LHC IMPEDANCE MODEL: EXPERIENCE WITH HIGH INTENSITY OPERATION IN THE LHC

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Abstract

The CERN Large Hadron Collider (LHC) is now in luminosity production mode and has been pushing its performance in the past months by increasing the proton beam brightness, the collision energy and the machine availability. As a consequence, collective effects have started to become more and more visible and have effectively slowed down the performance increase of the machine. Among these collective effects, the interaction of brighter LHC bunches with the longitudinal and transverse impedance of the machine has been observed to generate beam induced heating, as well as longitudinal and transverse instabilities since 2010. This contribution reviews the current LHC impedance model obtained from theory, simulations and bench measurements as well as a selection of measured effects with the LHC beam.

INTRODUCTION

The quest for higher LHC luminosity has required a significant increase of the proton beam brightness in 2010, 2011 and 2012, as well as a decrease of the β function β* at the interaction points (IP) in 2012 thanks to tight collimator settings [1]. Both number of bunches and bunch intensity were significantly ramped up during these runs, which - together with the smaller collimator gaps of the collimators at collision energy in 2012 - was observed to enhance instabilities and beam induced heating.

The impedance of the LHC was known to be a source for beam instabilities and beam induced heating and estimates of the LHC impedance model have been refined since the first impedance database ZBASE [2, 3].

In this proceeding, the LHC impedance model will be compared to observables obtained from beam measurements before reviewing current beam brightness limitations.

CURRENT LHC IMPEDANCE MODEL

The current impedance model [3] contains contributions from collimators, beam screens, warm beam pipe and a broadband impedance model described in the design report [4, p.101]. The longitudinal and transverse impedance models are shown in Figs. 1 and 2. It can be noticed that the horizontal and vertical impedances are of similar order of magnitude. Other impedance contributions obtained from 3D simulations of individual devices are planned to be added to the impedance model, but simulating very long wakes for multibunch multiturn macroparticle simulations has proved to be very difficult so far.

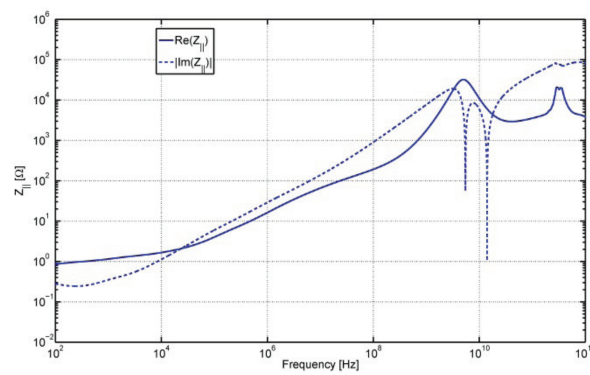

Figure 1: LHC longitudinal impedance model as a function of frequency at injection energy (2012).

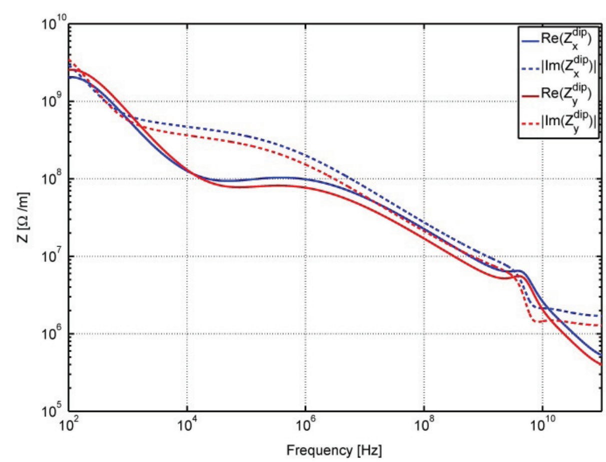

Figure 2: LHC transverse impedance model as a function of frequency at collision energy with squeezed optics (2012).

* Work partially supported by US-LARP.

ISBN 978-3-95450-118-2

Comparison between Impedance Model and Beam Based Measurements

Several measurements with beam were performed in the LHC in order to assess its longitudinal and transverse impedance. Transverse tune shift measurements with intensity were performed and they suggest that the measured impedance is larger by a factor of about 2 at top energy compared to impedance model predictions [5] (see Fig. 3).

