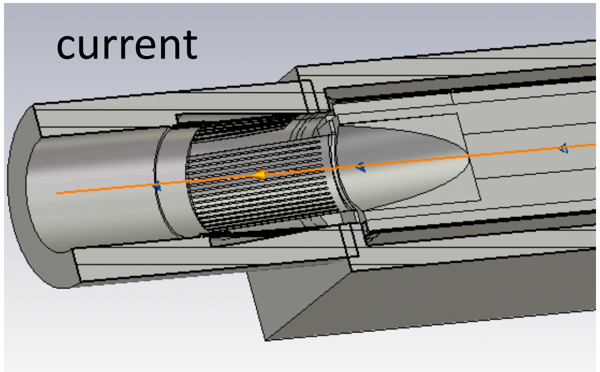
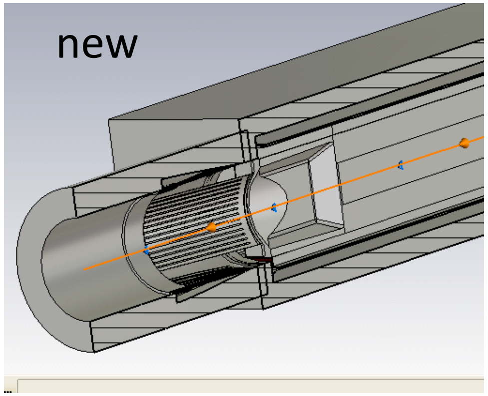
Ongoing impedance estimations

- New collimators with BPMs
  - Measurements needed on the prototype to validate predictions





- Computations ongoing for the schemes planned for HL-LHC (N. Mounet et al) and should be available shortly.

Preliminary collimation scenarios to be studied from the impedance point of view

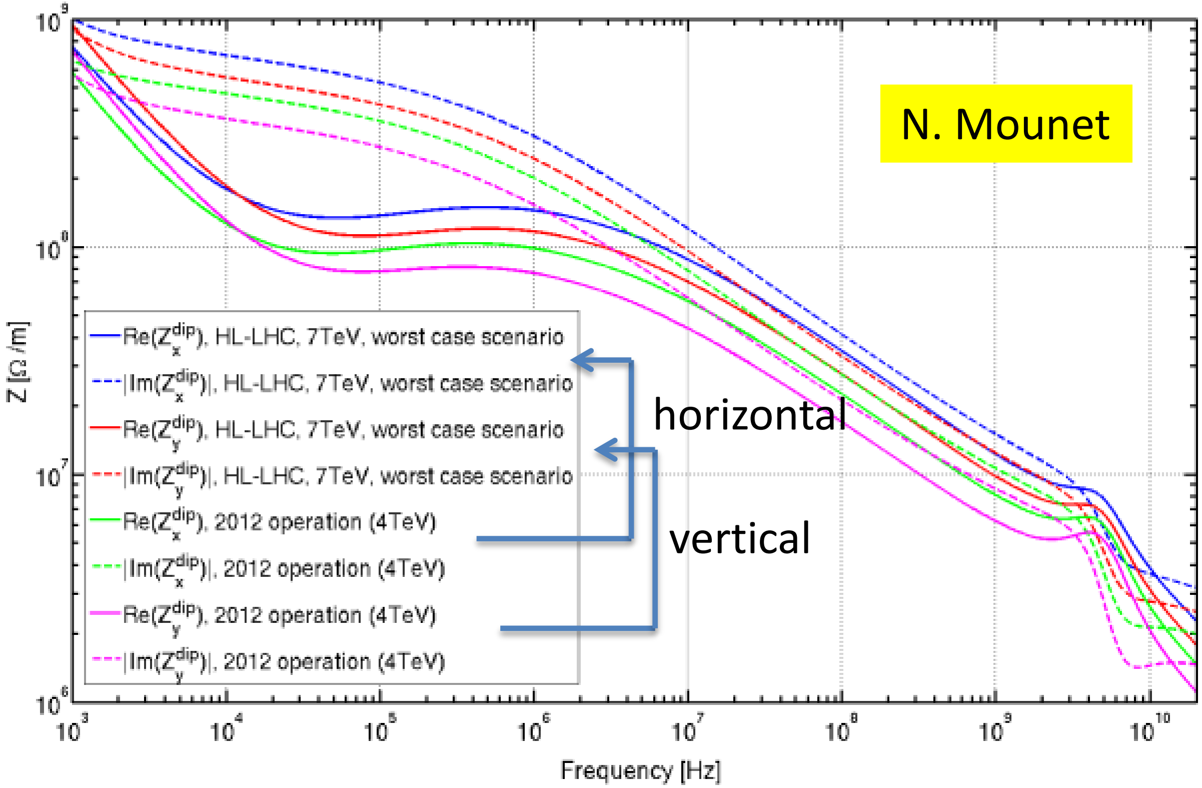
- 2 possible material configurations:
  - All collimators in the same material as now,
  - All collimators in the same material as now except for secondaries (TCS) in metal (molybdenum alloy) instead of carbon-reinforced carbon (CFC).

- 2 possible settings configurations:
  - relaxed: same half-gaps in mm as now: primaries (TCP) at 6 σ / TCS at 8.6 σ,
  - nominal: TCS half-gaps smaller than now: TCP 6 σ / TCS 7 σ.

- Addition of dispersion suppressor collimators in copper (as the current TCL) → to be studied in detail (with several possible optics options) in a second step.
- Possible changes in TCT / TCL → to be studied in detail in a second step.

Comparing the most unfavorable scheme (not relaxed, no molybdenum coating) with the current model (transverse impedance)

- all settings as now but rescaled by the energy (sqrt(4/7)~0.75)
- all the materials as now



→ Transverse impedance is larger with the new scheme (by 40% to a factor 2 depending on frequency)

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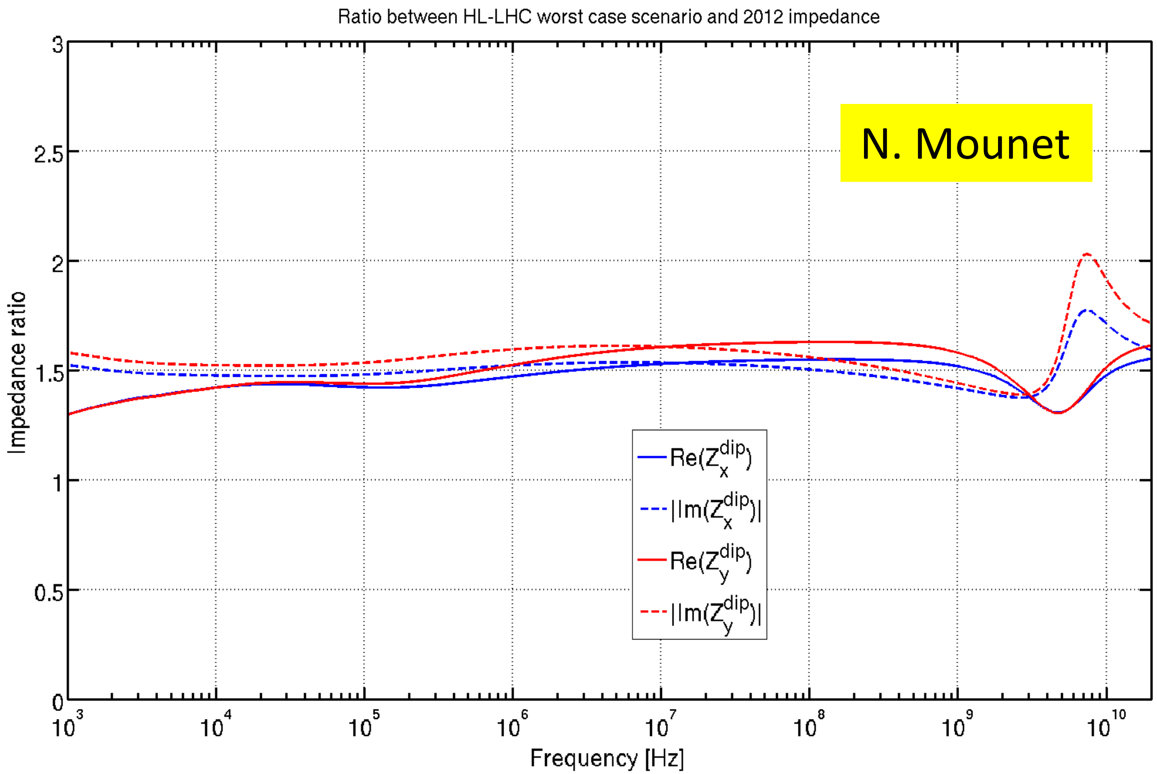
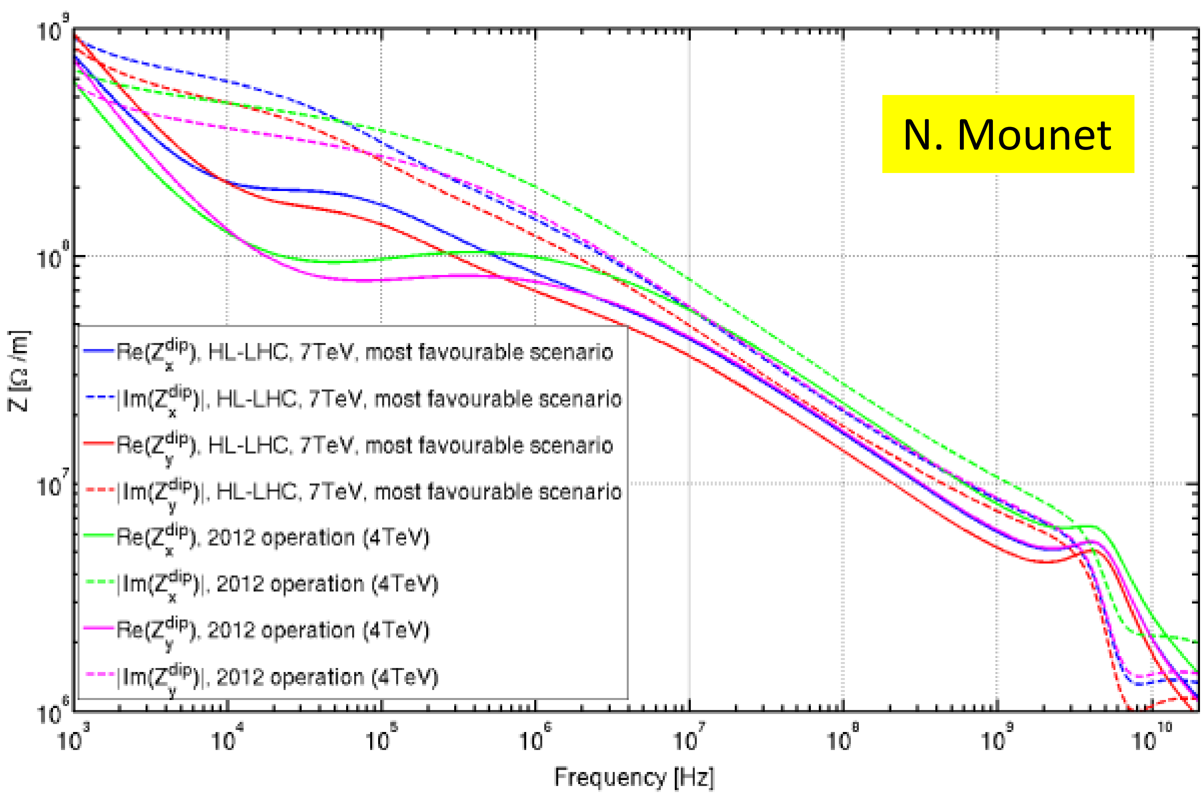


