Heat load from impedance on existing and new hardware in the LHC era

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Main messages

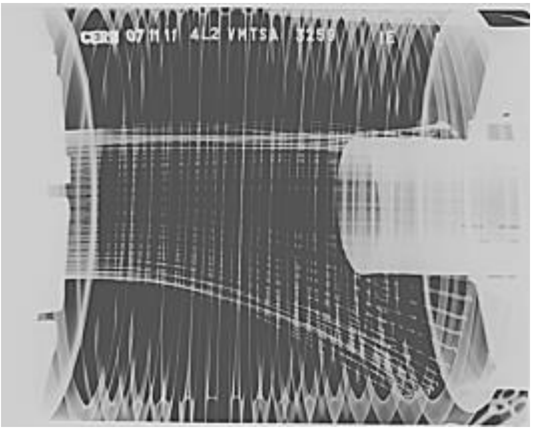
- Already many heating issues related to beam impedance in 2011 and 2012.
- Need to optimize LHC hardware as the conditions will be much tougher in HL-LHC era (~factor 5 more)
- Some hardware already at the limit will need modifications:
  - Injection kickers → upgrade underway
  - Injection dump collimators → consolidation of current TDI + new design is planned (WP14)
  - Synchrotron Light Monitor → new design underway
- Beware of non-conformities
  - Check carefully all devices and cooling that are supposed to be put in the LHC
  - Need of efficient temperature monitoring during intensity ramp up to detect problems early
- Strategies for mitigation:
  - Optimize designs to reduce heat load
  - If cavities are necessary, detune and localize the heat loss in ferrites.
  - Working now on extracting the heat from the system (longer term)
  - Higher harmonic system will give flexibility to tune the bunch distribution in case of problem

Agenda

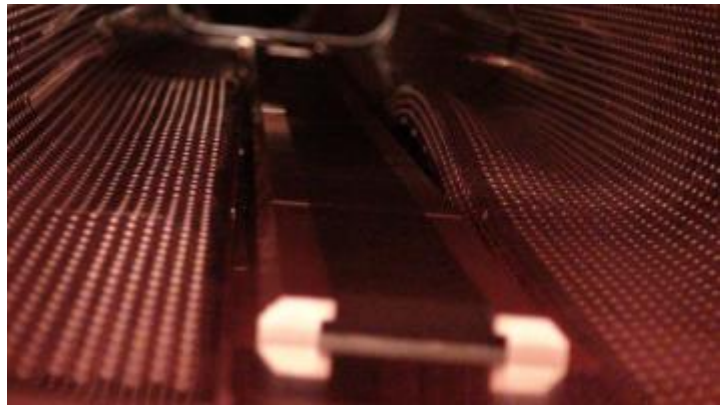
- Main messages
- Current issues in LHC
- Beam induced heating?
- Reaching HL-LHC parameters
- Possible mitigations
- Perspectives

Heating issues in LHC

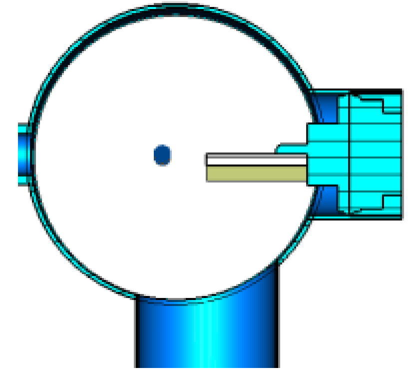
Damaged vacuum module in 2011
→ Repaired and reinforced



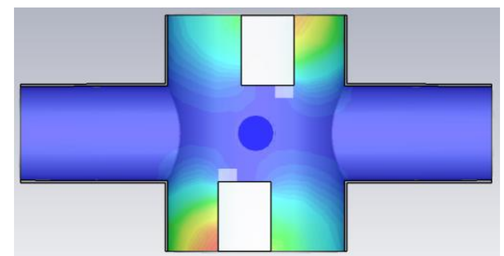
Damaged injection collimator
→ will be reinforced
→ New design underway



Damaged synchrotron light monitor
→ Temporary replacement
→ New design



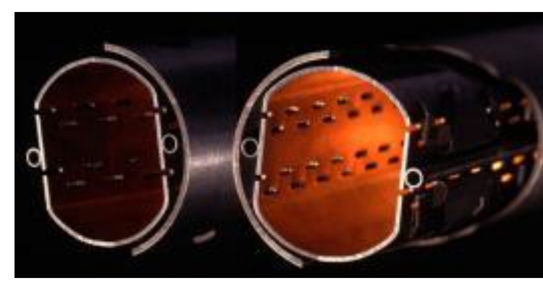
ALFA detector could be damaged
→ Cooling will be added



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.



