BEAM INDUCED HEATING

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Abstract

In 2011, the rapid increase of the luminosity performance of LHC came at the expense of increased temperature and pressure readings on several near-beam LHC equipments. In some cases, this beam induced heating was suspected to cause beam dumps and even degradation of the equipment.

This contribution aims at gathering the observations of beam induced heating due to beam coupling impedance, their current level of understanding and possible actions that could be implemented during the winter stop 2011-2012.

INTRODUCTION

The quest for higher LHC luminosity required a significant increase of the proton beam brightness in 2011. In particular, both number of bunches and bunch intensity were significantly ramped up during the run. Increasing these intensities is expected to enhance the sources for beam induced heating. In fact, many temperature and pressure diagnostics have been installed in near-beam LHC equipments, and several of these indicated significant temperature increase when proton beam was accumulated and/or ramped.

This contribution is a follow-up of J. Uythoven's presentation at the Mini-Chamonix workshop [1] and presents the mechanisms of beam induced heating, 2011 LHC observations and possible cures, with a particular focus on heating due to the beam coupling impedance.

MECHANISMS FOR BEAM INDUCED HEATING

Several mechanisms are expected to cause unwanted temperature rise in LHC near-beam equipments: exposure to synchrotron radiation generated by the beam, impact of protons lost from the beam, impact of photoelectrons generated by the beam and radio frequency field generated by the beam interacting with the beam coupling impedance of its surrounding equipment [2]. Other external sources of cooling and heating are also present but the following chapters focus on the heating that can be correlated to the beam.

The heat load due to synchrotron radiation and photo electron cloud in the LHC have been reported in particular in [2, 3, 4] and will not be addressed here.

Heating from beam coupling impedance

The RF fields generated by the proton beam interact with the beam surrounding materials and energy can be dissipated in the non-perfectly conducting walls, eventually leading to local heating, described for instance in [5, 6, 7].

In fact the power P_{loss} lost by a beam composed of M equispaced equipopulated bunches of N_b protons travelling in the aperture of an LHC equipment of longitudinal impedance Z_{long} is [6]:

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

where e is the proton charge, f_{rev} is the revolution frequency, *Powerspectrum(f)*is the power spectrum of the bunch as a function of frequency.

In the frame of this formalism, it is important to note that the power loss is proportional to the square of the total intensity N_bM for a sharp narrow band impedance at resonating frequency $f_{resonator}$:

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

if the resonating frequency coincides with one of the beam frequencies. On the other hand, the power loss is still proportional to the square of the bunch intensity N_b but linear with the number of bunches M for a broadband impedance:

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

The LHC beam spectrum was measured during the fill 2261 with 50 ns bunch spacing [8] (see Fig. 1). It can be seen that the power spectrum consisted of sharp lines spaced by 20 MHz contained in a multi-lobe envelope. Its frequency content above 1 GHz changed significantly during and after the ramp: the power spectrum of the lobes above 1 GHz is observed to decrease significantly in stable beams, so that the spectrum appears to be most critical during the ramp. It is however important to note that the ramp does not last very long (~11 min to 3.5 TeV/c).

In the following chapter, the observations of equipments subject to beam induced heating are gathered.

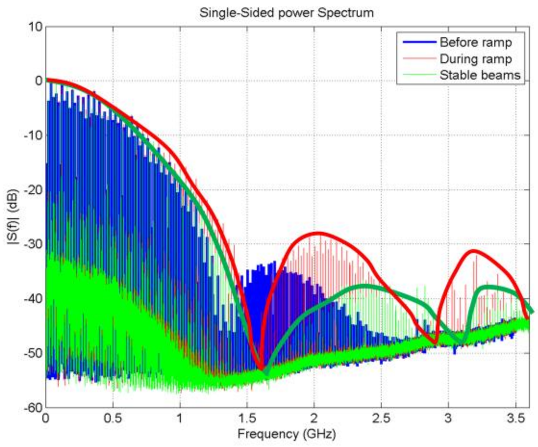

Fig. 1: LHC beam spectra measured during proton fill 2261 at injection energy (blue), during the ramp (red) and in stable beams (green) [8]. The red and green lines are coarse manual fits and their purpose is only to guide the eye.

