Heat loads due to impedance: update and required upgrades

M. Barnes, P. Baudrenghien, N. Biancacci, R. Calaga, F. Carra, F. Caspers, H. Day, J. Esteban Mueller, O. Frasciello, T. Jin, A. Lechner, E. Métral, G. Rumolo, B. Salvant, E. Shaposhnikova, J. Uythoven, N. Wang, R. Wanzenberg, O. Zagorodnova, C. Zannini, M. Zobov.

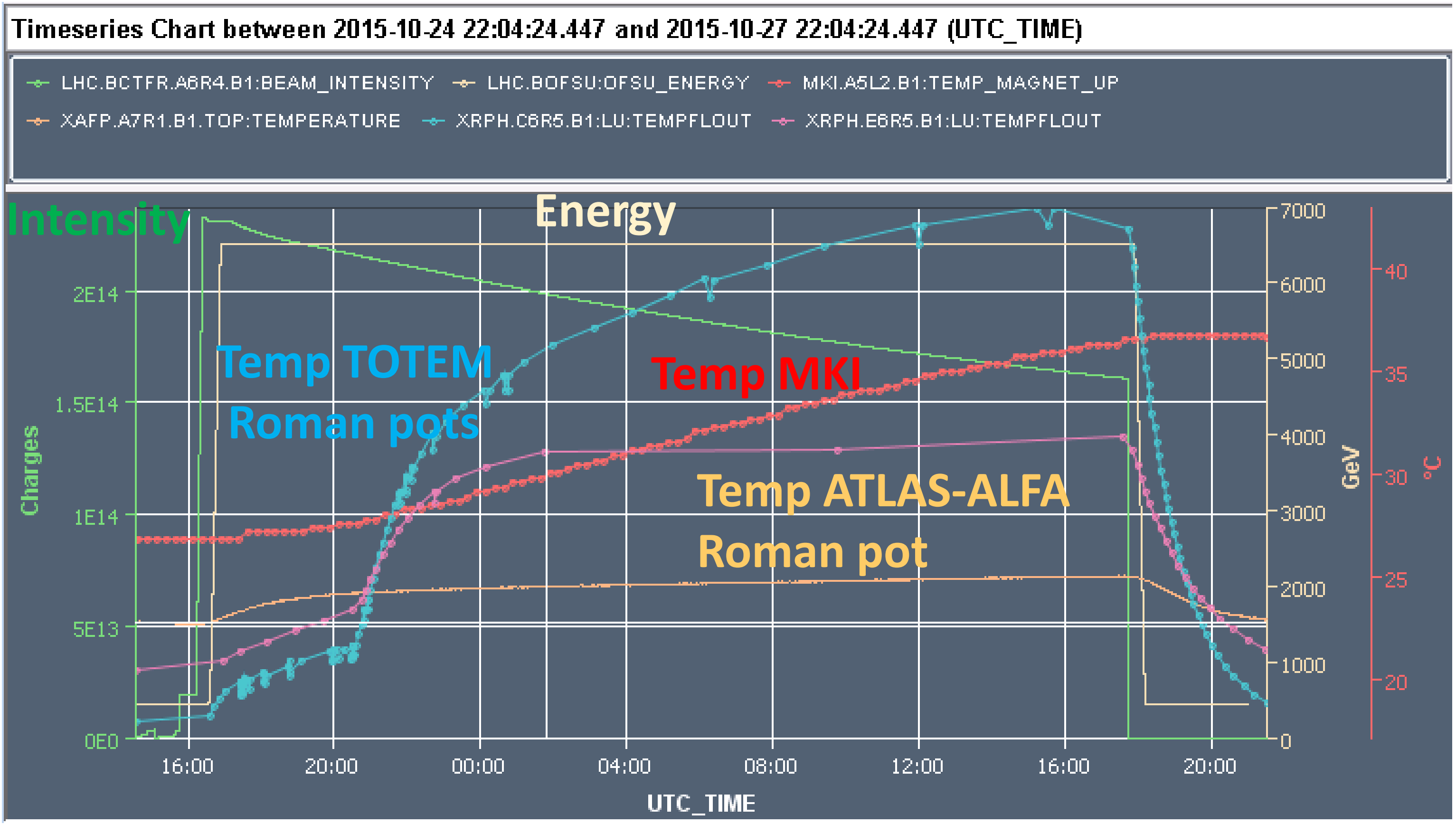
Many thanks to WP2 members and the relevant equipment groups for their input and for the very efficient teamwork over the years

- Follow up of many talks and work over the last years at the HiLumi meetings, WP2 task leader meetings and task 2.4 meetings.

Agenda

- Beam induced heating?
- Current issues
- Reaching HL-LHC parameters
  - Scaling heat load
  - Status of current issues
  - Current devices to monitor
  - What we do not know
- Possible mitigations
- Perspectives

Beam induced heating?



→ Example of temperature of certain LHC devices during physics fills

- → MKI: injection kicker
- → TOTEM Roman pots
- → ATLAS-ALFA Roman pots

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

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

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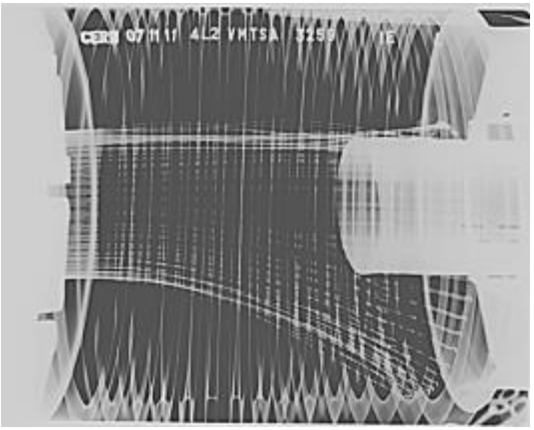
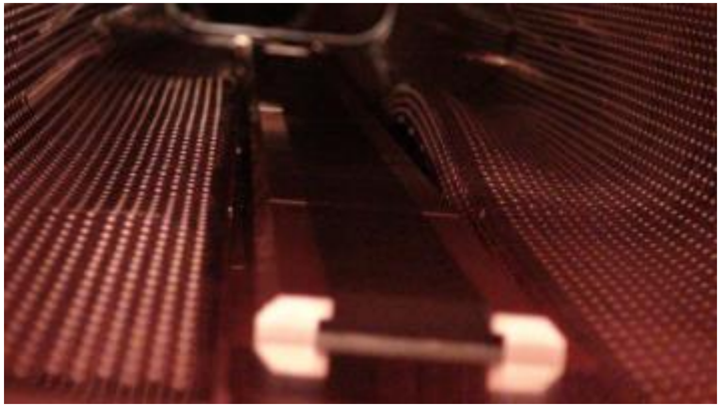
Heating issues in LHC

