# BEAM STABILITY WITH SEPARATED BEAMS AT 6.5 TeV

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## *Abstract*

We provide here a preliminary estimate of the available parameters space in terms of collimator settings, intensity, transverse emittances and bunch spacing, in order to allow stable single-beam and flat top operation at $6.5$ TeV after the 2013-2014 long shutdown (LS1), assuming the machine will operate in similar conditions as in 2012 in terms of chromaticity, damper gain and damper bandwidth. 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 the impedance model obtained for the possible collimator settings scenarios. We show that only the $25$ ns beam with a classical injection scheme can be stable with nominal collimator settings, while tight settings allow the operation with the BCMS (batch compression merging and splitting) $25$ ns beam. The $50$ ns beam will on the contrary probably require relaxed settings close to those of 2011.

## INTRODUCTION

Until recently, the analysis of beam stability in the LHC under the action of a beam-coupling impedance was considered separately from the action of the transverse feedback. Indeed, the feedback system, which is close to a bunch-by-bunch feedback with a flat time domain profile on the bunch length scale, in particular since the end of 2012 [1], was thought to act mainly on the rigid-bunch modes (also called headtail mode with azimuthal mode number $m = 0$), without significant impact on higher order modes which were supposed to be stabilized solely by Landau damping from lattice non-linearities (in single-beam or separated beams operation). The main purpose of the feedback was therefore to damp rigid-bunch multibunch modes present at zero chromaticity.

However, it was found during the year 2012 that a strong damper, i.e. with a damping rate comparable to the synchrotron frequency, has also an impact on higher order headtail modes, even if the damper is a low frequency bunch-by-bunch damper as in the LHC [2–5]. This damper effect on coherent modes can be beneficial or detrimental. Therefore, with such a strong damper, coherent modes can be put into several categories:

- those that can be damped with high enough damper gain: coupled-bunch rigid-bunch modes and diagonal headtail modes (i.e. the strongest headtail modes in the absence of a damper, such that the number of intra-bunch nodes matches the headtail mode number $m$),
- those that cannot be damped by the transverse feedback (or with great difficulty), typically modes with high order azimuthal or radial mode number, and such that bunch centroids stay close to zero. Such modes then require Landau damping to be stabilized.

Note that with a strong damper the threshold of the transverse mode-coupling instability [6] (TMCI) cannot be defined anymore according to these new findings [5].

Instability growth rates and tune shifts can be estimated thanks to

- the LHC impedance model [7]: (resistive-)wall impedance from collimators, beam-screens, vacuum pipe and broadband model from the design report, updated with the collimator half-gaps estimated for various post-LS1 scenarios,
- beam dynamics simulations (HEADTAIL [8] multibunch code with a bunch-by-bunch ideal damper) or analytical models (ABA [3], NHT [4, 5], DELPHI [9][1]).

In these proceedings we will first summarize the available single-beam 2012 observations in order to give a basis for the predictions at higher energy. Then we will briefly describe the various post-LS1 collimator scenarios and their implication in terms of impedance, and analyse the effect of the bunch spacing when a strong damper is on. Finally we will give preliminary estimates of the intensity limits in 2015, based on observed limits in 2012, the impedances calculated for the possible collimator scenarios and simple scaling laws. Our conclusions will follow.

## CURRENT KNOWLEDGE OF THE LHC TRANSVERSE IMPEDANCE

Two kinds of beam-based impedance indirect measurements took place in 2012: single-bunch tune shifts and multibunch instabilities. Both kinds of measurements are still under analysis; we provide for each of them the first main results.

