IMPEDANCE AND INSTABILITIES

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Abstract

In these proceedings we evaluate the impedance of the LHC in 2015 and the corresponding stability situation, up to the beginning of the squeeze, for various beam and machine parameters. As a starting point we use the current knowledge of the machine in terms of observed limits in single-beam operation, or in physics operation up to the beginning of the squeeze, and rescale them thanks to simulations and the impedance model obtained for the possible collimator settings scenarios. We also evaluate the possibility to mitigate instabilities thanks to an optimization of the chromaticity.

INTRODUCTION

During LHC run I and particularly in 2012, transverse coherent instabilities of the beams were observed routinely in normal operation and have become one of the limitations of the machine performance [1–3]. A particular area of concern is the single-beam stability, which must be ensured up to close to the end of the squeeze. Indeed, when beams are at flat top with collimator half-gaps down to their tightest settings of the cycle, the beam-coupling impedance is maximum while the beams still do not see each other so stability cannot benefit from any additional tune spread from beam-beam effects. During that laps of time of several tens of minutes, one can rely only on chromaticity, transverse damper and machine non-linearities (mainly from octupoles) to maintain beam stability.

In 2015, we can quickly and approximately sketch how more critical will be the situation. Assuming a constant impedance and chromaticity with respect to 2012 (we will discuss these assumptions below), the growth rates of instabilities will be reduced by around a factor of 1.6 thanks to the beneficial effect of energy (going from 4 to 6.5 TeV) while the stability area provided by octupoles will shrink by around a factor of 2.6 (1.6 coming from the shrinkage of physical emittances, and another 1.6 from the higher beam rigidity [4]). Even if we take into account the beneficial effect of a slightly higher possible octupole current (570 A instead of 510 at the end of 2012), in the end the situation will be worse by almost 50% if nothing changes fundamentally for the unstable modes, i.e. if everything remains the same in terms of impedance (in particular the collimator half-gaps in mm), chromaticity and damper gain. Given the fact that at flat top it seems in several observations [5] that during normal operation the beams were beyond the limit of stability even at maximum octupole current and high chromaticity, the situation might become very critical in 2015.

In these proceedings we will try to analyse the situation in more details. First we will summarize the available observations and the recent improvements made to the LHC impedance model. Then we will analyse the impact on the impedance of the localized change in optics foreseen in 2015, and the impact of bunch length on stability. The core of the proceedings will be then an updated analysis of the stability limits for several collimator scenarios. Finally we will give a few perspectives on how we could improve the situation, and our conclusions will then follow.

SUMMARY OF OBSERVATIONS AND UPDATED COMPARISONS WITH THE LHC IMPEDANCE MODEL

Refinement of the LHC impedance model

In 2013 a significant effort was undertaken to improve the LHC impedance model [6]. In particular the following updates or additions to the previous model [7] were performed[1]:

- the geometric impedance of collimators were re-evaluated [8] thanks to the Stupakov formula for flat tapers [9] (this is pessimistic, by up to a factor two),
- the resistive-wall impedance of beam screens and warm vacuum pipe was refined, including the NEG coating for the latter, and the effect of the stainless-steel weld for the former [10],
- the beam screen pumping holes impedance was updated, applying Kurennoy formula [11] with the polarizabilities of rounded slots from Ref. [12], using detailed beam screens dimensions,
- several equipments in the high-beta triplet region were more precisely taken into account, in particular the tapers, using the approach of Yokoya for round tapers [13], and the beam position monitors (BPM), using 3D electromagnetic fields simulations from the CST code [14],

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[1] Recently it was found that in the 2012 model the copper coating on the TCDQ collimators jaws was not taken into account as it should have been (while it is taken into account in the model of the new TCDQs put in place for the restart in 2015 – see below). At the time of the talk associated with these proceedings this was still not known so this modifcation is not implemented in the results shown here. The estimated impact on the total impedance model is estimated to be below 5%.

- the broad-band and high order modes of several cavities were updated: for RF cavities using Ref. [15], for the CMS cavity using Ref. [16], and for ALICE and LHCb experimental chambers using 3D electromagnetic fields simulations from the CST code [14],

- the cutoff frequency of all broad-band resonators was put to a very high value (50 GHz), to simulate better a constant inductive impedance up to arbitrarily large frequencies. This was done to avoid a dip in the wake at ~ 5 cm that was recently found [17], which otherwise had a tendency to reduce (in a non physical way) the instability growth rates at high chromaticity,

- the detailed machine optics was used to sum up the broad-band contributions of the model, in an analoguous way to what was done up to now only for the resistive-wall contributions (see Ref. [7])[2].

Many of these improvements were done using the Impedance library (also called PyZBASE) [18] which is a PYTHON tool enabling the computation of lumped impedance models in a relatively flexible way. This library is interfaced with the resistive-wall code ImpedanceWake2D [7] which was also used to compute all the (resistive-)wall impedances of the model, and is available in the IRIS repository [19].

In the end, these updates and additions have an impact mainly on the imaginary part of the impedance (responsible for the real coherent tune shift), at least below a few GHz, as can be seen in Figs. 1 and 2 where the 2012 4 TeV transverse dipolar impedance model is shown. On the other hand, close to 5 GHz, the change in cutoff frequency for the broad-band models affects both the real part and imaginary part of the impedance. The various impedance contributions in the new model are detailed in Figs. 3 to 6.