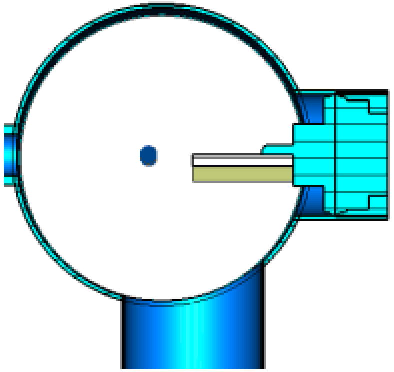
Damaged vacuum module in 2011



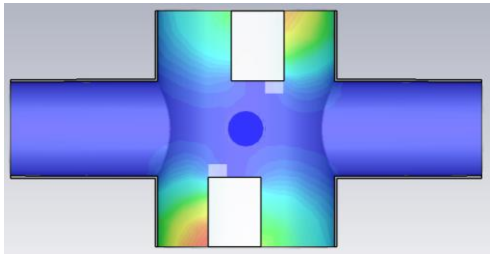
Damaged injection collimator in 2011



Damaged synchrotron light monitor in 2012



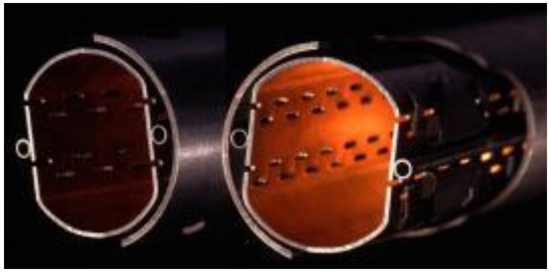
ALFA detector could be damaged



Injection kicker delays injection

Some collimators are heating

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



Summary table of LHC issues

equipment	Problem	2011	2012
VMTSA	Damage		
TDI	Damage		
MKI	Delay		
Collimators	Few dumps		
Beam screen Q6R5	Regulation at the limit		
ALFA	Risk of damage		
BSRT	Deformation suspected		
BGI	vacuum increase		

→ 2012 was a bad year for heating issues!

- Damage
- Limits operation
- Worry that can limit operation
- Should be fine

Summary table of LHC issues

equipment	Problem	2011	2012	2015
VMTSA	Damage			removed
TDI	Damage			Beam screen reinforced, ~~copper coating on the jaw~~
MKI	Delay			Beam screen upgrade and non conformity solved
Collimators	Few dumps			Non conformity solved. TCTVB removed
Beam screen Q6R5 and TOTEM	Regulation at the limit			Upgrade of the valves + TOTEM check
ALFA	Risk of damage			New design + cooling
BSRT	Deformation suspected			New design + cooling
BGI	vacuum increase			To be followed up

→ Most problems were seriously and efficiently addressed
→ 2015 went much better!
→ Other devices may show up in the list
→ Beam screen heating critical, but impedance contribution small

Damage
Limits operation
Worry that can limit operation
Should be fine

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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)	HL-LHC (25 ns)
M	**2808**	**2808**	**1374**	**2748**
Nb	**1.15**	**1.8**	**1.6**	**2.2**
Broadband ($M*N_b^2$)	1.1	2.6	1	3.8
Narrow band $(M*N_b)^2$	2.2	5.3	1	7.6

*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 8.1 cm (1.08 ns) -> 30% more heat load

Factor from situation before LS1	Nominal (25 ns)	ultimate (25 ns)	Before LS1 (50 ns)	HL-LHC (25 ns)
M	**2808**	**2808**	**1374**	**2748**
Nb	**1.15**	**1.8**	**1.6**	**2.2**
Broadband ($M*N_b^2$)	1.3	3.3	1	4.8
Narrow band $(M*N_b)^2$	2.7	6.7	1	9.6

*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
→ Bunch length decrease during the fill to 0.8 ns (~6 cm) would lead to a factor 2 increase (at constant intensity)

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

Summary table of LHC issues

equipment	Problem	2011	2012	2015	HL-LHC?
VMTSA	Damage			removed	removed
TDI	Damage			Beam screen reinforced, ~~copper coating on the jaw~~	New design underway
MKI	Delay			Beam screen upgrade and non conformity solved	Current upgrade may not be enough
Collimators	Few dumps			Non conformity solved. TCTVB removed	400 W expected for 7 kW cooling
Beam screen Q6R5 and TOTEM	Regulation at the limit			Upgrade of the valves + TOTEM check	Upgrade should be sufficient
ALFA	Risk of damage			New design + cooling	No forward physics after LS3?
BSRT	Deformation suspected			New design + cooling	New design underway
BGI	vacuum increase			To be followed up	To be followed up

→ Most problems were seriously and efficiently addressed
→ 2015 went much better!
→ Other devices may show up in the list
→ Beam screen impedance heat load increases, but ok alone

Damage
Limits operation
Worry that can limit operation
Should be fine

Why these good results in 2015?

- Very strong effort by equipment groups to improve the impedance of their device: only the TDI suggestions could not be implemented

- Strict rules enforced by impedance team for installation of new hardware into LHC or modification

- Effort on heating monitoring tools:
  - Additional monitoring requested and implemented
  - Temperature and vacuum fixed displays in control room and analyzers
  - Alarms by interlock system (SMS) to detect abnormal behavior (no dump)
  - Tools to display Synchronous phase error and beam spectra

  → allowed detecting issues already with low intensity beam

- Most heating issues are expected to be linked to broadband impedance:

  → 25 ns beam with 2000 bunches is less demanding than 50 ns before LS1 for broadband impedances.

