IMPEDANCE AND COMPONENT HEATING

E. Métral, F. Caspers, N. Mounet, T. Pieloni and B. Salvant

1. Introduction

As the beam intensity increases, the beam can no longer be considered as a collection of non-interacting single particles: in addition to the "single-particle phenomena", "collective effects" become significant [1]. At low intensity a beam of charged particles moves around an accelerator under the Lorentz force produced by the "external" electromagnetic fields (from the guiding and focusing magnets, RF cavities, etc.). However, the charged particles also interact with their environment, inducing charges and currents in the surrounding structures, which create electromagnetic fields called wake fields. In the ultra-relativistic limit, causality dictates that there can be no electromagnetic field in front of the beam, which explains the term "wake". It is often useful to examine the frequency content of the wake field (a time domain quantity) by performing a Fourier transform on it. This leads to the concept of impedance (a frequency domain quantity), which represents, for the plane under consideration (longitudinal, horizontal or vertical), the force, integrated over the length of an element, from a "source" to a "test" wave, function of their frequency and normalized by their charges. In general, the impedance in a given plane is a non-linear function of the test and source transverse coordinates, but it is most of the time sufficient to consider only the first few linear terms.

The wake fields (or impedances) can influence the motion of trailing particles, in the longitudinal and in one or both transverse directions, leading to energy loss, beam instabilities, or producing undesirable secondary effects such as excessive heating of sensitive components at or near the chamber wall (called beam-induced RF heating). Therefore, in practice the elements of the vacuum chamber should be designed to minimise the self-generated (secondary) electromagnetic fields. For example, chambers with different cross-sections should be connected with tapered transitions; non necessary cavities should be avoided; bellows should preferably be separated from the beam by shielding; plates should be grounded or terminated to avoid reflections; poorly conductive materials should be coated with a thin layer of very good conductor (such as copper) when possible, etc. In the case of beam instabilities, fortunately some stabilizing mechanisms exist, such as Landau damping, electronic feedback systems and linear coupling between the transverse planes if, for a transverse coherent instability, one plane is more critical than the other. Moreover, several beam or machine parameters can partly mitigate instabilities. All this translates into knobs which can be used in the control room to damp these instabilities: i) transverse chromaticities, ii) Landau octupoles current, iii) gain(s) of the electronic feedback system(s) and iv) bunch length (and/or longitudinal profile). In the case of the beam-induced RF heating, the bunch length (and sometimes longitudinal profile) is the main parameter (once the bunch intensity and number of bunches have been fixed): usually, the longer the bunch, the better.

Despite the excellent performance of the LHC in 2012, with a record peak luminosity at 4 TeV corresponding to 77% of the 7 TeV design luminosity of 10^{34} cm^{-2}s^{-1} (thanks to a beam brightness higher than nominal by more than a factor of two), the intensity ramp-up was perturbed by several types of transverse instabilities as well as beam-induced RF heating in many equipment. All these limitations need to be fully understood to allow future operation during the HL-LHC era [2]. This work is ongoing [3,4,5].

The performance limitations (linked to the impedances) encountered in 2010-2012 are reviewed in Section 2, while the currently expected situation during the HL-LHC era is discussed in Section 3.

2. 2010-2012 experience

2.1 *Transverse impedance model and beam instability*

A transverse instability remained at the end of the 2012 run, at the end of the betatron squeeze (at 4 TeV), with about maximum Landau octupoles current (550 A) and maximum transverse damper (called ADT) gain (corresponding to a damping time of 50 turns), after having increased the transverse chromaticities to about 15 units. This high value for the chromaticities was suggested after a new analytical approach, which includes the effect of the transverse damper [6,7]. Some tests, changing the bunch length and/or longitudinal profile, were performed but the instability did not disappear. This is therefore a potential worry for future operation at higher energies (and higher beam intensities) and a major concern for the HL-LHC. Work is still ongoing to try and better understand what happened but the current lessons from 2012 are the following:

1) The impedance model and Landau damping mechanism with one beam only is reasonably well understood as measurements revealed a mismatch of a factor around 2 (on average) between predictions and measurements over the last few years (at 3.5 or 4 TeV) [5,8,9]. Furthermore, a new global instability model including the transverse damper is now available, which gives us a better understanding of the single-beam phenomena. This factor ~ 2 needs, however, to be better understood. This work is ongoing in re-simulating in particular the geometric contribution to the impedance of the collimators.

