DESTABILISING EFFECT OF RESISTIVE TRANSVERSE DAMPERS

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Abstract

A resistive transverse damper is needed for multi-bunch operation in a machine like the CERN LHC and it is very efficient as it considerably reduces the necessary amount of nonlinearities (from octupoles) needed to reach beam stability through Landau damping. However, a resistive transverse damper also destabilizes the single-bunch motion below the Transverse Mode Coupling Instability (TMCI) intensity threshold (for zero chromaticity), introducing a new kind of instability, which has been called "ISR instability" (for Imaginary tune Split and Repulsion). The purpose of this contribution is to explain in detail this new instability mechanism and its mitigation.

INTRODUCTION

A Transverse Damper (TD) generates the following complex tune shift (with j the imaginary unit)

$$\Delta Q_{TD} = \frac{e^{j\phi}}{2\pi d} \ , \tag{1}$$

where ϕ is the betatron phase advance between the pick-up and the kicker, and d is the TD damping time in machine turns (equal to $2/G$ with G the gain of the TD). If $\phi = 90°$, the TD is called "resistive": it is a conventional damper/feedback system, which damps the centre-of-charge motion of the beam (see Fig. 1). If $\phi = 0°$, the TD is called "reactive": in this case, mode 0 is shifted (which can raise the intensity threshold in the presence of TMCI between modes 0 and -1).

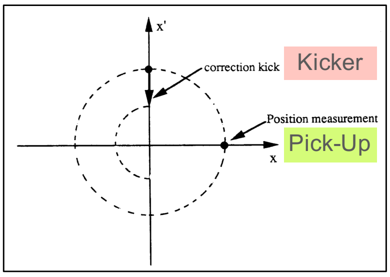

Figure 1: Schematic picture (in the horizontal phase space) of the action of a conventional TD, which damps the centre-of-charge motion of the beam.

A resistive TD is needed for multi-bunch operation in a machine like the LHC and it has been working very well over the past decade [1]. If we take the example of the LHC predictions in 2018 at 6.5 TeV, the beneficial effect of the TD on the amount of Landau octupole current needed to stabilise the beam is clearly visible (see Fig. 2).

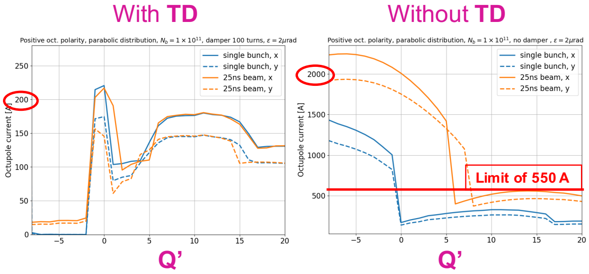

Figure 2: Required octupole current to reach beam stability, with (left) and without (right) a resistive TD, vs. chromaticity Q'. Courtesy of N. Mounet (using DELPHI Vlasov solver [2]).

A better control of the LHC has been achieved year after year, and at the end of Run 2 (2018), the following mitigation knobs were used at 6.5 TeV: Q' ~ +15; TD damping time of ~ 50-100 turns; Landau octupole current a factor ~ 2 higher than predicted (compared to the factor ~ 5 at the end of Run 1) [3]. The main lesson learned from Run 1 and Run 2 is that in a machine like the LHC, not only all the mechanisms have to be understood separately, but (all) the possible interplays between the different phenomena need to be analysed in detail [4]: the TD needs to be included in beam stability analyses (along with beam-beam); the sign of the Landau octupole has to be studied in detail together with beam-beam effects (considering both long-range and head-on effects); there is a destabilising effect of e-cloud; there is a destabilising effect of linear coupling; there is a destabilising effect of noise, which is currently under study and was demonstrated in 2018 for the first time in a machine as a possible contributor to the remaining missing factor ~ 2 in Landau octupole current; there is a destabilising effect of TD, which is the subject of this paper [5].

Several simulations performed with different (Vlasov solver and tracking) codes, considering a single bunch with zero chromaticity, revealed already in the past a more critical situation (as concerns the instability growth-rate or the required octupole current) with TD than without [2,6-10]. However, no model/explanation describing the cause/mechanism of this instability was given in any of these references (in Ref. [6] it is referred to as "a sort of TMCI"). It is worth mentioning also Ref. [11], which has been put to the attention of the author during this workshop, where a head-tail mode instability caused by a feedback is discussed. This should be reviewed in detail in the future and compared to the results presented in this manuscript.