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[1] The code DELPHI was developped after the presentation associated with these proceedings so is not used in the rest of the paper

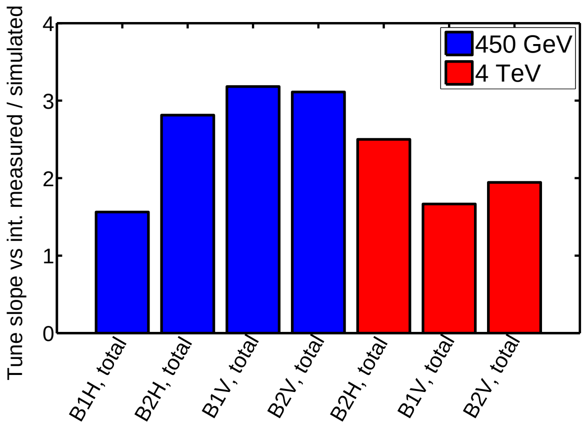

Figure 1: Discrepancy factor between measurements and simulations of the total LHC tune slopes vs. intensity, at injection and top energy, depending on the beam and plane.

## Single-bunch tune shift measurements

On June 20th, 2012, several measurements of the total tune shifts vs. intensity were done, at injection and 4 TeV, and for both beams and both planes [10]. Those were actually not strictly speaking single-bunch measurements since 8 bunches were present in the ring, some of them having different intensities, thus allowing the measurement of tune shifts with respect to intensity. Since bunches were equidistant in the ring, so very far apart, the influence of neighboring bunches on the tune shift was considered negligible in the analysis, which was confirmed by HEADTAIL simulations with the current impedance model.

In Fig. 1 we provide a comparison of the measurements given in terms of tune slope vs. intensity, with results from the simulation code HEADTAIL using the wake fields from the LHC impedance model. The quantity plotted is actually the discrepancy factor between measurements and simulations, which on average is around 3 at injection energy, and around 2 at flat top.

Another kind of measurement was performed on June 24th, 2012, giving the tune shifts of collimators upon moving their jaws back and forth [11]. Results, in terms of tune slope vs. intensity compared to HEADTAIL simulations, are shown in Fig. 2 for several collimator families (secondary collimators in the interaction region 7, called TCSG IR7, and primary collimators in the same interaction region, called TCP IR7), all at top energy (where the gaps are the smallest).

In the end, the values obtained for the discrepancy factors between model and measurements are $\sim 3$ at injection energy for the total tune shift, and $\sim 2$ for the total tune shifts as well as the collimators tune shifts at 4 TeV. These are consistent with most of the values obtained in 2010 and 2011 [12].

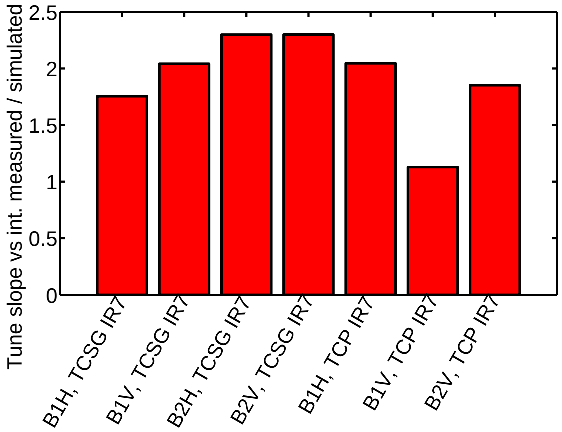

Figure 2: Discrepancy factor at 4 TeV between measurements and simulations of the tune slopes vs. intensity, for certain collimator families, beams and planes.

## *Instabilities with single or separated beams observed in 2012 with the feedback on*

During the year several instabilities were observed in physics operation at flat top before the squeeze, when the beams can be considered as independent from each other [13]. In addition, dedicated measurements with a single beam were performed during the year, in particular in June 2012 [14] and October 2012 [15]. All those observations, in multibunch situation (50 ns spacing, 1374 bunches) with similar conditions of emittances, bunch length and intensity per bunch, are summarized in Fig. 3 where the octupole current (in absolute value) at which instabilites were observed is plotted as a function of the chromaticity. The two possible octupole polarities are considered: the so-called “old” polarity (negative current in the focusing octupoles, postive in the defocusing ones), and the “new” polarity (positive current in the focusing octupoles, negative in the defocusing ones). The “old” polarity is more favourable in the single beam case because it gives a tune spread centered around negative tune shifts with respect to the unperturbed tune, which is well suited to damp coherent modes from the impedance since their tune shifts are most of the time negative.