The effect on the instability growth rate for the most unstable mode of a single-bunch at a high damper gain and with various chromaticities Q', can be seen in Figs. 7 and 8 where we compare results from the DELPHI Vlasov solver [20]) and the HEADTAIL macroparticle tracking code [21]. The two codes are in good agreement despite the fact that they compute the growth rates in a very different way, the latter solving an eigenvalue problem and picking the most unsable mode, while the former tracks many macroparticles along many turns, and fit the emerging instability with an exponential. It appears that the effect of the refinement of the model is relatively small on the growth rate except at high chromaticities, in particular close to $Q' = 12$ where the difference is up to 40%, and for $Q' > 20$ where the difference gets even larger. Those single-bunch results are very similar to those with a full 50 ns beam, since with such a high gain of the transverse damper and assuming it is perfect and acting bunch-by-bunch, the multibunch effect is rather small, as was also found out earlier in Ref. [22].

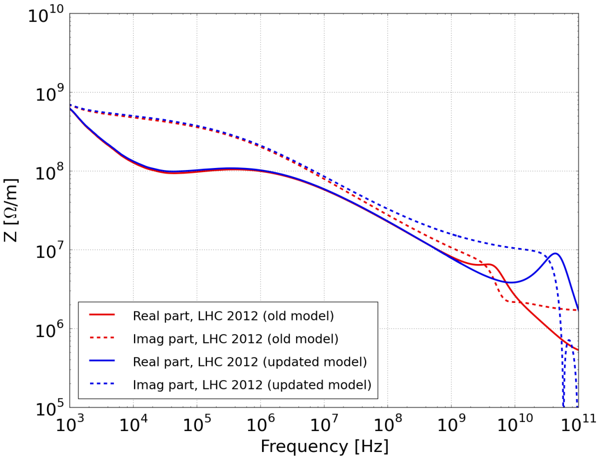

Figure 1: Horizontal dipolar impedances with both the previous and new LHC impedance models (real and imaginary parts), at 4 TeV with typical 2012 collimator settings.

All these results were obtained for beam 1; for beam 2 the model has only negligible differences with respect to the one of beam 1, as can be seen in Figs. 9 and 10.

Several of the refinements of the LHC impedance model described above were introduced in an attempt to understand better the discrepancy between measurements and simulations in terms of tuneshifts (in particular for a single bunch) that was found out in previous studies [23, 24]. In particular, the refinement of the collimator geometric impedance [8] has an impact on the tuneshifts simulated, increasing them by 10 to 20% as shown in Fig. 11, thus decreasing the discrepancy between measurements and model. Another source of discrepancy between measurements and simulations is currently investigated [25], as it was found that, depending on the simulation parameters, simulations of tuneshifts with HEADTAIL and DELPHI may differ by a significant amount [26].

Review of single-beam instabilities observed in 2012

In Fig. 12 we summarize all instabilities observed with single (or separated) beams in 2012 at 4 TeV, for each octupole polarity tested. Note that here and in the rest of the paper, "negative octupole polarity" refers to the polarity that was used in the LHC run I before the change of polarity in August 2012 (negative current in the focusing octupoles) while the positive polarity corresponds to the one used after that date, with the opposite sign of the currents. We plotted there, as a function of the chromaticity Q', the

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[2] At 4 TeV we use the squeezed optics ($\beta^* = 60$ cm in IP1 & 5, 3 m in IP2 and 8), despite the fact that we are focusing on the flat top situation before or at the beginning of the squeeze (when beams are separated). In terms of impedance alone, the squeeze has a local impact on the β functions around the IPs (plus an additional movements of tertiary collimators that anyway contribute little to the impedance), that is mainly detrimental, therefore we are slightly – and most probably unsignificantly – more pessimistic than reality on this aspect.

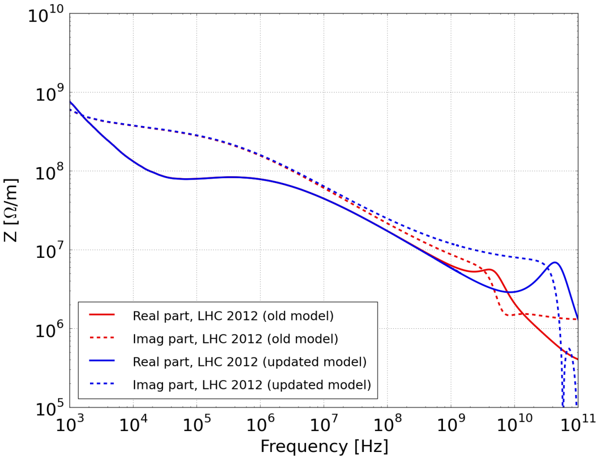

Figure 2: Vertical dipolar impedances with both the previous and new LHC impedance models (real and imaginary parts), at 4 TeV with typical 2012 collimator settings.

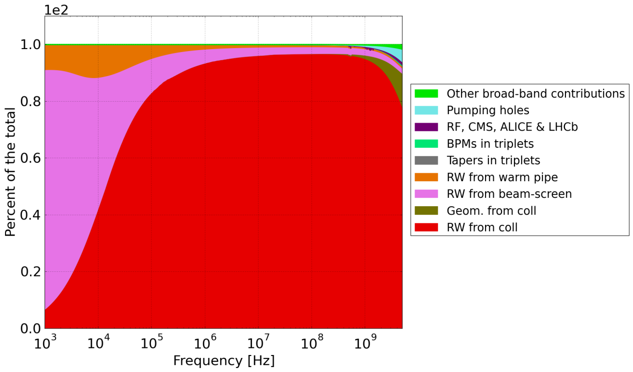

Figure 3: Horizontal dipolar impedance contributions with the new LHC impedance model (real part), at 4 TeV with typical 2012 collimator settings.

