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SPACE CHARGE AND TRANSVERSE INSTABILITIES AT THE CERN SPS AND LHC

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Abstract

At the CERN accelerator complex, it seems that only the highest energy machine in the sequence, the LHC, with space charge (SC) parameter close to one, sees the predicted beneficial effect of SC on transverse coherent instabilities. In the other circular machines of the LHC injector chain (PSB, PS and SPS), where the SC parameter is much bigger than one, SC does not seem to play a major (stabilising) role, and it is maybe the opposite in the SPS. All the measurements and simulations performed so far in both the SPS and LHC will be reviewed and analysed in detail.

INTRODUCTION

In the PSB, transverse instabilities (which still need to be fully characterized) are observed without damper during the ramp, where space charge could potentially play a role but no important change of instability onset was observed along the cycle when changing the bunch length (and shape) for constant intensity.

In the PS, a Head-Tail (HT) instability with six nodes is predicted at injection without space charge and observed with natural chromaticities and in the absence of Landau octupoles, linear coupling and damper.

In the SPS, a fast vertical single-bunch instability is observed at injection above a certain threshold (depending on the slip factor), with a travelling-wave pattern along the bunch. Several features are close to the ones from the predicted Transverse Mode-Coupling Instability (TMCI) between modes - 2 and - 3 without SC (for Q' ~ 0).

Finally, in the LHC, the predicted HT instability with one node for a chromaticity of about five units, with neither Landau octupoles nor damper, is observed only above a certain energy, as confirmed by simulations with space charge. Furthermore, the intensity threshold for the TMCI at injection for a chromaticity close to zero (which has not been measured yet as it is much higher than the current LHC intensities) is predicted to be significantly increased by space charge according to simulations.

Considering the case of a TMCI with zero chromaticity, a two-particle approach would conclude that both SC and/or a reactive transverse damper (ReaD) would affect TMCI in a similar way and could suppress it (see Fig. 1).

Using a two-mode approach (instead of the previous two-particle approach), a similar result would be obtained in the "short-bunch" regime (i.e. TMCI between modes 0 and – 1, such as in the LHC) as both a ReaD and SC are expected to be beneficial: the ReaD would shift the mode 0 up and SC would shift the mode – 1 down, but in both cases the coupling would therefore occur at higher intensities. However, the situation is more involved for the "long-bunch" regime (i.e. TMCI between higher-order modes, such as in the SPS). As the ReaD modifies only the (main) mode 0 and not the others (where the mode-coupling occurs), it is expected to have no effect for the main mode-coupling (as confirmed in Fig. 2, using the Vlasov solver GALACTIC [3]). As concerns SC, it modifies all the modes except 0, and the result is still in discussion and the subject of this paper, which is structured as follows: the first section is devoted to the many SPS studies, while the LHC results will be discussed in the second section before concluding and discussing the next steps.

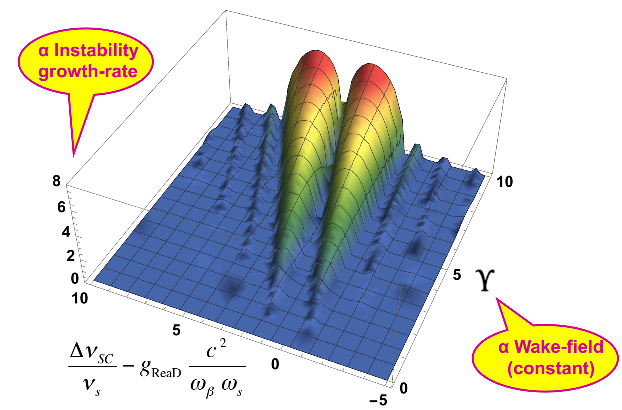

Figure 1: Two-particle approach for the TMCI following Ref. [1] but adding a reactive transverse damper (ReaD). This combines the results from Ref. [1] (with SC only) and Ref. [2] (with reactive damper only).