2) The main problem concerns the two-beam operation, for which much more Landau octupoles current than predicted is needed and the reason has not been identified yet [10]. Several observations have been made, some of which are clear and summarized below:

   i) Instabilities are observed only for β^* smaller than few m.

   ii) Increasing the Landau octupoles current helps. As we should be limited at higher energies, it would be good to have more octupoles current in the future. It seems that a factor ~ 2 could be gained with the spool piece correctors MCO and MCOX, depending on the available dynamic aperture [11].

   iii) Increasing chromaticities to ~ 15-20 units seems to help (but according to the new theory [7] a plateau has been reached and no further stability gain can be expected by increasing the chromaticity).

   iv) Once in collision, no instability is observed anymore due to the large beam-beam head-on tune spread [12]. This is why the current idea to solve the issue of the beam instability at the end of the squeeze for after the 2013-2014 long shutdown (LS1) is to collide the two beams at some point before the end of the squeeze.

   v) As a less clear observation, whereas some beam dumps have been observed when putting the beams into collision with the negative Landau octupoles polarity, no beam dumps have been observed anymore with the positive Landau octupoles polarity, as suggested in Ref. [13] (and higher chromaticities and ADT gain, which have been modified at the same time). Later, the collision beam process was also optimized to go faster through the critical points [12].

3) The plan for the future is to continue the data analyses and work more on interplays between the different mechanisms (incoherent and coherent): impedance, nonlinearities (machine and Landau octupoles), space charge (at low energy), transverse feedback, longitudinal bunch distribution, beam-beam when the beams start to see each other [14], electron cloud [15], etc.

2.2 *Beam-induced RF heating*

Beam-induced RF heating has been observed in several LHC components during the 2011 and 2012 runs when the bunch/beam intensity was increased and/or the bunch length reduced. This caused beam dumps and delays for beam operation (and thus less integrated luminosity) as well as considerable damages for some equipment. Furthermore, the rms bunch length used was ~ 10 cm in 2012 (it was ~ 9 cm in 2011) whereas the nominal value (which is also the value required by HL-LHC) is 7.5 cm. The RF heating of some equipment is therefore also worrisome for HL-LHC, and it is closely followed up [4,16,17].

Some successful impedance reductions have however been already achieved, as for instance on one of the modules forming the injection kicker [18], but further modifications will be required for the HL-LHC era [19]. Indeed, the design of the most critical module was improved during the second half of 2012 and the result was that it moved from the highest temperature measured to the lowest one.

The power loss, which is due to the real part of the longitudinal impedance, is always proportional to the square of the number of particles per bunch but depending on the shape of the impedance, it can be linear with the number of bunches (when the bunches are independent, i.e. for a sufficiently shortrange wake-field – or broad-band impedance – which does not couple the consecutive bunches) or proportional to the square of the number of bunches (when the bunches are not independent, i.e. for a sufficiently long-range wake-field – or narrow-band impedance – which couples the consecutive bunches) [17].