→ Transverse impedance is larger with the new scheme (by 40% to a factor 2 depending on frequency) over the whole frequency range

Comparing the most favorable scheme (relaxed, molybdenum coating) with the current model (transverse impedance)

- all settings as now but rescaled by the energy (sqrt(4/7)~0.75) except for all primaries all secondaries in IR7 (settings in mm exactly as now, i.e. no energy rescaling)
- all the materials as now except for the secondaries in IR7, which are in molybdenum coated graphite.



→ Transverse impedance is up to a factor 2 larger at low frequency with the new scheme (< 100 kHz for the imaginary part and < 500 kHz for the real part)
  → Expects to be worse for rigid bunch mode 0 instabilities

→ However it is smaller (by 20 to 30%) at larger frequencies
  → Expected to be better for higher order headtail modes and tune shift

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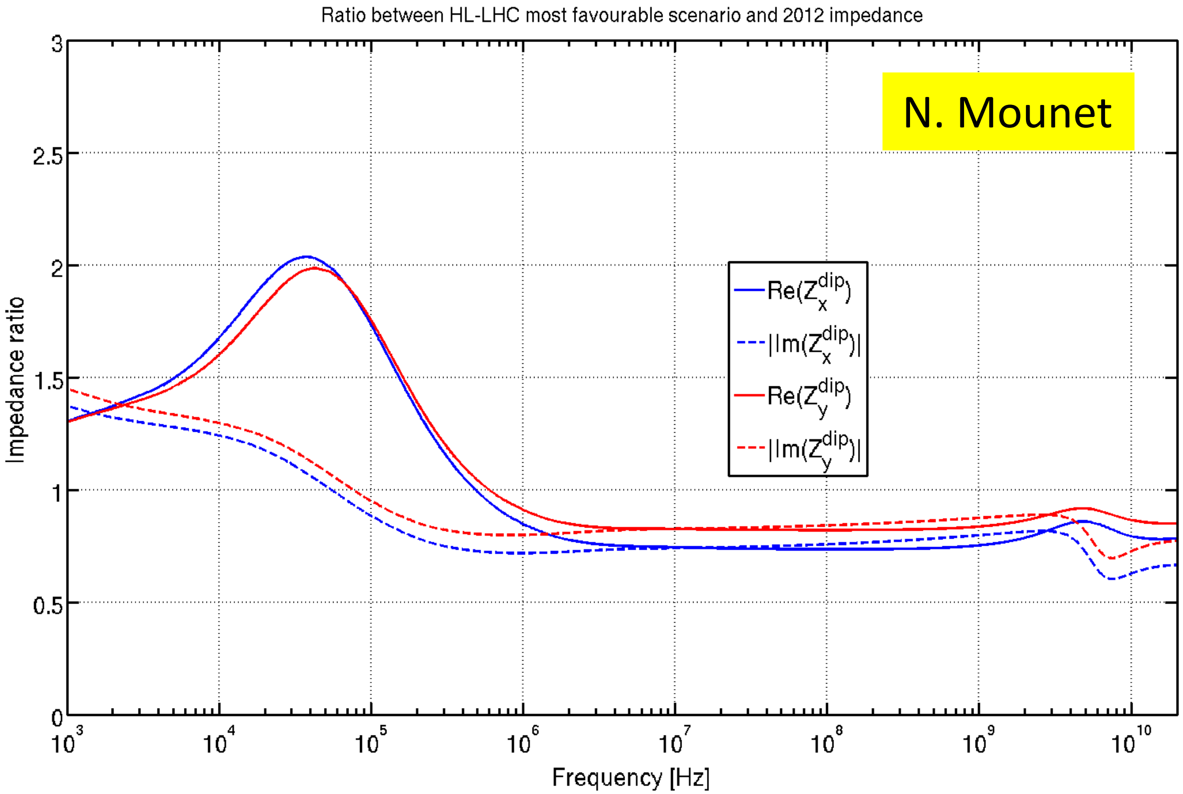

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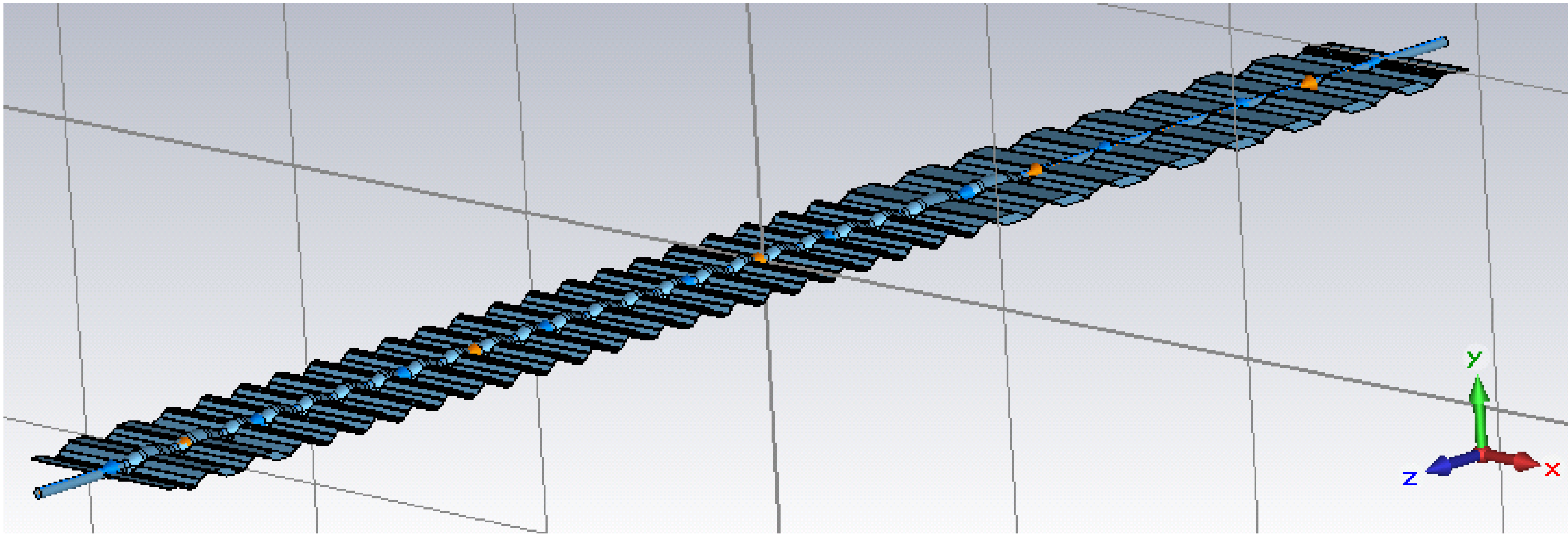
Main issue for experimental beam pipes
LHCb VELO radius reduction (5.5 mm to 3.5 mm)



The decrease leads to an increase of longitudinal and transverse impedance estimated to be up to 1% of the total LHC impedance for a roughly scaled geometry.
Actual impedance and power loss with HL-LHC parameters to be checked and optimized when final geometry is known.