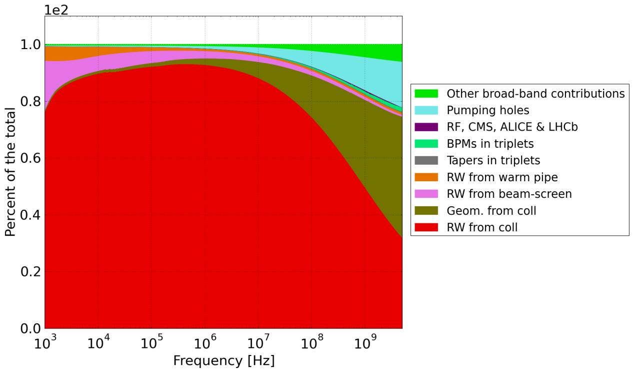

Figure 4: Horizontal dipolar impedance contributions with the new LHC impedance model (imaginary part), at 4 TeV with typical 2012 collimator settings.

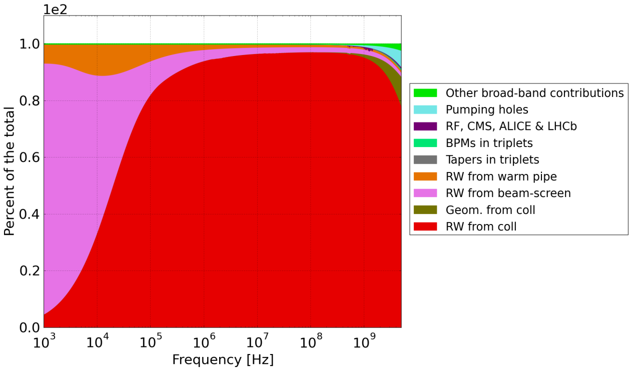

Figure 5: Vertical dipolar impedance contributions with the new LHC impedance model (real part), at 4 TeV with typical 2012 collimator settings.

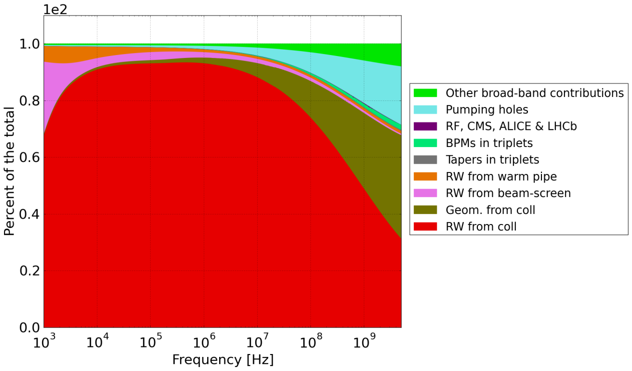

Figure 6: Vertical dipolar impedance contributions with the new LHC impedance model (imaginary part), at 4 TeV with typical 2012 collimator settings.

stability parameter defined as

$$\text{Stability parameter} = \mathcal{C}\frac{|I_{oct}| \cdot \varepsilon}{N_b}, \quad (1)$$

with I_{oct} the octupole current, ε the normalized emittance, N_b the bunch intensity, and $\mathcal{C}$ a normalization constant set in such a way that the stability parameter is 1 for $|I_{oct}| = 500$ A, $\varepsilon = 2$ mm.mrad and $N_b = 1.5 \cdot 10^{11}$ p^+/bunch, which were typical 2012 parameters. The physical meaning of the stability parameter is that the higher it is, the more the beam *should* have been stable, so the more worrisome is the instability that was actually observed at this point.

Most of the data of Fig. 12 actually comes from several machine development studies (MDs) [28, 29]. In addition, three instabilities were also observed during normal operation, while the beams were still separated [5]. These three cases can be identified as the highest point for each octupole polarity for chromaticities between 5 and 10 (actually, two out of the three cases are exactly superimposed – the ones with a negative polarity and $Q' = 7$).

The error bars along the vertical axis come from the error

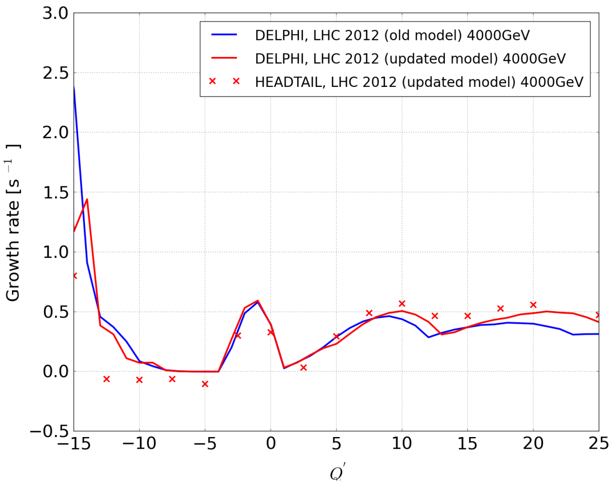

Figure 7: Horizontal growth rates vs chromaticity with both the previous and new LHC impedance models (from dipolar impedance only), at 4 TeV with typical 2012 collimator settings. We assume a perfect bunch-by-bunch damper with a damping time of 50 turns, a single bunch of intensity $1.5 \cdot 10^{11}$ p$^+$/bunch, 1.25 ns total bunch length and no Landau damping. For the updated model we compare results from the Vlasov solver DELPHI and from the HEADTAIL tracking code.