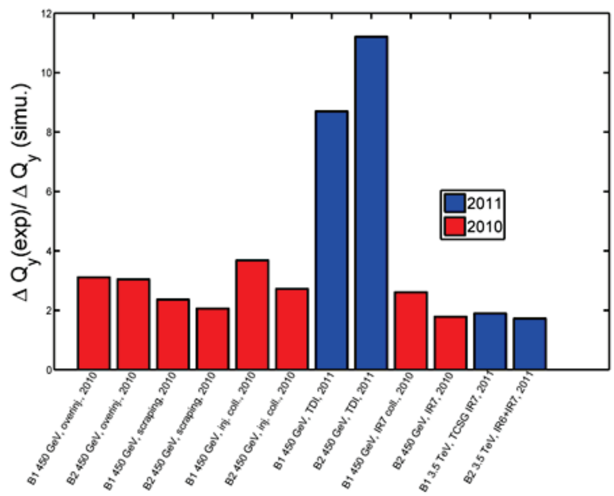

Figure 3: Discrepancy factor between tune shift measurements (*$\Delta Q_y(exp)$*) and simulated tune shifts ((*$\Delta Q_y(simu)$*) during beam measurement sessions in 2010 (injection) and 2011 (injection and collision).

A significant discrepancy (a factor of 2 to 6, depending on the assumed longitudinal bunch profile) was also observed between synchrotron phase shift measurements and synchrotron phase shift expected from the current longitudinal impedance model [6]. It is important to note that the impedance model was so far focused on the main contributors to the transverse impedance, so that more effort should now be also put to update the longitudinal impedance model.

On-going Work

Besides adding contributors to the LHC impedance model, the CERN RF and impedance teams have focused on providing reliable measurements of the properties of materials at high frequencies - such as ferrite and lossy dielectrics [7, 8] -, and on understanding the distribution of heat load in the presence of lossy materials. This latter study is important to predict the range of usability of ferrites as damper of resonant modes since ferrites lose their magnetic properties when their temperature reaches their Curie point.

HISTORY OF BEAM BRIGHTNESS LIMITATIONS DUE TO IMPEDANCE

Since the LHC start-up in 2008, impedance was observed to limit beam brightness at several occasions. Along the years, both the number of bunches and the bunch intensity were increased. The LHC impedance at collision energy was also increased between 2011 and 2012 with the tight collimator settings [1]. As a consequence, impedance effects were predicted to be more and more critical.

2010: The Year of the Single-bunch Instabilities

In 2010, single bunch limitations were observed and cured:

- Longitudinal loss of landau damping was observed during the ramp and at collision energy for small emittances and was cured by longitudinal emittance blow-up during the ramp [9].
- A horizontal single bunch coherent instability occurred during the ramp and could be stabilized with Landau octupoles [10].

2011: The Year of the Beam Induced Heating

In 2011, the steady ramp up in bunch number and bunch population lead to heating of LHC near beam components, allegedly causing [11, 12]:

- damage to VMTSA bellow modules and injection collimators (TDI);
- increasing turn-around time as the temperature of the ferrite of the injection kicker (MKI) was over the allowed temperature for safe injection;
- individual beam dumps due to temperature interlocks on a primary collimator (TCP) and a tertiary collimator (TCTVB);
- worry for the future operation with the synchrotron light monitors, the ATLAS-ALFA detectors and 1 cryomodule (Q6R5).

2012: The Year of the Transverse Instabilities

In 2012, beam induced heating continued to affect operation despite several actions, but – following in particular the implementation of the tight collimator settings – the main limitation came from several types of transverse instabilities that consistently occurred during the beam processes “Squeeze” (when β* at the IPs are squeezed), “Adjust” (when the separation bumps are collapsed and collisions prepared) and/or “Stable beams” (when physics data can be acquired).

The following sections will focus on detailing the current issues at LHC, namely beam induced heating and transverse instabilities.

