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UPDATE ON BEAM INDUCED RF HEATING IN THE LHC

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Abstract

Since June 2011 the rapid increase of the luminosity performance of the LHC has come at the expense of both increased temperature and pressure of specific, near-beam, LHC equipment. In some cases, this beam induced heating has caused delays while equipment cool-down, beam dumps and even degradation of some devices. This contribution gathers the observations of beam induced heating, attributed to longitudinal beam coupling impedance, their current level of understanding and possible actions planned to be implemented during the 1st LHC Long Shutdown (LS1) in 2013-2014.

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INTRODUCTION

The quest for higher LHC luminosity required a significant increase of the proton beam brightness [1]. In particular, both number of bunches and bunch population were pushed to the limits of what was available from the injectors and resulted in an increased beam induced heating. The beam induced heating problems encountered in the LHC are summarized in Table 1. Temperature increase in LHC devices can cause several issues (damage, delays or dumps). This contribution deals with heating caused by the RF fields generated by the beam interacting with the longitudinal beam coupling impedance of its surrounding equipment, and is a summary of many reviews performed over the past 2 years at CERN (for instance [2, 3]).

The equations for this beam induced RF heating have been covered in particular in [2]. The power P_{loss} lost by a beam composed of M equally spaced and populated bunches of N_b protons travelling in the aperture of an LHC equipment of longitudinal impedance Z_{long} is given by:

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

where e is the proton charge, f_{rev} the revolution frequency, and $PS(f)$ the power spectrum of the LHC beam as a function of frequency.

In the following section, the observations of beam induced heating on equipment during the 2012 run are summarized.

Table 1: Summary of LHC equipment heating in 2011, prospects for 2012 before the run and what really happened in 2012[*].

LHC device	**Problem**	**2011**	**Expected 2012**	**What happened in 2012**
VMTSA	Damage	⬛	🟩	🟩 replaced
TDI	Damage	⬛	⬛	⬛ Still problems
MKI	Delay	🟥	🟥	🟥 MKI8 (D then C)
TCP.B6 L7.B1	Few dumps	🟥	🟥	🟥 Interlock increased
TCTVB	Few dumps	🟨	🟨	🟨 Interlock increased
Beam screen Q6R5	Regulation at the limit	🟨	🟨	🟩 Disappeared since TS3. Correlation with TOTEM?
ALFA	Risk of damage	🟨	🟨	🟥 Due to Intensity increase
BSRT	Damage	🟨	🟨	⬛ damage

OBSERVATIONS AND LIMITATIONS DURING THE 2012 RUN

An example of temperature increase on kickers, collimators and ATLAS-ALFA detector for 4 fills in mid-November 2012 is shown in Fig. 1. The following paragraphs review the status of the elements listed in Table 1. More details can be found in [3].

VMTSA double bellow

At the end of the 2011 run, eight bellows of the VMTSA type (out of 20) were found to be damaged. Eight modules were reinstalled with new shorter RF fingers, ferrite plates and a reinforcement corset. No problem of heating has been observed since. The plans for LS1 are to remove all these modules and identify other module types that could fail.

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[*] The colour code indicates the need for follow up of the considered heating problem on LHC operation. Black means damaged equipment; red means detrimental impact on operation (dump or delay or reduction of luminosity); yellow indicates need for follow up; green means solved.

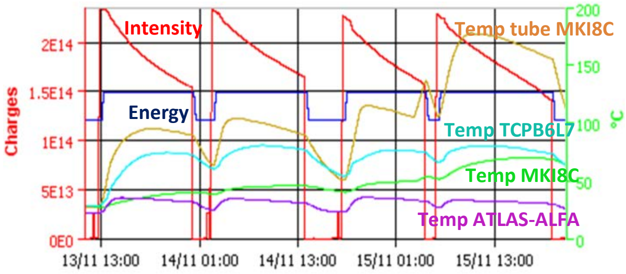

Fig.1: Measured LHC beam intensity (red) and energy (dark blue), along with the measured temperatures of the ceramic tube of the injection kicker MKI-8C (orange), of the skew primary collimator TCP.B6L7.B1 (light blue), of the magnet ferrite of the injection kicker MKI-8C (green) and of the ATLAS-ALFA detector (purple).

TDI injection protection collimator

Abnormal deformation of the two TDI beam screens was found during the winter shutdown 2011-2012 [4]. Temperature, vacuum, and jaw deformation measurements during the run suggested significant heating as the TDIs were not retracted to parking position, as it should have been as soon as the injection process was finished. Electromagnetic simulations confirmed that the heating can be significant. It is however not completely clear that beam induced heating alone generated the damage. Both TDIs were left in that state in 2012 as no TDI with an improved design was available.