Forward detectors represent a large impedance contribution, but are planned to be removed before LS3 (if installed)

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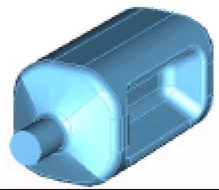
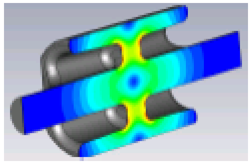
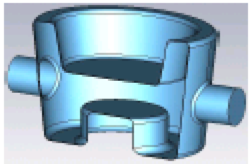
Crab cavities (courtesy R. Calaga, BNL, ODU and UK collaborations)

Performance Chart

Kick Voltage: 3 MV, 400 MHz



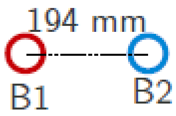




Geometrical

RF

	Double Ridge (ODU-SLAC)	4-Rod (UK)	¼ Wave (BNL)
Cavity Radius [mm]	**147.5**	**143/118**	**142.5/122**
Cavity length [mm]	597	500	405
Beam Pipe [mm]	84	84	84
Peak E-Field [MV/m]	33	32	43
Peak B-Field [mT]	56	60.5	61
R_T/Q [Ω]	287	915	345
Nearest Mode [MHz]	584	371-378	657

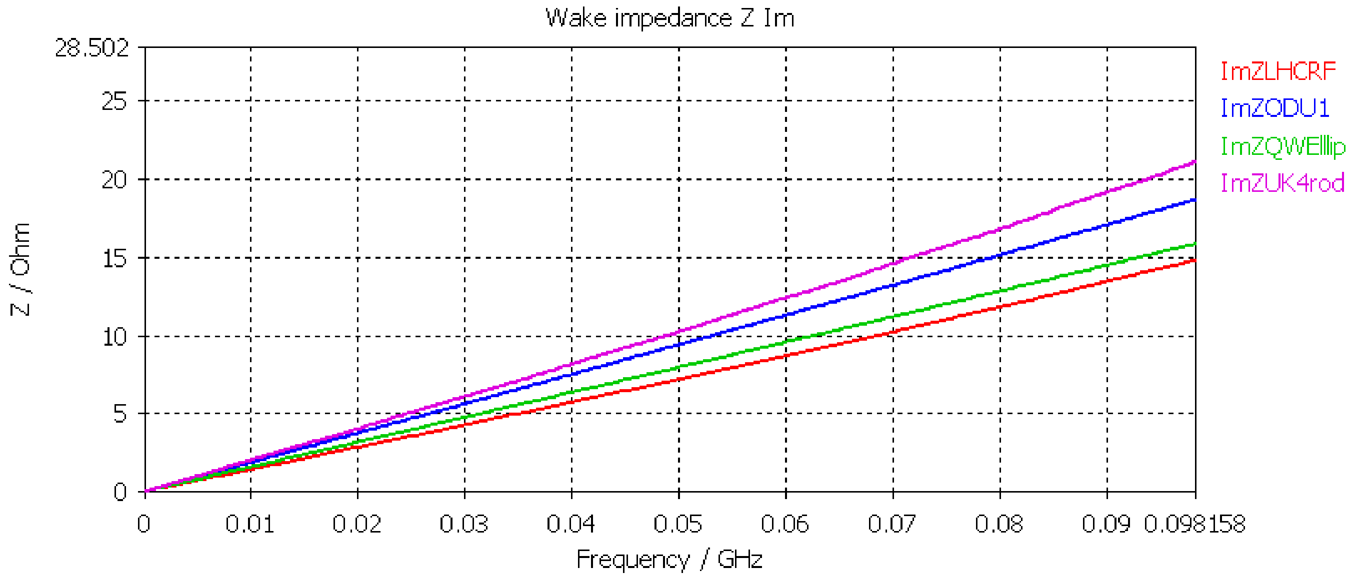


< 60 MV/m

< 100 mT

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

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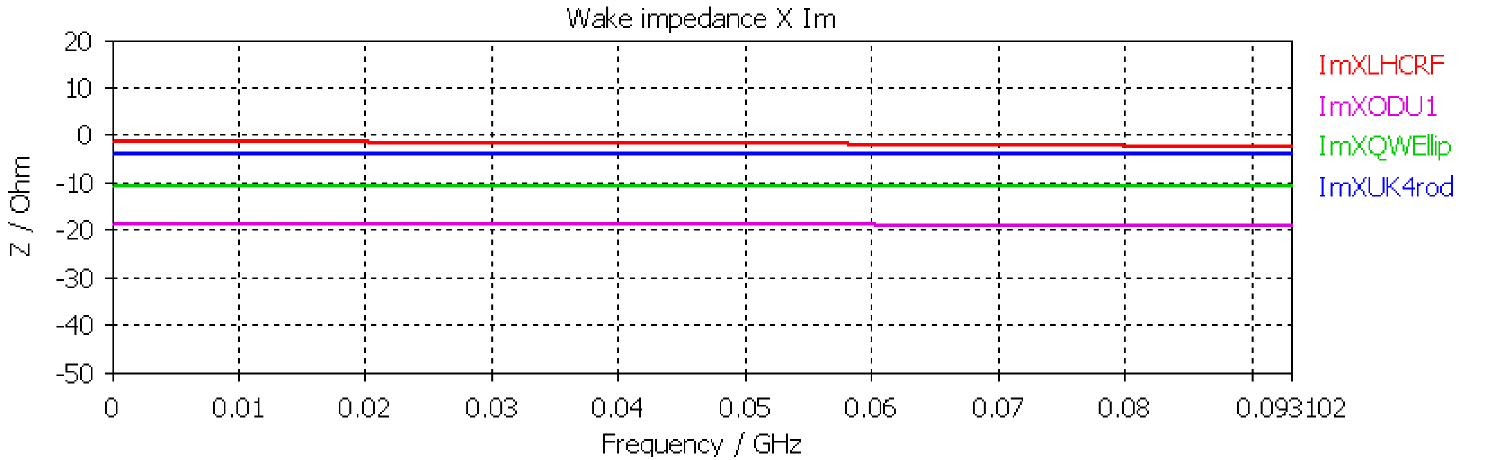
Very large contribution (20% to 30%) to be followed up with BE/RF-BR

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



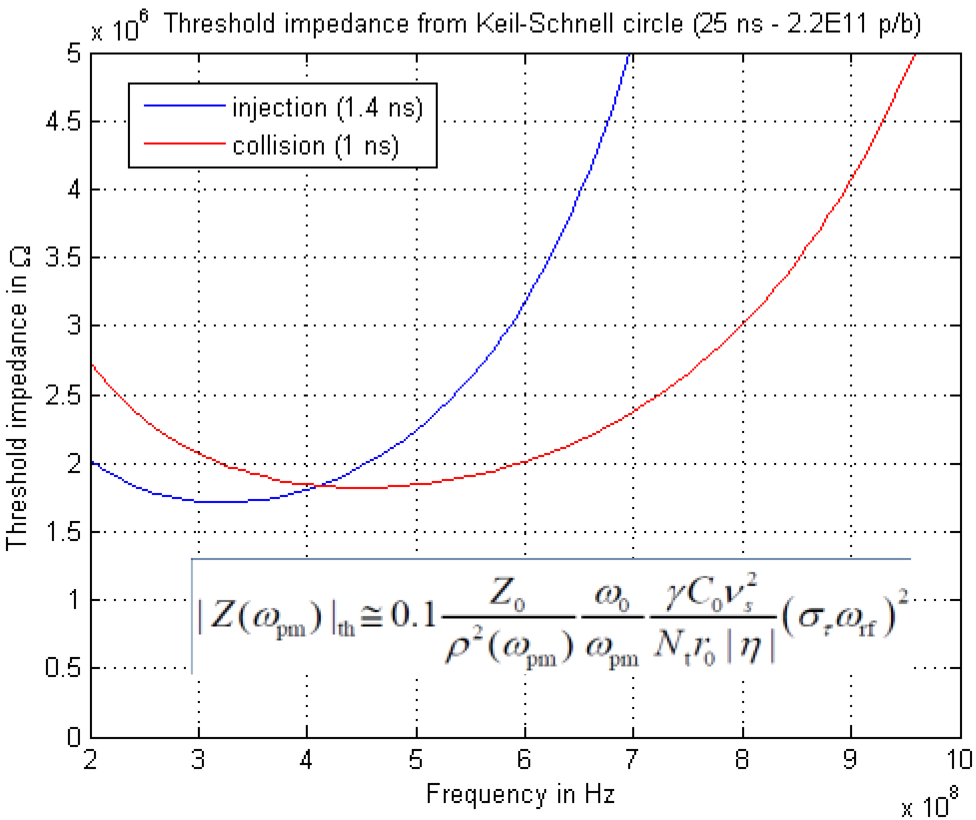
	1 cavity Zx in Ω	1 cavity Zy in Ω	1 cavity <Z>= (Zx+Zy)/(2*d) in Ω/m	1 cavity Zeff=<Z>*β/<β> in Ω/m	12 cavity Zeff=<Z>*β/<β> in Ω/m
LHCRF	6	2	800	800	6.4E+03 (8 cav)
BNL	18	10	2800	93E03	1.1E+06
ODU	10	19	2900	97E03	1.2E+06
UK	25	4	2900	97E03	1.2E+06

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.