BEAM INDUCED HEATING

Theoretical Considerations

The power lost P_{loss} by a particle beam made of M equispaced bunches of identical bunch population N_b in a device of impedance Z_{long} can be written [12]:

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

with e the electric charge, f_{rev} the revolution frequency, and *PowerSpectrum(f)* the so-called power spectrum (in fact it is the square modulus of the Fourier Transform of the single bunch longitudinal line density

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normalized to charge) as a function of frequency *f*. This power loss in the beam surrounding induces a temperature increase if the device is not sufficiently cooled: measured temperatures are shown in Fig. 4.

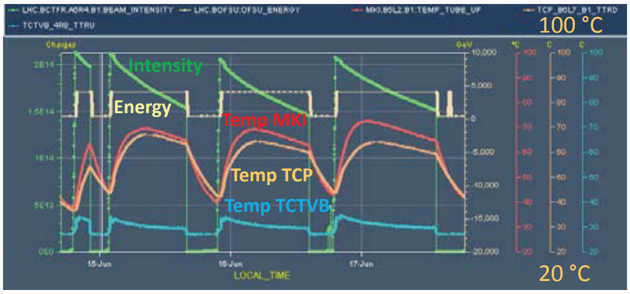

Figure 4: Example of temperature of certain LHC devices during 4 physics fills in June 2012: an MKI in red (for which the interlock for injection was at ~62°C), TCP.B6L7 in orange, and TCTVB.4R8 in blue. The total beam 1 intensity is in green and the beam energy in white.

As mentioned in [11, 12], for the calculation of beam induced power, for the case of a broadband impedance, the sum can be replaced by an integral, and the power loss is proportional to MN_b^2. For the case of a narrow band impedance, the sum can be replaced by a single term of the sum and the power is proportional to $M^2N_b^2$ (if the resonant frequency coincides with the frequency of a beam spectrum line, otherwise the power loss is much reduced with a fully filled machine).

It is interesting to assess what will happen after the Long Shutdown 1, as both bunch spacing and bunch length are planned to be changed to nominal settings [4].

Predictions with 25 ns Bunch Spacing

In 2015, the LHC is planned to restart with 25 ns bunch spacing (2808 bunches with 1.15 10^{11} p/b) instead of the current 50 ns bunch spacing scheme (1374 bunches with 1.6 10^{11} p/b). In that case, neglecting the perturbation generated by the empty buckets between subsequent batches and assuming the same bunch distribution and bunch length for both schemes, the power loss should:

- increase by ~5% for a broadband impedance;
- increase by a factor 2 for a narrow band impedance falling on a harmonic of 40 MHz;
- become negligible for a narrow band impedance falling on a harmonic of 20 MHz but not 40 MHz.

It is important to note that assuming similar bunch distribution for 50 ns and 25 ns bunch spacing is very coarse. Measurements of the beam spectrum for a physics beam with 50 ns spacing have been performed in 2011 [13] (see Fig. 5) and further measurements with various bunch length, longitudinal blow up and bunch spacings are planned in 2012.

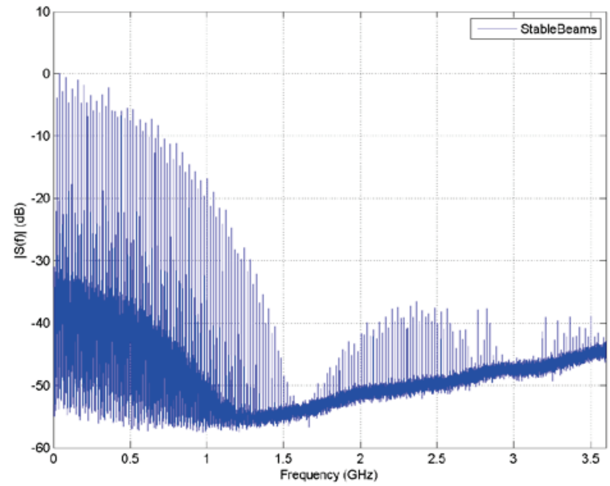

Figure 5: Amplitude of single-sided LHC beam spectrum measured with a wall current monitor in “Stable Beams” (50 ns spacing). The strong 20 MHz lines are created by the 50 ns bunch spacing. Smaller lines in between these strong 20 MHz lines are caused by the uneven filling (this is needed to allow for the abort gap and the kicker gaps), resulting in a modulation of the beam envelope at the revolution frequency, creating lines at multiple of the revolution frequency between the main 20 MHz lines [13].

