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DESTABILISING EFFECT OF THE LHC TRANSVERSE DAMPER

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Abstract

Three questions motivated this study for the CERN Large Hadron Collider in terms of beam stability: (i) why a chromaticity close to zero seemed more critical than predicted during Run 1 (in 2011 and 2012) and during Run 2 (in 2015)?; (ii) why some past simulations with a chromaticity close to zero revealed a more critical situation with the transverse damper than without?; (iii) what should be the minimum operational chromaticity in the future in the LHC and High-Luminosity LHC? A new Vlasov solver (called GALACTIC) was developed to shed light on the destabilising mechanism of the transverse damper, which is a potential contributor to explain the LHC observation. Due to the features, which are discussed in this paper, the name "ISR (for Imaginary tune Split and Repulsion) instability" is suggested for this new kind of single-bunch instability with zero chromaticity.

INTRODUCTION

Numerous transverse beam instabilities have been observed in the LHC since 2010 and several mechanisms have been identified, which can explain some of them [1]. However, one of them, which remains a mystery, concerns the case of a single bunch with a low chromaticity at high energy, which requires much more current in the Landau octupoles than predicted using the usual stability diagram, which assumes independent head-tail modes [1,2]. In addition to this observation, several simulations performed with different (Vlasov solver and tracking) codes, considering a single bunch with zero chromaticity, revealed a more critical situation with transverse damper than without [3-8]. However, the exact instability mechanism was not given yet (in Ref. [3] it is referred to as "a sort of TMCI") and the purpose of this contribution is to explain it in detail: this is the first step of a two-step approach, where the second one is to fully review the Landau damping mechanism. The current status of the studies for the second step is briefly discussed at the end of this manuscript.

This paper is structured as follows: in the first section, the new Vlasov solver (in the presence of a transverse damper) is presented. It is then applied, in the following two sections, to the CERN SPS and LHC machines, which are working in the long-bunch and short-bunch regimes, respectively. The new instability mechanism and its impact on Landau damping are then explained in the fourth and fifth sections before concluding and discussing the next steps.

NEW VLASOV SOLVER: GALACTIC

The transverse damper is needed to damp the Transverse Coupled-Bunch Instabilities (TCBI) in machines like the LHC and SPS [9], and depending on the feedback phase, it can be resistive (as currently in the LHC and SPS) or reactive (or both). A detailed analysis of the efficiency of transverse dampers for the suppression of transverse instabilities was recently performed [10].

Starting from the Vlasov equation and using a decomposition on the low-intensity eigenvectors, as proposed by Laclare and Garnier [11,12], the effect of a transverse damper was added and a new Vlasov solver code was developed, called GALACTIC (for GArnier-LAclare Coherent Transverse Instabilities Code). In this code, the following eigenvalue system needs to be solved (e.g. in the horizontal plane) [13]

$$\sigma_x(l) = \sum_{i\,j} a_{ij}\, \sigma_{x,ij}(l), \qquad \frac{\omega_c}{\omega}\, a_{kl} = H^x\, a_{ij}\,, \tag{1}$$

where the coefficient of the matrix (to be diagonalised) is

$$\begin{aligned} H^x_{kl,ij} &= k\, \delta_{ki}\, \delta_{lj} \\ &+ \Delta\omega_{ckl} \sum_{p=-\infty}^{p=+\infty} \sigma^*_{x,kl}(p) \left[-j\, \frac{Z_x(p)}{\left| Z_x(0) \right|} + \delta_{p0}\, \frac{F_{damper}\, f_0}{n_d\, \omega_s \left(-x\, 2\, \pi\, \omega_s\, B \right)} \right] \sigma_{x,ij}(p). \end{aligned} \tag{2}$$

Here, the $\sigma_{x,ij}$ are the eigenvectors solutions of the low-intensity eigenvalue problem with constant inductive impedance

$$\Delta\omega^x_{cm}\, \sigma_{x,m}(l) = \sum_{p=-\infty}^{p=+\infty} K^{x,m}_{lp}\, \sigma_{x,m}(p), \tag{3}$$

with

$$K^{x,m}_{lp} = \frac{j\, e\, I_b}{2\, \gamma\, m_0\, c\, Q_{x0}}\, Z_x(p) \int_{\hat{\tau}=0}^{\hat{\tau}=+\infty} J_{m,x}(l, \hat{\tau})\, J_{m,x}(p, \hat{\tau})\, g_0(\hat{\tau})\, \hat{\tau}\, d\hat{\tau}\,, \tag{4}$$