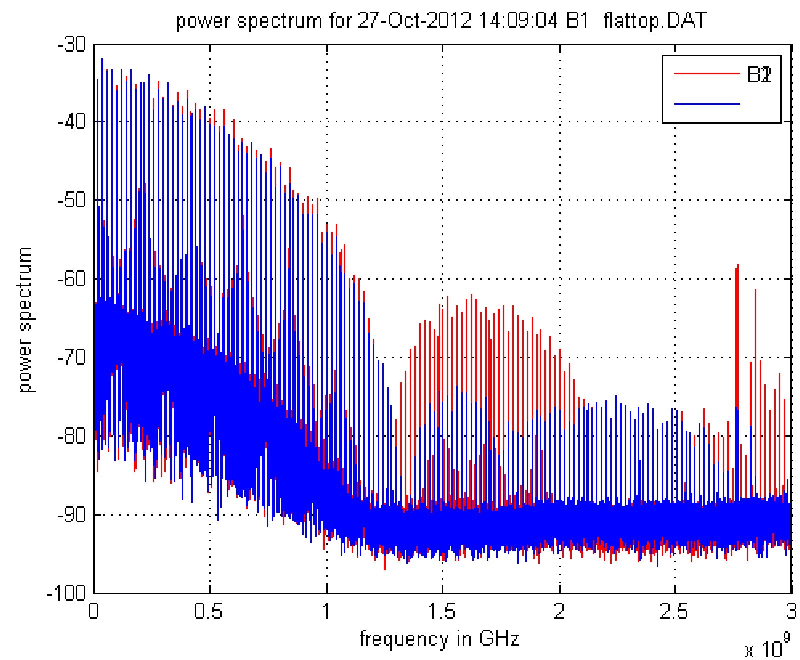
At injection, 12 cavities represent 2% of the full LHC impedance, in collisions 4%

Thresholds for longitudinal impedance of resonant modes

Follow up of Alexey Burov and Elena Shaposhnikova's talk at the Crab Cavity workshop in 2010 and 2011. Alexey's formula for the Keil-Schnell circle was used with actual parameters.



The spectrum at higher frequencies can also be significant beyond 1.2 GHz



With the number of cavities now 8 or 12, the threshold becomes 1.7MOhm/12 ~ 150 kOhm
Hence, with these assumptions, we would aim at $Q_{//} = 2\pi Z_{//} / Z_0 < 2500$.

Thresholds for transverse impedance of resonant modes

Follow up of Alexey Burov and Elena Shaposhnikova's talk at the Crab Cavity workshop in 2010 and 2011. Alexey's formula for the transverse coupled bunch instability was used with actual parameters.

$$-\mathrm{Re}\, Z_{x,y}(\omega_{pm})\beta_{x,y} \leq Z_0 \frac{\gamma c T_0^{\;2}}{2\pi \tau_d N_t r_0}$$

	injection	collision	injection	collision
gamma	479.6	7461	479.6	7461
Damper damping time (ms)	60	60	5	5
Nt (Nb*M)	6.18E+14	6.18E+14	6.18E+14	6.18E+14
Beta (in m)	150	4000	150	4000
Zth (for all 12 cavities) in MOhm/m	8.3	4.9	96	56
Zth (per cavity) in MOhm/m	0.7	0.4	8	4.7

Currently at 4 TeV, the damping time could be as low as ~50 turns and therefore we also looked at the case of 5 ms damping time. However, modifications will be needed to get this order of damping rate up to 20 MHz.

Hence, we would aim at a quality factor Q=Zt/Z_0 =1000 (60 ms) or Q= 10000 (5 ms).

Potential damper damping times (W. Hofle)

- 60 ms: possible without modifying the gain vs. frequency characteristics

- 4 ms: within reach, if concerns a few coupled bunch modes with known stable frequency and we specifically address these modes by bandpass filters (no impact from noise expected), this needs a study for signal processing

- 4 ms: across the entire range of frequencies up to 20 MHz, possible with signal processing, but expect some increase of blow-up due to effects of noise; the issue of noise needs to be addressed in the hardware upgrade we are planning, difficult to commit to a number at this stage

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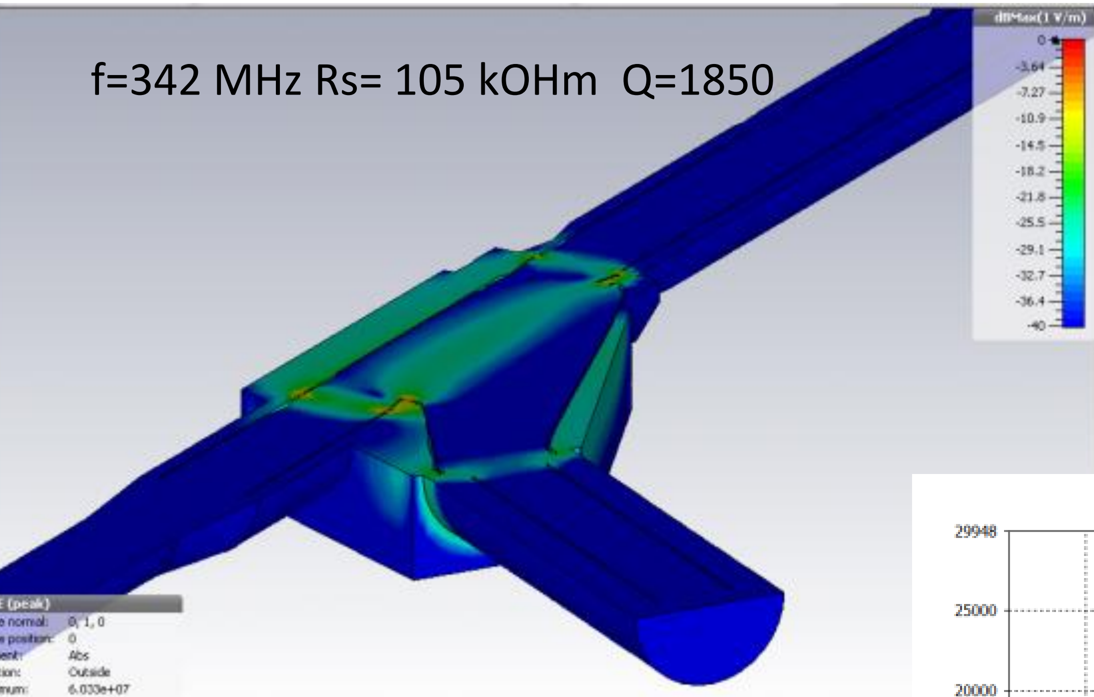
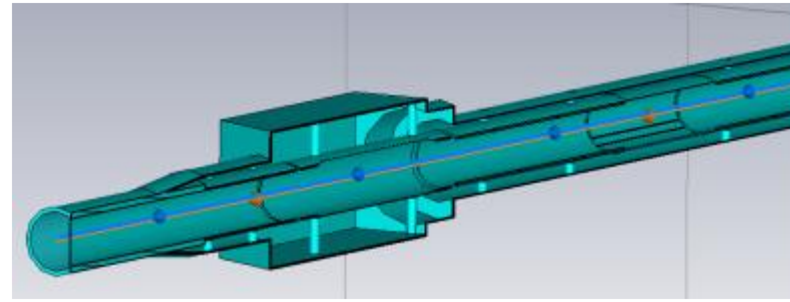
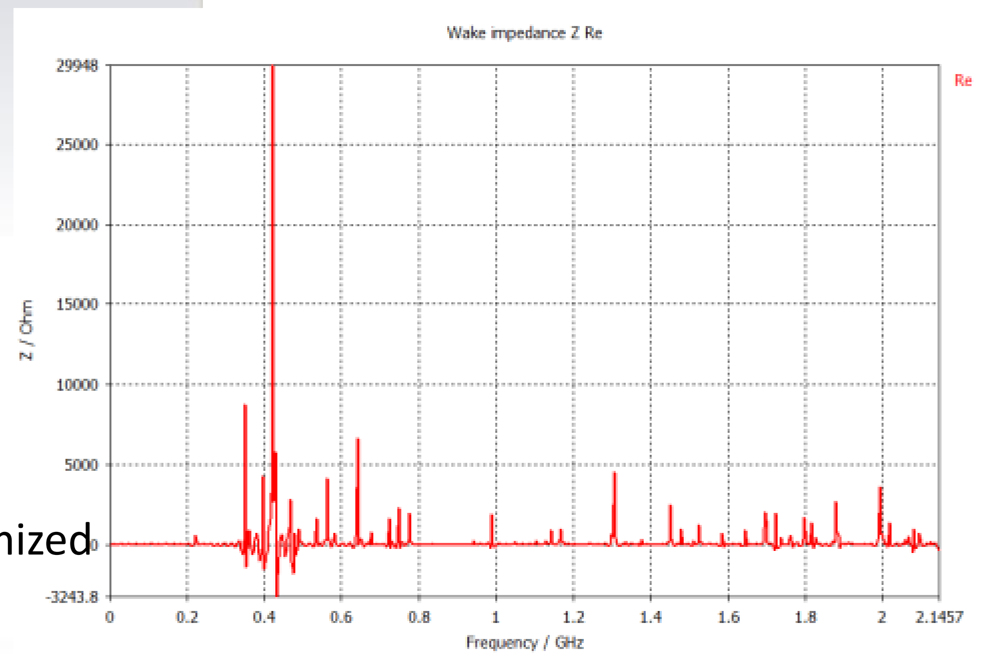
Hollow electron lens