Predictions with 1 ns Bunch Length

The nominal LHC 4-sigma bunch length was 1 ns in the design report [4]. In operation, it was decided to use the target of 1.25 ns in 2011 to limit beam induced heating of certain devices [14]. It was not firmly decided yet whether nominal bunch length will be the target upon restart in 2015, as running with this nominal bunch length would result in slightly higher theoretical peak luminosity than running with 1.25 ns. If it were, then it is expected that the beam spectrum envelope extends homothetically to higher frequencies, assuming that the bunch distribution remains similar (this is a very coarse assumption). In this case, heating from broadband resonances should increase steadily as most devices broadband resonant frequencies are larger than the first beam spectrum notch. For narrow band resonances, their interaction with the new spectrum will have a stronger or weaker effect depending on their frequency. However, new ranges of frequencies would be sampled by the beam spectrum, and some surprises can be expected as many simulated devices show large resonant modes beyond 2 GHz.

Current issues have been detailed in [15] and more 3D impedance simulations, measurements with beam as well as follow up on the non-conformities will take place before the restart in 2015.

TRANSVERSE INSTABILITIES IN 2012

Since 2012, transverse instabilities during the “Squeeze”, “Adjust” and “Stable Beam” beam processes

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have limited the bunch intensity and affected performance (see an example for fill 2992 in Figs. 6 and 7).

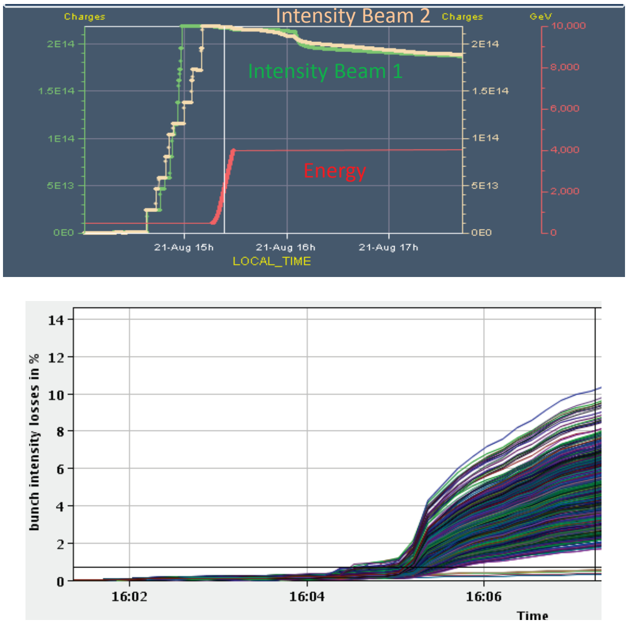

Figure 6: Example of LHC fill 2992 affected by beam 1 instabilities shortly after 16h. Top plot: total beam 1 intensity in green, total beam 2 intensity in white and beam energy in red. Bottom plot: single bunch losses.

These losses have affected most physics fills since May 2012 and were discussed at length in most LHC meetings and studied in detail by the CERN beam-beam and instability teams [16-25]. Four main types of instabilities were observed:

- Before the "Squeeze";
- At the end of the "Squeeze";
- In "Adjust";
- In "Stable beams" on selected bunches.

Several beam tests showed that:

- Landau octupoles were needed for single bunch stability;
- Transverse damper was needed for single batch stability at collision energy;
- When only one beam circulated during a dedicated measurement study, it was stable at flat top (before the squeeze) with Landau octupole current as low as ~ 100 A and chromaticities of $Q'_x \sim 8$ and $Q'_y \sim 4$.

As a consequence, it looked like one beam was stable, but in similar conditions two beams were not. These instabilities could then be linked to the presence of the two beams in the machine.

Possible explanations include:

- Beam-beam coherent excitation. However, it would then not be clear why one beam is in general much more affected than the other.
- Reduction of the incoherent tune spread due to beam-beam long range interactions.
- Enhancement of beam impedance due to the excitation of wake fields in a 2-beam-device (such as tertiary collimators, injection protection collimators or Y chambers).
- Increase of non-linearities in the triplets during the squeeze.