Considering the latter case of a sharp resonance (i.e. when only one line of the bunch spectrum is significant) at a resonance frequency f_r (just to illustrate), the power loss is given by

$$P_{loss} = 2\, R\, I^2 \times F \,, \tag{1}$$

where R is the (maximum) value of the impedance at the resonance frequency and I is the total beam current (i.e. the product of the bunch current times the number of bunches). The factor F describes the frequency dependence of the power loss, which depends on the longitudinal bunch length and profile. It converges to 1 at zero frequency and it is between 0 and 1 for any frequency. Assuming for instance the bunch profile of Fig. 1 (left), close to a Gaussian distribution but with finite tails, the power spectrum (in dB) P_{dB} is depicted in Fig. 2 (right), from which the factor F is deduced by

$$F = 10^{\frac{P_{dB}(f_r)}{10}} \,. \tag{2}$$

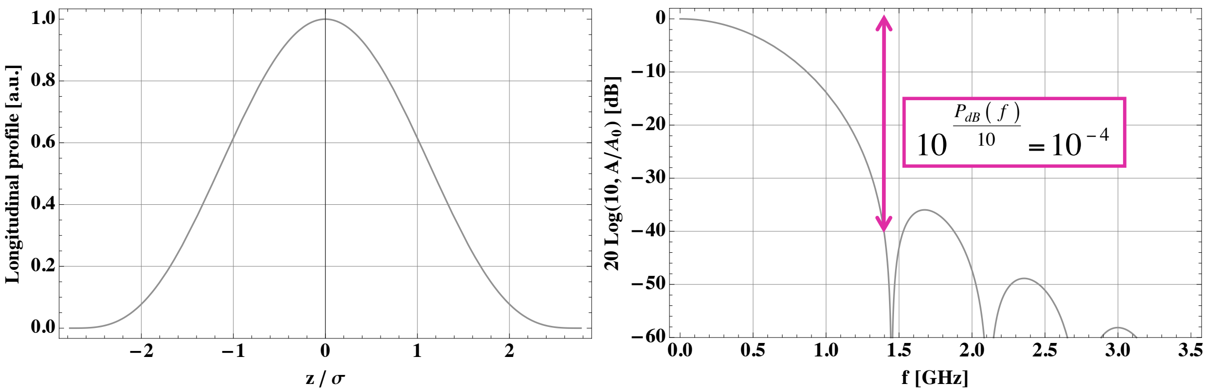

Figure 1: (Left) Example of longitudinal bunch profile (with an rms bunch length σ = 9 cm, which was used in 2011) and (right) corresponding power spectrum (in dB) P_{dB}.

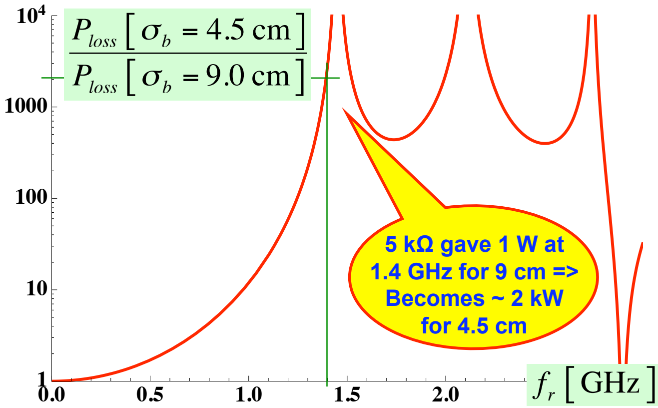

Figure 2: Increased power loss factor (vs. frequency) between 4.5 and 9 cm rms bunch length.

As the power loss is quadratic with the total intensity, if we compare to the situation of 2012 (with 1380 bunches of 1.6 10^{11} p/b spaced by 50 ns), the nominal case (2808 bunches of 1.15 10^{11} p/b spaced by 25 ns) will correspond to an increase by a factor ~ 2.1, the 25 ns HL-LHC beam (2808 bunches of 2.2 10^{11} p/b) will correspond to an increase by a factor ~ 7.8, and the 50 ns HL-LHC beam (1404 bunches of 3.5 10^{11} p/b) will correspond to an increase by a factor ~ 5. Assuming now for instance an impedance R = 5 kΩ (as an example of a single moderate cavity mode with long memory) at the resonance frequency f_r = 1.4 GHz (i.e. $F = 10^{-4}$ from Fig. 1(right)) and a total beam current I = 1 A (close to the HL-LHC value), the power loss would be therefore 1 W. To illustrate the (huge) effect of the bunch length, let's consider the case of an rms bunch length of 4.5 cm (i.e. two times smaller), assuming the same longitudinal bunch profile. The increased factor in power loss is represented in Fig. 2: reducing the bunch length by a factor 2 increases the power loss by a factor ~ 2000!