MOTIVATION

Three questions motivated this study for the LHC in terms of beam stability: (1) why a chromaticity close to

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zero seemed to require a higher octupole current than predicted during Run 1 (in 2011 and 2012) and during Run 2 (in 2015)? [12]; (2) why some past simulations with a chromaticity close to zero revealed an instability with the TD, which is absent without TD? [2,6-10]; and (3) what should be the minimum operational chromaticity in the future in the LHC and High-Luminosity LHC? To try and shed some light on these questions, a new Vlasov solver (called GALACTIC) was developed [5,13]. Thanks to it, it is possible to answer to the following two questions: (1) what is the exact predicted instability mechanism at low chromaticity in the presence of a resistive TD? (2) Is a stability diagram, which assumes independent head-tail modes, a sufficiently accurate method for computing the effect of Landau damping in this case?

VLASOV SOLVERS GALACTIC AND GALACLIC

Starting from the Vlasov equation and using a basis of the low-intensity eigenvectors of the problem, as proposed by Laclare and Garnier [14,15], the effect of a TD was added and a new Vlasov solver code was developed, called GALACTIC (for GArnier-LAclare Coherent Transverse Instabilities Code) [5,13]. Note that a similar approach can be used in the longitudinal plane (leading to GALACLIC, for GArnier-LAclare Coherent Longitudinal Instabilities Code), which helped to understand the details of mode coupling behind some longitudinal microwave instabilities [13,16].

Predictions of transverse and longitudinal mode coupling instabilities from GALACTIC and GALACLIC can be found in Fig. 3 for the case of a single proton bunch above transition interacting with a broad-band ($Q = 1$) resonator impedance with a resonance frequency equal to 2.8 divided by the full ($4\,\sigma$) bunch length τ_b (in s). The predictions from Laclare (only real parts) [14] are shown in black, revealing a very good agreement for both transverse and longitudinal planes. The model of Potential-Well Distortion (PWD) used here does not take into account the real part of the longitudinal impedance and therefore the associated asymmetry in the longitudinal bunch profile (linked to the shift of the synchronous phase) is neglected, as it is assumed to be small for the case under study.

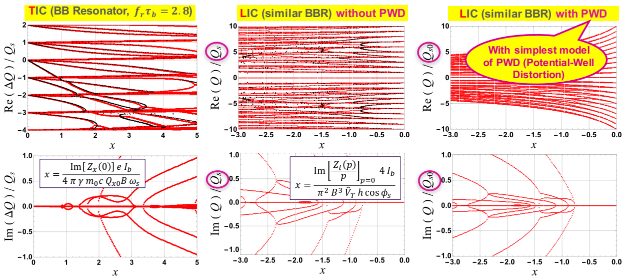

Figure 3: Usual TMCI plots vs. the normalised bunch intensity x (with Q_s the synchrotron tune), comparing GALACTIC and GALACLIC with Laclare's approach in black (only real parts) [14], for the case of a single proton bunch above transition interacting with a broad-band ($Q = 1$) resonator impedance with a resonance frequency equal to 2.8 divided by the full ($4\,\sigma$) bunch length.

A detailed comparison between GALACTIC and GALACLIC with simulation tracking codes has also been performed, revealing an excellent agreement as can be observed in Figs. 4 and 5. An even better agreement could be reached in longitudinal by implementing a more realistic PWD model, which will be done in the future.

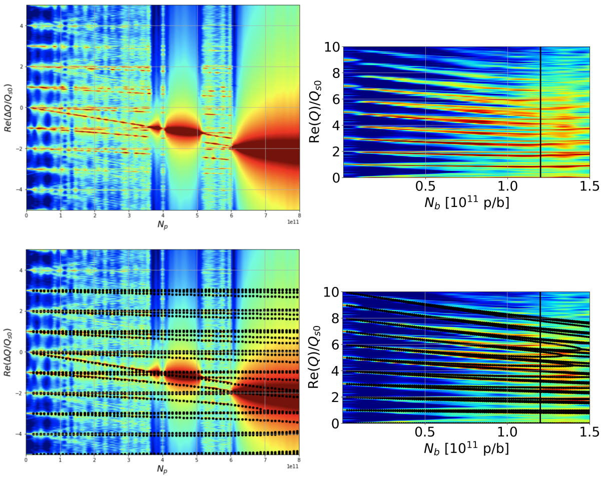

Figure 4: (Left) comparison between pyHEADTAIL [17] macroparticle tracking code (top) and GALACTIC (black dots, bottom) and (right) comparison between SBSC [18] macroparticle tracking code (top) and GALACLIC (black dots, bottom), for the case of a single proton bunch above transition interacting with a broad-band ($Q = 1$) resonator impedance with a resonance frequency equal to 2.7 divided by the full ($4\,\sigma$) bunch length. Courtesy of M. Migliorati for the PyHEADTAIL and SBSC tracking simulations (with a new mode analysis) [16].