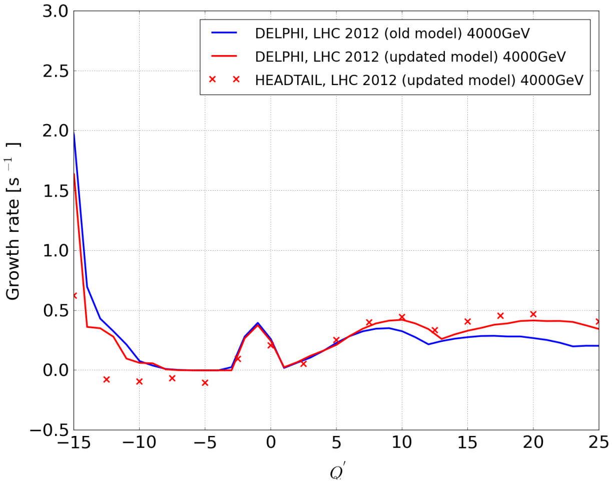

Figure 8: Vertical growth rates vs chromaticity with both the previous and new LHC impedance models (from dipolar impedance only), at 4 TeV with typical 2012 collimator settings. We assume a perfect bunch-by-bunch damper with a damping time of 50 turns, a single bunch of intensity $1.5 \cdot 10^{11}$ p$^+$/bunch, 1.25 ns total bunch length and no Landau damping. For the updated model we compare results from the Vlasov solver DELPHI and from the HEADTAIL tracking code.

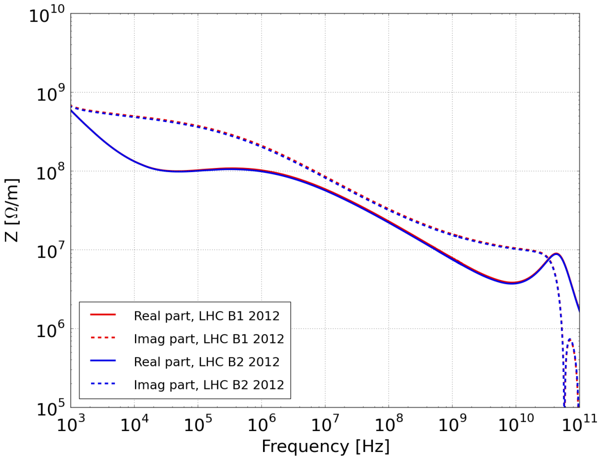

Figure 9: Horizontal dipolar impedances with the new LHC impedance model, for beam 1 and 2 (real and imaginary parts), at 4 TeV with typical 2012 collimator settings.

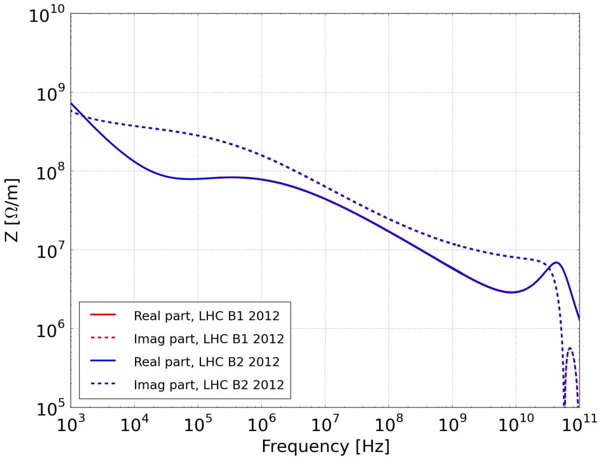

Figure 10: Vertical dipolar impedances with the new LHC impedance model, for beam 1 and 2 (real and imaginary parts), at 4 TeV with typical 2012 collimator settings. In this case the curves for the two beams (red and blue) are hardly distinguishable.

on emittance (estimated to be around 0.5 mm.mrad) and the RMS spread of intensities along the bunch train, while in horizontal the chromaticity is assumed to be known within 2 units. Note that the octupole feed-down effect to the chromaticity was taken into account in the MD measurements (and the calibration of this effect performed right before or after the MDs).

The transverse damper gain has slightly different values in these measurements (ranging from 50 turns of damping time to 200 turns), which is not expected to have a strong effect at least in the high chromaticity region [26], which is the region that will be used to compute the stability limits (see below). Also, both planes and beams are mixed, which

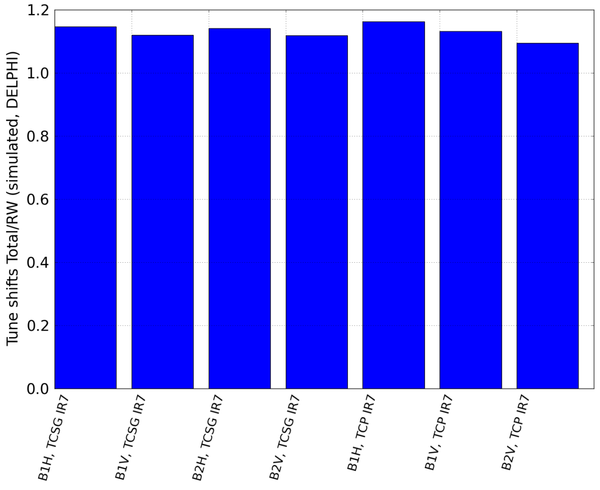

Figure 11: Ratio of the total simulated tuneshifts with the new LHC impedance model, vs. the tuneshifts obtained with the resistive-wall impedance only, for various collimator families under certain conditions (described in Ref. [23]). Simulations were done using the DELPHI Vlasov solver.