f=342 MHz Rs= 105 kOHm Q=1850





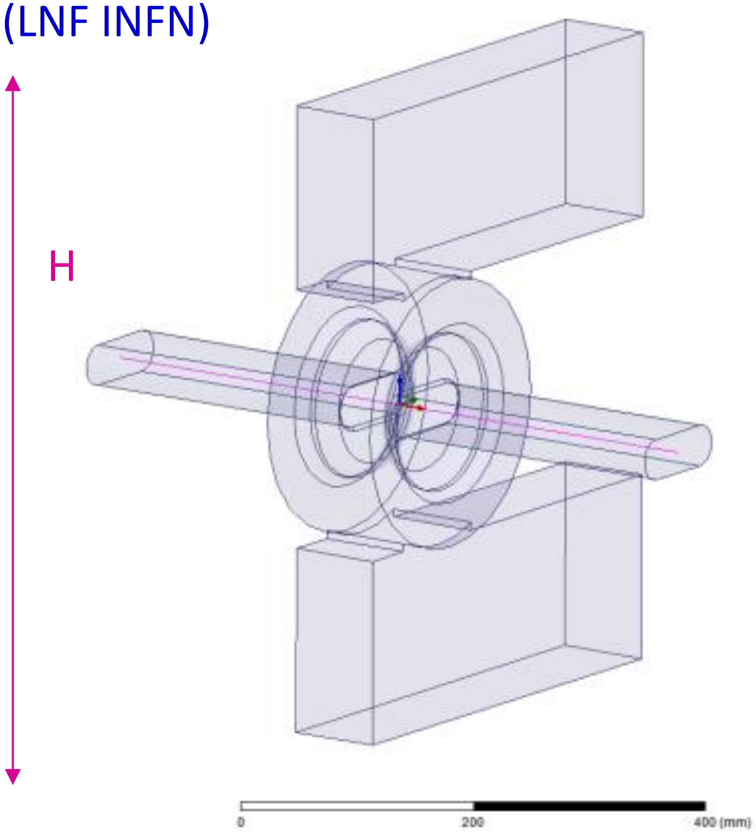


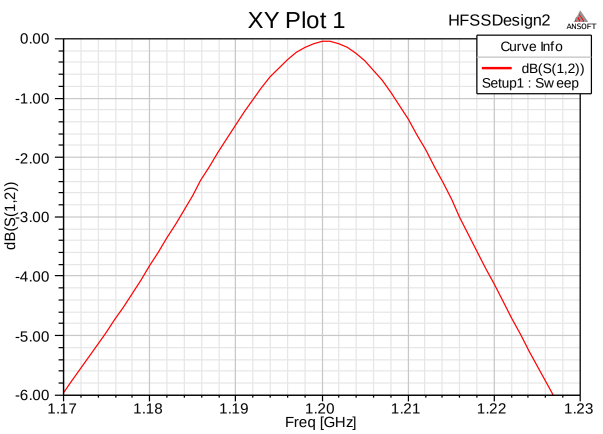
With the help of V. Previtali, G. Stancari,
 A. Valishev

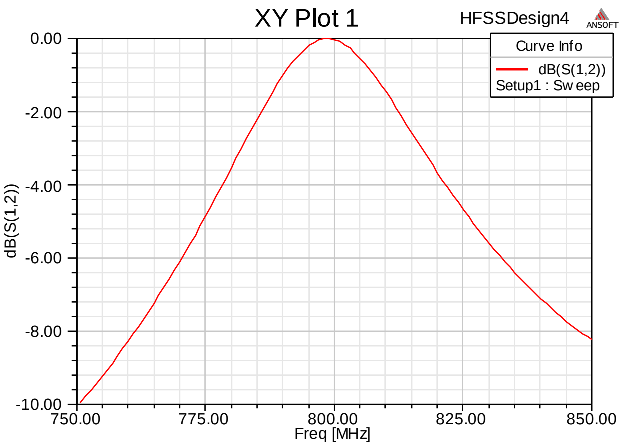
The longitudinal impedance of this device seems significant and will need to be optimized

Broad-band kicker for SPS intrabunch feedback system

F. Marcellini
(LNF INFN)







Frequency	0.8GHz	1.2 GHz
Q	23	38
Vertical shunt impedance	2.1 kΩ	3.3 kΩ
H	≈ 100 cm	≈ 60 cm

Agenda

- Context
- Current impedance model and related limitations
  - Beam instabilities
  - Beam induced heating
- What is planned to change
- On-going impedance computations for HL-LHC
  - Collimators
  - Experimental pipes and forward detectors
  - Crab cavities
  - Hollow electron lens
  - High bandwidth feedback
- Summary

Summary: where are we going?

- There are already impedance related issues in the current LHC

  → we will have to reduce the impedance and/or improve mitigating mechanisms (damping for instabilities and cooling for power loss) to have the possibility to run at much higher intensities

- Devices critical for heating will undergo significant improvement campaign during LS1
- The impedance model is being modified to include all new devices
- The impedance of these new devices is sometimes significant and should be followed up and minimized
- Questions:
  - Will we want to go to shorter bunch lengths (1 ns or less)?

High Luminosity LHC

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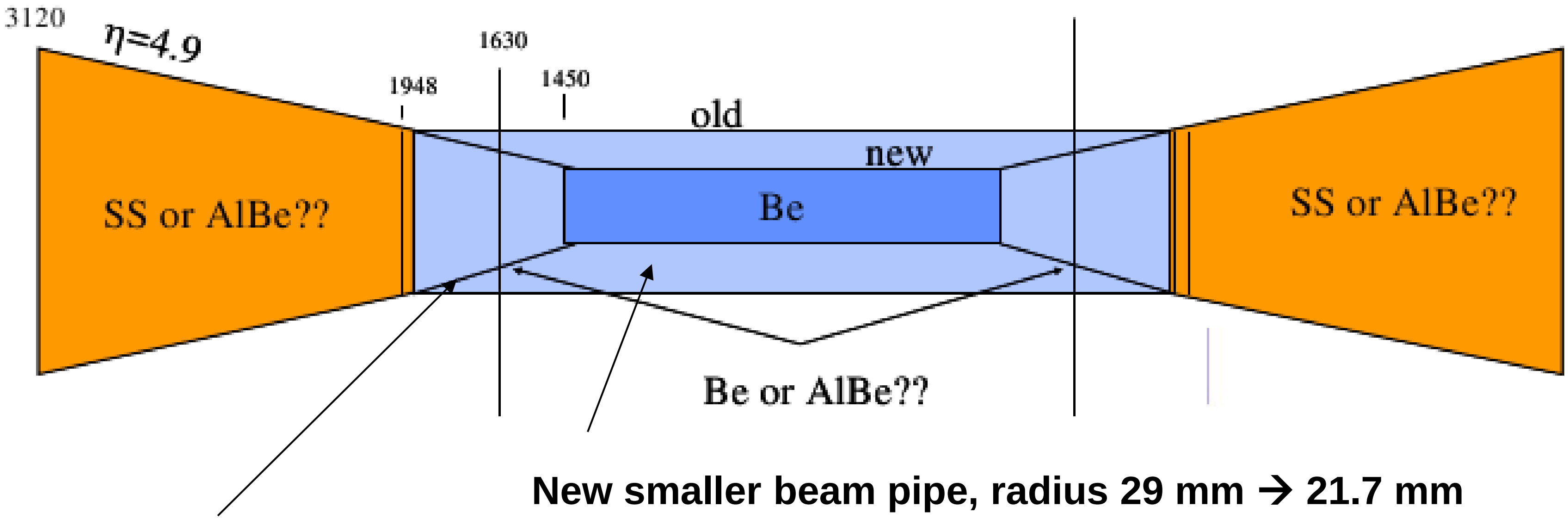
Vacuum chamber in the CMS experiment



New smaller beam pipe, radius 29 mm → 21.7 mm

Existing cone (orange) will be extended

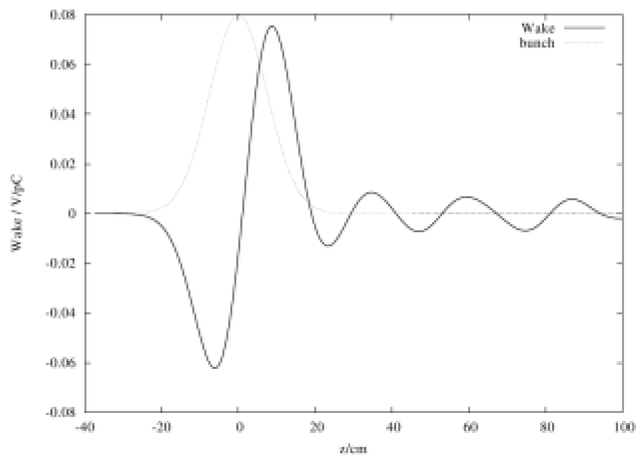
Z = 1948 mm ➔ 1450 mm

Calculation of Wakefields and Higher Order Modes
R. Wanzenberg and O. Zagorodnova
DESY, Hamburg, Germany