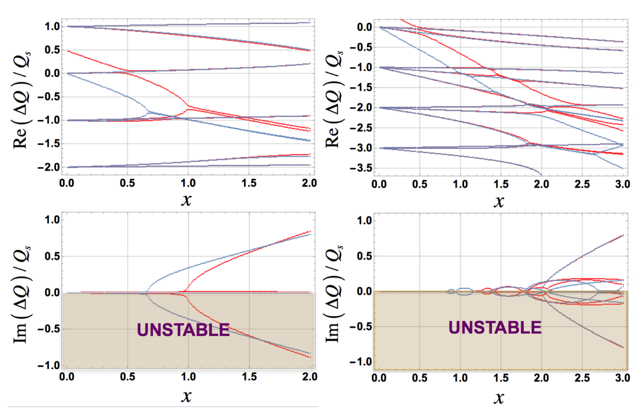

Figure 2: Usual TMCI plots for the LHC (left) and SPS (right) assuming a Broad-Band resonator impedance (with Q' = 0), without / with ReaD (50 turns) in blue / red [3].

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SPS

A fast vertical single-bunch instability with protons (p^+) was observed at the SPS injection in 2003 using a longitudinal emittance of ~ 0.2 eVs, i.e. much smaller than the nominal one of 0.35 eVs, to probe the transverse single-bunch limit of the machine (see Fig. 3) [4].

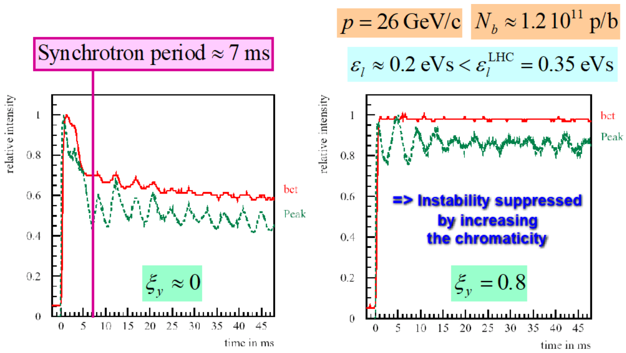

Figure 3: (Left) observation of a fast (compared to the synchrotron period) vertical single-bunch instability with protons (p^+) at the SPS injection in 2003. (Right) stabilisation by increasing the chromaticity. bct stands for beam current transformer, which measures the total intensity, whereas Peak measures a bunch length dependent bunch intensity.

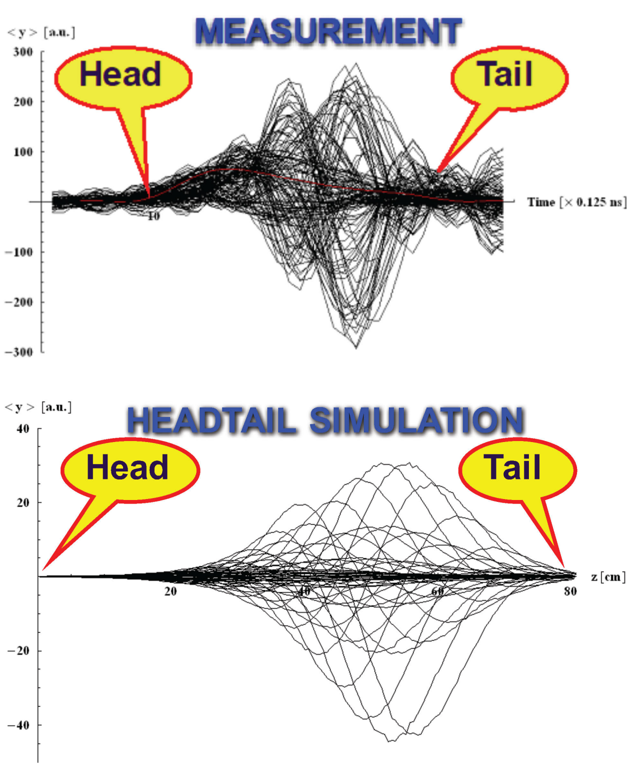

Figure 4: Comparison of the intra-bunch motion between measurements (upper) and HEADTAIL [5] simulations (lower) using a single bunch with 1.2 10^{11} p/b, an rms bunch length of 0.7 ns and zero chromaticity, interacting with a Broad-Band resonator (with a resonance frequency of 1 GHz, a quality factor of 1 and a shunt impedance of 20 MΩ/m).