In this plot one can clearly observe the effect of the change of octupole polarity during the year, increasing the octupole current at which instabilities were seen so degrading the situation, as expected. On the other hand the increase of chromaticity to values between 10 and 20 clearly improved the situation. Unfortunately the impact of such an increase of chromaticity for the “old” polarity is not known experimentally, as the maximum chromaticity tested with the old polarity is $Q' = 7$. From Fig. 3 it is seen that with the damper on the best stability region is at high chromaticity ($Q'$ between 10 and 20), which according to A. Burov [5] is also a region where the exact value of chromaticity matters less than close to $Q' = 0$. Then, for the highest chromaticities tested, instabilities were observed with at maximum

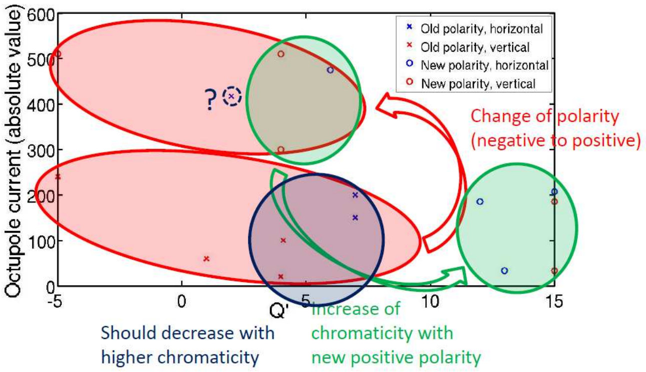

Figure 3: Octupole current (absolute value) vs. chromaticity for the separated beams instabilities observed during the year. The measurement point indicated with a question mark is very different from the others and is therefore ignored in the analysis. Note that emittances, intensity and bunch length are around 2012 operational values (respectively $2.5\mu$m in both planes, $1.5 \cdot 10^{11}$ protons per bunch and $9.4$ cm RMS) but can vary slightly between each observation.

$\sim 200$ A in the octupoles in absolute value, for both polarities. Note that this value does not really represent an octupole threshold since at this value some instability was observed. Therefore, we prefer to take a margin and assume that the separated beams are stable with $250$ A in the octupoles (in absolute value)[2].

## POST-LS1 IMPEDANCE SCENARIOS

Three different impedance scenarios were considered for 2015 operation at $6.5$ TeV. They are based on different collimator settings described in details in Ref. [16]:

- “nominal settings”: most critical ones, where IR7 collimators are closer to the beam than now (except for primary collimators),
- “tight settings”: close to $4$ TeV 2012 settings,
- “relaxed settings”: close to $3.5$ TeV 2011 settings.

Comparison between the transverse dipolar impedances in each of these scenarios and those at $4$ TeV during the 2012 run is shown in Figs. 4 to 6. For each of the three scenarios, the maximum ratio between the post-LS1 total impedance and the $4$ TeV 2012 one, above $1$ MHz frequency (low frequencies do not matter since we assume operation at high chromaticity), is $1.53$ for the nominal settings, $1.13$ for the tight ones and $0.77$ for the relaxed ones.

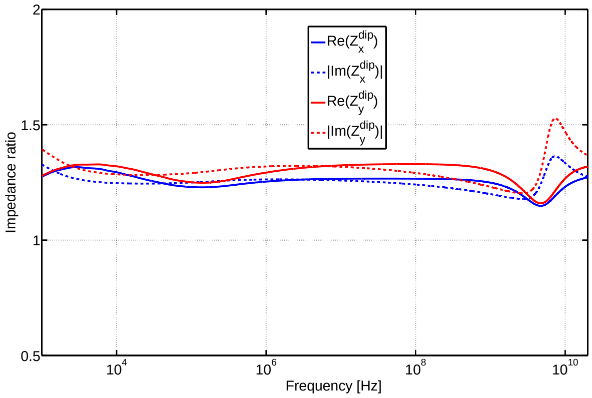

Figure 4: Ratio between the transverse dipolar impedances with the “nominal settings” post-LS1 collimator scenario and the 2012 $4$ TeV flat top settings.