In the opposite situation of a broad-band impedance, consider for instance the case of the resistive-wall impedance, and, as an example, the particular case of the beam screen (neglecting the holes, whose contribution has been estimated to be small in the past, and the longitudinal weld). Assuming a Gaussian longitudinal profile (other similar distributions would give more or less the same result), the power loss (per unit of length) is given by

$$P_{loss/m} = \frac{1}{C}\,\Gamma\!\left(\frac{3}{4}\right)\frac{M}{b}\left(\frac{N_b\, e}{2\,\pi}\right)^2 \sqrt{\frac{c\,\rho\,Z_0}{2}}\;\sigma_t^{-3/2}\,, \tag{3}$$

where C = 26658.883 m is the average LHC radius, Γ the Euler gamma function, M the number of bunches, b the beam screen half height (assumed to be 18.4 mm), N_b the number of particles per bunch, e the elementary charge, c the speed of light, ρ the resistivity (assumed to be 7.7 10^{-10} Ωm for copper at 20 K and 7 TeV), Z_0 the free-space impedance and σ_t the rms bunch length (expressed in unit of time). Assuming the nominal beam parameters (M = 2808, N_b = 1.15 10^{11} p/b and σ_t = 0.25 ns), Eq. (3) yields ~ 101 mW/m. For the 25 ns beam in the HL-LHC era (M = 2808, N_b = 2.2 10^{11} p/b and σ_t = 0.25 ns), this would give ~ 368 mW/m and for the 50 ns beam in the HL-LHC era (M = 1404, N_b = 3.5 10^{11} p/b and σ_t = 0.25 ns), this would give ~ 466 mW/m.

The usual solutions to avoid beam-induced RF heating are the following, depending on the situation:

i) Increase the distance between the beam and the equipment.

ii) Coat with a good conductor if the heating is predominantly due to resistive losses and not geometric losses.

iii) Close large volumes (which could lead to resonances at low frequency) and add a smooth transition. This is why beam screens and RF fingers are installed.

iv) Put some ferrite with high Curie temperature and good vacuum properties (close to the maximum of the magnetic field of the mode and not seen directly by the beam) or other damping materials. Adding a material with losses (the type of ferrite should be optimized depending on the mode frequency), the width of the resonance will increase (the impedance will become broader) and the (maximum) impedance will decrease by the same amount. The power loss will therefore be (much) smaller. However, the ferrite will then have to absorb the remaining power. Even if much smaller, the heating of the ferrite can still be a problem if the temperature reached is above the Curie point, or is above the maximum temperature allowed by the device. To cool the ferrite one should try and improve the thermal conduction from the ferrite as most of the time only radiation is used (given the general brittleness of the ferrite it is difficult to apply a big contact force).

v) Improve the subsequent heat transfer:

- Convection: there is none in vacuum.
- Radiation: usually, the temperature is already quite high for the radiation to be efficient. One should therefore try and improve the emissivities of surrounding materials.
- Conduction: good contacts and thermal conductivity are needed.
- Active cooling: the LHC strategy was to water cool all the near beam equipment.

vi) Try and design an All Modes Damper (AMD) if possible, to remove the heat as much as possible to an external load outside vacuum, where it can be more easily cooled away. This can also work together with a damping ferrite.

vii) Increase the bunch length, but then the luminosity will be decreased due to the geometric reduction factor in the absence of crab cavities (and possible losses from the RF bucket). The longitudinal distribution can also play a very important role for some devices, and it should be kept under tight control (in particular during the ramp when a controlled longitudinal emittance blow-up is applied).

viii) Install temperature monitoring on critical devices to avoid possible damages. It is worth mentioning that the mirror and support of the beam 2 synchrotron light monitor (used to measure the beam transverse emittances) suffered from damage in 2012 and that there is currently a heavy effort to find a robust design for after LS1. The precise knowledge of the material properties (dielectric losses in the microwave range) of the glass used for the mirror is required as well as a need to keep in mind the possibility of dielectric structure resonances in the microwave range.