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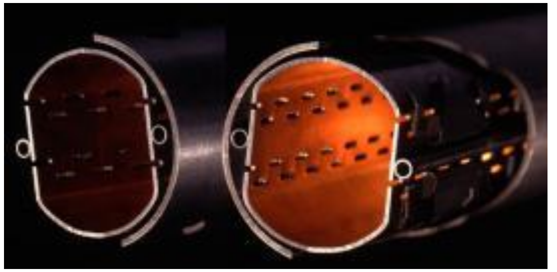
HL-LHC heat load on existing beam screen

- Theory including weld (+44%, see PhD of Andrea Mostacci and Carlo Zannini).
- Heat load on arc beam screen (18.4 mm radius):
  - Nominal: 290 mW/m (15 W/half cell)
  - HL-LHC: 930 mW/m (50 W/half cell)



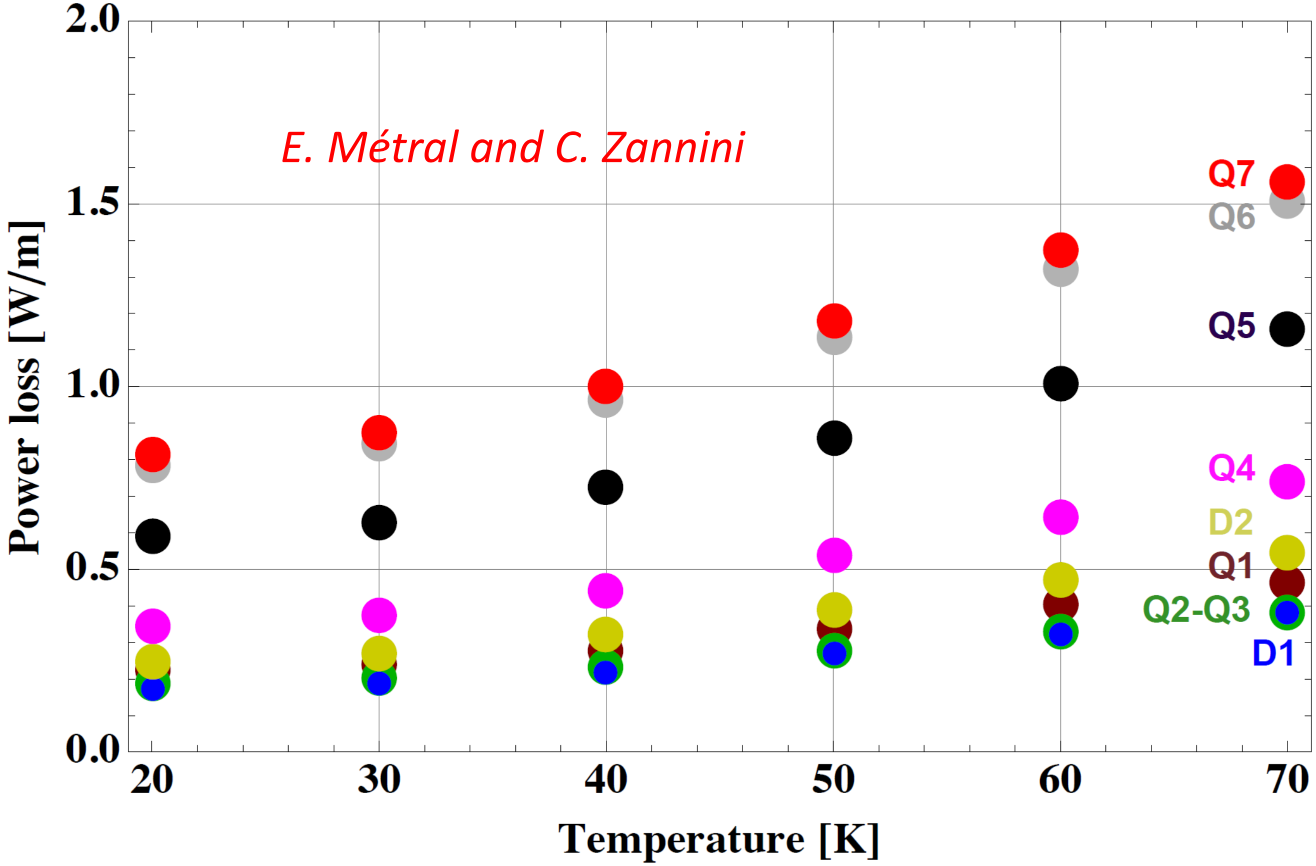
→ With currently 160 W/half cell cooling capacity, need enough margin for electron cloud.

- Heat load on existing triplets (17.3 mm for Q1 and 24 mm for Q2/Q3):
  - Nominal: 618mW/m (Q1) and 445 mW/m (Q2/Q3)
  - HL-LHC: 985 mW/m (Q1) and 710 mW/m (Q2/Q3)

→Enough margin for electron cloud?

Triplet beam screen heat load vs beam screen temperature

E. Métral and C. Zannini, "Temperature effects on image current losses in the triplets",
33rd HiLumi WP2 Task Leader Meeting, Friday, September 5, 2014



G. Iadarola at KEK 2014:

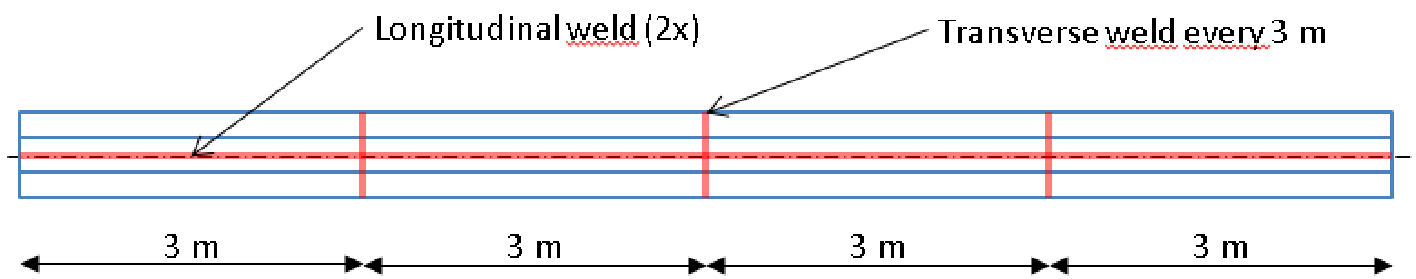
Impact of the **operating temperature** up to about **factor 2**

→ Values **well within the available cooling capacity** (4.8 W/m)

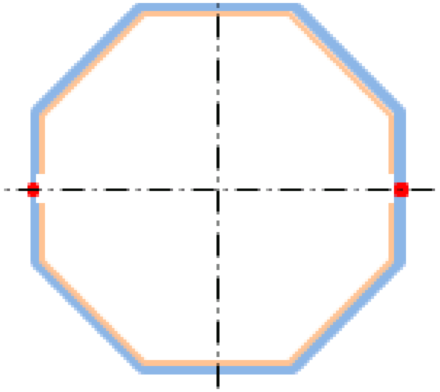
→ Is there enough margin left for electron cloud?