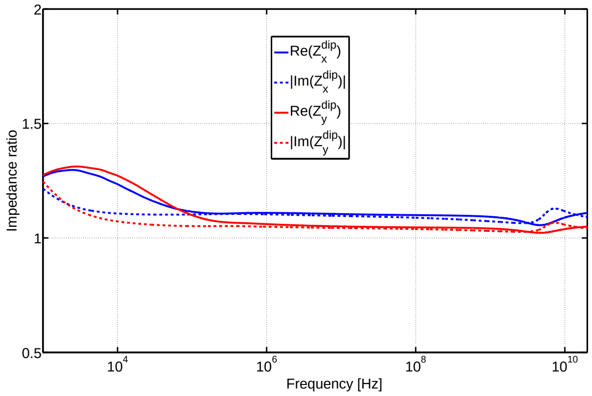

Figure 5: Ratio between the transverse dipolar impedances with the “tight settings” post-LS1 collimator scenario and the 2012 $4$ TeV flat top settings.

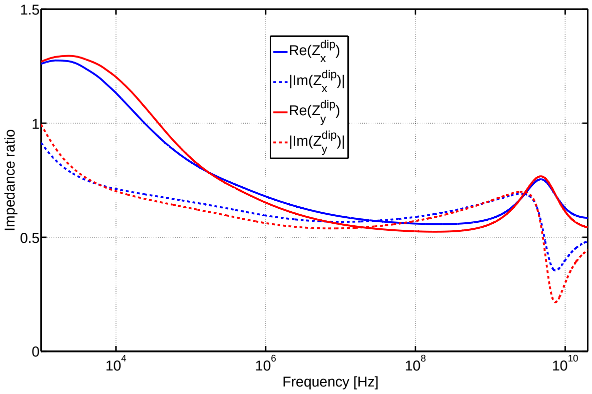

Figure 6: Ratio between the transverse dipolar impedances with the “relaxed settings” post-LS1 collimator scenario and the 2012 $4$ TeV flat top settings.

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[2] This additional margin of $50$ A was not considered during the presentation associated with these proceedings, hence the slightly more pessimistic results here for post-LS1 predictions (see below).

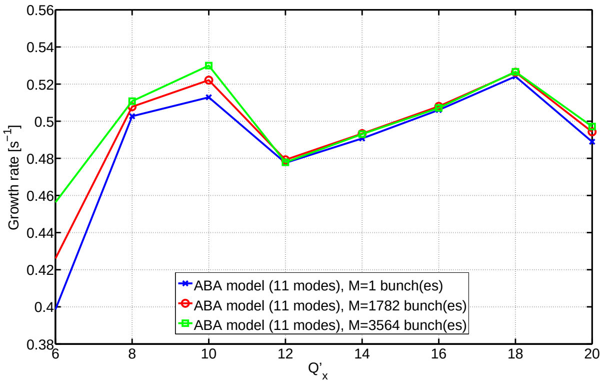

Figure 7: Effect of the bunch spacing in horizontal: comparison between single-bunch, 50 ns and 25 ns spacing (entirely filled machine), with $1.5 \cdot 10^{11}$ protons per bunch, 50 turns of damping (with a flat bunch-by-bunch damper) and $9.4$ cm RMS bunch length.

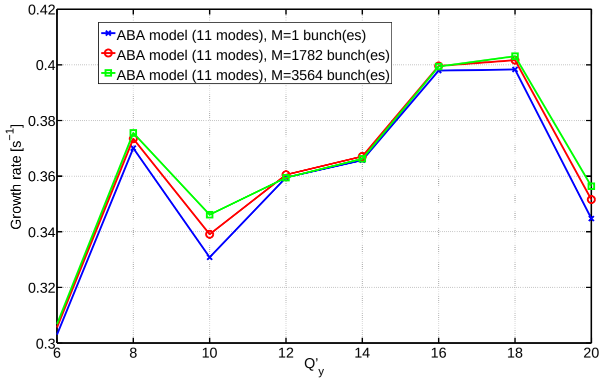

Figure 8: Effect of the bunch spacing in vertical: comparison between single-bunch, 50 ns and 25 ns spacing (entirely filled machine), with $1.5 \cdot 10^{11}$ protons per bunch, 50 turns of damping (with a flat bunch-by-bunch damper) and $9.4$ cm RMS bunch length.