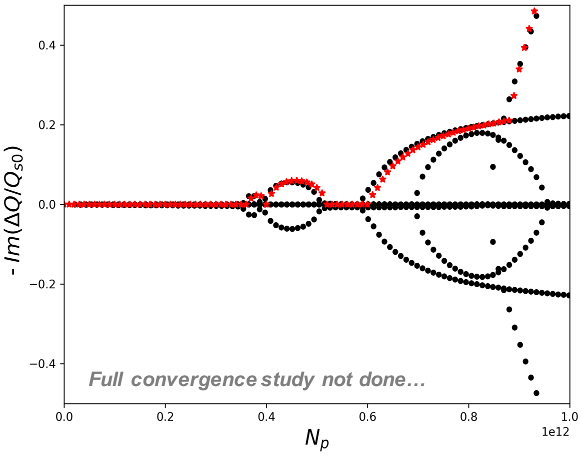

Figure 5: Comparison between pyHEADTAIL [17] macroparticle tracking code (red dots) and GALACTIC (black dots) for the case of a single proton bunch interacting with a broad-band ($Q = 1$) resonator impedance with a resonance frequency equal to 2.7 divided by the full ($4\,\sigma$) bunch length. Courtesy of M. Migliorati for the PyHEADTAIL tracking simulations.

INSTABILITY MECHANISM WITH Q’ = 0

It is important to distinguish between the long bunch and short bunch regimes as the impact of a TD is very different for the two regimes. In the long bunch regime (see Fig. 6), the main mode coupling takes place between high-order modes and the TD will not be able to modify it whatever its phase. This is not the case for the short bunch regime (see Fig. 7), for which the mode coupling takes place between the modes 0 and -1. In this case, a reactive TD is beneficial as it increases the TMCI intensity threshold, modifying the shift of mode 0 and pushing the mode-coupling towards higher bunch intensities (see Fig. 7 left). A resistive TD, on the other hand, is detrimental as it decreases the intensity threshold (see Fig. 7 right). The exact mechanism [5] will be reviewed below.

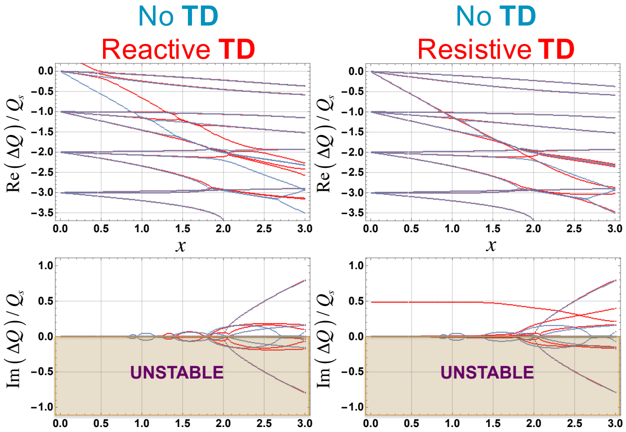

Figure 6: Usual TMCI plots from GALACTIC for the case of the long bunch regime ($f_r\,\tau_b = 2.8$), which approximately describe the CERN SPS case, assuming a TD with a damping time $d = 100$ turns.

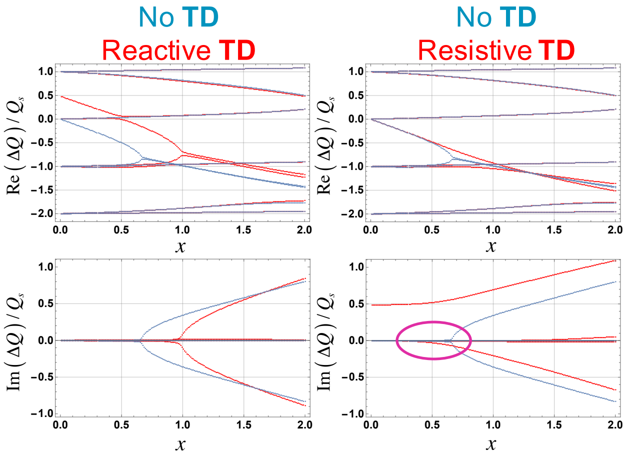

Figure 7: Usual TMCI plots from GALACTIC for the case of the short bunch regime ($f_r\,\tau_b = 0.8$), which approximately describe the CERN LHC case, assuming a TD with a damping time $d = 100$ turns.