All these mechanisms, including the interplay of a subset of these mechanisms, are currently being thoroughly studied by the beam-beam, impedance, instability and optics teams at CERN.

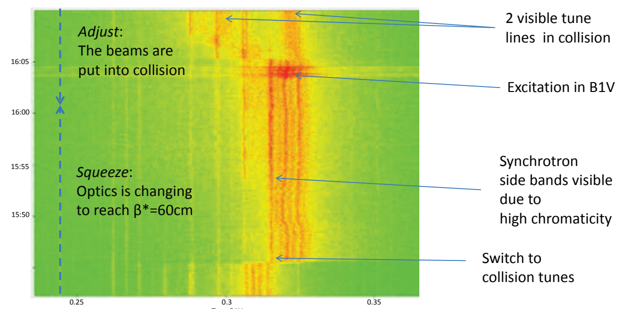

Figure 7: Waterfall plot of the beam 1 vertical tune spectra for LHC fill 2992 affected by beam 1 instabilities shortly after 16h in the "Adjust" beam mode. Many noise lines are visible and make it difficult to measure accurately the tune.

On-going Studies

In addition to the findings on the impact of beam-beam interactions on the Landau damping of excitation due to the LHC transverse impedance detailed in [26], new predictions and simulations were elaborated to understand the interplay of beam-beam and Landau octupoles tune spreads during the squeeze and collapse [20, 25], as well as new theories to understand the interplay of impedance, chromaticity, Landau octupoles and transverse damper [23, 24].

These studies lead to many tests with beam: stability measurements with one beam only, stability measurements with various settings of Landau octupole current, chromaticity and damper gain. In particular, following recommendations in [19] and [20], the sign of the octupole current was switched to see if avoiding partial compensation of the long range beam-beam and octupole tune spreads could help. This was implemented together with much higher chromaticity (as recommended in [23] and [24]), and it was observed that the extent of the instabilities was reduced, but not completely eradicated. It is interesting to note that the change of sign of the octupoles current lead to change the most affected plane from B2H to B1V.

Possible cures to these instabilities include:

- Increasing Landau octupole current to increase Landau damping (but they are at 510 A, i.e. already almost at the 550 A limit);

ISBN 978-3-95450-118-2

- Increasing chromaticity temporarily and reducing it after collisions, but predictions do not expect benefits to increase it further than what has already recently been used in operation (Q'~15);
- Increasing damper gain (but it already is close to the limit: ~ 50 turns);
- Colliding beams earlier as recommended in [16, 21] to limit the time spent with critical parameters. This solution seems to present the best potential, and a first step (colliding first in IP1 and 5 before tilting in IP 8) has been implemented by the LHC operation team and is currently being tested. It is also planned to test the possibility of colliding beams in IP1 and 5 already during the squeeze [21, 27].

Issues That Remain to be Solved to Move Forward

Besides limited machine time to perform these studies, noisy tune and chromaticity measurements have made it difficult to measure and control these crucial parameters for transverse instabilities. Single bunch and intrabunch transverse position diagnostics have also not been dimensioned to observe these types of instabilities and cope with the huge required data rate. The Schottky monitor was installed but it has not been usable yet despite significant effort to make it work.

Finally, the nature of these instabilities has intermittently changed from fill to fill, often affecting the ends of batches but not systematically, and affecting - seemingly randomly - various beam processes of the fill. This intermittent nature of the instabilities makes it difficult to monitor and diagnose their source.

OUTLOOK

As a consequence of the steady proton beam brightness ramp-up over the past 3 years, collective effects have started to slow down the performance increase of LHC. Beam induced heating and transverse beam instabilities are among the current limitations to increase the beam brightness in LHC, and both find their origin in the interaction of the beam with the LHC longitudinal and transverse impedances.

These current limitations justify the effort that was put to strictly control the impedance of the LHC at the design stage, and calls for a reduction of the LHC impedance at any possible occasion in order to possibly reach the ambitious goals set by the High Luminosity LHC project [28].

ACKNOWLEDGMENTS

The authors would like to warmly thank the LHC operation team for its help and support, S. Fartoukh, W. Höfle, G. Papotti, R. Steinhagen and D. Valuch for their help, and the controls team for the *Timber* tool.

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ISBN 978-3-95450-118-2