During the 2012 run, suspicious pressure curves could indicate that additional heating occurred in or close to the TDI4L2 since mid-2012. Many mechanical issues occurred on both TDIs towards the end of the 2012 run [5], and RF heating during operation could potentially have made things worse. Current plans for LS1 include increasing the beam screen thickness and the possibility to add a thin copper coating is now being studied to limit RF heating of the jaw. TDIs following a completely new design are foreseen for the following long shutdown LS2.

MKI injection kickers

Some MKIs have delayed injection by up to a few hours, to allow the ferrite yoke to cool down [6]. Electromagnetic simulations and measurements as well as thermal simulations are consistent with observations (despite the very high complexity of the device). Extensive studies have been performed to reduce the electric field on screen conductors, reduce the longitudinal impedance, and improve heat radiation from the ferrite by increasing the tank emissivity. These studies are presented in more detail in [7]. It is foreseen to upgrade all MKI magnets during LS1.

TCP.B6L7.B1 skew primary collimator

The TCP.B6L7.B1 collimator caused beam dumps in 2011 and 2012. The steady increase of its jaws' temperature during physics fills, with increasing beam intensity, required increasing the interlock to 95°C (see Fig. 1), while the temperatures of all other primary collimators (including the temperature of its equivalent for beam 2) have increased to less than 38°C. The pattern of temperature increase indicates that it is due to either beam losses or beam induced RF heating. Joint analysis of heat deposition and measured temperatures points to an absence of efficient cooling, and hence a non-conformity of the cooling system is suspected [8, 9]. However nothing wrong was seen, with visual and X-ray inspections, on cooling systems or RF fingers. Plans for LS1 include a thorough check of the cooling system and the replacement of this collimator for inspection.

TCTVB tertiary collimators

Despite active cooling, the two TCTVBs in point 8 consistently heated by around 10 degrees in most fills. It is interesting to note that beams were dumped by TCTVB.4L8 temperature when the longitudinal blow up stopped working during a ramp in May 2012. This could be a worry if the bunch length is significantly reduced in physics. The two remaining TCTVBs in IR8 are foreseen to be replaced by single beam TCTPs during LS1.

Beam screen temperature regulation (Q6R5)

Until the beginning of Sept. 2012, the beam screen of the standalone quadrupole magnet Q6R5 standalone had no margin for increased cryogenic cooling. This could represent an issue for 7 TeV operation. Tests were performed (X-rays on both bellows and cooling circuit) but no non-conformity was seen that could explain the above behaviour. Since September 2012, the situation improved significantly. Only a few fills have been affected since, in particular the fills following a movement of the neighbouring TOTEM roman pot, indicating a possible correlation (through vacuum, dust, and/or losses). During LS1 the valves for standalones will be replaced to allow a higher cooling flux.

ATLAS-ALFA Roman pot

The ATLAS-ALFA detectors' temperature (see Fig. 1) reached 42°C close to the inner detector and entered the range that is expected to lead to detector damage (around 45°C). The ATLAS-ALFA temperature became particularly critical at the end of October 2012 on beam 2 when strong changes in the longitudinal beam spectrum at flat-top were observed [3]. Simulations and bench measurements showed that the temperature increase is consistent with impedance heating of the ferrite damper ring (which is efficiently preventing more harmful heating) [9]. As emergency measures, the ATLAS-ALFA team removed the bake-out jackets and added some fans. Plans for LS1 foresee the implementation of a new design with reduced impedance and active cooling in order to allow for a more comfortable operational margin in 2015.

BSRT synchrotron light monitor

The beam 2 synchrotron light monitor (BSRT) mirror, ferrites and support suffered from damage that is believed to be due to significant heating. Studies were performed to understand the heat deposition, and to look for adequate solutions for after LS1 and are presented in [11].

EXPECTATIONS AFTER LS1

After LS1, possible beam parameters include (1) 25 ns bunch spacing at 6.5 TeV with 1.15 10^{11} protons per bunch (p/b) or (2) 50 ns bunch spacing at 6.5 TeV with 1.6 10^{11} protons per bunch [12]. The effect of bunch spacing and bunch length on beam induced heating is discussed in the following paragraphs.

Effect of bunch spacing

Assuming the same bunch length and same longitudinal distribution for 50 and 25 ns bunch spacing, the same beam spectrum with 25 ns spacing as with 50 ns is expected from Eq. 1, but with half of the peaks. In the frame of this assumption, switching to 25 ns for the case of a broadband impedance should yield an increase by a factor $M^{(25)}*(N_b^{(25)})^2/\ M^{(50)}*(N_b^{(50)})^2 = 1.05$, where $M^{(50)}$=1380, $M^{(25)}$=2808, $N_b^{(50)}$=1.6 10^{11} p/b, $N_b^{(25)}$=1.15 10^{11} p/b. Switching to 25 ns for the case of a narrow band impedance falling on a beam harmonic line (i.e. its resonant frequency is $f_{res}= k*20$ MHz with k an integer) should yield an increase by a factor $(M^{(25)}*\ N_b^{(25)})^2/(M^{(50)}*\ N_b^{(50)})^2 = 2$ if $f_{res}= 2*k*20$ MHz with k an integer, or a total suppression if $f_{res}= (2*k+1)*20$ MHz.