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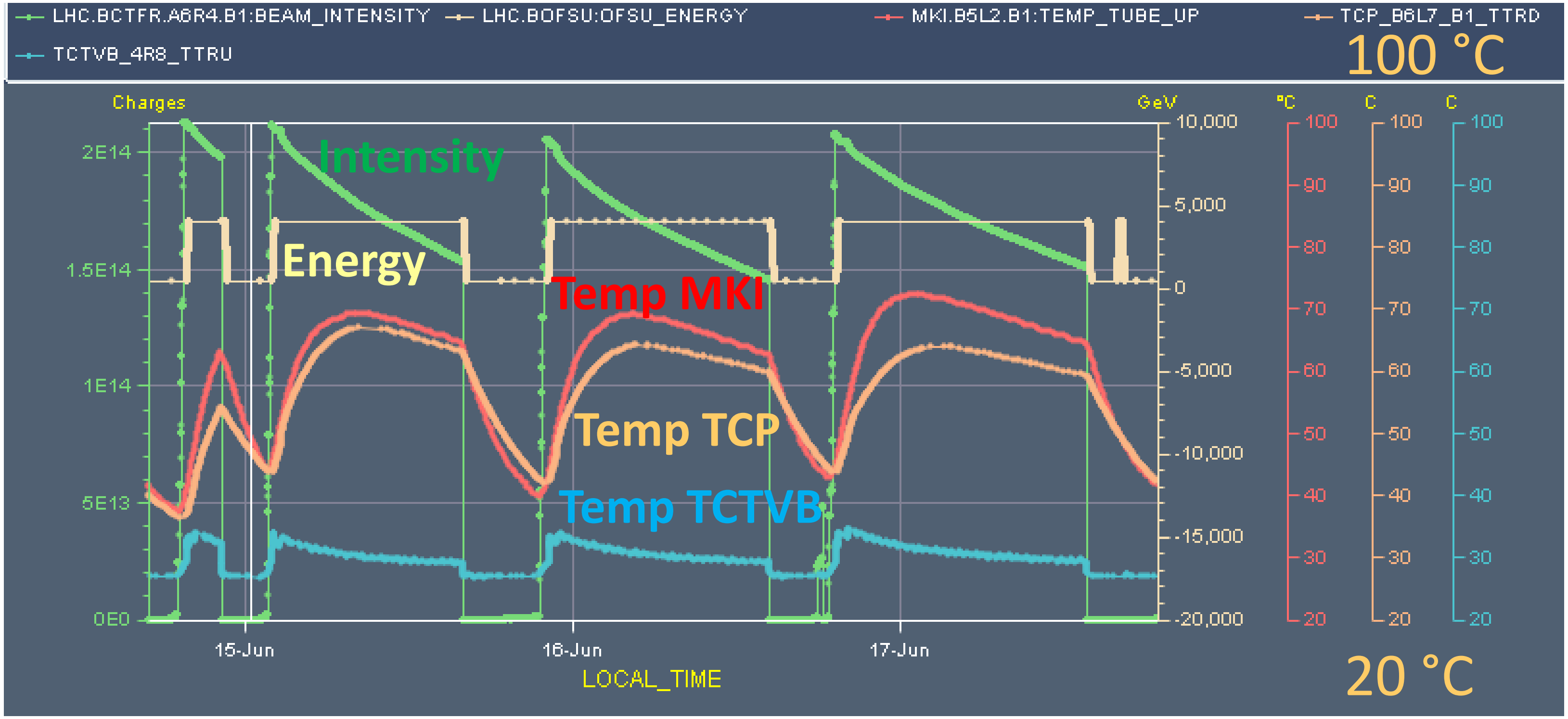
Beam induced heating?



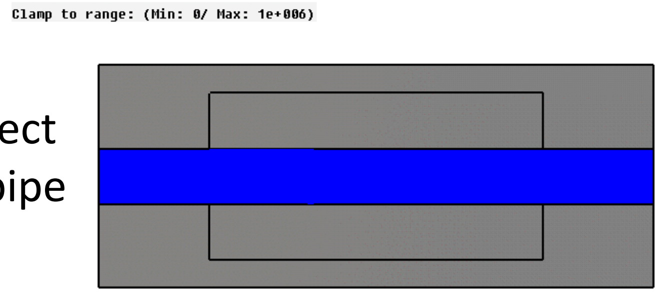
→ Example of temperature of certain LHC devices during physics fills
  - → MKI: injection kicker (interlock for injection at ~61 degrees C)
  - → TCP: primary collimator
  - → TCTVB: 2-beam tertiary collimator

→ 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

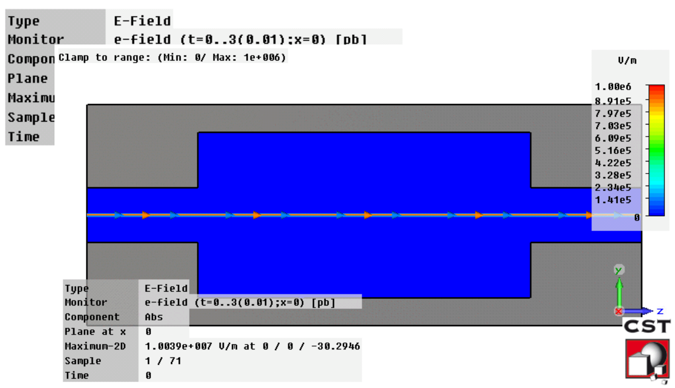
Perturbation of surrounding geometry to the electromagnetic fields of the beam