$$J_{m,x}(p, \hat{\tau}) = J_m\left\{ \left[(p + Q_{x0})\, \Omega_0 - \omega_{\xi_x} \right] \hat{\tau} \right\}, \quad \omega_{\xi_x} = Q_{x0}\, \Omega_0\, \frac{\xi_x}{\eta}\,, \tag{5}$$

where $\Delta\omega_{cm}$ is the complex angular betatron frequency shift of the azimuthal mode m that we are looking for (with $\Delta\omega_{ckl}$ the eigenvalue), (k, l, i, j, p) are integers, ω_c is the (complex) angular betatron frequency and ω_s the angular synchrotron frequency, j the imaginary unit (not to be confused with the index j also used in the matrix coefficient), e the elementary charge, $I_b = N_b\, e\, f_0$ the bunch current (with N_b the number of charges and $f_0 = \Omega_0 / 2\pi$ the revolution frequency), γ the relativistic mass factor, m_0 the rest mass, c the speed of light, Q_{x0} the horizontal tune, $Z_x(p)$ the horizontal (dipolar) impedance at angular frequency $(p+Q_{x0})\,\Omega_0$, J_m the Bessel function of mth order, g_0 the distribution function of the longitudinal synchrotron amplitudes ($\hat{\tau}$), ξ the (relative) chromaticity and η the slippage factor. Furthermore, δ_{ki} is the Kronecker

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delta, * stands for the complex conjugate, F_{damper} = {0, j, 1} in the case {no, "+" resistive, "+" reactive} damper (which can be generalised for any feedback phase), n_d is the damper damping time in machine turns (it is defined as 1 / G with G the damper gain and the related instability damping time is d = 2 n_d [4,14]), B the bunching factor and x is the absolute value of the coherent tune shift from a constant inductive impedance normalised by the synchrotron tune, given by

$$x = \frac{\mathrm{Im}\left[Z_x(0)\right] e\, I_b}{4\,\pi\,\gamma\, m_0\, c\, Q_{x0}\, B\, \omega_s} = \frac{\left|\Delta Q_{coh}^{ind}\right|}{Q_s}. \quad (6)$$

In the present paper, for simplicity and to clearly identify the destabilising mechanism of the transverse damper, a single bunch (with a "water-bag" longitudinal distribution) with zero chromaticity interacting with a broad-band resonator impedance is assumed to discuss the effect of the transverse damper on the Transverse Mode-Coupling Instability (TMCI). However, it should be stressed that GALACTIC is also valid in the general case and some benchmarks with Laclare [11] and DELPHI [6] are discussed in Ref. [13], revealing an excellent agreement.

LONG-BUNCH REGIME: CERN SPS

Assuming a broad-band resonator model (with a quality factor of 1) and a resonance frequency f_r such that $f_r\, \tau_b$ = 2.8 (with τ_b the full - 4σ - bunch length in second), Fig. 1 is obtained (a similar picture is obtained with the real impedance model). This represents the case of the long-bunch regime as the main/strong instability is obtained by coupling between higher-order modes (in contrast to a coupling of modes 0 and -1). In this case, almost no effect is observed for the main TMCI intensity threshold whatever the damper (resistive or reactive), which can be understood as the damper acts mainly on the mode 0 while the (main) mode-coupling happens between higher-order modes.

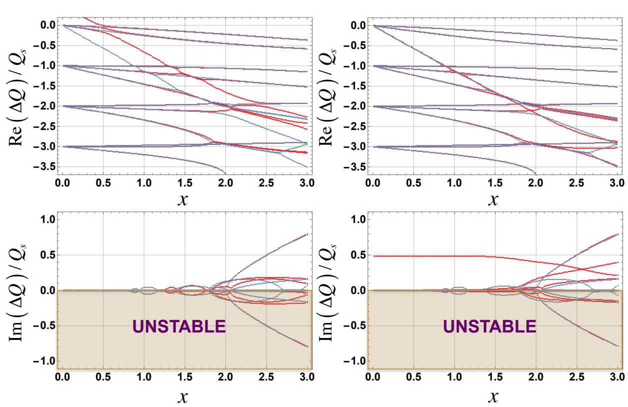

Figure 1: Usual TMCI plots (for $f_r\, \tau_b$ = 2.8) showing the real and imaginary parts of the normalised complex tune shift vs. the normalised coherent tune shift without (in blue) and with (in red) a transverse damper with n_d = 50 turns: (left) reactive and (right) resistive.