LHC OBSERVATIONS IN 2011

Example of heating during a physics fill

The example of fill 2216 on October 15th, 2011 is shown in Fig. 2. Similar smooth steady increase of temperature is observed for both the MKI-8D kicker (up to more than 60˚C measured) and for the TCP.B6L7 collimator (up to more than 50˚C) when the beam is injected and the ramp starts. Meanwhile, odd erratic beam-related temperature behaviour is observed for the TCTVB.4R2 collimator. There is no temperature probe inside the TDI collimator and the only available TDI observable is the pressure at a neighbouring gauge, and a significant pressure increase has been observed.

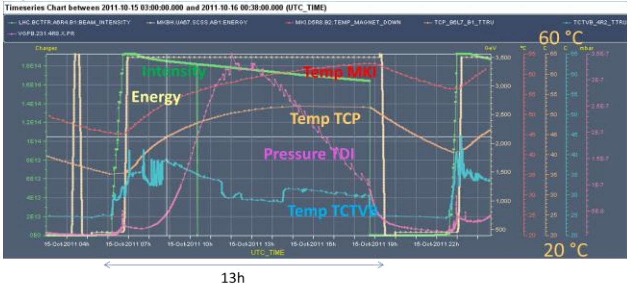

Fig.2: extraction from the logging database for the physics fill 2216 of the Beam 1 intensity (green) and energy (yellow), along with the temperature of the injection kicker MKI-8D (red), the temperature of the skew primary collimator TCP.B6L7.B1 (orange), the temperature of the two-beam tertiary collimator TCTVB.4R2 (blue) and the pressure near the two-beam injection protection collimator TDI (purple, VGPB.231.4R8).

It is important to note at this point that the measured temperature and pressure signals are indirect diagnostics of the heating of the near-beam equipments due to the distance to the location of the heat load. For the collimators, the probes are located inside the jaws. For the injection kickers they are at both ends of the kicker, on the ground plates, and thus ferrite temperature (especially near the beam aperture) can be considerably higher than the measured temperature [9].

The suspected beam induced heating limitations reported by/to the impedance team in 2011 have been gathered in Table 1.

Table 1: Summary of suspected heating LHC equipments*

LHC equipment	observable	Limits operation?	Is it happening to all similar devices ?
TCP.B6L7.B1	Temperature	Yes (dump)	No (1/6)
TCTVB.4R2	Temperature	Yes (dump)	No (1/4)
TDI	Vacuum Temperature (outside tank)	Not anymore (after increasing parking position)	Yes (2/2)
MKI	Temperature, pulsed rise time and delay	Yes (need to wait for cooldown)	All are heating but MKI-8D is heating most (1/8)
Beam screen	Heat load computed from regulation response	No, except in one cell Q6R5	No (only one stand alone)
ALFA	Temperature on the roman pots	Not yet	Yes, but cooling was installed in TOTEM and not in ALFA.
VMTSA	Vacuum Spring broken after May	Yes (spring broken and dangling fingers)	Yes (8/10)
BSRT Mirror	Jitter in BSRT measurement with beam	mirror is deforming?	N/A
BGI	Vacuum	Probably not a heating issue	N/A

The following paragraphs will review the studies on these LHC equipments in more detail.

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[*] The colour code indicates the need for follow up of the considered heating problem on LHC operation at the time of the Evian workshop 2011. As it will be discovered shortly after the workshop, the TDI beam screen had been deformed and the need for follow-up quickly changed from green to red [7, 10]. On the other hand, the TCTVB.4R2 was removed from the machine during the winter stop and the need for follow up switched from yellow to green.

TCP.B6L7.B1 collimator

TCP.B6L7.B1 is a single-beam skew primary collimator in IR7 and its interlock on the jaws' temperature measurement caused a beam dump of fill 2217 on Sept 17th 2011. Following this beam dump, the temperature interlocks were raised from 50˚C to 55˚C (on Sept. 17th) for both skew TCPs, and to 70˚C (on Oct. 16th) only for TCP.B6L7.