Smooth perfect conducting pipe

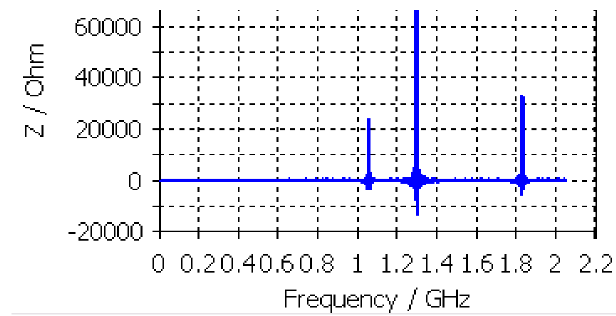


No additional perturbation due to the device

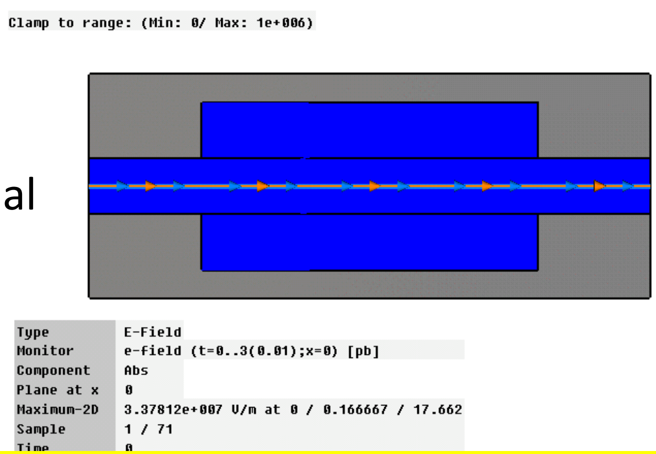
Cavity



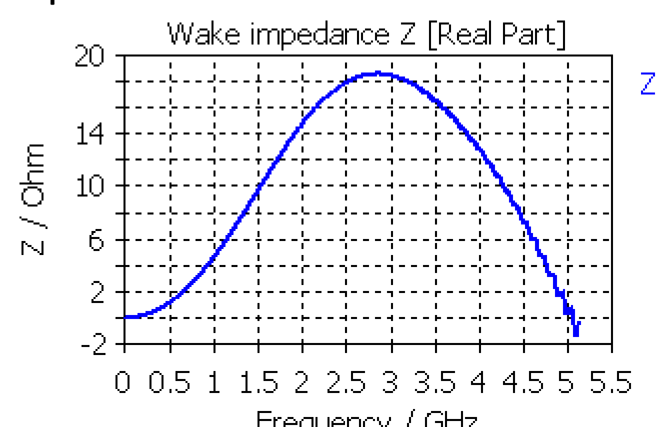
Perturbation at discrete frequencies → narrow band resonances



Lossy material



Perturbation over a wide range of frequencies→ Broadband resonances



Energy lost by the bunch will heat the surrounding

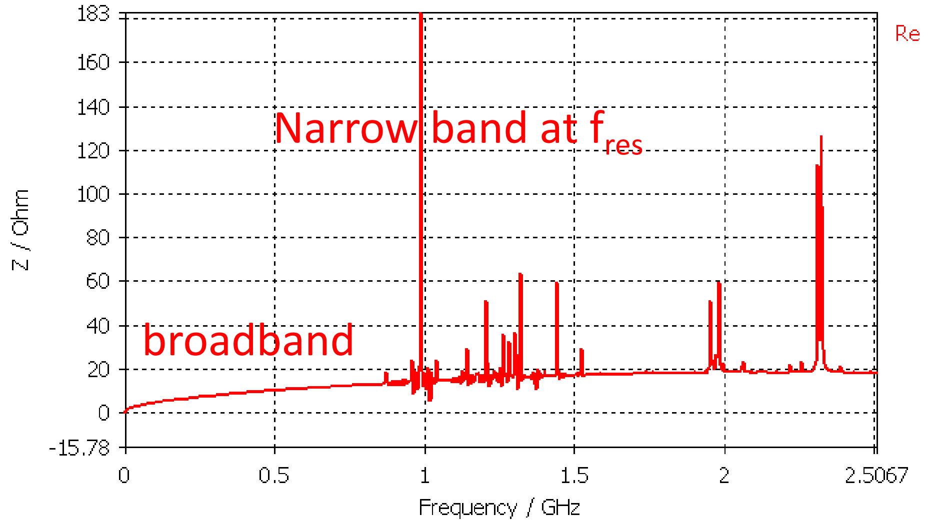
Computing power loss

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

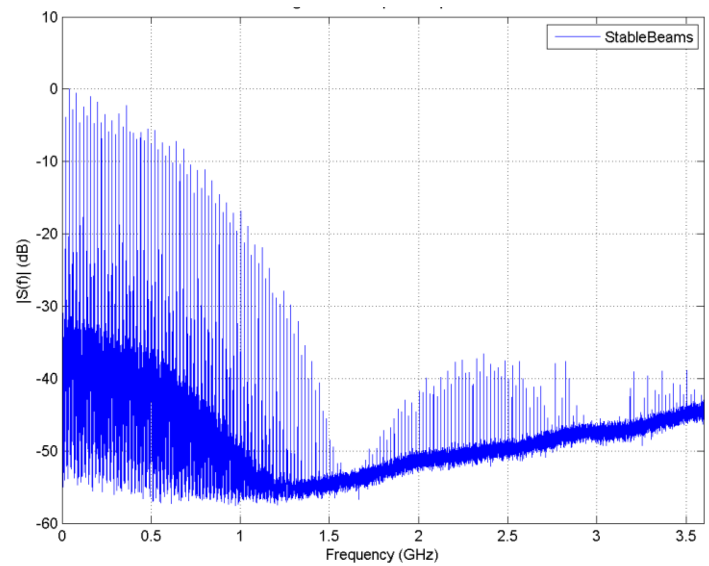
$$P_{loss} = 2(eMN_b f_{rev})^2 \left(\sum_{p=1}^{\infty} \mathrm{Re}\left[Z_{long}(2\pi p M f_{rev})\right] \times Powerspectrum(2\pi p M f_{rev}) \right)$$

M= number of bunches
N_b=intensity per bunch

Impedance Re(Z_{long}) of simulated primary collimator



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



Broadband contribution: sum can be replaced by an integral

$$P_{loss} = 2(eMN_b f_{rev})^2 \left(\frac{1}{Mf_{rev}} \int_0^{+\infty} \mathrm{Re}\left[Z_{long}(2\pi f)\right] \times Powerspectrum(2\pi f)\, df \right) \Rightarrow P_{loss} \propto M$$

Narrow band contribution: sum can be replaced by a single term

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

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  - Scaling heat load
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Increase in heat load only from intensity increase

Factor from situation before LS1	Nominal (25 ns)	ultimate (25 ns)	Before LS1 (50 ns)	US2 (25 ns)	HL-LHC (25 ns)	HL-LHC (50 ns)
M	**2808**	**2808**	**1374**	**2748**	**2808**	**1404**
Nb	**1.15**	**1.8**	**1.6**	**2.2**	**2.2**	**3.5**
Broadband ($M*N_b^2$)	1.06	2.59	1	3.78	3.86	4.89
Narrow band $(M*N_b)^2$	2.16	5.29	1	7.56	7.9	5

*Narrow band is a worst case scenario assuming that the resonance stands exactly at a multiple of 40 MHz

Significant increase in heat load from impedance with HL-LHC intensity (factor 4 to 7)