Effect of the weld(s)

- "Transverse" weld



- "Longitudinal" weld

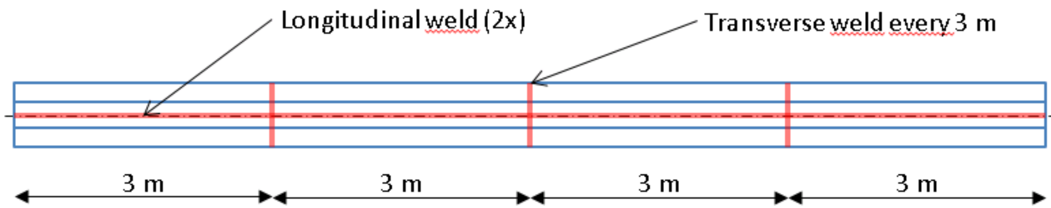


→ note: not easy to get convergence with CST simulations for this case
→ Requires refined mesh near the weld.

Effect of transverse weld (IP1, IP5 new beam screen)

→ Power loss for 2*2748 bunches at 2.2e11 p/b

Element	Length [mm]	Number	Power loss [W]
Q1	8	4	0.2
Q2	8	8	0.32
Q3	8	4	0.16
D1	8	4	0.16
D2	16	4	0.46
Q4	8	4	0.28
Total	--	--	1.6



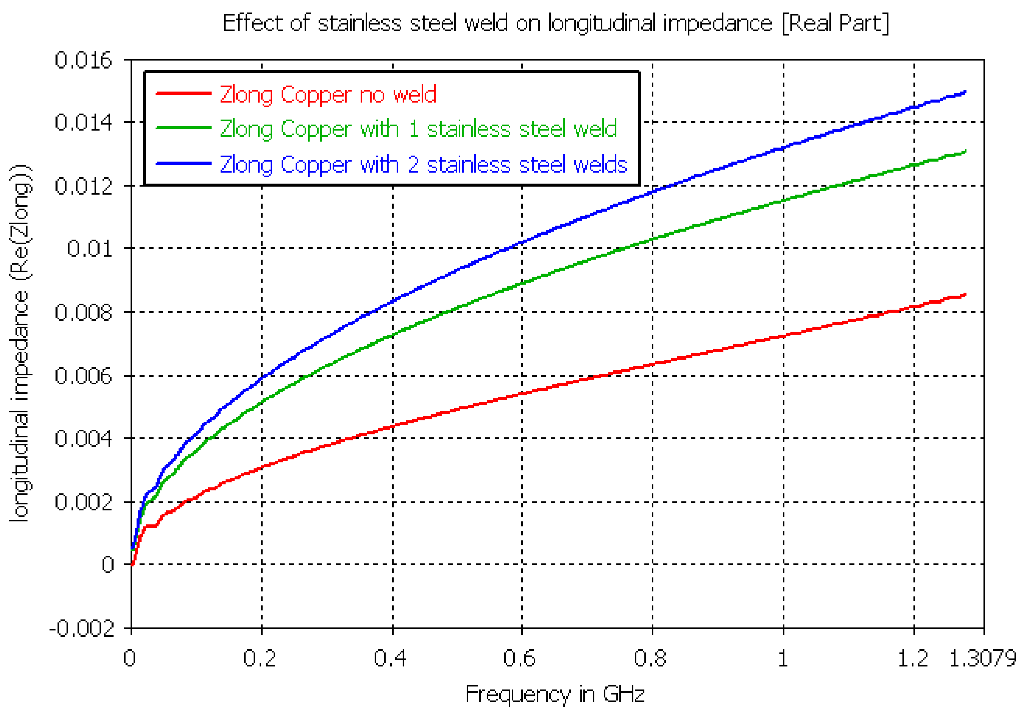
Power loss per meter for 1 beam (for D2)
in weld: 3.6 [W/m]
in beam screen:0.13 [W/m]

→ Small increase expected for the whole length
→ However, this will generate longitudinal hot spots. Is that an issue?

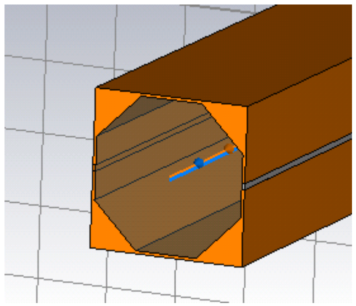
Study for new design of triplet beam screen *(in collaboration with TE-VSC)*

- Coating with amorphous carbon for electron cloud reduction
  - → Small impact only on imaginary part of impedance.
  - → No impact on beam induced RF heating.