As can be seen on Fig. 3, the temperature of TCP.B6L7 increased steadily over the year together with the beam intensity, and the zoom seen on the example fill on Fig. 1 shows the clear heating dependence to the beam presence and ramp.

While the 4 temperature probes on the jaws of TCP.B6L7 display temperature increases of 10 to 25˚C, its symmetric counterpart for B2 (TCP.B6R7), along with all other IR7 primaries, show temperature increases of 1 to 2˚C.

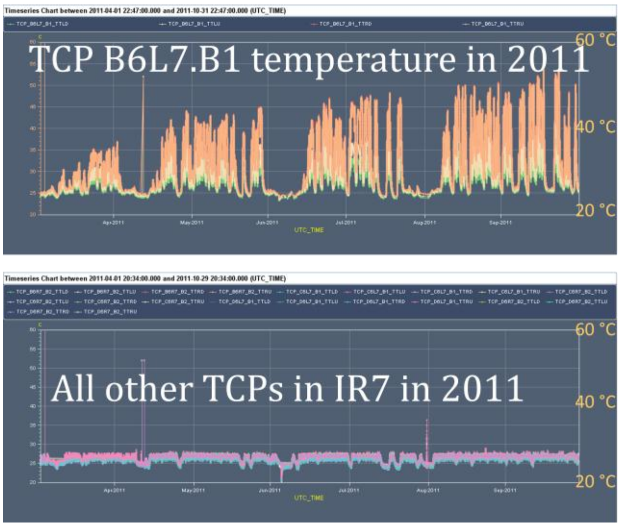

Fig. 3: measured jaw temperatures by the 4 probes of TCP.B6L7 (top) and for all other primaries (bottom) during the 2011 proton run (April 1st to October 29th 2011).

If this heating were due to the collimator impedance, this abnormality would point to a non-conforming TCP.B6L7 system compared to the other collimators, either its impedance reduction system or its cooling system. Non invasive checks of the cooling system and external fiducialization as well as X-rays of the RF fingers are planned before the end of the technical stop as the sector is not planned to be opened.

As seen on Fig. 4, extrapolating crudely to higher stored beam intensities planned for 2012 (1380 bunches with 1.6 10^{11} p/b) enables to estimate that the TCP.B6L7 temperature at saturation could reach more than 65˚C. Even though it is difficult to conclude, the observed increased slope of the temperature behaviour above 1.5E14 protons per beam could be a sign that the effect of increasing the number of bunches is smaller than the effect of increasing the bunch intensity. This would indicate that the TCP.B6L7 heating source would be a broadband and not a narrow band.

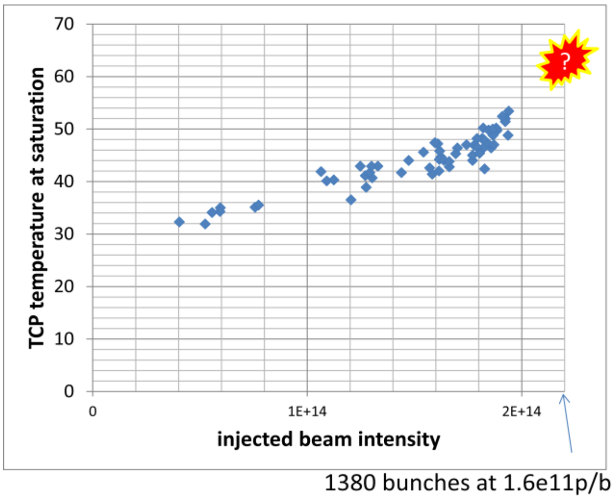

Fig. 4: TCP.B6L7 temperature at saturation as a function of beam intensity in number of protons (blue) extracted from the logging database for the 2011 run. The extrapolation is very hazardous and there are hints of a slope/power law change above 1.8E14 p. This behaviour could be consistent with a linear scaling with the number of bunches (up to 1.5E14 p) and a quadratic behaviour with the number of particles per bunch (above 1.5E14 p).