This instability featured a travelling-wave pattern along the bunch (with a frequency close to 1 GHz), which was in relatively good agreement with HEADTAIL simulations using a Broad-Band resonator model (with a resonance frequency of 1 GHz, a quality factor of 1 and a shunt impedance of 20 MΩ/m), as can be seen in Fig. 4. A travelling-wave pattern along the bunch should be the sign of a TMCI as the coupling between two HT modes (which are standing-wave patterns) generates a travelling wave, as can be seen in Fig. 5 [6]. This was confirmed in Fig. 6 for the case of the SPS, using a Broad-Band resonator with a shunt impedance of 10 MΩ/m. A TMCI between modes – 2 and – 3 (for the main mode-coupling, i.e. after some mode-coupling decoupling due to the "long-bunch" regime) is predicted in the absence of SC. A similar result was predicted with the full impedance model which was developed in parallel [9,10].

The next question was: why do we observe "what looks like a TMCI (with a travelling-wave along the bunch)" whereas space charge should suppress it, according to some past theoretical analyses, with the pioneer work of M. Blaskiewicz in 1998 [11] followed by several other analyses [12-15]? Can we observe the coupling of the (negative or positive) modes? How do measurements compare to HEADTAIL simulations? According to Ref. [11], the negative modes should rapidly disappear for a strong SC parameter, defined as the ratio between the space charge tune spread (for a KV distribution or half the tune spread for a Gaussian distribution) and the synchrotron tune (see Fig. 7). So do we still see the negative modes predicted without SC (or do we see the positive ones or another mechanism taking place)?

First simulations with the combined effect of an impedance and SC, using a 3rd order symplectic integrator for the equation of motion, taking into account non-linear SC forces coming from a Gaussian shaped bunch revealed a minor beneficial effect of SC, raising the intensity threshold by ~ 5-10%, as shown in Fig. 8. It is more difficult to see what happens exactly to the modes but it could still be compatible with a mode-coupling between modes – 2 and – 3, as the main activity appears at about the same position as without SC.

Direct measurements of the modes in the SPS were tried and resulted in Fig. 9. Here again, it is difficult to conclude but it could still be compatible with a mode-coupling between modes – 2 and – 3, as the main activity appears at about the same position as without SC.

An indirect measurement of mode-coupling (in addition to the travelling-wave pattern resulting from mode-coupling between two HT modes with standing-wave patterns) in the "long-bunch" regime consists of measuring the beam stability vs. increasing bunch intensity, as the bunch should be first stable until mode-coupling (of the low-order modes) and then stable again after decoupling before becoming very unstable at the main mode-coupling. This is what was predicted from HEADTAIL simulations using both a Broad-Band resonator model and a more realistic impedance model of the SPS and this is what was measured, as reported in Fig. 10.

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This observation was another argument to state that mode-coupling was taking place even if the direct measurement of mode-coupling was still missing…

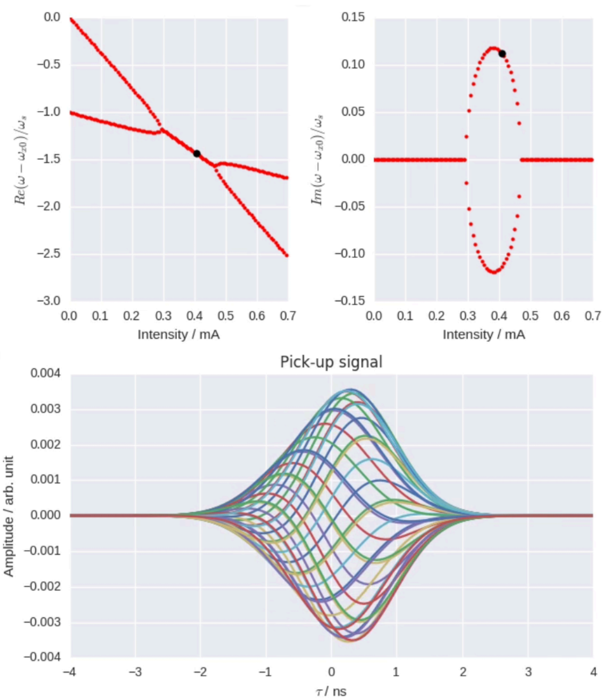
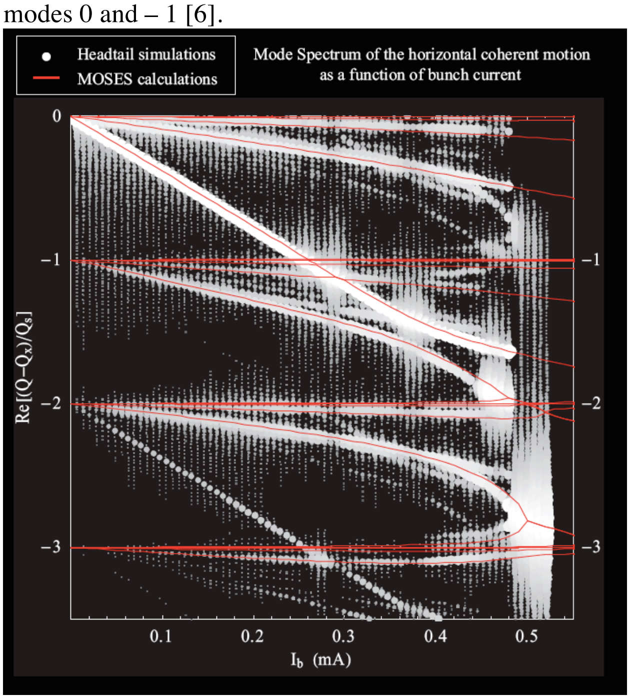