- Proposed geometry with two welds instead of one



Octogonal beam screen with 2 welds (4 mm wide)

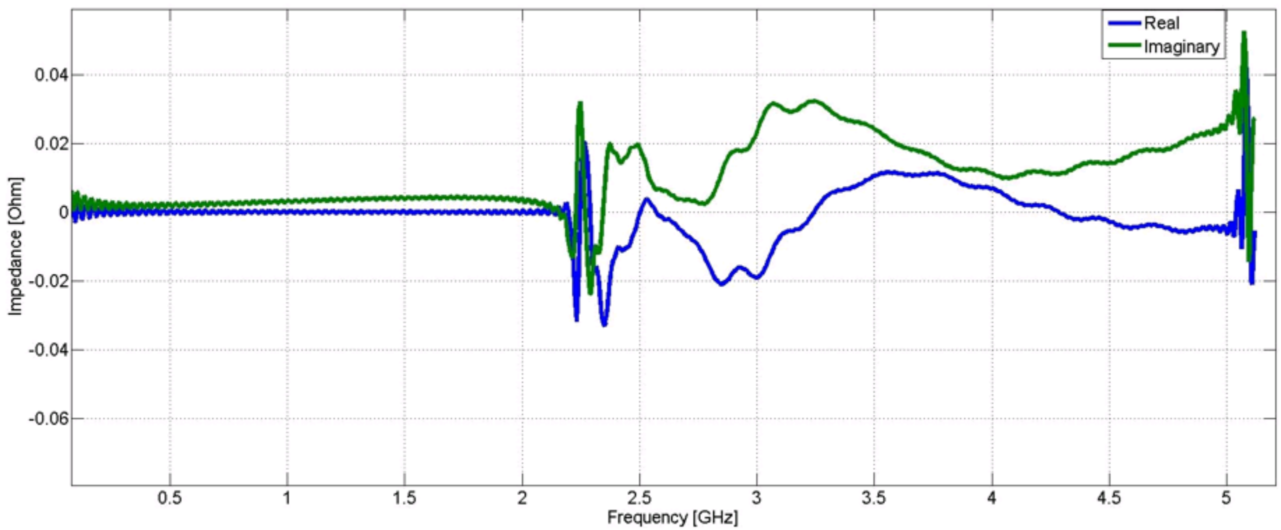


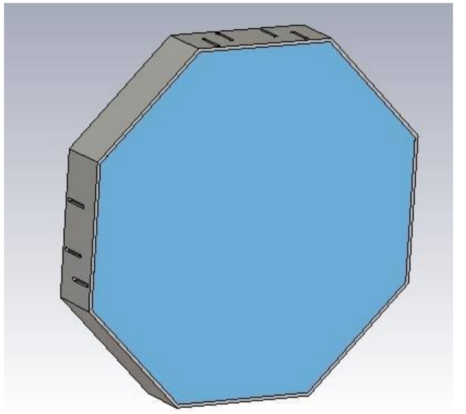
→ 1 weld : 70% increase in heat load with respect to no weld
→ 2 welds : 20% increase in heat load with respect to 1 weld

Started study on triplet beam screen holes

Introduction | Convergence studies | LHC Beam screen | HL-LHC Beam screen | Conclusions

Preliminary studies of the impedance





→ Very small impact of holes on beam screen heat load

F. Riminucci et al

As a consequence,

→Heat load to beam screen from impedance will increase significantly and is expected not to be minor anymore with respect to cooling capacity.

→Important to assess whether the existing cooling capacity will be enough for impedance together with all other contributions (static, electron cloud, synchrotron radiation).

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See also talk of J. Uythoven at this workshop

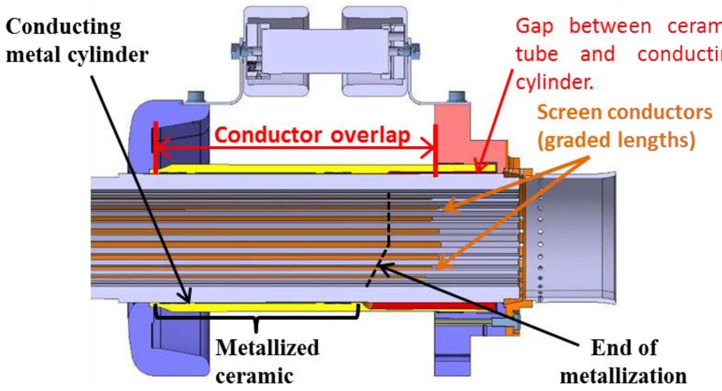
Injection kicker MKI

M. Barnes, H. Day et al

- LHC Run 1:
  - heating on one non-conforming kicker limited Run1 performance (+1-2h turnaround, on a few occasions) → was due to a twisted beam screen.
  - Ferrites reached Curie temperature of 120 °C with an estimated power loss of 160 W/m (averaged over the length) for this non-conforming magnet.

- Significant effort of the TE-ABT team during LS1:
  - Increase number of screen conductors from 15 to 24 to better screen the ferrite
  - Change of geometry at capacitively coupled end of the ceramic chamber to reduce electric field

→ Upgrade worked very well: no further limitation!



MKI: expectation for HL-LHC

M. Barnes, H. Day, L. Vega Cid et al

	2012	Run 2	HL-LHC
Power deposition	161 W/m	42 W/m (max 52 W/m)	138 W/m (max 170 W/m)

HL-LHC:
2748 bunches
2.2e11 p/b and 1.08 ns

Different geometry
→ The power loss will not be deposited at the same location
→ Was more spread along the MKI length
→ Expected to be now more localized at the upstream end (simulations and measurements in 2015 agree)
→ Need to be careful as the upstream end could reach Curie temperature well before the rest

→ In case bunch length is too short, possibility to blow up at the start of the ramp and during the fill

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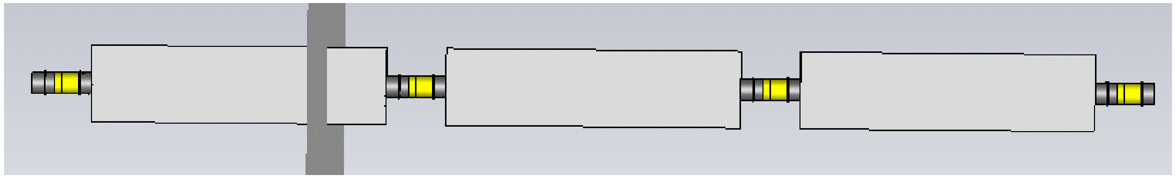
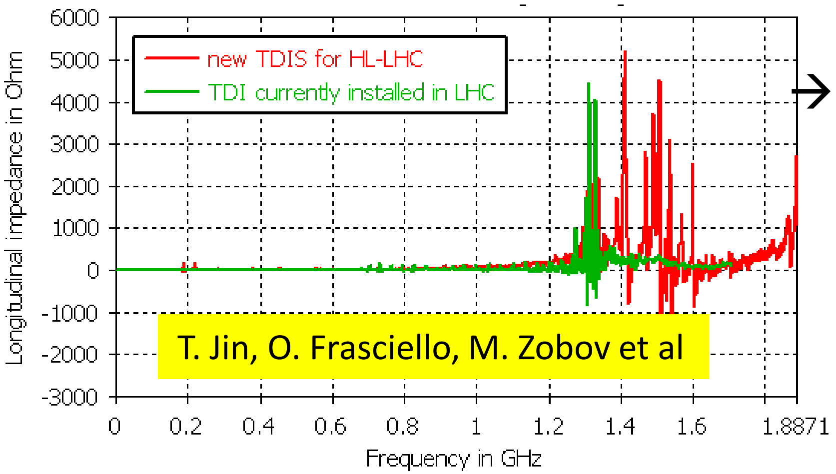
Injection protection collimators (TDIS)