The matrix which needs to be diagonalised in GALACTIC can be reasonably well approximated (for the purpose of the current study) by this 2×2 matrix (taking into account only the modes 0 and -1),

$$\begin{pmatrix} -1 & -0.23\,j\,x \\ -0.55\,j\,x & -0.92\,x+0.48\,j \end{pmatrix}, \tag{2}$$

where the term “+0.48 j” is the contribution from the “+” resistive TD with a damping time $d = 100$ turns (it would be “+0.48” for a “+” reactive TD and its general form is given by $\Delta Q_{TD}/Q_s$). The mode -1 is described by the top-left term while the mode 0 is described by the bottom-right one (the mode coupling terms being the off-diagonal ones). Figure 8 depicts the evolution of the eigenvalues for both cases with and without the TD and it can be observed that similar results as in Fig. 7 right are obtained. It is found indeed that introducing a resistive TD 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. [6]): the bunch is unstable whatever the intensity. Without TD, an instability appears as a consequence of the coupling between two modes (0 and -1). In the presence of the resistive TD, the mode coupling is suppressed but the interaction between the modes 0 and -1 in the presence of the TD pushes apart the imaginary parts and as the imaginary part of the mode -1 is 0, it becomes negative and leads to an instability.

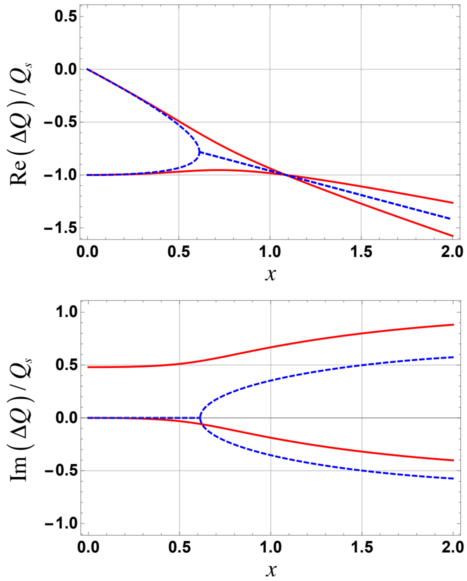

Figure 8: Solutions of the diagonalisation of the 2×2 matrix of Eq. (2): without (blue) and with (red) the resistive TD.

The fact that the TD term in Eq. (2) is given by $\Delta Q_{TD}/Q_s$ explains why a TD is not very effective for machines with a large synchrotron tune Q_s. Indeed, assuming for instance $Q_s = 0.1$, a resistive TD with a damping time $d = 50$ turns would almost not modify the TMCI picture, as can be seen in Fig. 9.

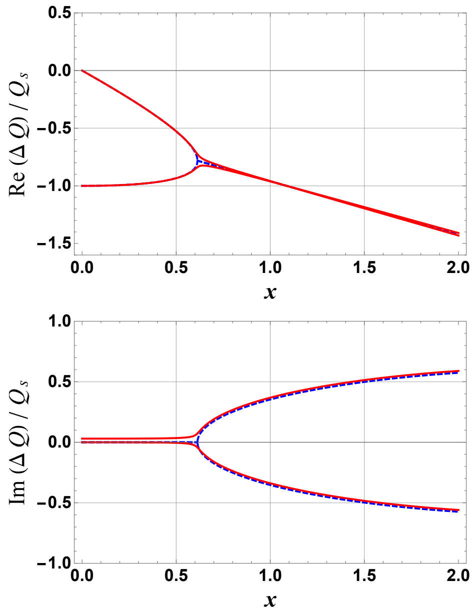

Figure 9: Solutions of the diagonalisation of the 2×2 matrix of Eq. (2): without (blue) and with (red) the resistive TD, assuming $Q_s = 0.1$ and $d = 50$ turns.