TCTVB.4R2

TCTVB.4R2 is a two-beam vertical tertiary collimator, and its interlock on the jaw's temperature measurement caused a beam dump of fill 2198 on Oct 9th 2011. As seen on Fig. 2, the beam induced temperature increase is clear, but its behaviour seems erratic along the year on Fig. 5 and appears to be non monotonous with intensity or bunch length. Figures 6, 7 and 8 show that heating also affects the 3 other TCTVBs installed in the machine (up to 35˚C at worst), but to a lesser extent than TCTVB.4R2 (up to 55˚C).

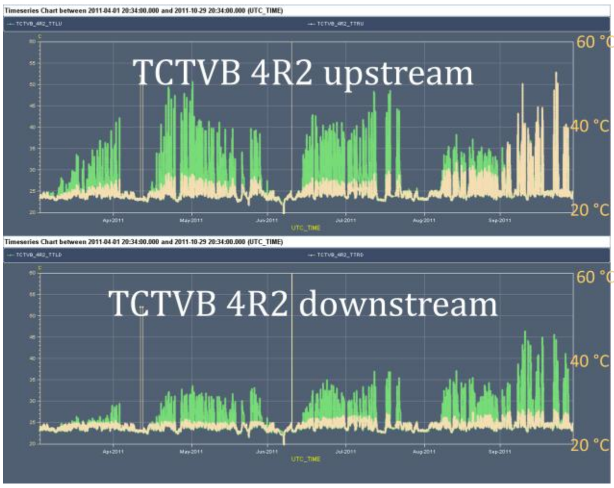

Fig. 5: measured jaw temperatures for TCTVB.4R2 upstream (top,) and downstream (bottom) during the 2011 proton run (April 1st to October 29th 2011). Using the

classical collimation convention, the “left” jaw is in green and the “right” jaw is in beige.

Due to the lack of monotonic dependence with beam parameters and the very rapid changes of temperature observed on Fig. 2 for instance, the heating source of the TCTVB.4R2 was not clear at the time of the workshop.† Some correlations of the rapid changes of temperature could be noticed with the losses on BLM2I.04R2.B1|10_MRBC:LOSS_RS01, but this should be investigated further.

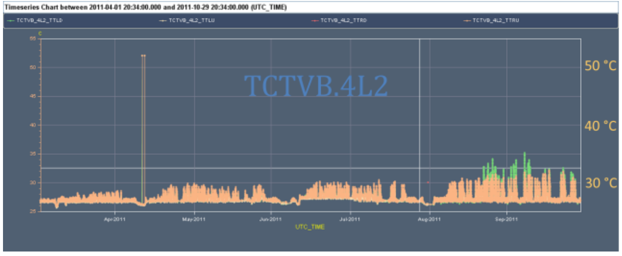

Fig. 6: measured jaw temperatures for the 4 probes of the TCTVB.4L2 during the 2011 proton run (April 1st to October 29th 2011).

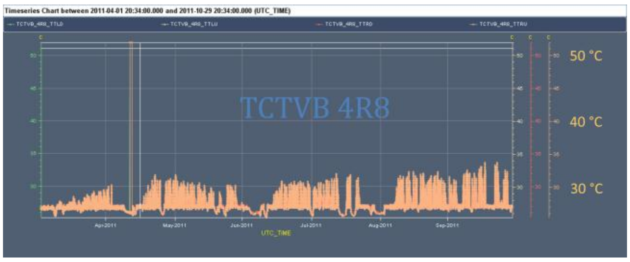

Fig. 7: measured jaw temperatures for the 4 probes of the TCTVB.4L2 during the 2011 proton run (April 1st to October 29th 2011).

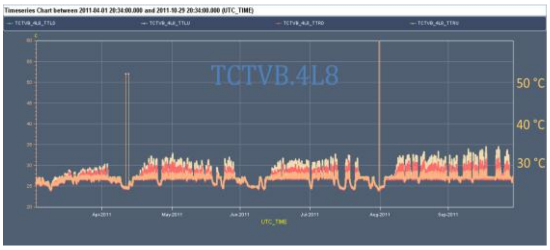

Fig. 8: measured jaw temperatures for the 4 probes of the TCTVB.4L8 during the 2011 proton run (April 1st to October 29th 2011).