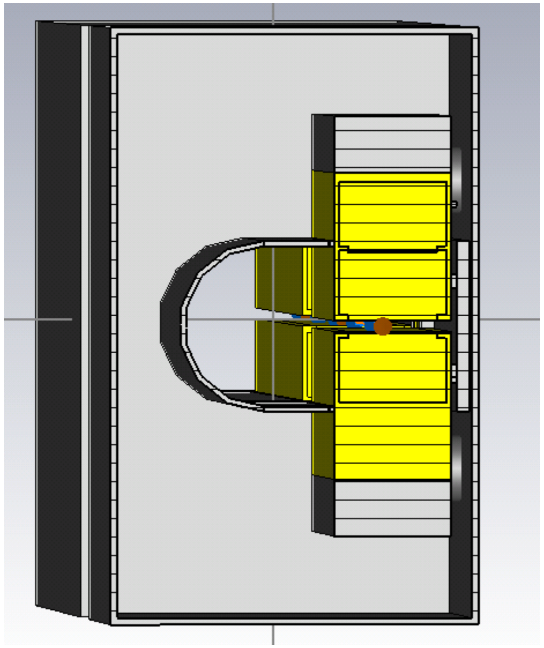
- Serious issues with the current TDIs (in particular TDI8) → very careful check of the new TDIS
- Optimization of impedance and improvement of cooling has high priority:
  - → Recommended in particular:
  - To reduce resistive contribution: Copper coating on the jaw
  - To reduce geometric contribution:
    - Closing the gap between the jaws and the beam screen with RF fingers
    - Avoiding cavities and steps at the transitions (difficult due to dose constraints)
    - Find a good compromise between low impedance at injection and flat top





T. Jin, O. Frasciello, M. Zobov et al

→ Geometry not finalized



→ Need to see the effect of reducing the resistive wall impedance with copper coating in 2016

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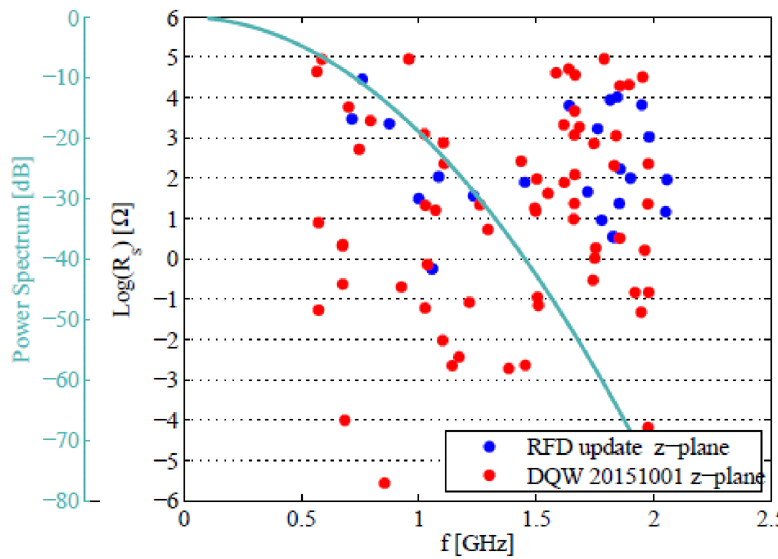
Crab cavities

N. Biancacci et al

Longitudinal HOM distribution for the DQW and RFD designs, compared with an HL-LHC bunch spectrum assuming gaussian longitudinal profile with $\sigma_z = 8.1$ cm:



→ Many modes below 1.2 GHz can lead to high heating especially for the DQW design.

N. Biancacci et al

Procedure adopted for the study of the heating from HOMS:

- From each HOM in the table we construct the longitudinal impedance as a resonator with resonant frequency f_r, merit factor Q, shunt impedance R_s in Ω:

$$Z_l(\omega) = \frac{R_s}{1 + j\,Q(\omega_r/\omega - \omega/\omega_r)}$$

- This leads to a power loss equal to:

$$P_{loss} = M^2 I_b^2 \sum_{p=-\infty}^{\infty} Z_l(pM\omega_0) S(pM\omega_0)$$

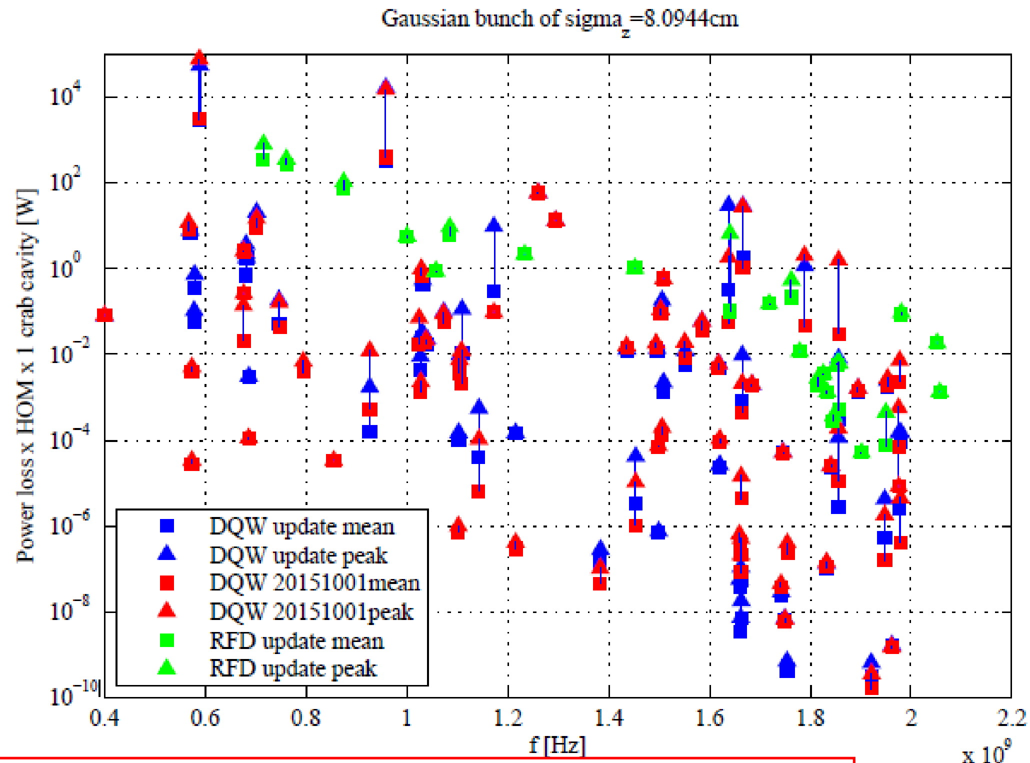
with M number of bunches, $I_b = N_b\, e\, f_0$ beam current, N_b bunch population, e proton charge, f_0 revolution frequency and $\omega_0 = 2\pi f_0$ angular revolution frequency, $S(\omega)$ the power spectrum of the bunch.

- We study each HOM accounting for a uniform distribution of f_r whitin $\pm$ 3 MHz in 1000 simulations. The study is done for 1 cavity.
- From the statistical study we derive the heating probability density function $p(X)$ from which we get the average power per HOM as:

$$\bar{X} = \int_{-\infty}^{+\infty} p(X) X \,\mathrm{d}X$$

and we extract as well the peak power dissipated (HOM and coupled bunch spectral line on top).

N. Biancacci et al



In summary we get:

- The RFD HOMs induce up to 100 W.
- The DQW HOMs induce few kW up to more than 10 kW.

→ This has been also studied in CERN-ACC-NOTE-2015-0024 and kW couplers have been designed in order to absorb this power.

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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
  - LHCb VELO: reduction of aperture with colliding beams from 5 mm to 3.5 mm.

- 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

- Dump MKD kicker is shielded behind a thin metallic coating

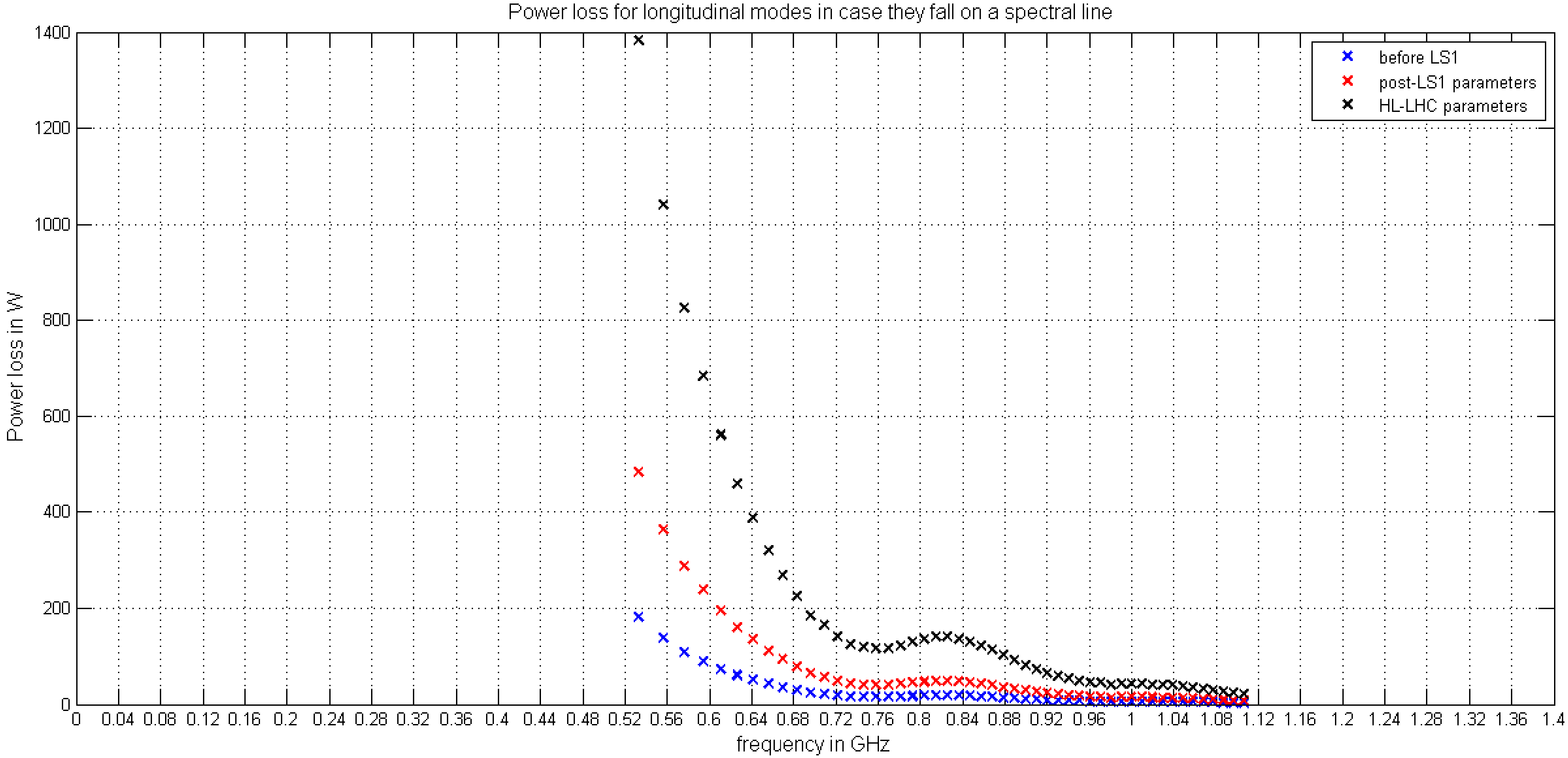
  →preliminary computations: from 6 W before LS1 to 25 W for HL-LHC (in fact small temperature increase was measured → J. Uythoven)