is justified by the fact they are all very similar in terms of impedance (see above). Note that for beam 1, only one case is reported here: it is the case with the highest stability parameter at negative octupole polarity and $Q' > 0$ (more precisely the one with $Q' = 7$) observed during normal operation at flat top [5].

The main obvious feature of Fig. 12 is that for positive chromaticity there is a huge spread in the measurements, in particular for the positive octupole polarity, which is neither explained nor correlated with any observed beam property, and means basically that measurements are not at all reproducible. This will in turn generate enormous uncertainties on the stability limits foreseen for 2015, as we will see below.

The main conclusion from this plot is then that the negative octupole polarity seems more favorable than the postive one, as was also expected from the stability diagram theory [27].

EFFECT OF THE OPTICS CHANGE IN IR4 AND IR8

In 2015 a change in optics is foreseen, in particular in IR4 [31]. We show in Figs. 13 and 14 the expected impact on the transverse dipolar impedances, in terms of ratio between the 2015 impedance at injection and that of 2012. Injection energy was chosen because it's the configuration in which the change will have the highest possible effect, as the impedance is then less dominated by collimator contributions (which is not modified by this optics change). Clearly, from these plots we see that the optics change has a negligible impact on impedance.

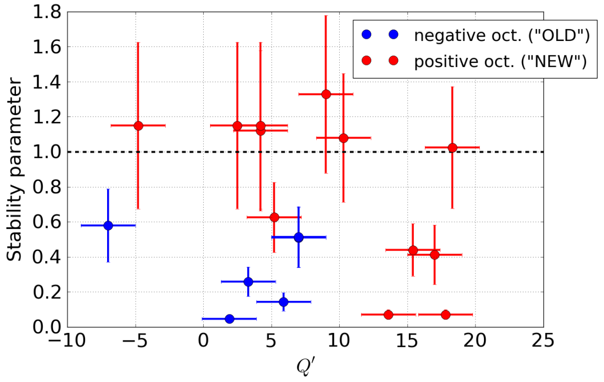

Figure 12: Summary of single-beam instabilities observed in 2012 at 4 TeV, for the two octupole polarities.

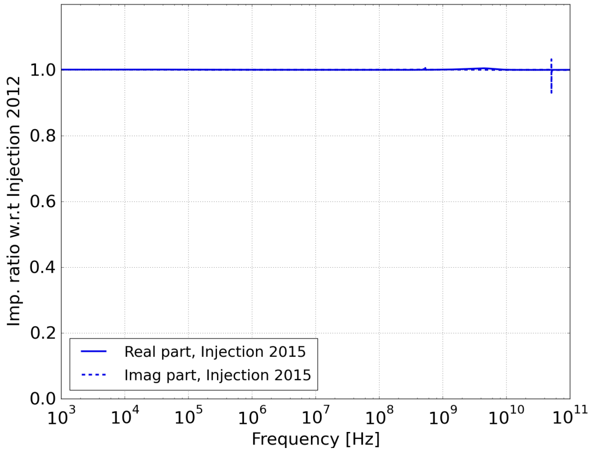

Figure 13: Horizontal dipolar impedance ratio between the 2015 (new optics) and 2012 configurations, at injection with the new LHC impedance model.

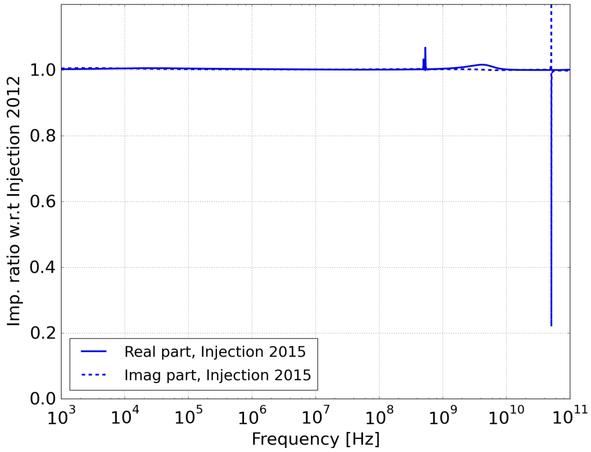

Figure 14: Vertical dipolar impedance ratio between the 2015 (new optics) and 2012 configurations, at injection with the new LHC impedance model.