## EFFECT OF THE BUNCH SPACING

According to recent theoretical developments [5], the bunch spacing ($25$ ns vs. $50$ ns) should have a negligible effect on the instabilities when the transverse feedback is on and strong enough, and the chromaticity high enough. Actually, the single-beam instabilities should then be dominated by single-bunch effects. This is confirmed by the ABA model [3] (applied to the current LHC impedance model at $4$ TeV) in Figs. 7 and 8 showing the growth rate vs. chromaticity of the most unstable mode for equidistant and equipopulated bunches along the ring. According to this model at high chromaticity ($Q'$ between $10$ and $20$), the bunch spacing has a negligible effect on instabilities with a strong damper.

## BEAM PARAMETER SPACE WITH SEPARATED BEAMS FOR POST-LS1 OPERATION

To give a preliminary estimate of the available parameters space in terms of intensity and emittance for the three different collimator scenarios foreseen (see above), we adopt here a purely empirical approach based on simple scaling laws applied to the observed limits in 2012. The assumptions on the scaling laws are the following:

- The tunespread is proportional to the geometric emittances as well as the detuning coefficient which is itself proportional to the octupolar field and inversely proportional to the magnetic rigidity [17]. Therefore [18], the stability diagram for Landau damping is proportional to the current in the octupoles and goes as $\frac{1}{\gamma^2}$ where $\gamma$ is the relativistic mass factor.
- The coherent tune shifts from the impedance decrease as $\frac{1}{\gamma}$ [19] and increase proportionally to the intensity [19, 20].
- The coherent tune shifts are proportional to the impedance factor found in the previous section. This is a pessimistic assumption which is equivalent in assumming that the ratio between the post-LS1 impedance and the $4$ TeV one is at all frequencies the same as the maximum ratio between the two.
- The bunch spacing (or number of bunches) has no impact in itself assuming we run at high enough $Q'$ (see previous section).

Those assumptions are rather strong and gives here therefore only rough estimates of the final limitations for 2015 operation. This approach is justified by the lack of knowldege of the impedance of the machine in particular at high frequency as well as the lack of reproducibility of the octupole current threshold measurements, which a priori do not allow a fine estimate of the limitations. Work is ongoing to exploit and understand better the accumulated data in 2012, as well as to refine the impedance model, in order to allow a more precise determination of the limitations. Such assumptions neglect in particular mode coupling (responsible for a deviation from the proportionality between coherent tune shift and intensity), external non-linearities that may change with higher energy, and the impact of the bunches longitudinal and transverse distributions which also may vary.
Under the validity of these assumptions, one can obtain the following relation between normalized transverse emittance $\varepsilon$ and intensity per bunch $N_b$:

$$\frac{I^{oct}\varepsilon}{E} = \mathcal{C} I_{fact} N_b, \qquad (1)$$

with $I^{oct}$ the absolute value of the current in the octupoles at the stability threshold, $E$ the particles energy at flat top, $I_{fact}$ the impedance factor found in the previous section (depending on the collimator scenario chosen) and $\mathcal{C}$ a constant multiplicative factor which is determined from the knowledge at $4$ TeV, i.e. the fact that the beams are stable for $I^{oct} = 250$ A (pessimistic value with a margin taken into account, see above) with $\varepsilon = 2.5\mu$m, $I_{fact} = 1$ and $N_b = 1.5 \cdot 10^{11}$ protons per bunch. Then one can easily obtain a line describing for each collimator scenario the stability limit in terms of intensity as a function of the emittance, taking the maximum possible octupole current (550 A) at 6.5 TeV. The corresponding lines are drawn in Fig. 9, where we have also put the points corresponding to the possible post-LS1 scenarios depending on the bunch spacing chosen (25 or 50 ns) and injection scheme, namely classical or “batch compression merging and splitting” (BCMS) scheme, the latter allowing lower transverse emittances [21]. The beam parameters for these four different options are summarized in Table 1. It appears that the only possible beam parameter scenario compatible with nominal settings is the $25$ ns beam with the classical scheme. With tight settings one can stabilize both $25$ ns scenarios, but for any of the $50$ ns scheme, one would be able to stabilize the beam only with the relaxed settings (and in the case of the BCMS scheme we would still stand quite close to the limit).