Figure 5: The coupling of two HT modes (standing-wave patterns) generates a travelling-wave pattern. Example from the DELPHI Vlasov solver for a coupling between modes 0 and – 1 [6].



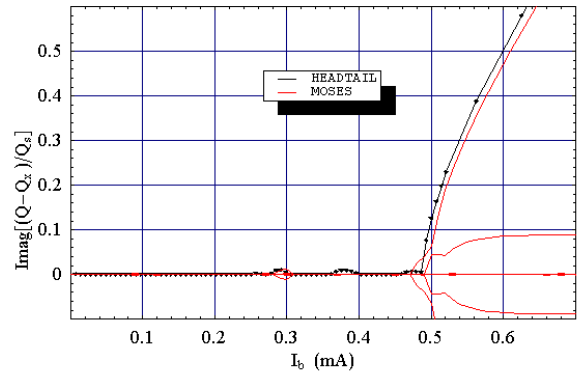


Figure 6: Comparison between MOSES [7] and HEADTAIL simulations (using SUSSIX [8] to process the output data) using the parameters of Table B.3 (for MOSES) and B.4 (for HEADTAIL) of Ref. [9].

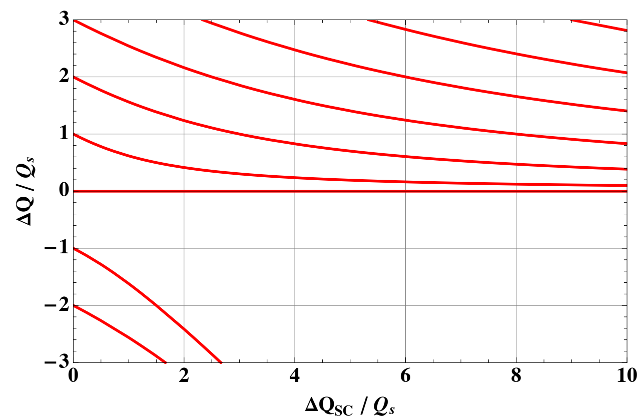


Figure 7: Mode-frequency shifts vs. the SC parameter for the case of the Air-Bag Square well (or ABS) model [11].

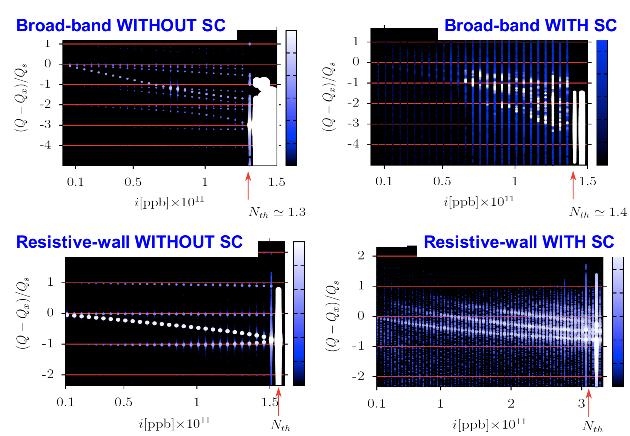


Figure 8: Simulations with both impedance and SC, revealing a minor beneficial effect from SC for the SPS case (upper) [16].