Following some issues with RF fingers on some equipment (double-bellow modules, called VMTSA), a task force was set up during 2012 to review the design of all the components of the LHC equipped with RF fingers. The lessons learnt and the mitigation measures for the CERN LHC equipment with RF Fingers were reported in Ref. [20] (the important item of the Plug-In Modules, which were studied in great detail in the past, was also reviewed). For all the cases studied, no problem with impedance was revealed for conforming RF fingers. Therefore, no (big) problem is expected for HL-LHC bunch populations (i.e. up to 2.2 10^{11} p/b for the 25 ns beam and 3.5 10^{11} p/b for the 50 ns beam). But the top priority for the future should be to try and reach robust mechanical designs to keep the contacts of all the RF fingers (e.g. with the concept of funnelling as for the Plug-In Modules or using fixed extremities or any other robust designs) and to do a very careful installation. An impedance police is in place to try and follow the evolution of the impedance(s) when some equipment are removed, modified or added. The impedance(s) of all these devices should be simulated and measured on a bench to confirm the predictions. Finally, despite all these efforts, if impedance issues are discovered in the future, an impedance reduction campaign can/should be envisaged.

3. Expected situation during the HL-LHC era

Within the framework of the HL-LHC project, Work Package 2, Task 2.4 on collective effects [21], a first impedance estimation was done concerning the new high beta region of IR1 and IR5, i.e. in and around the triplets close to CMS and ATLAS experiments [22]. From this preliminary study the impedance in these regions cloud increase by around a factor 2 or 3 with respect to the current layout, accounting for up to 10% of the total impedance budget (close to the main bunch spectrum frequency).

Moreover, the impedance of the 3 potential options for the crab cavities was studied and, besides the higher - lower for one of the options - order modes that should be taken care of by ad-hoc mode dampers at the design stage, the low frequency imaginary impedances (i.e. the constant values from 0 Hz to typically ~ 100 MHz, which give the upper limits for the effective imaginary impedances) were computed [23]. Both longitudinal and transverse contributions turned out to be significant for 12 crab cavities: 20 to 30 mΩ depending on the option to be compared to ~ 90 mΩ for the current situation; 10 to 100 kΩ/m at injection energy to be compared to ~ 2 MΩ/m estimated for the full machine; 300 kΩ/m to 2 MΩ/m at collision energy assuming a beta function at the location of the crab cavities of 4 km, to be compared to ~ 25 MΩ/m estimated for the full machine.

The impedance of the upgraded experimental beam pipes was also studied, since a reduction of diameter of the inner detector of ATLAS (inner radius from 29 mm to 22.5 mm), CMS (inner radius from 29 mm to 21.7 mm), and ALICE (inner radius from 29 mm to 17.5 mm) as well as of the wakefield suppressor of LHCb (outer radius from 5 mm to 3.5 mm) was proposed to increase their performance [24]. Studies showed an expected increase of ~ 30% of the power loss for CMS and ATLAS (VI) chambers (from 1.4 to 1.9 W per meter length), a factor 4 increase of the transverse inductive impedance at low frequency (from 150 Ω/m to 600 Ω/m), and a 20% increase of the longitudinal inductive impedance at low frequency (from 0.011 mΩ to 0.013 mΩ at injection energy) [25, 26]. The increase of the impedance contributions for the proposed reduction of the ALICE radius was higher (+ 70% for the power loss, factor 9 for the effective transverse impedance and + 50% for the effective longitudinal impedance) but the overall contributions compared to the rest of the machine remained small [27]. Finally, detailed studies of the kick factors, resonant modes and power loss generated by the upgraded vacuum chamber of CMS were performed and showed that differences between the old and new chambers are expected to be small since the trapped fields of the largest resonant modes are not located where the vacuum chamber was planned to be changed [28]. However, this study also confirmed that very large power loss (of the order of 2 kW) could be experienced by the beam pipe if the rms bunch length was reduced to 4 cm as it was planned in some initial HL-LHC scenarios.