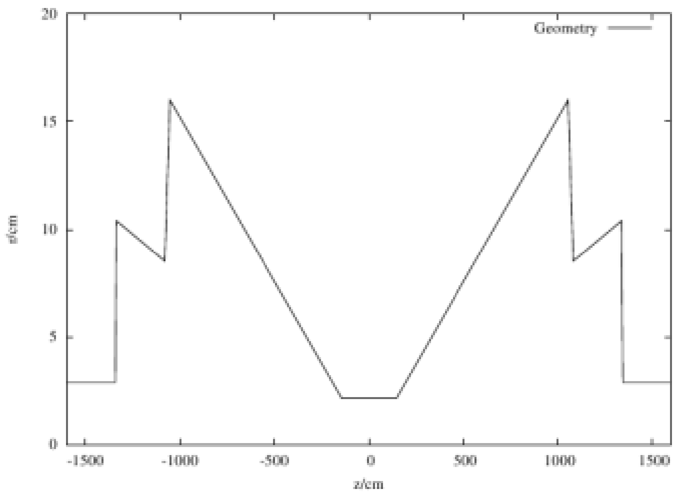
High Luminosity LHC

Wakefields

Longitudinal wakepotential



Geometry used for ECHO2D calculations



Calculation of loss and kick parameters

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

$$k_{\perp}^{(1)} = \int ds\; W_{\perp}^{(1)}(s)\; g(s)$$

Transient power loss

$$P = N_b\, f_R\, {q_b}^2\, k_{||\mathrm{tot}}^{(0)}$$

Effective impedance

$$(Z_{\perp})_{\mathrm{eff}} = 2\sqrt{\pi}\,\frac{\sigma_z}{c}\,k_{\perp}^{(1)}$$

Wakefields (results)

rms bunch length 7.5 cm, small increase of the transverse impedance

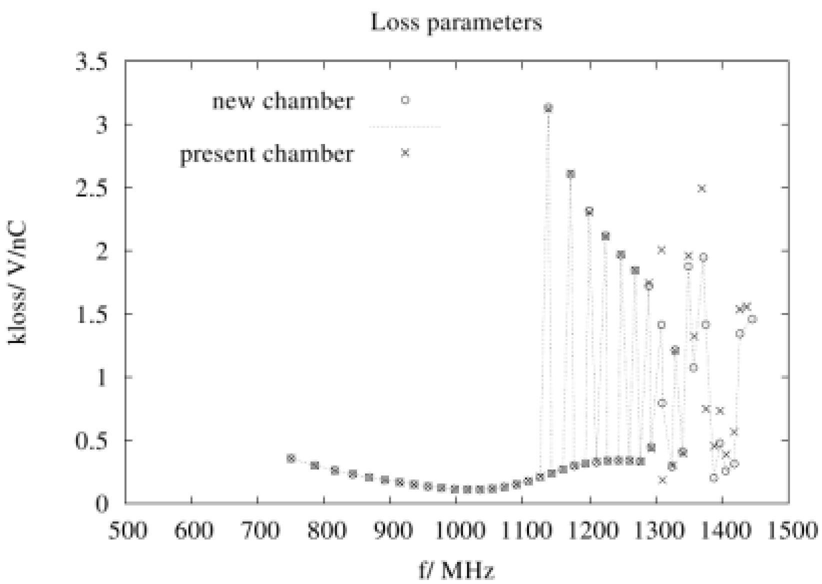
Parameter	New chamber	Present chamber	Δz/cm	Δr/cm
$k^{(0)}_{\|\|\mathrm{tot}}$ (V/nC)	2.35	2.35	0.15	0.01
$k^{(1)}_{\perp}$ (V/pCm)	2.38	2.35	0.1	0.01

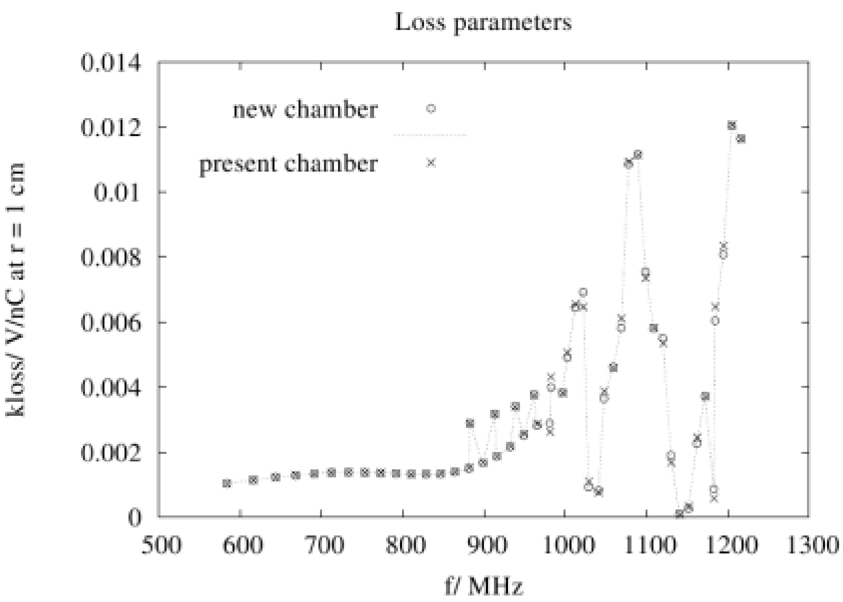
Effective impedance: 2.1 kOhm/m $(Z_\perp)_{\mathrm{eff}} = 2\sqrt{\pi}\,\frac{\sigma_z}{c}\,k^{(1)}_{\perp}$

Transient power loss about 100 W $P = N_b\, f_R\, {q_b}^2\, k^{(0)}_{||\mathrm{tot}}$

HOMs

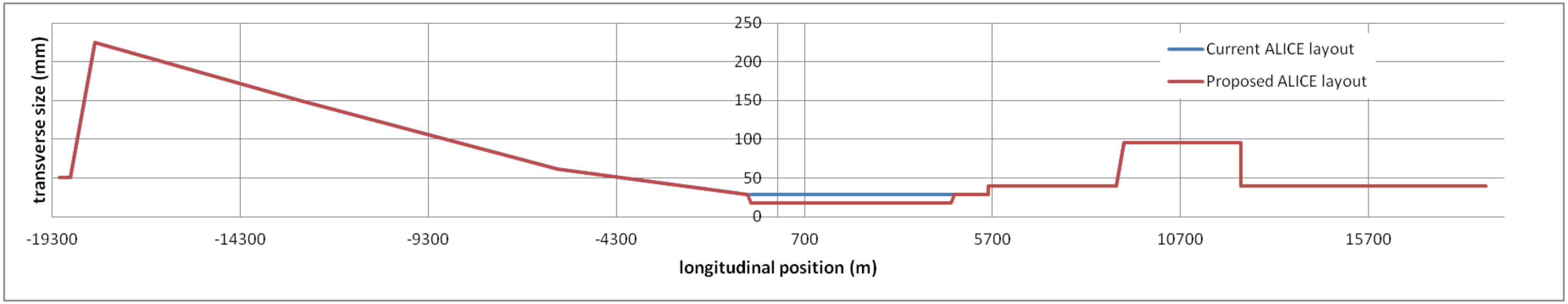
50 monopole and dipole modes have been calculated:
(plot of the loss parameter)





The loss parameters or R/Q of the HOMs of the new chamber do not differ much from the parameters of the present geometry (LHC Project Note 418) since fhe geometry is unchanged in the region where most of the modes are trapped.

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	

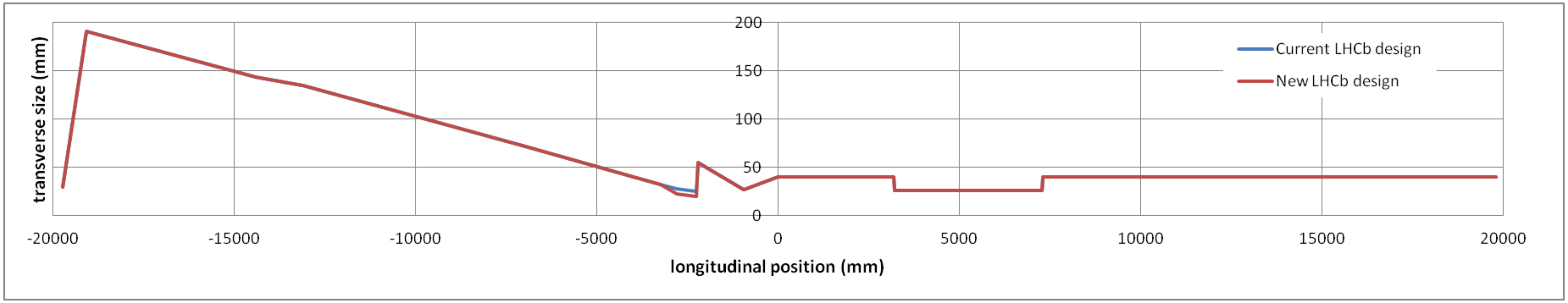
Longitudinal

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

New LHCb design



Length : ~ 0.5 m and very small change. Looked at worst case scenario.