Increase in heat load from intensity increase and bunch length decrease to 1 ns

Factor from situation before LS1	Nominal (25 ns)	ultimate (25 ns)	Before LS1 (50 ns)	US2 (25 ns)	HL-LHC (25 ns)	HL-LHC (50 ns)
M	**2808**	**2808**	**1374**	**2748**	**2808**	**1404**
Nb	**1.15**	**1.8**	**1.6**	**2.2**	**2.2**	**3.5**
Broadband ($M*N_b^2$)	1.48	3.62	1	5.29	5.41	6.85
Narrow band $(M*N_b)^2$	3.02	7.40	1	10.59	11.05	6.99

*Narrow band is a worst case scenario assuming that the resonance stands exactly at a multiple of 40 MHz

Significant increase in heat load from impedance with HL-LHC parameters (factor 5 to 10)

→ Hardware that are limiting now or marginal need to be upgraded for HL-LHC

Note: a further reduction of bunch length to 4 cm leads to an additional factor of at least 3 in power loss

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Summary table of LHC issues

equipment	Problem	2011	2012	Hopes after LS1
VMTSA	Damage			removed
TDI	Damage			Beam screen reinforced
MKI	Delay			Beam screen and tank emissivity upgrade
TCP_B6L7_B1	Few dumps			Cooling system checked
TCTVB	Few dumps			removed
Beam screen Q6R5	Regulation at the limit			Upgrade of the valves + TOTEM check
ALFA	Risk of damage			New design
BSRT	Deformation suspected			New design

→ Most problems are efficiently addressed
→ Other devices may show up in the list

Damage
Limits operation
Worry that can limit operation
Should be fine

Summary table of LHC issues

equipment	Problem	2011	2012	Hopes after LS1	OK for HL-LHC?
VMTSA	Damage			removed	removed
TDI	Damage			Beam screen reinforced	New design underway
MKI	Delay			Beam screen and tank emissivity upgrade	Current upgrade may not be enough
TCP_B6L7_B1	Few dumps			Cooling system checked	400 W expected for 7 kW cooling
TCTVB	Few dumps			removed	removed
Beam screen Q6R5	Regulation at the limit			Upgrade of the valves + TOTEM check	Upgrade should be sufficient
ALFA	Risk of damage			New design	No forward physics after LS3?
BSRT	Deformation suspected			New design	New design installed

→ Most problems are efficiently addressed
→ Other devices may show up in the list

Damage
Limits operation
Worry that can limit operation
Should be fine

Devices to monitor for HL-LHC: arc beam screens

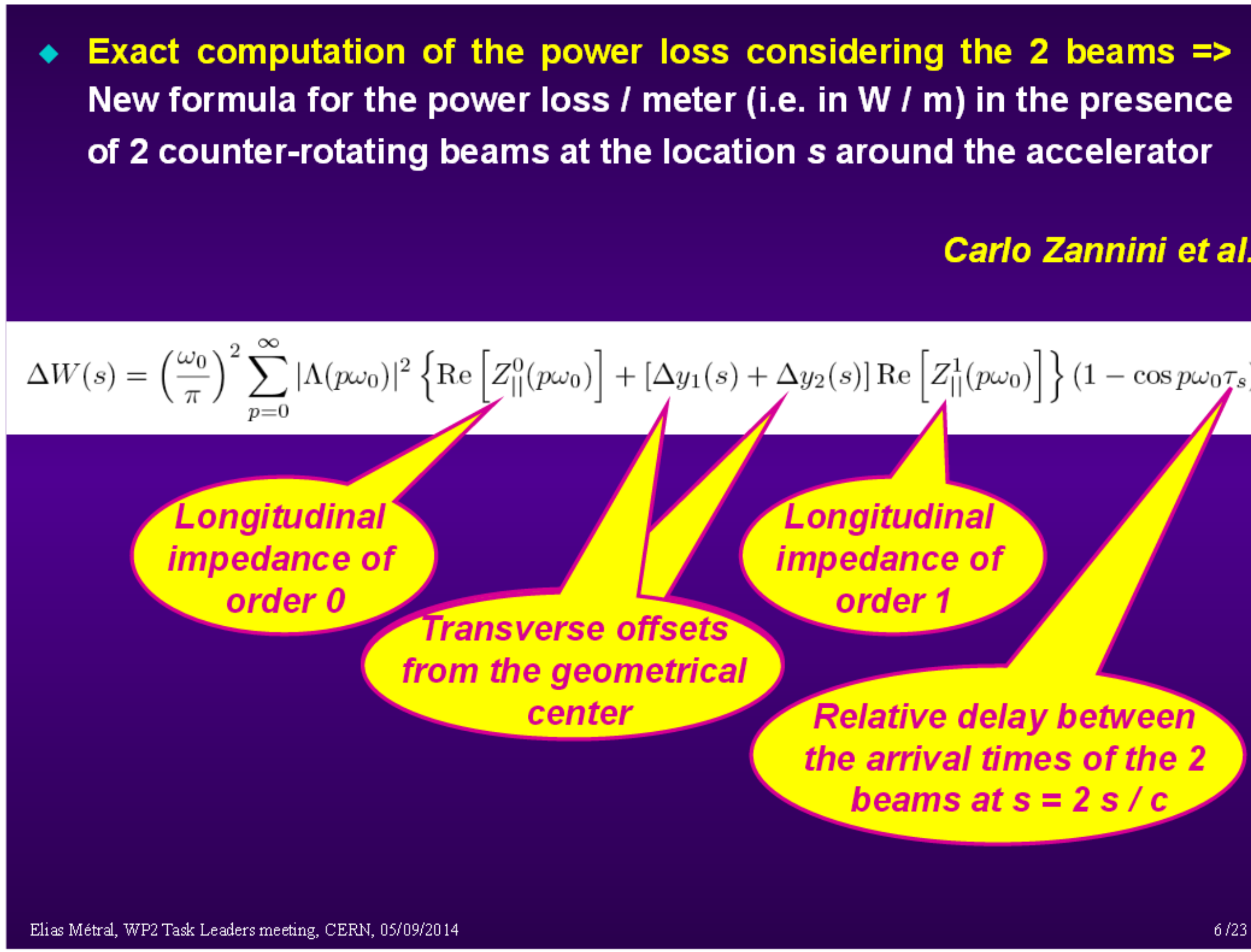
Expected from theory, accounting for the weld on the side (+44%, see PhD of Andrea Mostacci and Carlo Zannini) and magnetoresistance (for instance in PhD of Nicolas Mounet, pessimistic for quadrupoles),
Note: LHC design report aperture chosen instead of mechanical aperture (more pessimistic).