More generally, the plan is to have an initial estimate of the machine impedance by November 2013 and an initial estimate of the intensity limitations by May 2014. The final report on beam intensity limitations and specification of machine and beam parameters should be available in November 2014.

Concerning the devices that showed signs of beam-induced RF heating before LS1, the expected situation after LS1 and during the HL-LHC era (with the knowledge at the time of writing) is summarized in Table 1.

Element	Problem	2011	2012	Expected situation after LS1	Expected situation in the HL-LHC era (very preliminary)
Double-bellow VMTSA	Damage			All VMTSA should be removed	All VMTSA should be removed
Injection protection collimator TDI	Damage			Beam screen reinforced; maybe copper coating on the jaws	New design in preparation
Injection kicker MKI	Delay			Beam screen and tank emissivity upgrade	Increased power loss with HL-LHC parameters should be monitored
Primary collimator TCP B6L7.B1	Few dumps			Cooling system; geometry checked, non-conformity should be removed	Depends on the baseline for the HL-LHC collimation
Tertiary collimators TCTVB	Few dumps			All TCTVBs should be removed; situation with new TCTP should be followed up	All TCTVBs should be removed; situation with new TCTP should be followed up
Beam screen standalone Q6R5	Regulation at the limit			Upgrade of the valves; TOTEM check	Upgrade of the valves; forward detectors are not part of the HL-LHC baseline
ALFA roman pot	Risk of damage			New design in preparation	Forward detectors are not part of the HL-LHC baseline
Synchrotron light telescope BSRT	Deformation suspected			New design in preparation	

Table 1: Summary of the situation for the equipment, which showed sign of beam-induced RF heating before LS1. 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.

Preliminary computations of heat loads with the HL-LHC beam parameters for several key systems were already performed for the:

i) Beam screen (see above the application of Eq. (3)).

ii) New collimator design with integrated BPMs (Beam Position Monitors) and ferrites: 100 W (25 ns with 2.2 10^{11} p/b) to 150 W (50 ns with 3.3 10^{11} p/b) were predicted, of which 5 to 7 W

would be dissipated in the ferrites, and 4 to 6 W in the RF fingers [18,29]; more thorough simulation studies as well as bench measurements are under way to confirm these results.
iii) Injection kickers (MKIs): simulations for the new design of MKI screen conductors with HL-LHC parameters were performed and predicted 140 W (25 ns with 2.5 10^{11} p/b) to 200 W (50 ns with 3.8 10^{11} p/b) [18]. These values are of the order of heat loads estimated with pre-LS1 parameters for the old MKI design that required significant time to cool down after physics fills. However, the improved understanding of the mechanisms of beam-induced heating to the MKIs, of heat dissipation, and the discovery of non-conforming issues provide a set of solutions that could be used in case of issues.

References

[1] S. Fartoukh and F. Zimmermann, "The Accelerator Physics Challenge", these proceedings (chap. 4).

[2] O. Bruning, "HL-LHC Parameter Space and Scenarios", Proc. of the LHC Performance workshop, Chamonix, France, 06-10/02/2012.

[3] E. Métral et al., "Review of the Instabilities Observed during the 2012 Run and Actions Taken", Proc. of the LHC Beam Operation workshop, Evian, France, 17-20/12/2012.

[4] B. Salvant et al., "Beam Induced RF Heating", Proc. of the LHC Beam Operation workshop, Evian, France, 17-20/12/2012.

[5] N. Mounet et al., "Beam Stability with Separated Beams at 6.5 TeV", Proc. of the LHC Beam Operation workshop, Evian, France, 17-20/12/2012.