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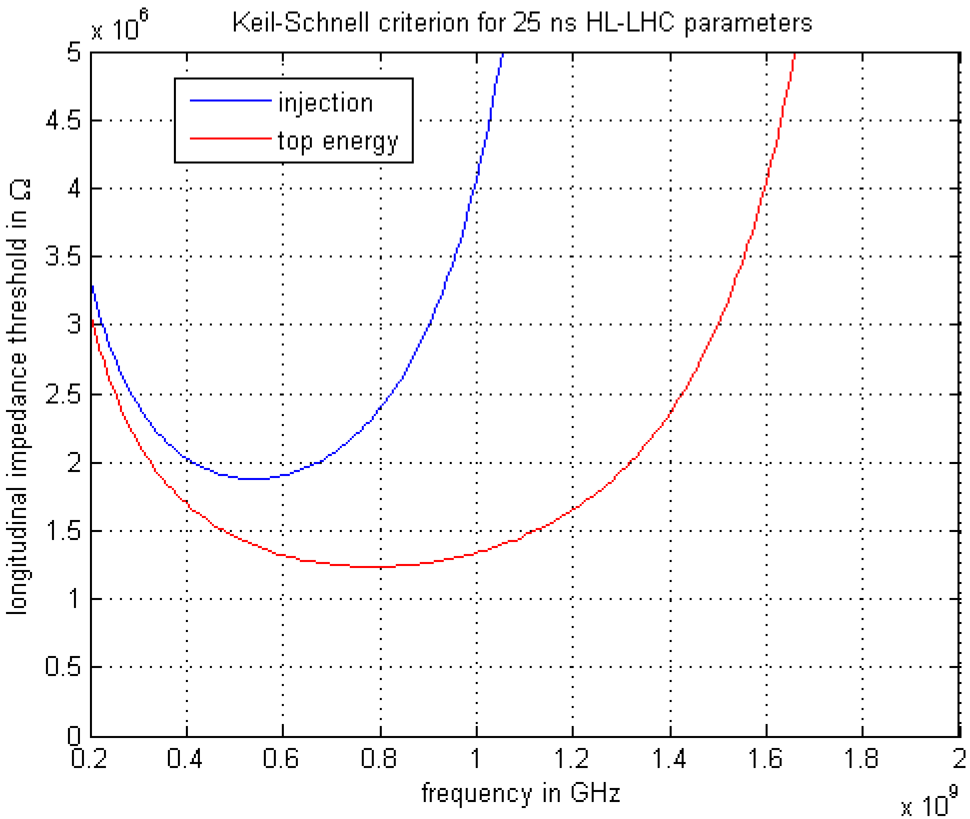


Keil-Schnell criterion for 25 ns HL-LHC parameters
x 10^6
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
injection
top energy
longitudinal impedance threshold in Ω
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
frequency in GHz
x 10^9

LHCb (Beryllium - length 0.5 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	25 mm	1.3 ns	20	600	~2.4
450 GeV	20 mm	1.3 ns	38		
7 TeV	25 mm	1 ns (nominal)	17	600	~25
7 TeV	20 mm	1 ns (nominal)	33		

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	25 mm	1.4 ns (MD)	$j\,0.09\ 10^{-5}$	$j\,0.09$	1.2
450 GeV	20 mm	1.4 ns (MD)	$j\,0.1\ 10^{-5}$		1.5
7 TeV	25 mm	1 ns (nominal)	$j\,0.06\ 10^{-5}$	$j\,0.085$	1.1
7 TeV	20 mm	1 ns (nominal)	$j\,0.07\ 10^{-5}$		1.4

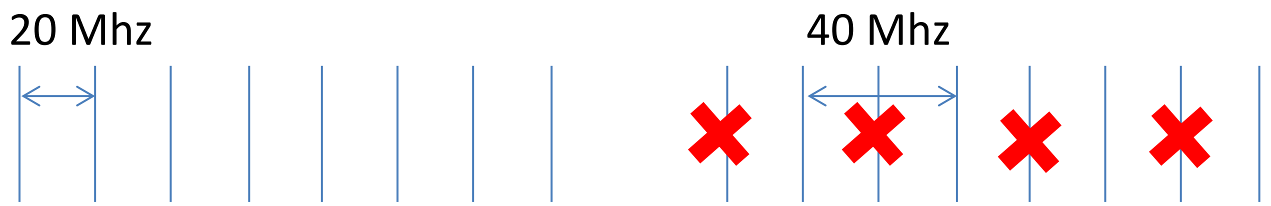
→ small increase of impedance with the new geometry. However, it remains tiny compared to the total LHC impedance. Is a 25% increase in power loss ok?

Also: geometric $Im(Z/n)=1.5\ 10^{-4}$ Ohm

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

Current beam: 50 ns spacing
M=1374 bunches
N_b=1.6 10^{11} p/b

After the long shutdown 1: 25 ns spacing
M=2808 bunches
N_b=1.15 10^{11} p/b



Assuming the same bunch distribution and bunch length

→ switching to 25 ns for broadband:

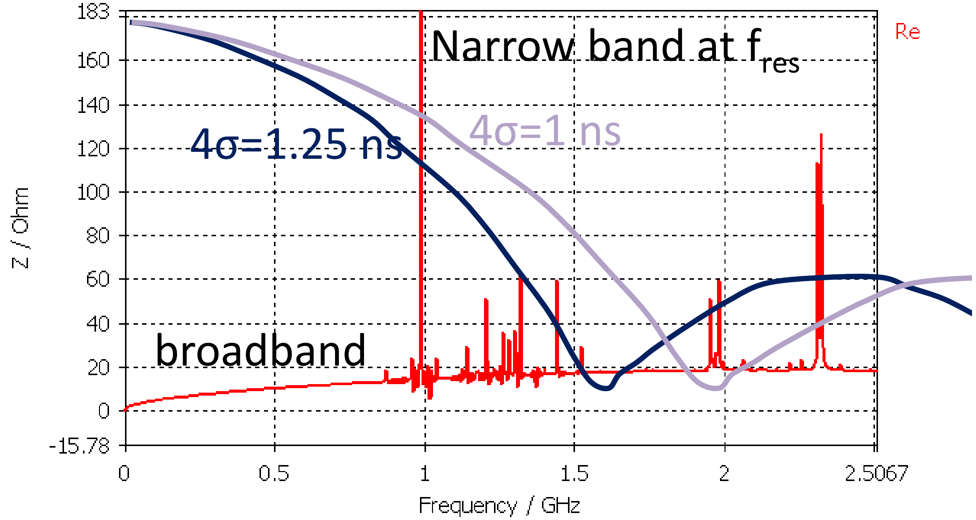
increase by factor $\frac{M^{25} *(Nb^{25})^\wedge 2}{M^{50} *(Nb^{50})^\wedge 2} = 1.05$

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

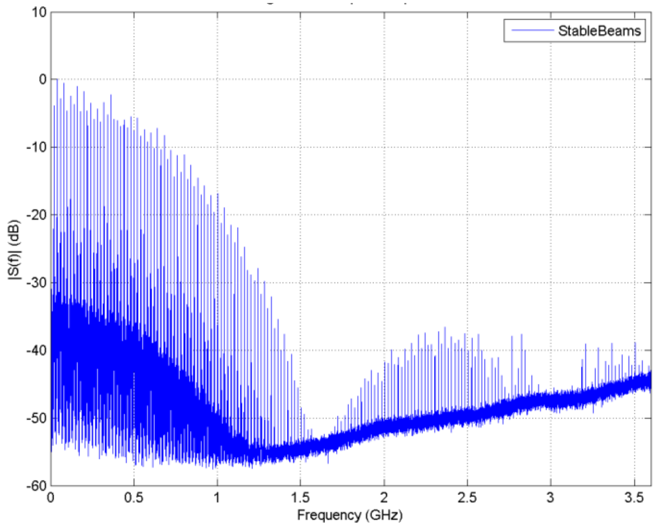
increase by factor $\frac{(M^{25} *Nb^{25})^\wedge 2}{(M^{50} *Nb^{50})^\wedge 2} = 2$ (if f_{res}=2*k*20 MHz) or 0 (if f_{res}=(2*k+1)*20 MHz)

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

Impedance Re(Z_{long})



Power spectrum measured on 50 ns (1.25 ns) by P. Baudrenghien and T. Mastoridis



- Assumption: same bunch distribution for both bunch lengths
  → **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 and damps others → we could have some surprises!!!