Operation with 25 ns spacing could therefore have a detrimental impact on some of the undamped narrow band resonances. Among the elements which are observed to suffer from beam induced heating, most are expected to be broadband and therefore they should not be affected significantly by the change of bunch spacing.

Effect of bunch length

Assuming the same longitudinal distribution, reducing the bunch length is expected to enlarge the beam spectrum (see Fig. 2). Hence, switching to lower bunch length for broadband impedance with a resonant frequency below 1.2 GHz leads to a regular increase of beam induced heating. Switching to lower bunch length enhances some narrow band resonances, damps others, and may excite new resonances at higher frequency.

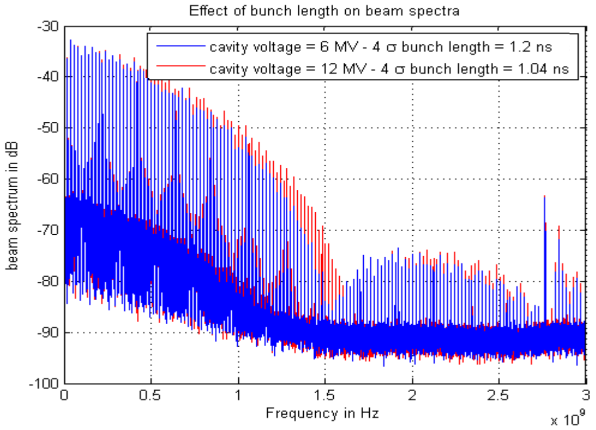

Fig. 2: Effect of reducing bunch length on measured LHC beam spectrum (in dB) from 1.2 ns (in blue) to 1.04 ns (in red). The first notch of the distribution is observed to shift from 1.5 GHz to 1.7 GHz. The peaks beyond 2.7 GHz are believed to be due to the acquisition system bandwidth.

OUTLOOK

Many LHC devices have heated significantly following the bunch intensity ramp-up in 2011 and 2012. Actions are planned to be taken in LS1 to prepare safe and smooth running in 2015: (a) All MKIs will be upgraded by magnets which have impedance reduction measures (b) Efficient cooling should be installed for all near beam equipment (in particular BSRT, TDI, ALFA); (b) RF contacts should be consolidated according to the conclusions of the LHC RF Fingers working group [13]; (c) suspected non-conformities should be investigated (TCPB6L7, MKI8C, and Q6R5 with its correlation with TOTEM movements); (d) more temperature monitoring of critical equipment should be installed (e) the longitudinal beam distribution should be controlled and optimized to reduce heating (if it is technically possible and as long as it does not impact longitudinal stability). Since most devices that heated have shown predominantly broadband impedance, the operation with 25 ns is expected to lead to slightly larger power loss (for the same bunch length and bunch distribution and for nominal bunch intensity). TDI and maybe BSRTs, which also exhibit large narrow band impedances should be monitored closely.

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REFERENCES

[1] M. Pojer, Introduction and review of the year including OP issues, LHC Beam Operation workshop, Evian (2011).

[2] E. Métral et al, Beam-induced Heating/Bunch Length/RF and lessons from 2012, LHC Performance workshop, Chamonix (2012).

[3] B. Salvant, Beam induced RF heating in LHC, LHC Beam Operation workshop, Evian (2012).

[4] R. Losito, CERN LHC Machine Committee 119, 2012.

[5] C. Bracco, Injection and Dump Systems, LHC Beam Operation workshop, Evian (2012).

[6] M.J. Barnes et al., “Beam Induced Ferrite Heating of the LHC Injection Kickers and Proposals for Improved Cooling”, these proceedings, MOPWA031.

[7] H. Day, Impedance Studies of improved beam screens for the LHC Injection Kickers, these proceedings.

[8] M. Garlasche, TCP.B6L7.B1: analytical and numerical evaluation of unexpected heating, CERN collimation working group 148, Sept 10 (2012).

[9] B. Salvant, TCP heating and impedance issues, CERN LHC collimation working group 148, Sept 10 (2012).

[10] S. Jakobsen, B. Salvant et al, Update on heating and impedance studies for ALFA, ATLAS-ALFA community general meeting, Dec 4th 2012.

[11] F. Roncarolo et al, Electromagnetic coupling between high intensity LHC beams and the synchrotron radiation monitor light extraction system, these proceedings.

[12] R. Steerenberg, Post LS1 25 ns and 50 ns options from the injectors, LHC Beam Operation workshop, Evian (2012).

[13] E. Métral et al., Lessons learnt and mitigation measures for the CERN LHC equipment with RF fingers, these proceedings