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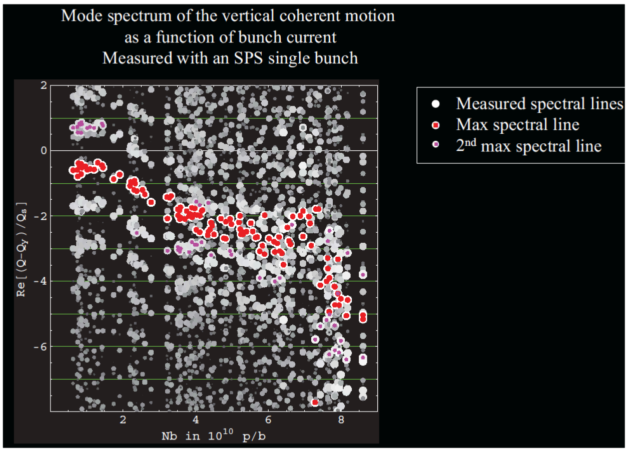

Figure 9: Direct measurements of the modes in the SPS [9].

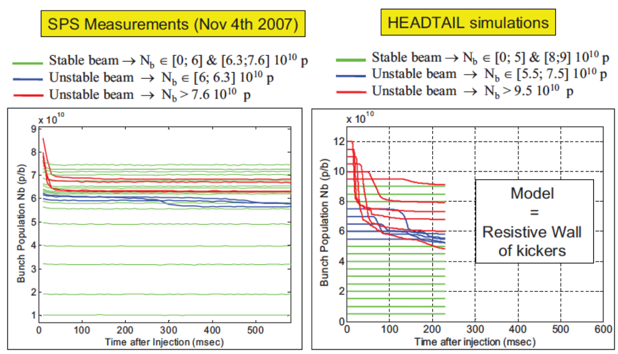

Figure 10: Indirect measurement of mode-coupling by trying to identify in the SPS the regions of stable and unstable bunch intensities (see Fig. 6.26 in Ref. [9]). These measurements were performed for a longitudinal emittance of 0.16 eVs, and rms bunch length of 0.7 ns and a chromaticity as close to zero as possible.

As i) the SPS instability seemed to be relatively well described by TMCI using a Broad-Band resonator (without SC) and ii) in this case ("long-bunch" regime) a simple formula exists within a numerical factor 2 as mentioned in Refs. [17-18] (see Eq. (1)), which was recently checked in Ref. [19], it was proposed to modify the optics to increase the slip factor [20]: the "Q20" optics (named like this as the integer part of the tune is 20) replaced the previous "Q26" optics (where the integer part of the tune was 26). Within the TMCI formalism, the simple formula can be derived using a two-mode approach (considering the two most critical modes overlapping the maximum of the real part of the impedance): bunch stability is reached when the head and the tail are swapped sufficiently rapidly (due to synchrotron oscillations) compared to the instability rise-time, i.e. when the synchrotron period divided by π is equal to the instability rise-time derived from this simple model (sm): $T_s = \pi\, \tau^{sm}_{TMCI}$. This leads to the following stability criterion for the threshold number of protons $N_{b,th}$, which can be written in two forms (e.g. in the vertical plane)

$$N_{b,th} = \frac{4\pi^3 f_s\, Q_{y0}\, E\, \tau_b^2}{e\, c} \times \frac{f_r}{\left|Z_y\right|}$$

$$N_{b,th} = \frac{8\pi\, Q_{y0} \left|\eta\right| \varepsilon_l}{e\, \beta^2\, c} \times \frac{f_r}{\left|Z_y\right|} \qquad (1)$$

where f_s is the synchrotron frequency, Q_{y0} the unperturbed (low-intensity) vertical tune, E the total energy, τ_b the full (4σ) bunch length in s, e the elementary charge, c the speed of light, f_r the resonance frequency of the Broad-Band (Q = 1) resonator, Z_y the shunt impedance, β the relativistic velocity factor, ε_l the longitudinal emittance and η the slip factor, given by

$$\eta = -\frac{df_{rev} / f_{rev}}{dp / p} = \alpha_p - \frac{1}{\gamma^2} = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$$