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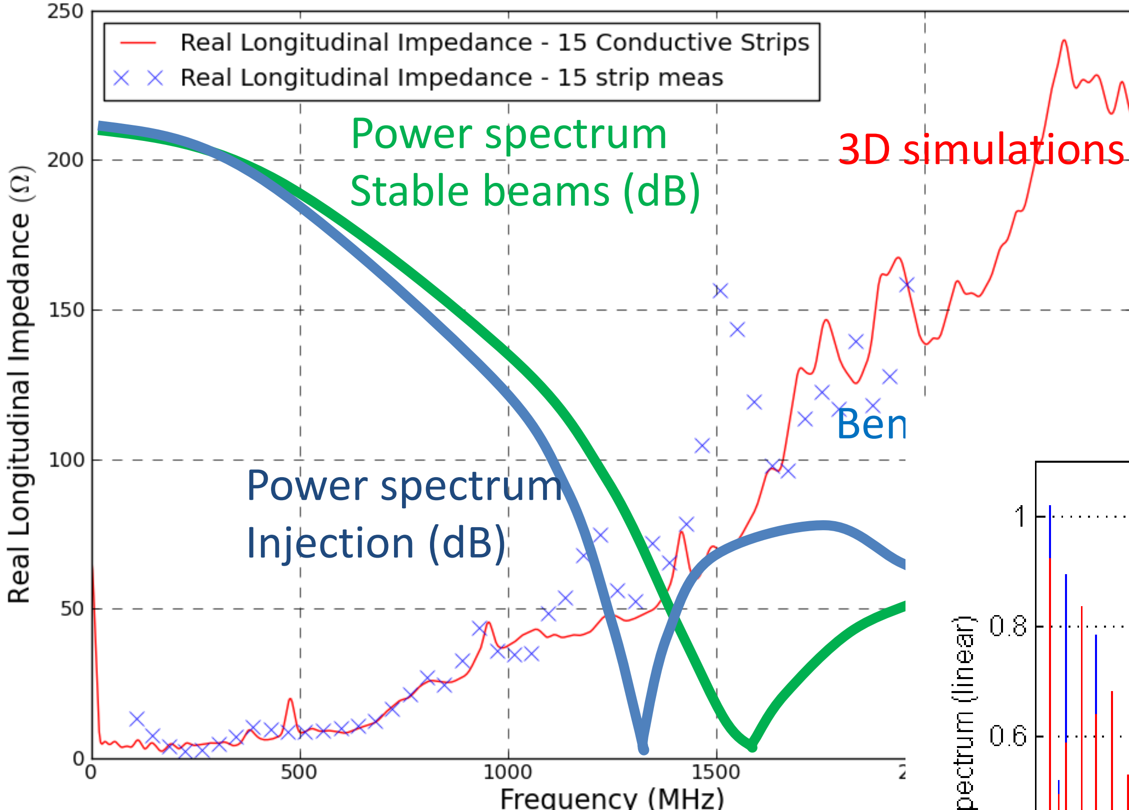
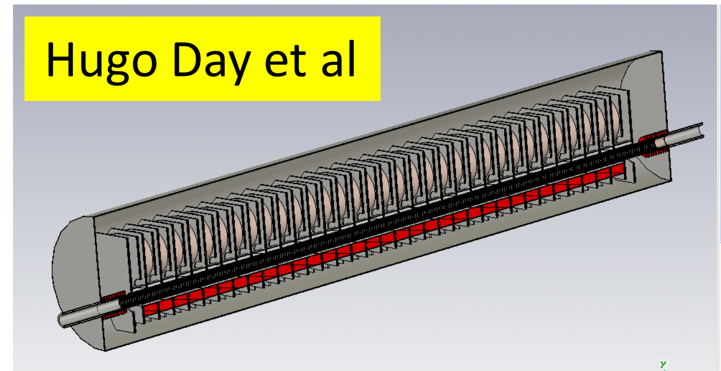
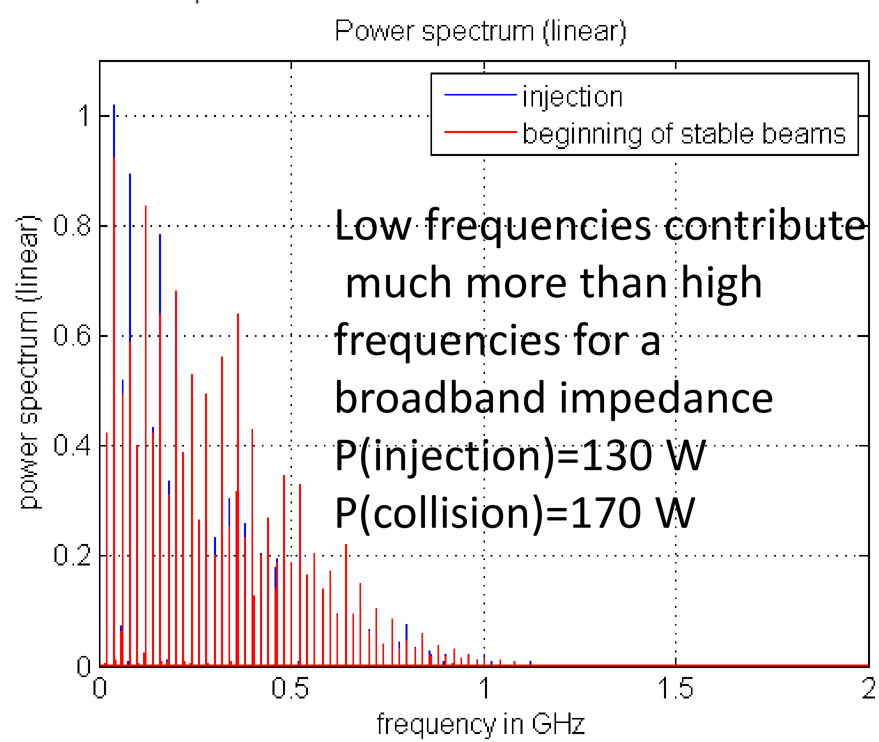
Example: simulations and bench measurements of the impedance of the LHC injection kicker (MKI)

This injection kicker heats too much and one needs to wait hours that it cools down to reinject





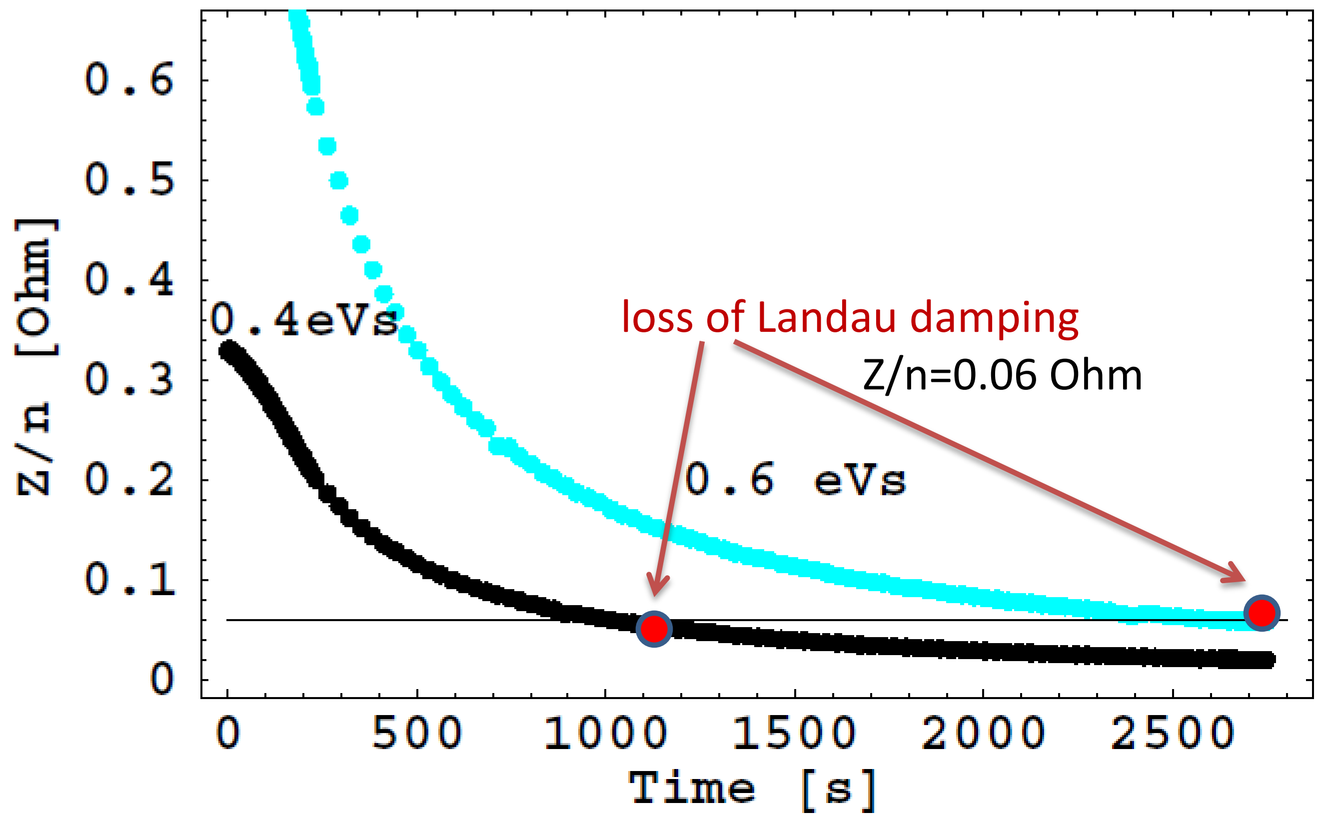


Low frequencies contribute much more than high frequencies for a broadband impedance
P(injection)=130 W
P(collision)=170 W

Very complicated 3D model (4 m long ferrite kicker with
shielding done with ceramic and conducting strips)

good agreement between simulations and bench measurement!

Loss of Landau damping:
threshold through the cycle (Elena Shaposhnikova)



•mode m=2 → 0.09 Ohm. LHC DR impedance budget - 0.08 Ohm

•Minimum emittance for ultimate intensities is 1.5 eVs @ 7 TeV

High Luminosity LHC