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. (3) needs to be solved

$$\begin{vmatrix} I_{m=-1}^{-1} & -0.23\, j\, x \\ -0.55\, j\, x & I_{m=0}^{-1} + 0.92\, x - 0.48\, j \end{vmatrix} = 0\,, \tag{3}$$

where I_m is the dispersion integral. I have solved Eq. (3) assuming an externally given elliptical tune spread, which leads to the "circle stability diagram" for the one-mode approach. In this case, the dispersion integral is given by [19] (with y the unknown we are looking for)

$$I_m = \frac{2}{y - m - j\sqrt{\Delta q^2 - \left(y - m\right)^2}}\,, \tag{4}$$

where Δq is the tune spread (half width at the bottom of the distribution) normalised by the synchrotron tune. The solution of Eq. (3), characterizing the two-mode approach, is compared to the one-mode approach in Fig. 10: it can be seen that below the TMCI intensity threshold (without TD), the one-mode approach (usual stability diagram) seems fine, whereas above the TMCI intensity threshold (without TD), the two-mode approach is needed and more tune spread is required. As the LHC has been operated until now below the TMCI intensity threshold (without TD), the one-mode approach used until now seems fully justified, which was also in agreement with some first tracking results [20]. It can also be concluded from Fig. 10 that a resistive TD has a detrimental effect below and a beneficial effect above the TMCI intensity threshold, as much less octupole current is needed for the latter case to reach beam stability through Landau damping than without a TD.

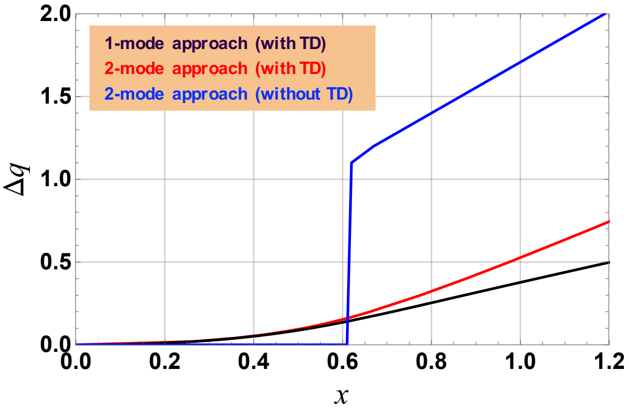

Figure 10: Required tune spread (normalised by Q_s) to reach bunch stability vs. the normalised bunch intensity: using the one-mode approach, leading to the usual stability diagram (black line) and the two-mode approach from Eq. (3) (red line) assuming an elliptical tune spread. The blue line corresponds to the case without TD but considering the mode coupling between modes 0 and -1.

COMPARISON WITH PYHEADTAIL

The previous analytical description has been checked in detail through pyHEADTAIL macroparticle tracking simulations, revealing that most of the physics was captured by the simplified model (see Fig. 11).

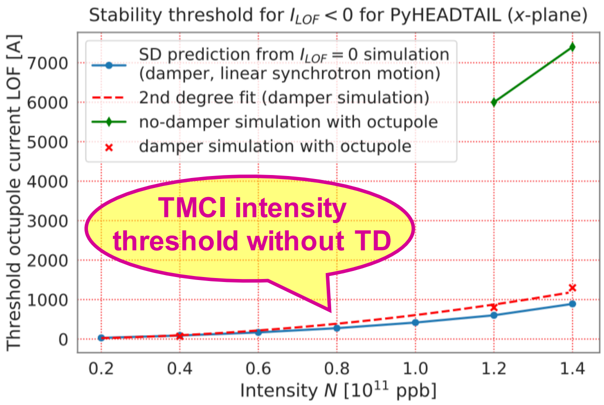

Figure 11: Case of Fig. 10 re-analysed in detail through pyHEADTAIL tracking simulations, revealing a good agreement between the two approaches. Courtesy of A. Oeftiger [21].

DESTABILISING EFFECT OF LANDAU DAMPING FOR TMCI

In the framework of this study, it is worth mentioning that below the TMCI intensity threshold without TD, the tune spread provided by Landau octupoles (to generate some Landau damping) is also detrimental if it is not high enough (of the order of the synchrotron tune) but already quite important. This destabilising effect was already revealed a long time ago in Ref. [22]. It has been revisited with the simplified model of Eq. (3) in the absence of TD [23], confirming the results from Ref. [22] (see Fig. 12).