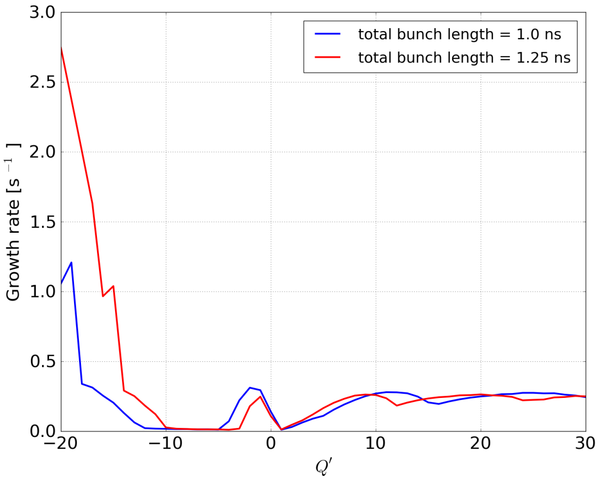

Figure 15: Horizontal growth rates vs chromaticity with the new LHC impedance model (from dipolar impedance only), at 6.5 TeV with "mm-kept" collimator settings. We assume a perfect bunch-by-bunch damper with a damping time of 50 turns, a 25 ns beam with $1.3 \cdot 10^{11}$ p$^+$/bunch and no Landau damping, for two different bunch lengths.

EFFECT OF THE BUNCH LENGTH

We evaluate here the potential impact of changing the bunch length. In Fig. 15 we plot the horizontal growth rate vs Q' at 6.5 TeV, in a possible collimator scenario ("2012 mm-kept" settings, see next section – the exact collimator scenario does not matter here), when the bunch length is changed from 1 ns to 1.25 ns (total length, i.e. 4 times RMS), with a 25 ns beam (equidistant and equipopulated bunches), $1.3{\cdot}10^{11}$ p$^+$/bunch and 50 turns of damping time (bunch-by-bunch perfect damper). We see that in the high chromaticity region (for $Q' > 10$), the minimum growth rate over the region is not changing much between these bunch lengths, only the exact chromaticity at the minimum is changing. This means that the bunch length has little impact on the stability, provided we choose appropriately the chromaticity for the bunch length chosen.

SINGLE BEAM STABILITY LIMITS FORESEEN FOR SEVERAL COLLIMATOR SCENARIOS

We analyse now the stability situation in 2015 with the new LHC impedance model. Despite the refinements of the model, since it's only partly able to explain quantitatively the observations in the real LHC machine we have to resort to scaling laws to predict stability limits after LS1. The strategy is based on 2012 observations but is slightly more complicated than the one adopted previously [24], and enables the computation of error bars on the stability limits (instead of considering only the most pessimistic cases as was done in e.g. Ref. [24]):

- for each of the highest chromaticity cases in Fig. 12 (i.e. for $Q' > 5$ with negative octupole polarity and $Q' > 9$ with the positive one), the beam is assumed to be at the threshold of instability at 4 TeV with the beam parameters measured at the time of the instability. For each of these cases we can compute the "stability factor" F as

$$F = \frac{|I_{oct}| \cdot \varepsilon}{E^2 \Im(\Delta Q_{coh})}, \tag{2}$$

  with the same notations as for Eq. (1), E the beam energy and $\Im(\Delta Q_{coh})$ the imaginary tune shift of the most critical mode (without Landau damping), computed with the parameters from this particular case (in particular taking into account the chromaticity and the damper gain) with the DELPHI Vlasov solver.

- For each octupole polarity one can then compute the average and standard deviation of all such F for the cases considered.

- Assuming then that in 2015, $E = 6.5$ TeV, $I_{oct} = \pm 570$ A in the octupoles, and that at the threshold of stability we must have the same "stability factor" F as in 2012, reversing Eq. (2) we can get $\Im(\Delta Q_{coh})$ vs normalized emittance ε at the stability limit, that we can translate into a number of particles per bunch N_b through, again, DELPHI simulations where we assume a high chromaticity (as at the end of 2012) $Q' = 15 \pm 1$ and a high bunch-by-bunch damper gain (50 turns).

Note that in the simulations we use the nominal bunch length (1 ns), and the same bunch spacing (25 or 50 ns) as the beam for which we want to compute the stability.
This procedure is very approximate and reflects our lack of reliable and reproducible measurements. Error bars are therefore very large.
We analyse the stability for several kinds of beam parameters detailed in Table 1 and several possible collimator scenarios shown in Table 2, which we can briefly describe as:

- the "mm-kept" scenario, where the collimator settings are very similar to those of 2012 in mm,
- the "2 σ retraction" scenario, where both the IR3 collimators and the secondaries and subsequent collimators of IR7 are closer than in the "mm-kept" scenario,
- the nominal settings, which are those defined in the LHC design report [32] and are put here for reference only.

For the two first collimator scenarios above, we show in Figs. 16 and 17 the average stability limits as the curve $N_b = f(\varepsilon)$ above which the intensity should be too high for the beam to stay stable. We also show there the error bars (in the form of shaded error zones around the average stability curve) related to the uncertainty in the measurements shown in Fig. 12. Clearly, the error zone is very large and prevents clear quantitative predictions. Nevertheless one can state that even with the safest (in terms of impedance) “mm-kept” collimator settings, only the standard 25 ns beam is almost guaranteed to stay stable at flat top, while the BCMS and 8b+4e 25 ns beams can be stable with the negative octupole polarity but have a high probably to be unstable with the positive polarity. Then for the 2σ retraction scenario the situation is even worse, as the BCMS and 8b+4e 25 ns beams can barely be stabilized even with the negative octupole polarity, while the standard 25 ns beam should remain stable with negative polarity but could already become unstable with positive polarity.

The three collimator scenarios are put together (without the error bars) in Figs. 18 and 19 for respectively the positive and negative octupole polarity, giving essentially the same conclusions as above, with the additional fact that the nominal collimator settings should lead to even lower stability limits than the two other scenarios.