SHORT-BUNCH REGIME: CERN LHC

Assuming a broad-band resonator model (with a quality factor of 1) and a resonance frequency f_r such that $f_r\, \tau_b$ = 0.8, Fig. 2 is obtained (a similar picture is obtained with the real impedance model). This represents the case of the short-bunch regime as the main/strong instability is obtained by coupling between modes 0 and -1. Roughly speaking, the TMCI takes place when the (negative) tune shift of mode 0 is about equal to the synchrotron tune. In this case, some effects from the damper are expected as it modifies mainly mode 0. In the presence of a reactive damper (with the correct sign, i.e. compensating the negative tune shift) it is indeed expected that the TMCI intensity threshold can be significantly increased, as it is observed in Fig. 2 (left). However, what is surprising (at first sight) is that the presence of a resistive damper leads to a lower intensity threshold than without (see Fig. 2 (right)), and if one looks at the evolution of the real part of the tune shift, the mode-coupling between modes 0 and -1 appears at a higher intensity than without damper.

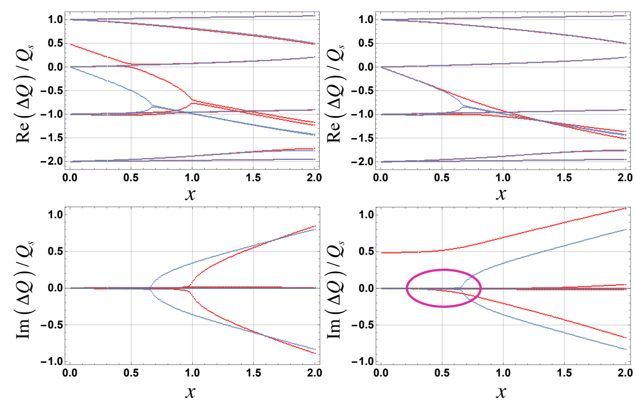

Figure 2: Usual TMCI plots (for $f_r\, \tau_b$ = 0.8) showing the real and imaginary parts of the normalised complex tune shift vs. the normalised coherent tune shift without (in blue) and with (in red) a transverse damper with n_d = 50 turns: (left) reactive and (right) resistive.

NEW INSTABILITY MECHANISM

To be able to understand this new instability mechanism, it is important to be able to select each mode individually, which is possible in GALACTIC. Looking at the mode 0 only (first radial mode) or the mode -1 only, but in the presence of the damper, it is seen that they are both stable. It can be also clearly observed with the simplified model of Eq. (7) discussed below, by neglecting the mode-coupling (off-diagonal) terms. The instability appears only when both modes 0 and -1 (with only the first radial mode) are considered in the presence of the damper: this is the interaction between modes 0 and -1 through the damper, which creates the instability by pushing apart the instability growth rates. As the lowest one (from mode -1) is 0, it becomes negative and leads to an instability. This can be nicely seen if one looks at the 2×2 matrix to be diagonalised (taking into account only the modes 0 and -1), which can be approximated by

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$$\begin{pmatrix} -1 & -0.23\,j\,x \\ -0.55\,j\,x & -0.92\,x + 0.48\,j \end{pmatrix}, \tag{7}$$

where the term "+0.48 j" is the contribution from the "+" resistive damper with n_d = 50 turns: 0.48 = 1 / (2 π d Q_s). Note that this term would be "+0.48" for a "+" reactive damper. Figure 3 depicts the evolution of the eigenvalues for both cases with and without the transverse damper. It is found indeed that introducing a resistive damper lowers the intensity threshold. In fact, it completely changes the nature of the instability as no intensity threshold is observed anymore (as already spotted in Ref. [3]): the bunch is unstable whatever the intensity. Without transverse damper, an instability appears at $x \approx 0.6$ as a consequence of the coupling between two modes (0 and -1). In the presence of the resistive transverse damper, the mode-coupling is suppressed but the interaction between the modes 0 and -1 through the damper pushes apart the imaginary parts and as the imaginary part of the mode -1 is 0, it becomes negative.