Power loss for 2 beams in mW/m	Nominal (25 ns)	ultimate (25 ns)	Before LS1 (50 ns)	US2 (25 ns)	HL-LHC (25 ns)	HL-LHC (50 ns)
M	2808	2808	1374	2748	2808	1404
Nb	1.15	1.8	1.6	2.2	2.2	3.5
Arc beam screens (18.4 mm)	290	509	165	1040	1060	1350

→ For the arcs, cooling power is 200 W per half cell (i.e. 3800 mW/m).
Is that enough margin for synchrotron radiation and electron cloud?
→ Could also be limiting for standalones and triplets (if cooling power is 250 W → 8300 mW/m).

Devices to monitor for HL-LHC: triplets beam screens

- Slides by E. Metral and C. Zannini at the work package 2.4 task leader meeting in September



Devices to monitor for HL-LHC: triplets beam screens

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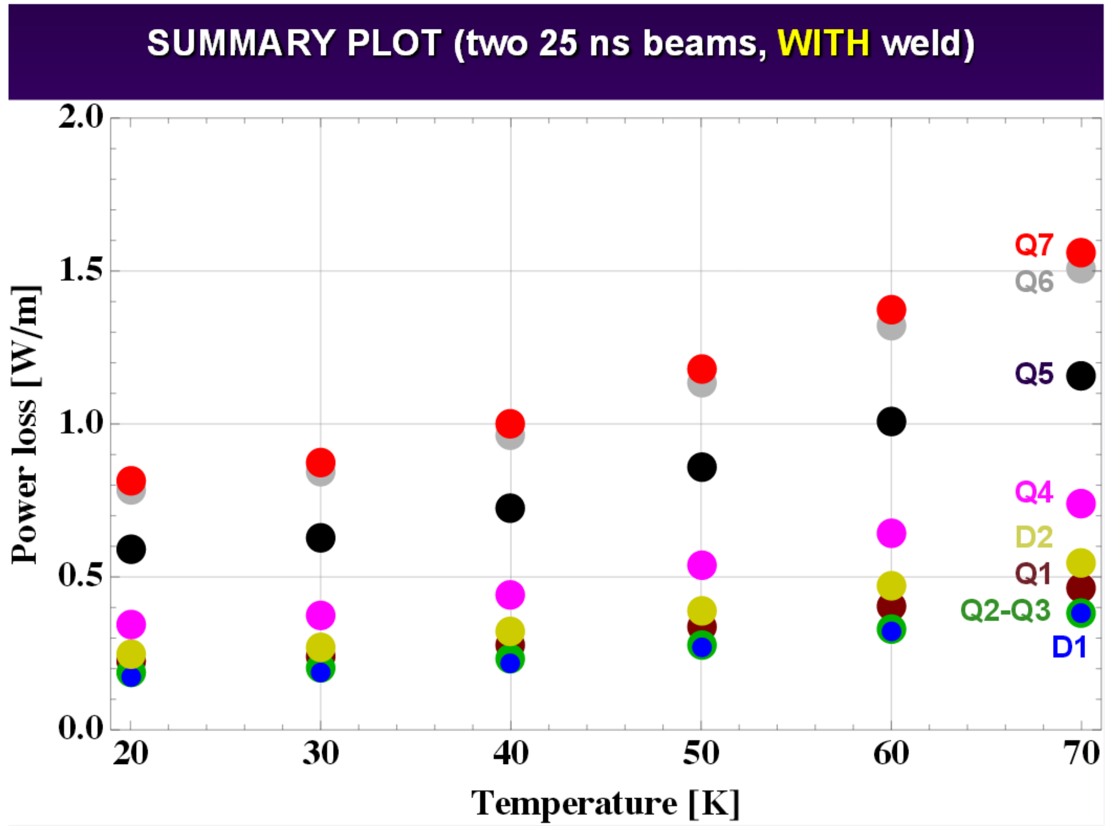


→ To be compared (and matched) with the expected cooling capacity for HiLumi, to give enough margin for scrubbing, synchrotron radiation and non beam induced heat load.

→ Need also to check the beam screens in IR2 and IR8 which are not planned to be changed

Devices to monitor for HL-LHC: Injection kickers

- Data from Mike Barnes and Hugo Day et al obtained by measurements on upgraded MKIs, to be installed during LS1

Power loss in W	Nominal 25 ns (2808*1.15, 1 ns, 7 TeV)	Before LS1 50 ns (1380*1.6e11 @1.2 ns, 4 TeV)	US2 25 ns (2748*2.2e11)	HL-LHC 25 ns (2808*2.2e11)	HL-LHC 50 ns (1404*3.5e11)
Non conform MKI8D (limiting for LHC)	-	**161 W/m**		-	-
Upgraded MKI	34-52 W/m	20-34 W/m	**106-180 W/m**	124-191 W/m	151-240 W/m

→ The HL-LHC parameters will bring the power loss back to limiting values.
→ However, the heat distribution should be quite different (less power in ferrite), and heavy effort of the kicker team to evacuate the heat by improving tank emissivity
→ need to wait for run 2 to assess if the upgraded MKI can withstand HL-LHC parameters

Other devices to monitor for HL-LHC

- Experimental beam pipes (CMS and ATLAS data from R. Wanzenberg and O. Zagorodnova - DESY)
  - CMS chamber (e.g. mode 750 MHz, R=1.5 kOhm): from 50 W before LS1 to potentially more than 350 W
  - ATLAS chamber: no significant mode expected
  - ALICE chamber (e.g. mode 530 MHz, R=1.5 kOhm): from 150 W before LS1 to potentially more than 1 kW
  - LHCb chamber (e.g. mode 620 MHz, R=0.6 kOhm): from 30 W before LS1 to potentially more than 250 W

- Instrumentation
  - Upgraded BSRT
  - striplines, button BPMs, wall current monitor → some electronics may need to be changed to accept more power

- RF cavities
  - R. Calaga: very small power extracted from the RF couplers before LS1 (a few Watts). Possibility to detune the modes

- Stochastic cooling
  - possibility to shield completely during proton operation?