Finally, for reference we sketch in Fig. 20 the stability limits (with error zones) for the 50 ns beam with typical 2012 parameters (except for the higher energy) and the “mm-kept” settings. It appears that the beam is barely stable even with the negative octupole polarity.

Table 1: Possible beam parameters scenarios for post-LS1 operation, as achievable by the injectors [33]. A tranverse emittance blow-up of 0.6% mm.mrad was assumed in the LHC, except for the standard 25 ns beam where the nominal design report emittance was used [32].

	N_b (p+/bunch)	ε (mm.mrad)
25 ns, standard	$1.3 \cdot 10^{11}$	3.75
25 ns, BCMS	$1.3 \cdot 10^{11}$	1.9
25 ns, standard, 8b+4e	$1.8 \cdot 10^{11}$	2.9
50 ns, standard (2012)	$1.7 \cdot 10^{11}$	2.2

Table 2: Collimator settings (in number of σ) for the three collimator options analysed.

Collimator family	2012 mm-kept	2σ retraction	Nominal
TCP IR3	15	12	12
TCS IR3	18	15.6	15.6
TCLA IR3	20	17.6	17.6
TCP IR7	5.5	5.5	6
TCS IR7	8	7.5	7
TCLA IR7	10.6	9.5	10
TCL IR 1 & 5 (except TCL6)	12	10	10
TCL6 IR 1 & 5	retracted	retracted	10
TCT IR 1 & 5	11.6	10.3	8.3
TCT IR 2 & 8	15	15	15
TCDQ IR6	9.6	8.8	8
TCS IR6	9.1	8.3	7.5
TDI & TCLI	retracted	retracted	retracted

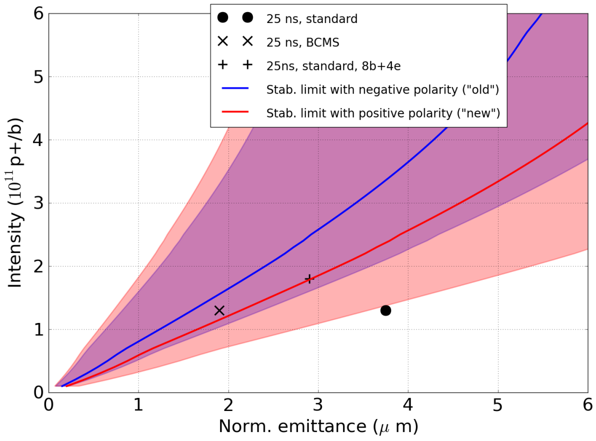

Figure 16: Intensity limit for the 25 ns beam at 6.5 TeV, as a function of transverse normalized emittance, for the “2012 mm-kept” collimator scenario as shown in Table 2 and for both octupole polarities. Beam parameters scenarios as achievable by the injectors have been indicated as well (see Table 1). The shaded areas represent the uncertainty on the stability limit.

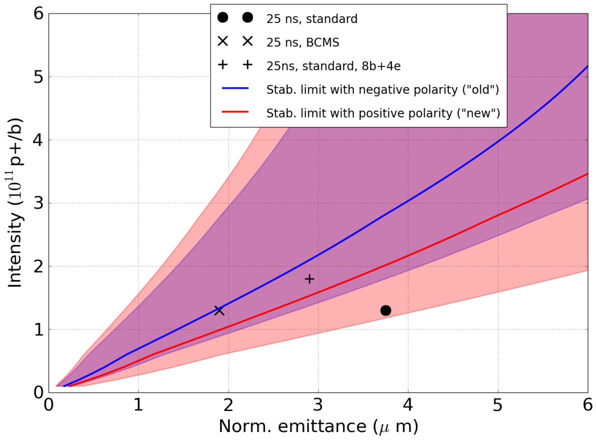

Figure 17: Intensity limit for the 25 ns beam at 6.5 TeV, as a function of transverse normalized emittance, for the “2σ retraction” collimator scenario as shown in Table 2 and for both octupole polarities. Beam parameters scenarios as achievable by the injectors have been indicated as well (see Table 1). The shaded areas represent the uncertainty on the stability limit.

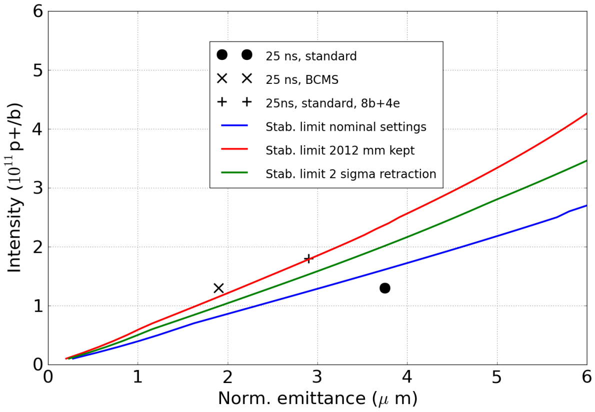

Figure 18: Average intensity limit for the 25 ns beam at 6.5 TeV, as a function of transverse normalized emittance, for all the collimator scenarios shown in Table 2 and for positive octupole polarity. Beam parameters scenarios as achievable by the injectors have been indicated as well (see Table 1).