It is interesting to note that i) within the framework of this model the simple formula giving the instability rise-time well above the TMCI threshold (which was checked with MOSES and HEADTAIL, within the same factor 2 as before for the intensity threshold [21]) can be written as $\tau^{sm}_{TMCI} = (T_s / \pi) \times (N_{b,th} / N_b)$ and ii) in the second form of Eq. (1), the notion of synchrotron oscillations disappears. This equation is the same as for coasting beams, but written with peak values, where the Landau damping is provided by the momentum spread. What is important is the product of the longitudinal emittance and the slip factor, i.e. the distance to transition. As the longitudinal emittance should be kept at 0.35 eVs for the beams to be sent from the SPS to the LHC, the only parameter on which one can act is the product of the vertical tune times the slip factor. For machines made of simple FODO cells it can be shown that the slip factor is approximately given by the horizontal tune ($\gamma_t \approx Q_{x0}$), which means that if one wants to modify γ_t, one should modify the horizontal tune. The SPS slip factor as a function of the horizontal tune is depicted in Fig. 11. For the Q26 optics, $\gamma_t \approx 22.8$, whereas for the Q20 optics, $\gamma_t \approx 18$. This means that for the Q20 optics, the product of the slip factor times the horizontal tune gives $1.80\ 10^{-3} \times 20.13 \approx 0.0362$, whereas for the Q26 optics it gives $0.62\ 10^{-3} \times 26.13 \approx 0.0162$ (considering for this case a non-integer part of the tune of 0.13, which can be slightly different in practice but this does not change the picture). Therefore, according to Eq. (1) the intensity threshold should be increased by the factor 0.0362 / 0.0162 ≈ 2.2. This is in good agreement with measurements, as can be seen in Fig. 12, where an intensity increase of a factor 4.0 / 1.6 ≈ 2.5 was observed.

These results are also in good agreement with HEADTAIL simulations from 2014 for different optics (adding also the case of the Q22 optics, which is a better optics for

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some RF considerations), with full impedance model but still without SC (see Fig. 13).

A good agreement was also achieved between measurements and simulations looking at different longitudinal emittances, using the full impedance model but still without SC (see Fig. 14), even if the Q26 was maybe a bit more critical in measurements than in simulations.

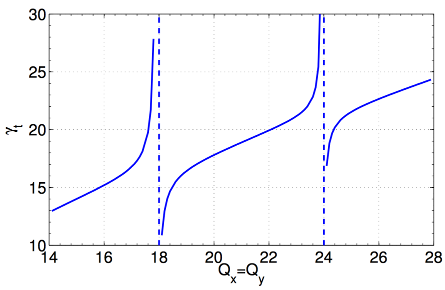

Figure 11: SPS slip factor as a function of the horizontal tune [20].

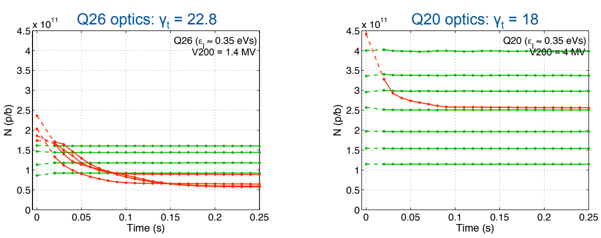

Figure 12: Comparison of the measured bunch intensity thresholds between the Q26 and Q20 optics. The longitudinal emittance is 0.35 eVs, i.e. about two times larger than in Fig. 10, which explains why the intensity threshold with Q26 is about two times larger than in Fig. 10.

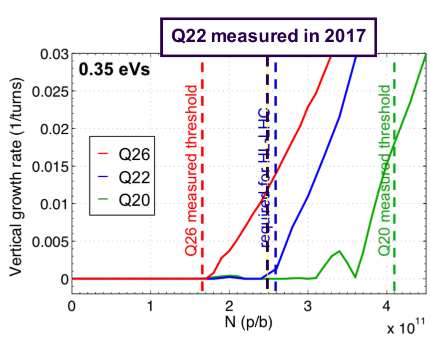

Figure 13: Comparison of the bunch intensity thresholds between measurements and HEADTAIL simulations.

Finally, a good agreement was also reached between measurements and pyHEADTAIL [22] simulations with SC this time for the Q20 optics, still considering the Broad-Band resonator model, as the intensity threshold was found close to the no-SC case (see Fig. 15). However, a detailed analysis of the modes involved seems to reveal different modes involved at the start of the instability: without SC, a mode-coupling between azimuthal modes – 2 and – 3 (with radial mode 0) is observed while with SC, a mode-coupling between azimuthal modes 1 and 2 (with radial mode 1) seems to be found [23].