It is worth noticing that many of the assumptions made here are on the pessimistic side. In particular, with the “old” (negative) octupole polarity and with $Q'$ higher than $10$, one could probably gain in stability, but this has not been tested yet. Furthermore, we have taken a safety margin with respect to 2012 measurements, assuming that $250$ A stabilize the beam at flat top (this value has been increased with respect to the presentation made during the workshop where the value of $200$ A was used instead, thus the slightly more pessimistic results given here). Finally, some additional Landau damping could be gained by using the triplet octupoles to provide extra amplitude detuning [22].

We should finally stress that the stability treated here concerns only separated beams; more critical limitations might arise in the squeezed beams situation [23] where many strong instabilities were observed in 2012 [24].

Table 1: Beam parameters scenarios for post-LS1 operation, as achievable by the injectors [21] (i.e. without taking into account limitations from the LHC). A tranverse emittance blow-up of $33\%$ was assumed in the LHC.

| | $N_b$ (p+/bunch) | $\varepsilon$ ($\mu$m) | Nb. bunches |
|---|---|---|---|
| 25 ns, classical | $1.35 \cdot 10^{11}$ | 3.75 | 2760 |
| 25 ns, BCMS | $1.15 \cdot 10^{11}$ | 1.9 | 2520 |
| 50 ns, classical | $1.65 \cdot 10^{11}$ | 2.2 | 1380 |
| 50 ns, BCMS | $1.6 \cdot 10^{11}$ | 1.6 | 1260 |

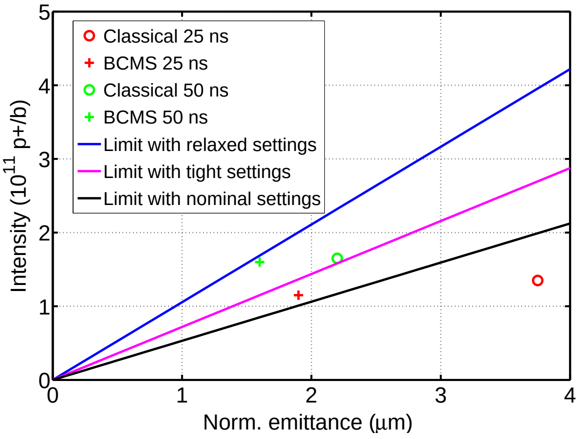

Figure 9: Intensity limit at $6.5$ TeV with $550$ A in the octupoles and high chromaticity, as a function of transverse normalized emittance. Beam parameters scenarios as achievable by the injectors have been indicated as well (see Ref. [21] and Table $1$).

## CONCLUSION

At $4$ TeV, total single-bunch tune shifts measurements show a discrepancy factor of $\sim 2$ at $4$ TeV with respect to the impedance model, and single-beam stability occurs for octupole currents of more than $\pm 250$ A at high $Q'$. However, values above $7$ for $Q'$ were never much tested with the “old” negative polarity in the octupoles; going further in $Q'$ could then reduce the octupole current needed.

Collimator settings scenarios at $6.5$ TeV give an impedance between $0.75$ and $1.5$ times the 2012 $4$ TeV one. The bunch spacing and number of bunches have essentially no impact on the single-beam stability (when taking into account only the impedance) at high enough $Q'$ and when the transverse damper is sufficiently strong.

Concerning beam stability in the post-LS1 era, assuming maximum octupole current (i.e. $\pm 550$ A) we are close or above the limit for $50$ ns beam parameters except with the relaxed collimator settings, and fine with $25$ ns parameters except for the BCMS scheme with nominal collimator settings. Such limitations could be in principle relaxed by using additional octupolar non-linearities [22].

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