- Dump MKD kicker is shielded behind a thin metallic coating

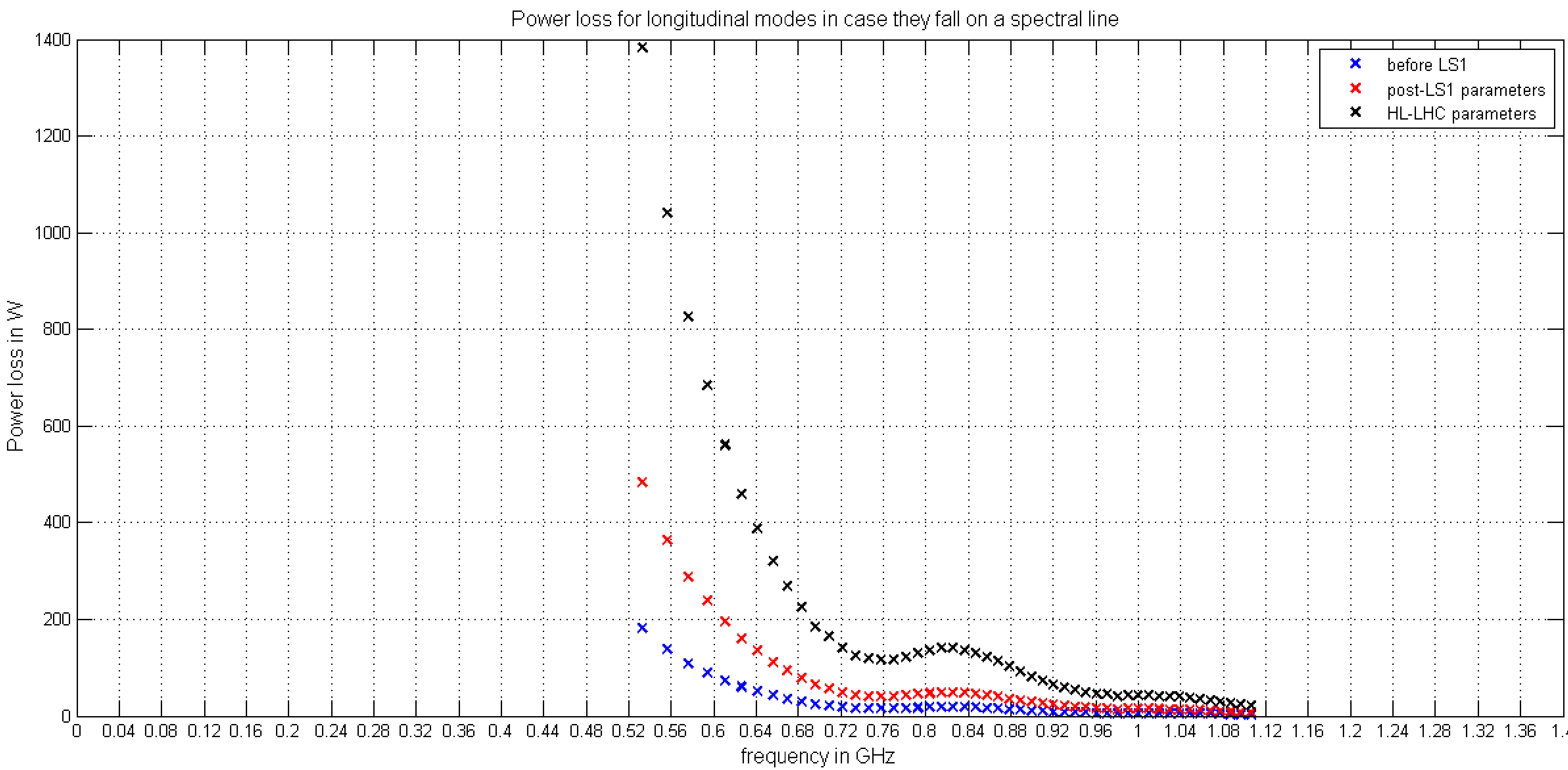
  →preliminary computations: from 6 W before LS1 to 25 W for HL-LHC (in fact small temperature increase was measured → J. Uythoven)

- Collimators, recombination chambers, electron lens, beam-beam compensation (strong impact expected if outside of collimator)

- Other ideas?

Power from resonant modes for ALICE

Modes from R. Wanzenberg and O. Zagorodnova, DESY



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)

→ Similar case for CMS and LHCb

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What we don’t know

- Many devices are not yet designed (e.g. TDI, LHCb VELO)
- Non conformities
  - → Need more systematic temperature monitoring on near beam hardware
  - → Need to check cooling system before/during installation
  - → Need to measure longitudinal impedance of new equipment before installation to detect problems
- Longitudinal bunch distribution along the fill (could be controlled)
- Fruitful work with thermal simulation experts to predict temperature distribution, but still a difficult process