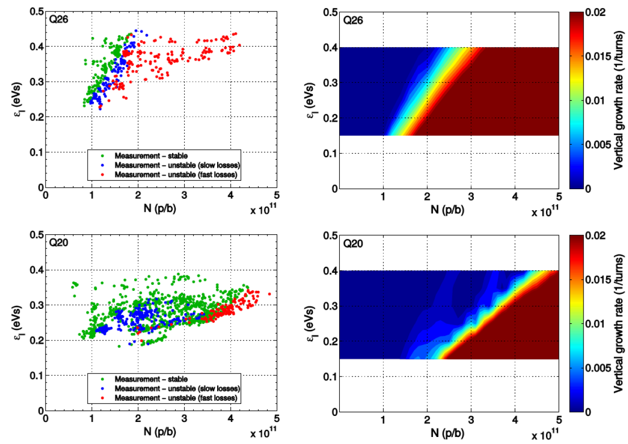

Figure 14: Comparison of the bunch intensity thresholds between measurements (left) and HEADTAIL simulations (right) looking at different longitudinal emittances, using the full impedance model but still without SC.

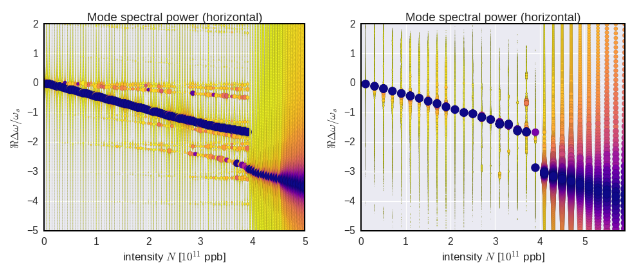

Figure 15: pyHEADTAIL simulations with the Q20 optics comparing the cases without SC (left) and with SC (right).

The comparison of the intra-bunch motions in Fig. 16 between measurements and HEADTAIL simulations without SC reveals also a good agreement in particular for the Q20 optics. For the Q26 optics, the measured intra-bunch motion seems to be more towards the tail than in the simulations, as recently pointed out by A. Burov, who discovered a new destabilising effect of SC, which could be responsible for this effect [24]. This disagreement was not present in the first studies (without SC) of Fig. 4, which means that both impedance and SC could have a similar effect, which needs to be disentangled. The Q20 optics seems less subject to this effect but it is true that the Q26 optics has a much higher SC parameter (~ 27) compared to Q20 (~ 5).

New pyHEADTAIL simulations without and with SC were performed for different shunt impedances of Broad-Band resonators and the very interesting results are depicted in Fig. 17. It is seen that in the absence of SC, a higher shunt impedance leads to an intra-bunch motion pushed towards the tail. The effect of SC seems threefold: i) its pushes the intra-bunch motion even more towards the tail; ii) it increases the frequency of oscillation and iii) it increases or reduces the oscillation amplitude.

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The (simple) 2-mode approach (with a mode-coupling between two consecutive modes m and $m + 1$), which was used in the past in the case of the (very) "long-bunch" bunch regime to reveal almost no effect of SC on TMCI [25,26], can be extended also to the general case, leading to the intensity threshold of Eq. (2)

$$Q_s \left[\sqrt{q_{SC}^2 + (q+1)^2} - \sqrt{q_{SC}^2 + q^2}\right] = 2\left|\Delta Q_{q,q+1}^{S,y}\right| \quad (2)$$

where $q_{sc} = \Delta Q_{sc} / (2\, Q_s)$ and $q = |m| + 2\,k$ (with $0 \leq k \leq +\infty$ defining the radial mode number). This means that the same intensity threshold as the no-SC case is obtained, i.e. it is the same as Eq. (1), except that Q_s is now multiplied by the term $\sqrt{q_{SC}^2 + (q+1)^2} - \sqrt{q_{SC}^2 + q^2}$, which is equal to 1 when $q >> q_{sc}$ and to 0 when $q_{sc} >> q$. In particular, the same scaling with respect to the other parameters is obtained and therefore the same mitigation measure should be applied.

Based on these new results, another measurement campaign is planned to try and disentangle between the impedance and SC effects by varying the SC tune spread. However, it is worth emphasizing that a solution has been already found in practice for this instability in the SPS and that it is not a performance limitation anymore.

LHC

Using the impedance model of the High-Luminosity (HL-) LHC at injection and considering the case of zero chromaticity, it was found with pyHEADTAIL simulations that the TMCI between modes 0 and -1 without SC is suppressed over the intensity range studied [26].