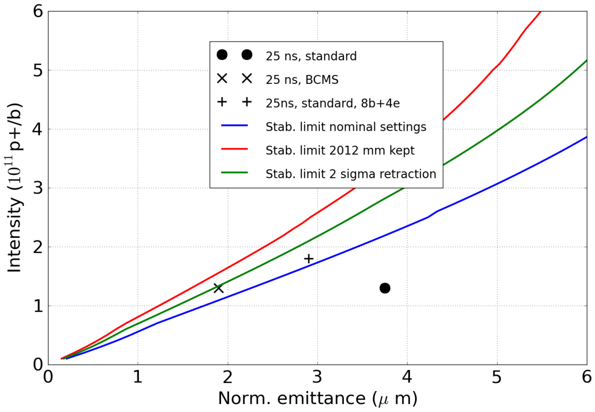

Figure 19: Average intensity limit for the 25 ns beam at 6.5 TeV, as a function of transverse normalized emittance, for all the collimator scenarios of Table 2 and for negative octupole polarity. Beam parameters scenarios as achievable by the injectors have been indicated as well (see Table 1).

PERSPECTIVES OF IMPROVEMENT

To improve the stability situation for a given impedance, several means coud be employed. First, the negative octupole polarity with high chromaticity was never tested in MDs nor on many successive operational fills, therefore its real impact on beam stability is unknown and could well be better that what is foreseen from the above plots (which are based on measurements taken at much lower chromaticities – see Fig. 12).

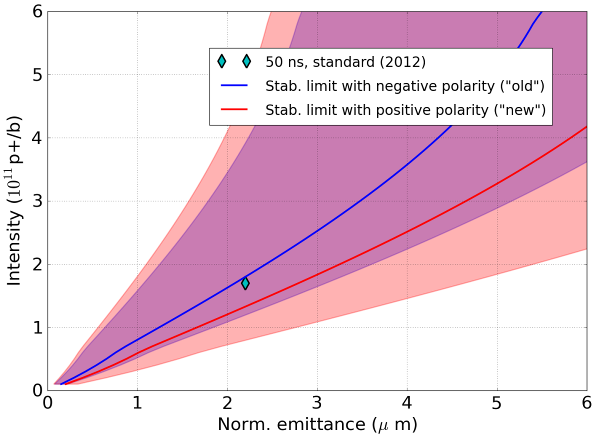

Figure 20: Intensity limit for the 50 ns beam at 6.5 TeV, as a function of transverse normalized emittance, for the “2012 mm-kept” collimator scenario as shown in Table 2 and for both octupole polarities. Beam parameters scenarios as achievable by the injectors have been indicated as well (see Table 1). The shaded areas represens the uncertainty on the stability limit.

Secondly, it was already seen in e.g. Fig. 15 that the chromaticity could have very strong beneficial impact on stability, especially with a bunch-by-bunch ideal damper: at negative chromaticities and also for Q' close to 1, some regions of high stability (without any need for Landau damping) appear. Therefore one could think that with a fine tuning of chromaticity a much better stability could be achieved.
Nevertheless, recent studies show that taking into account damper imperfections can lead to very different results, as shown in Fig. 21. Clearly, a fine model of the transverse damper is needed, and ultimately the same kind of curve from measurements in the machine.

CONCLUSIONS

The LHC impedance model has been refined, leading mainly to an increase in its imaginary part, and to a significant but limited impact on tuneshifts and growth rates predicted by the model. The impact of bunch length and optics changes that will potentially occur in 2015 were analysed through this new model, showing respectively a small and negligible impact on the instabilities.
The single-beam instabilities observed in 2012 at 4 TeV have been reviewed, and clearly exhibit a lack of reproducibility. Based on the limited statistics that can be obtained from these measurements, scaling laws, and simulations of growth rates from the LHC impedance model together with a bunch-by-bunch damper and a high chromaticity, the single-beam stability limits in 2015 were obtained, for different beam and collimator scenarios. Overall the only safe configuration in terms of instabilities remains the high emittance standard 25 ns beam.

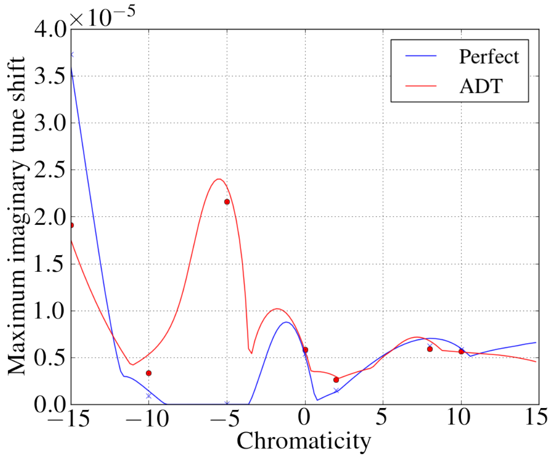

Figure 21: Single-bunch imaginary tune shift (=growth rate/revolution angular frequency) vs. Q' with typical 2012 4 TeV beam (50 turns damper, $1.5 \cdot 10^{11}$ p^+/bunch), for a perfect and a more realistic ("ADT") damper model. For this plot we used the old LHC impedance model (not updated). Solid lines are from the linear matrix model from Ref. [34] while the dots are from macroparticle tracking simulations done with the COMBI code [35].

To improve the situation, one might try to perform a fine tuning of the chromaticity, taking into account the damper imperfections. Such a procedure would have to rely on extensive, systematic and reproducible measurements in the real machine, if possible without the octupoles.

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