[6] E. Métral, "Impedances, Instabilities and Implications for the Future", CMAC meeting #6, CERN, 16-17/08/2012.

[7] A. Burov, "Nested Head Tail Vlasov Solver: Impedance, Damper, Radial Modes, Coupled Bunches, Beam-Beam and More…", CERN AP forum, 04/12/2012.

[8] E. Métral, "Pushing the Limits: Beam", Proc. of the LHC Performance workshop, Chamonix, France, 24-28/01/2011.

[9] N. Mounet, "The LHC Transverse Coupled-Bunch Instability", EPFL PhD Thesis 5305 (2012).

[10] T. Pieloni et al., "Beam Stability with Colliding Beams at 6.5 TeV: in the Betatron Squeeze and Collisions", Proc. of the LHC Beam Operation workshop, Evian, France, 17-20/12/2012.

[11] R. Tomas, "Optics and Non-Linear Beam Dynamics at 4 and 6.5 TeV", Proc. of the LHC Beam Operation workshop, Evian, France, 17-20/12/2012.

[12] X. Buffat, "Stability Considerations with Beam-Beam and Octupoles", CERN LMC meeting, 29/08/2012.

[13] S. Fartoukh, "…The Sign of the LHC Octupoles", CERN LMC meeting, 11/07/2012.

[14] S. White, "Beam-beam and Impedance", Proc. of the ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders (BB2013), CERN, 18-22/03/2013.

[15] A. Burov, "Three-Beam Instability in the LHC", CERN-ATS-Note-2013-012 PERF.

[16] E. Métral et al., "Beam-Induced Heating / Bunch Length / RF and Lessons for 2012", Proc. of the LHC Performance workshop, Chamonix, France, 06-10/02/2012.

[17] E. Métral et al., "Beam-Induced RF Heating in the LHC", Diamond Light Source mini-workshop, 30/01/2013.

[18] H. Day, "Measurements and Simulations of Impedance Reduction Techniques in Particle Accelerators", Manchester university PhD thesis to be published (2013).

[19] B. Goddard and V. Mertens, "Challenges for the Injection and Beam Dump Components", these proceedings (chap. 19).

[20] E. Métral et al., "Lessons Learnt and Mitigation Measures for the CERN LHC Equipment with RF Fingers", Proc. of the IPAC'13 conference, Shanghai, China, 12-17 May, 2013.

[21] Web page of the HL-LHC WP2 Task 2.4 on collective effects: https://espace.cern.ch/HiLumi/WP2/task4/SitePages/Home.aspx.

[22] N. Mounet et al., "HL LHC: Impedance Considerations for the New Triplet Layout in IR1 & 5", 11th HiLumi WP2 Task Leader Meeting, CERN, 01/07/2013.

[23] B. Salvant et al, "The Impedance Model of the HL-LHC with DS Collimators and Crab-Cavities", 2nd Joint HiLumi LHC-LARP Annual Meeting, Frascati, 14/11/2012.

[24] R. Veness et al, "Specification of New Vacuum Chambers for the LHC Experimental Interactions", Proc. of the IPAC'13 conference, Shanghai, China, 12-17 May, 2013.

[25] B. Salvant et al, "Impedance Heating", 9th CERN LEB Technical Meeting, 21/01/2011.

[26] N. Mounet et al, "Summary of Impedance Heating for the 45 mm ID ATLAS VI", 10th CERN LEB Technical Meeting, 04/02/2011.

[27] B. Salvant et al, "RF Analysis of ALICE, LHCb and AFP", 10th CERN LEB Technical Meeting, 15/06/2012.

[28] R. Wanzenberg and O. Zagorodnova, "Calculation of Wakefields and Higher Order Modes for the New Design of the Vacuum Chamber of the CMS Experiment for the HL-LHC", CERN-ATS-Note-2013-018 TECH, 10/04/2013.

[29] H. Day et al., "TCTP Summary of Power Loss and Heat Load Calculations (with attention paid to the heat load of the ferrite damping material)", LHC collimation working group, 01/10/2012.