TDI injection protection collimators

During the 2011 run, pressure gauges near the TDI in points 2 and 8 recorded significant beam induced pressure rise that appeared to affect the experiments, in particular the ALICE background in point 2 [12]. Temperature probes were installed and also detected a temperature increase during the fill [13]. Increasing the parking gap of the TDI in physics from +/-20mm to +/-55mm from fill 2219 damped the pressure increase, but not the temperature increase [13]. Decreasing the gap on Beam 2 back to +/-20mm for fill 2261 generated pressure rise again, which confirmed the clear correlation of the pressure rise with the gap [14]. The problem therefore seemed to be solved at the time.

Besides, a thorough HFSS/CST simulation campaign was ongoing and CST time domain simulations predicted several sharp resonances at low gaps (4 mm and 20 mm half gaps), which would result in a reduction of power loss by a factor of 10 when the nominal parking gap position was used (55 mm half gap), see Fig. 9.

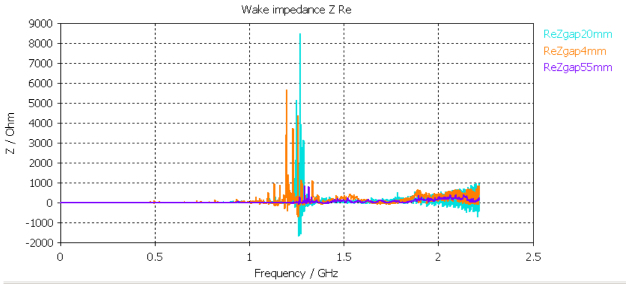

Fig. 9: longitudinal impedance as a function of frequency for the TDI model with jaw half gaps of 4 mm (orange), 20 mm (cyan), 55 mm (purple). Signal increase above 1.8 GHz should be discarded, as caused mainly by noise enhanced by the finiteness of the simulated source bunch.

Besides, MDs on measuring the transverse impedance of both TDIs gave hints that the TDI impedance was larger than predicted by the resistive wall and trapped modes model and may have degraded since the previous MD in May 2010 [14, 15]. This discrepancy in transverse impedance could be due to a problem with the coating integrity and/or thickness and it was therefore asked to check in-situ the status of the Titanium coating before the 2012 start-up.

Finally, measurements of the synchronous phase during the TDI MD will also be studied in more detail to see if the power loss due to the TDI jaws can be accurately estimated from the logged data.

MKI-8D injection kicker

As observed in Fig. 10, the MKI injection kickers were affected by a steady increase of beam induced heating during the 2011 run. The temperature interlock was initially set at 50˚C, and raised during the run to 62˚C for MKI-8 after carefully checking that the ferrite yoke of the kicker magnets did not show evidence of reaching the Curie temperature: this increase speeded up turnaround time and no obvious issue was seen with the heating rate of 2011. However, the probe is far from the ferrite and there is no guarantee that this interlock level will be ok with higher heating rates expected next year.

For MKI-8D, a significant reduction in current rise time was already noted during SoftStart at the measured temperature of 68˚C, which would correlate to a reduction

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† After the workshop, the TCTVB.4R2 was removed from the machine to solve an interference problem with the ALICE ZDC and replaced by a single beam TCTV [10].

in kick strength, and a degradation of the performance of the kicker [9]. From the rise time, all other 7 MKIs did not seem to have reached that limit, but it is not possible to know at what temperature the limit would be, due to lack of cross-calibration of the probes and locations [9]. As can be seen on Fig. 10, MKI8D reached measured temperature of 68˚C, MKI8B 57˚C, all the other MKIs are below 45˚C.

CST simulations and bench measurements of the MKI both show that beam induced heating is expected for the kicker and that installing the 24 screen conductors as initially planned should significantly reduce the heat load on the MKIs [16]. As seen on Fig. 11, increasing the bunch length from 1.2 ns to 1.3 ns is expected to be marginally beneficial.