For the chromaticity Q' = + 5, a HT instability with one node (m = - 1) is observed without SC whereas it is completely suppressed with SC [26]. Studying the effect of energy during the ramp, which reduces the SC tune spread (by increasing the transverse emittances at injection energy), the instability re-appears at ~ 2 TeV. This energy is the energy at which the first transverse single-bunch instability was observed in the LHC during the first ramp performed in 2010 with neither Landau octupoles nor transverse damper [27].

CONCLUSION

A beneficial effect of SC is predicted in the (HL-) LHC (working in the "short-bunch" regime) for both the HT instability and TMCI. SC simulation with pyHEADTAIL gives an explanation of the first single-bunch HT instability observed in the LHC in 2010 with neither Landau octupoles nor transverse damper. This might be good to re-do a controlled experiment to confirm it. Furthermore, SC simulation also predicts that SC increases significantly the TMCI intensity threshold (Q' = 0) at (HL-) LHC injection. This could not be studied at the moment as the TMCI is currently out of reach in the LHC.

As concerns the SPS (working in the "long-bunch" regime), several past measurements were close to the case without SC. The intensity threshold was increased considerably in practice by increasing the slip factor (based on theoretical analysis without SC) and this is working very well: Q20 optics has replaced Q26 optics in the SPS for all the beams to be sent to the LHC. However, a recent theoretical analysis by A. Burov [24] predicts a detrimental effect of SC (even below the TMCI intensity threshold without SC), which was confirmed by recent SC simulations with Q26. The (simple) 2-mode approach was also extended to the general case and the same intensity threshold as the no-SC case is obtained, except that the synchrotron tune is now reduced by SC. However, the same scaling as without SC is obtained and therefore the same mitigation measure should be applied. A new measurement campaign is planned to analyze all this in detail.

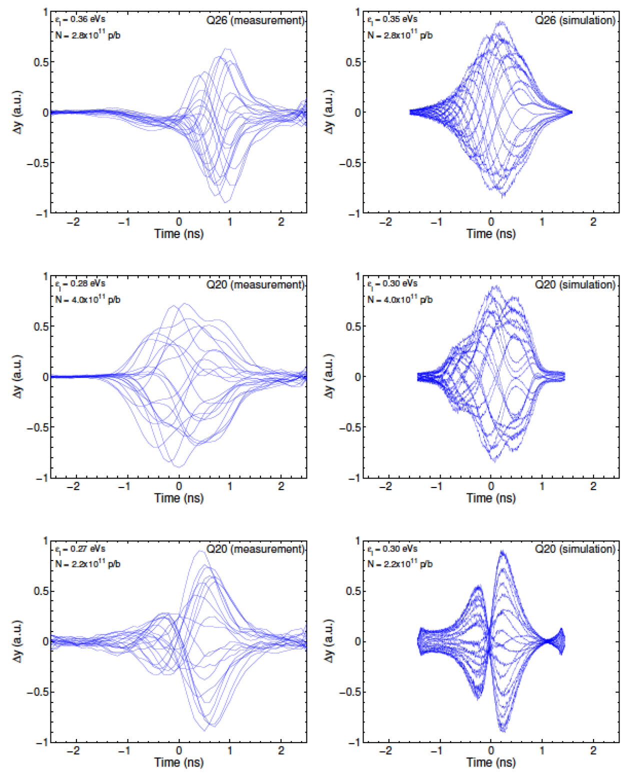

Figure 16: Comparison of intra-bunch motions between measurements (left) and simulations with HEADTAIL (right) for different cases with Q26 and Q20 optics.

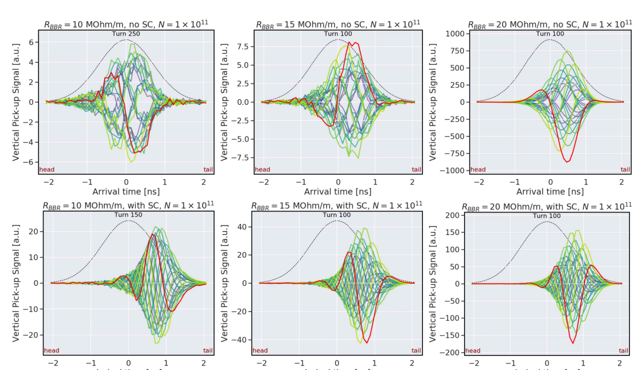

Figure 17: Intra-bunch motion from pyHEADTAIL simulations without and with SC for different shunt impedances of Broad-Band resonator impedances.

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