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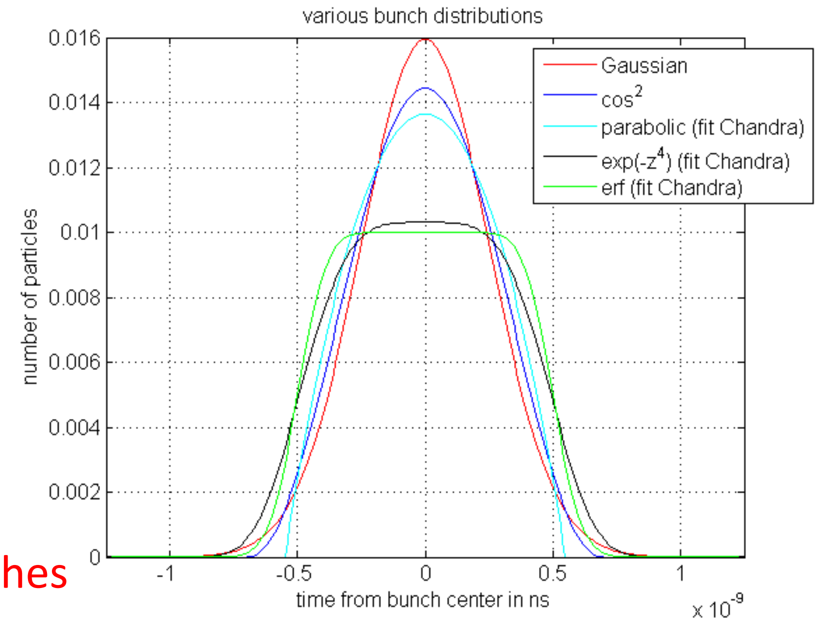
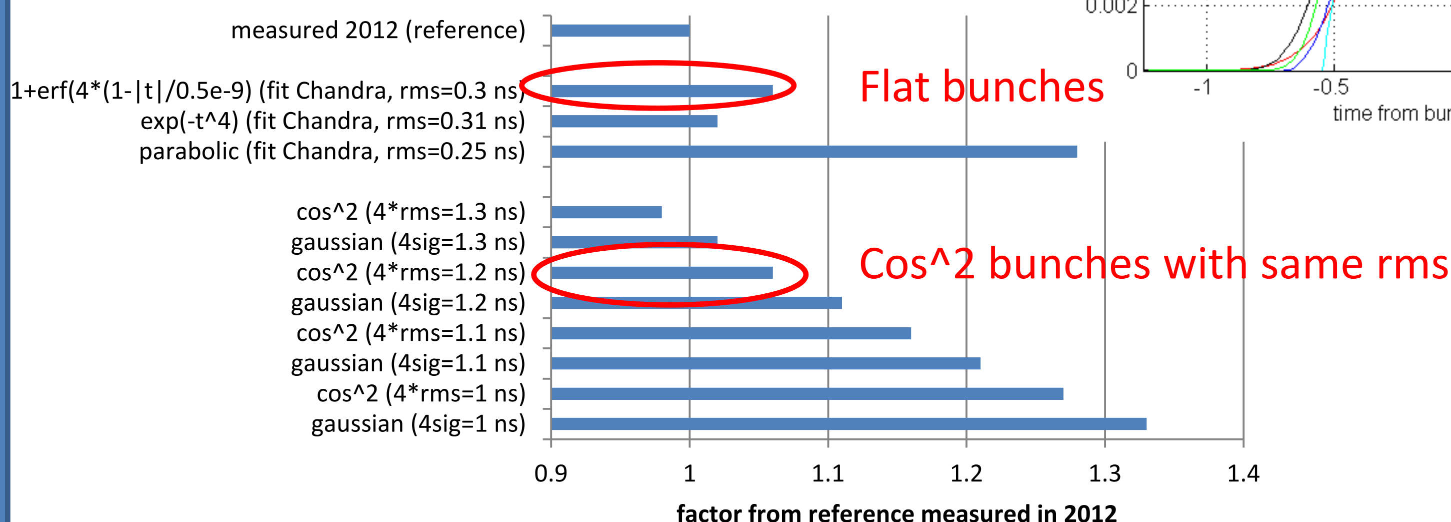
Possible mitigations in case of issues

- Reduce longitudinal impedance
  - Avoid unnecessary cavities (contact RF fingers, elliptical bellows for elliptical chambers, tapered transitions)
  - If the heating is due to resistive wall, increase material conductivity
  - If the heating is due to trapped modes, reduce material conductivity
- Reduce impedance overlap with beam spectrum
  - For resistive wall or broad resonance, increase bunch length.
  - For narrow resonance, detune the resonant mode (with ferrite or coupler)
  - Possibility to tune the beam spectrum with the longitudinal distribution (higher harmonic cavity)
  - For narrow resonances, switch to smaller bunch spacing
- Reduce bunch or beam intensity
- Extract the heat from critical locations (ferrite, RF fingers, springs)

Possible mitigations: Effect of flat bunches?

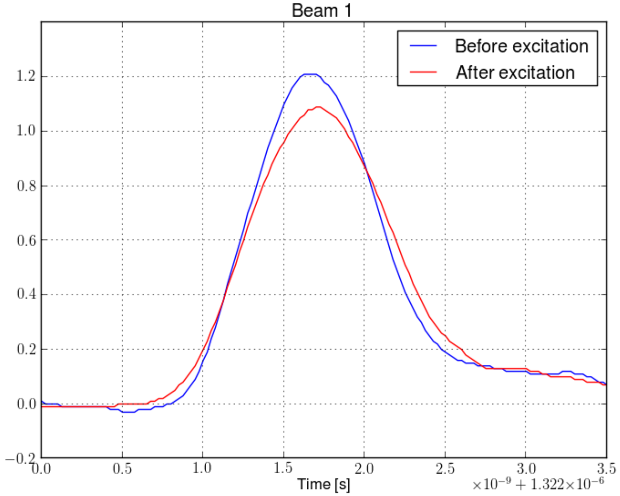


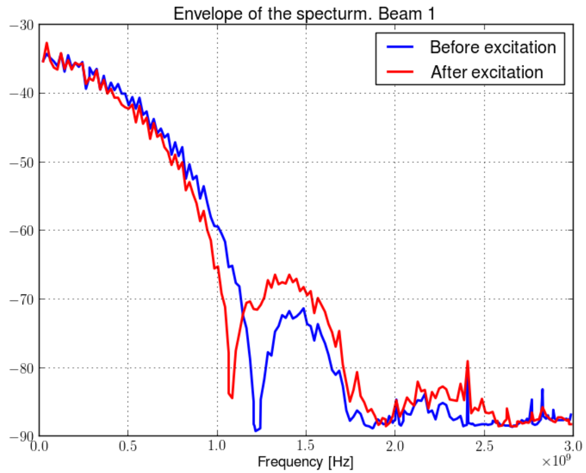
Power loss for a constant impedance
(with reference to measured 2012 spectrum)