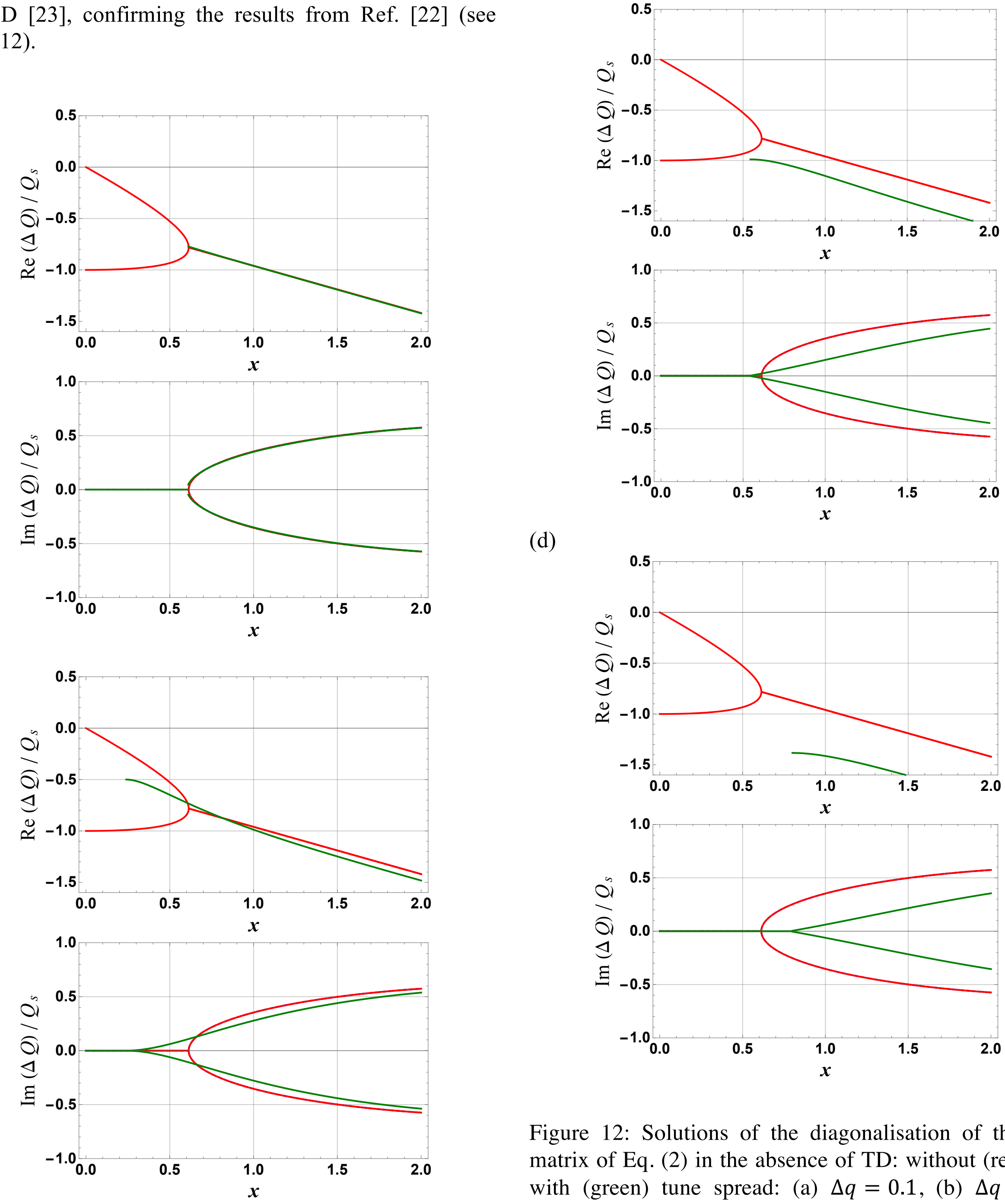

Figure 12: Solutions of the diagonalisation of the 2×2 matrix of Eq. (2) in the absence of TD: without (red) and with (green) tune spread: (a) $\Delta q = 0.1$, (b) $\Delta q = 0.5$, (c) $\Delta q = 1.0$, (d) $\Delta q = 1.4$.

CONCLUSION

A new single-bunch instability mechanism is revealed for zero chromaticity in the presence of a resistive transverse damper. The explanation provided in this paper (and already documented in Ref. [5]) was confirmed by two other Vlasov solvers, DELPHI (using a Gaussian distribution) [24] and NHTVS (using either a Gaussian or air-bag distribution) [25], which could reproduce Figs. 7 and 8.

The detailed instability mechanism could not be identified with PyHEADTAIL macroparticle tracking simulations only. However, the impact on Landau damping could be analysed in detail with PyHEADTAIL [21], confirming the detrimental effect of resistive transverse dampers below the TMCI intensity threshold and the beneficial effect of resistive transverse dampers above the TMCI intensity threshold (see Figs. 10 and 11).

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