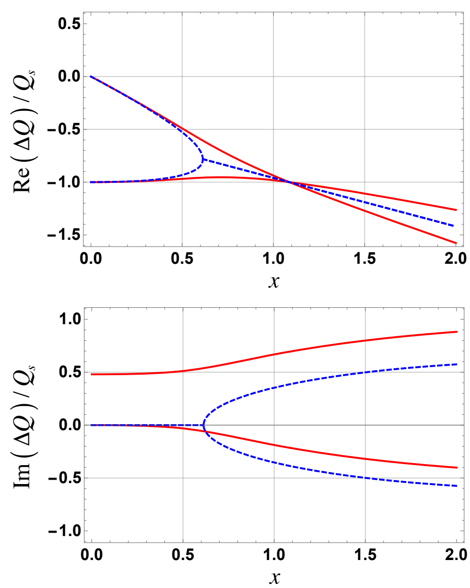

Figure 3: Solutions of the diagonalisation of the 2×2 matrix of Eq. (7): without (blue) and with (red) the damper.

IMPACT ON LANDAU DAMPING

As the instability mechanism involves the two modes 0 and -1, the impact on Landau damping has to be studied by considering both modes and Eq. (8) needs to be solved [15,16]

$$\begin{vmatrix} I^{-1}_{m=-1} & -0.23\,j\,x \\ -0.55\,j\,x & I^{-1}_{m=0} + 0.92\,x - 0.48\,j \end{vmatrix} = 0, \tag{8}$$

where I_m is the dispersion integral. Equation (8) has been solved assuming an externally given elliptical tune spread, which leads to the "circle stability diagram" with only one mode. The associated dispersion integral is given by [17] (with y the unknown we are looking for)

$$I_m = \frac{2}{y - m - j\sqrt{\Delta q^2 - (y-m)^2}}, \tag{9}$$

where Δq is the tune spread (half width at the bottom of the distribution) normalised by the synchrotron tune. The solution of Eq. (8), characterizing the two-mode approach, is compared to the one-mode approach in Fig. 4: it can be seen that below about the TMCI intensity threshold (without damper), the one-mode approach (usual stability diagram) seems fine, whereas above about the TMCI intensity threshold (without damper), the two-mode approach is needed and more tune spread is required to reach bunch stability. As the LHC has been operated until now (well) below the TMCI intensity threshold (without damper), the one-mode approach used so far seems fully justified, which is also in agreement with recent tracking results [18] and past estimates [4].

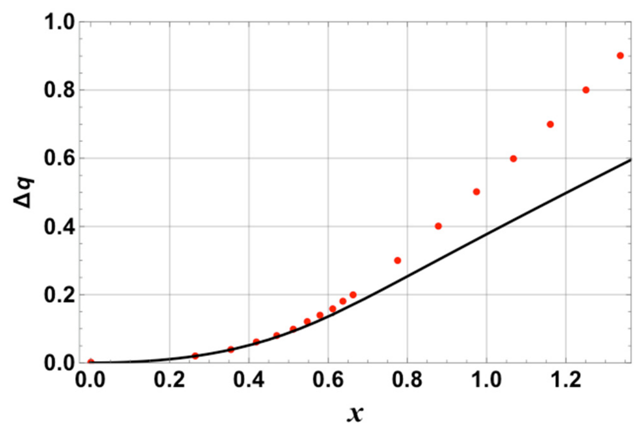

Figure 4: Required normalised tune spread to reach bunch stability vs. the normalised coherent tune shift: using the one-mode approach, leading to the usual stability diagram (black full line) and the two-mode approach from Eq. (8) (red dots) assuming an elliptical tune spread.

CONCLUSION

A new single-bunch instability mechanism is revealed for zero chromaticity in the presence of a resistive transverse damper, which is needed for the multi-bunch operation in a machine like the LHC. The explanation provided in this paper was confirmed by two other Vlasov solvers, DELPHI (using a Gaussian distribution) [14] and NHTVS (using either a Gaussian or "air-bag" distribution) [19].

As the instability mechanism involves two modes, the impact on Landau damping has to be studied by considering both modes together. Preliminary results are shown in Fig. 4, which seem to indicate that the one-mode approach (leading to the usual stability diagram used so far) is fully justified for the LHC, which is operated below the TMCI intensity threshold (without damper). If this is confirmed, another mechanism needs to be identified to explain the LHC observation at low chromaticity [2].

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