- 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 (here with 1.2 ns)

→ 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
- Non conformities
  - → Need more systematic temperature monitoring on near beam hardware
  - → Need to check cooling system before/during installation
  - → Need to check longitudinal impedance of new equipment before installation to detect problems
- Fruitful work with thermal simulation experts to predict temperature distribution, but still a difficult process (already started within TE-ABT fro MKIs)

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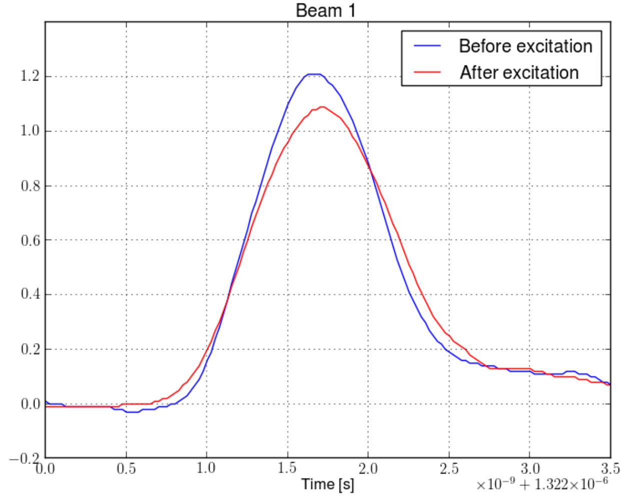
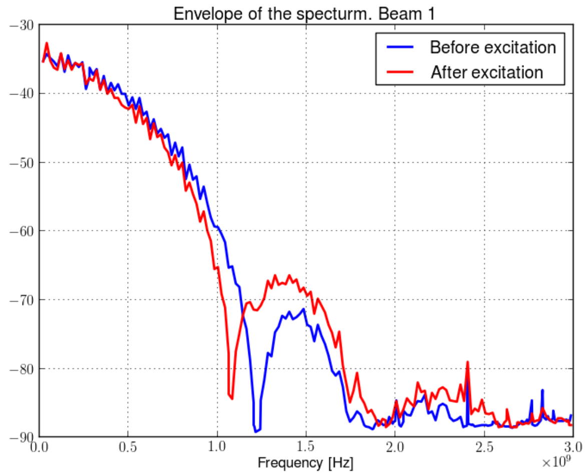
Possible mitigations in case of issues

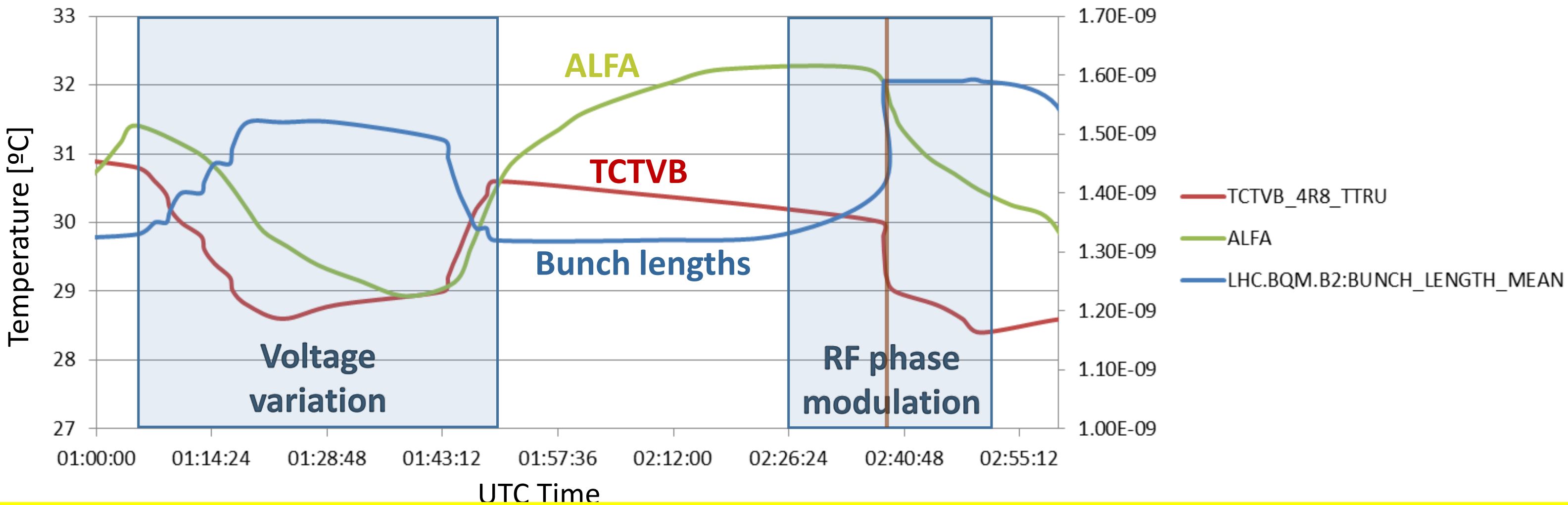
- Reduce longitudinal impedance
  - Avoid unnecessary cavities (contact RF fingers, elliptical bellows for elliptical chambers, tapered transitions)
  - If the heating is due to resistive wall, increase material conductivity
  - If the heating is due to trapped modes, reduce material conductivity
- Reduce 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)
- Reduce bunch or beam intensity
- Use flat bunches (very successful MDs by E. Shaposhnikova et al)
- Extract the heat from critical locations (ferrite, RF fingers, all mode coupler)

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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Main messages

- Many heating issues related to beam impedance in 2011 and 2012.
- Strong effort by equipment groups to modify existing hardware and optimize new ones paid off → less issues in 2015 so far.
- Still need to optimize LHC hardware as the conditions will be much tougher in HL-LHC era (~factor 5 more) → Hardware already at the limit will likely require modifications:
  - TDI (planned for LS2), already significant improvement expected after this YETS
  - MKI (still need to address the limits)
  - Beam screen cooling needs to be assessed in collaboration with WP9
- 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

Thank you very much for your attention!