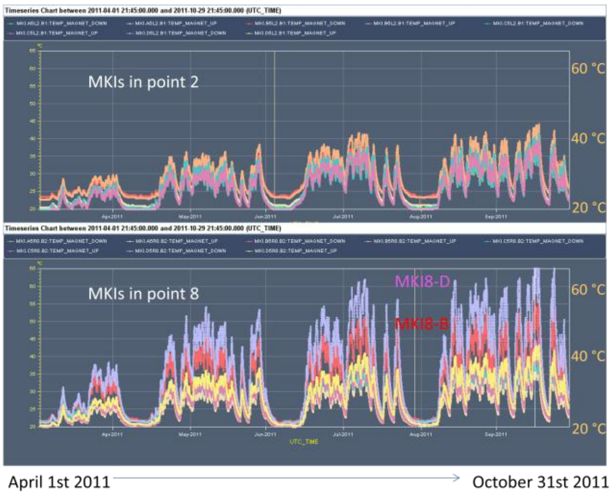

Fig. 10: measured temperatures for MKI-2 (top) and MKI-8 (bottom) during the 2011 proton run (April 1st to October 29th 2011). MKI8-D (in purple, bottom plot) and MKI8-B (in red, bottom plot) clearly stick out compared to all other measured temperatures.

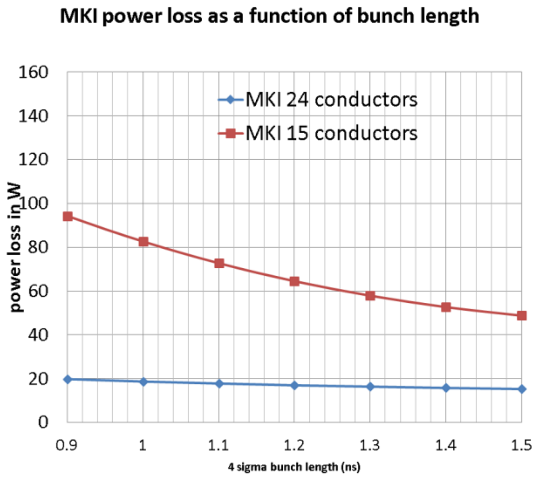

Fig. 11: power loss simulated as a function of bunch length for the MKI with 24 screen conductors (blue) and 15 screen conductors (red) with a $\cos^2$ bunch distribution. Courtesy H. Day et al.

Finally, the turnaround times were extrapolated for 2012 from a simple model fitting the temperature build up and decrease in 2011 and predicted that 50 ns operation at 2 10^{11} p/b in 2012 would be significantly affected as 4h would be needed after a dump to cool down the MKI-8D [17]. 25 ns operation seems to have more margin [17].

For safe operation in 2012, it was recommended to continue analyzing systematically SoftStart data to check that the kicker is in a good state before injection if the temperature approaches SIS level. In addition a higher resolution digitizer will be installed during the 2011-2012 winter stop to allow monitoring of the delay of the MKIs, which will provide an additional diagnostic for heating of the ferrite yoke. Once sufficient experience and confidence is established in using the rise-time and delay to assess the status of the ferrite yoke, TE/ABT plans to automate the analysis of these diagnostics.

Longer term actions include work on the impedance reduction of the full kicker assembly, impedance measurements on MKI-8D to understand higher heating on this kicker, and building spares with, if possible, 24 screen conductors (1 spare is available with 15 screen conductors).

Possible actions during the winter stop would be to assess the RF fingers state of MKI-8D using X-rays, as this kicker contains the original design of RF fingers[‡]. Replacing MKI-8D with a spare was ruled out to keep a spare that could be installed in both points 2 and 8.

Stand alone Q6R5

For the beam screens in general, a strong dependence of the peak value of beam induced heating with the bunch length was observed [2]. After the regulation tuning and the slight bunch length increase in June 2011 the heat load on the beam screens with 50 ns beam could be managed [2, 3].

During the scrubbing run, the 25 ns heat load appeared to be initially dominated by electron cloud, but it was converging towards predictions, which was manageable by the cryo [5].

There was also the worry that the heat load generated by the nominal beam might be just manageable for the triplets if scaling laws were applied. However the cryo team mentioned that more cooling power could be applied within a few days if needed.

Only one outlier was reported: the standalone in Q6R5, which appeared to have no margin for additional cooling (see Fig. 12). The valve at Q6R5 is now open at almost 100% and the baseline cannot be lowered anymore. If additional heat load is generated by increased bunch intensity in 2012, the temperature would then increase above 17K, which could then become a potential issue for vacuum.