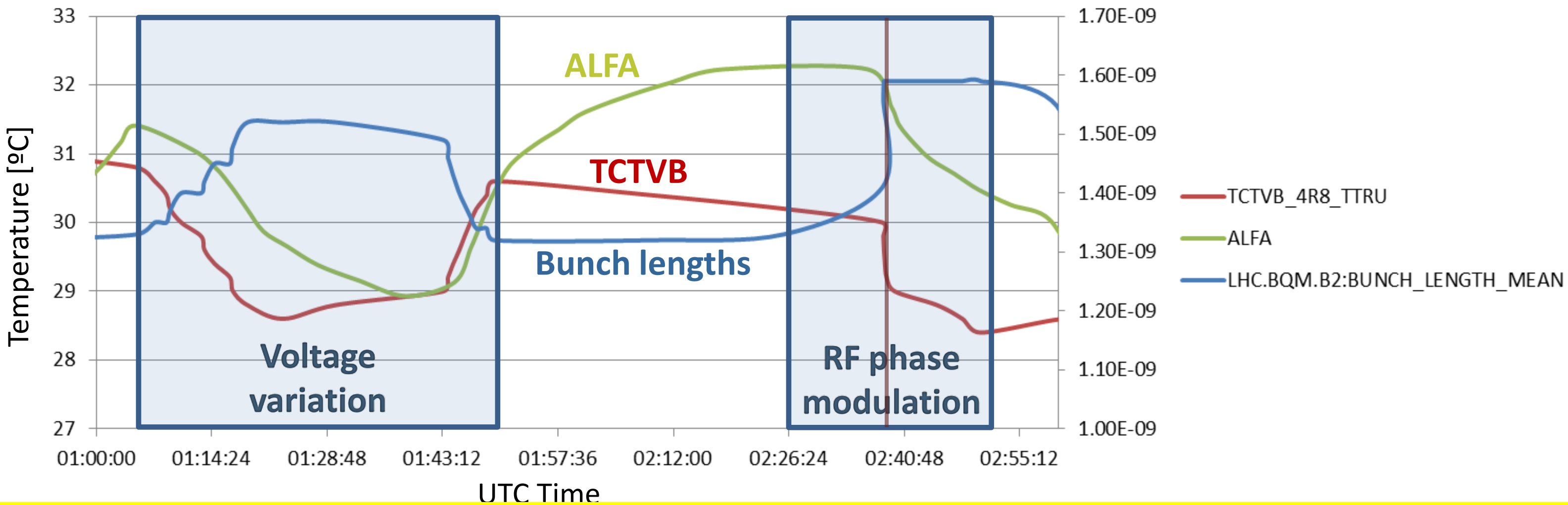
Flat bunches not far from single RF situation in terms of heating for very broadband impedances (constant over frequency). Effect will depend on the spectrum of each device.

Flat bunches:
another degree of freedom in case of abnormal heating





Juan Esteban Mueller, Elena Shaposhnikova et al



→ LHC MD in 2012: excitation to flatten bunches reduced temperature on TCTVB and ALFA

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Perspectives

- No brick wall showstopper found so far to reach HL-LHC parameters, but many worries, in particular non-conformities.

- Proposed actions for early detection of heating issues:
  - Careful simulation/measurement validation of all new and potentially critical devices
  - Appropriate dimensioning and validation of cooling system
  - Need temperature monitoring in suspected regions
  - Near beam temperature probes are not installed everywhere: vacuum and cryo data are our only eyes in the major part of the machine

    → Need a tool to extract vacuum patterns that indicate potential heating
  - Need to define alarms (in collaboration with equipment groups and machine protection
  - Be ready to implement mitigation to reduce impedance, beam spectrum or extract heat.

- Need to compute the power loss, but also the distribution of the temperature increase to assess the damage potential: 100 W on a 2 mm thick cooled beam pipe may not be an issue while a fraction of W on a 0.3 mm RF finger can be dramatic.

- Significant effort should continue to be put on:
  - Understanding underlying mechanisms (impact of filling schemes, 2 beams)
  - Robustness and sensitivity of impedance simulations and measurements
  - Impedance/thermal co-simulations
  - Can we use couplers to extract the heat instead of ferrites

Devices to monitor for HL-LHC: beam screens

Expected from theory, accounting for the weld on the side (+44%, see PhD of Andrea Mostacci and Carlo Zannini) and magnetoresistance (for instance in PhD of Nicolas Mounet, pessimistic for quadrupoles), accounting for factor 2 in addition (worst case for 2 beams in same aperture, pessimistic). Note: LHC design report aperture chosen instead of mechanical aperture (more pessimistic).

See talk of N. Mounet for more details

Power loss for 2 beams in mW/m	**Nominal (25 ns)**	**ultimate (25 ns)**	**Before LS1 (50 ns)**	**US2 (25 ns)**	**HL-LHC (25 ns)**	**HL-LHC (50 ns)**
M **Nb**	**2808** **1.15**	**2808** **1.8**	**1374** **1.6**	**2748** **2.2**	**2808** **2.2**	**1404** **3.5**
Arc beam screens (18.4 mm)	290	509	165	1040	1060	1350
Inner triplets Q2 and Q3 (24 mm → 59 mm)	445	781	253	563 *(1590)*	575 *(1630)*	728 *(2060)*
inner triplets Q1 (17.3 mm → 49 mm)	618	1082	351	678 *(2212)*	693 *(2261)*	877 *(2861)*

→ Beneficial effect of new triplet

→ For the arcs, cooling power is 200 W per half cell (i.e. 3800 mW/m). Is that enough margin for synchrotron radiation and electron cloud?

→ Could also be limiting for standalones and triplets (if cooling power is 250 W → 8300 mW/m).