It is interesting to note that the added heat load seems to be directly correlated with the ramp (not the beam accumulation) and that the symmetric standalone in Q6L5

[‡] X-rays were made during the 2011-2012 but were inconclusive as available space for X-raying the RF fingers was very limited between the kicker tank and vacuum valves.

requires only additional opening of the valve in the percent level when the beam is ramped.

Xrays of the cooling system were performed but no obstruction or obvious non-conformity could be found. As the sector is not planned to be opened, not much can be done before LS1 to better understand the problem.

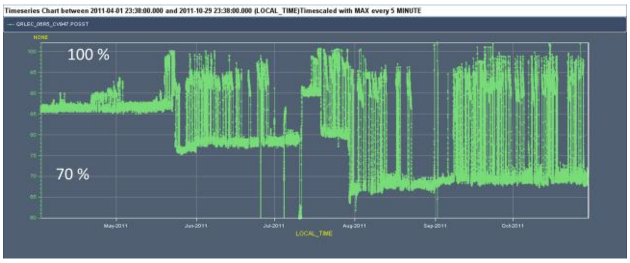

Fig. 12: valve opening for standalone Q6R5 during the 2011 run (April 1st to October 29th 2011).

VMTSA double bellow

Xrays showed non-conforming RF fingers in several VMTSA modules, apparently due to springs that broke between May and November 2011[18].

These bellows are very special (only 10 modules in the LHC) as (1) they contain very long RF fingers - 28 cm instead of 17 cm – (2) the contact force between the fingers and the beam screen is smaller than in other modules as the fingers are preconstrained to open as a flower, (3) there is no groove to hold the fingers in case the spring breaks, and (4) the cylindrical surrounding cavity around the fingers is very large compared to other modules. All these characteristics make these modules much more subject to non-conformities than the smaller bellows. Since simulations with the ideal conforming module does not predict a large impedance, a runaway effect is feared with a possibility of electro-magnetico-thermo-mechanical fatigue of the spring, leading to loss of contact of the fingers, and eventually large impedance and heating.

Impedance measurements and simulations were being performed at the time of the workshop and a consolidation of the module was being planned during the winter stop to improve both the impedance shielding and the spring thermal resistance [19].

Other equipments

The studies for the ALFA detector had just started at the time of the workshop and were not mentioned in detail. Further information can be found in [7, 20, 21].

The BSRT offset issue was not studied at the moment of the workshop.

Not enough information could be gathered on the BGI pressure increase with 12 bunches to conclude that it was due to beam induced heating.

POSSIBLE ACTIONS FOR THE WINTER STOP 2011-2012

- Consolidation of the VMTSA is ongoing.

- Further checks of non-conformities of the RF shielding and cooling systems are proposed, when possible:
    - RF fingers and cooling for TCP.B6L7.B1,
    - RF fingers of TCTVB.4R2,
    - RF fingers of MKI-8D,
    - Bellow modules around the standalone in Q6R5,
    - Check of the coating of the TDI.

- Additional diagnostics would help, in particular:
    - Temperature probe closer to the TDI jaws,
    - Temperature diagnostics in Q6R5.

- Significant impedance simulation and measurement effort is ongoing for:
    - VMTSA bellow module,
    - TDI collimator,
    - MKI kicker,
    - ALFA roman pot.

OUTLOOK

In 2011, several beam induced heating problems in LHC could be temporarily overcome (by increasing the bunch length or moving out the TDI jaws for instance).

For the 2012 run, the most limiting equipment for operation appears to be the MKI, which may increase the turnaround time for higher bunch intensities.

Additional diagnostics and checks of the impact of larger bunch length with a few fills could be tried. However, it is expected that the full bunch length cannot be reasonably increased beyond 1.35-1.4 ns as an increased bunch length leads to both luminosity reduction due to the geometric factor and in faster beam losses [22].

Finally heavy effort is put on impedance simulations to understand to what extent impedance is the reason of observed heat load in LHC equipment and to find mitigation solutions.

ACKNOWLEDGMENTS

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