INTERPLAY OF TRANSVERSE DAMPER AND HEAD-TAIL INSTABILITY*

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Abstract

Transverse head-tail instability is a major limitation for the single-bunch beam current in circular accelerators. Beam-based feedback is one of the potential tools to suppress this type of instability. The feedback systems (transverse dampers) provide active suppression of the beam oscillations by electromagnetic fields, the amplitude of which is calculated in real time from the measured beam position. The efficiency of the transverse dampers in combination with various chromaticity settings is discussed.

HEAD-TAIL INSTABILITY

Collective instabilities of the transverse motion of particle beams in circular accelerators have been studied already since the early 1960s. Among one of the first instabilities observed and studied was likely the coherent instability caused by the beam interaction with the resistive-wall impedance of the vacuum chamber [1]. Now, this kind of instability usually affects the beams with a multi-bunch filling pattern used for the operation of most synchrotron light sources. The reason for the instability has been understood at that time, it is the bunch-to-bunch interaction via wakefields generated by the beam moving in a resistive chamber. For a coasting beam, the theoretical explanation of the instability was proposed and the stabilizing mechanisms were examined by means of the Vlasov Equation [2].

For azimuthally bunched beams, the transverse coupled-bunch instability was theoretically studied using the rigid-bunch model [3]. The modes of oscillation, stability criteria and the small-amplitude growth rates were derived by solving the eigenvalue problem. For a short single bunch, stabilization of the coherent transverse instability by Landau damping was also explored [4].

The single-bunch head-tail effect was observed in the VEPP-2 [5], ACO, and ADONE [6] electron-positron rings. The fast damping of coherent betatron oscillations, as well as the transverse head-tail instabilities, were experimentally studied with the varied beam current. As it was found, the fast damping can not be explained by resistive walls, it was caused by the beam interaction with the broad-band impedance of electrostatic e^+/e^- separators.

Interaction of a bunched beam with short-range transverse wakefields characterized by the broadband impedance results in the head-tail instability. The wakefields induced by the head of a bunch act on particles of its tail; the head and tail of the bunch exchange places periodically due to synchrotron oscillations; the instability occurs if certain conditions of resonance excitation exist. The simplest two-particle model [7] assumes the bunch consisting of two macroparticles, which oscillate longitudinally with the constant amplitude.

The early studies of head-tail instability are summarized and discussed in detail in the review [8] presented at PAC-1969. The results of experimental studies of the feedback performance with varied chromaticity carried out at the ADONE ring are compared to analytical estimations. The first theoretical explanations of the head-tail effect published in [6, 7] include two-particle and multi-particle models as well as formulation and solution of an eigenvalue problem to determine the growth rates and frequency shifts of the head-tail modes.

Advanced theories were developed later using a number of approaches, such as macro-particle models, linearizing Vlasov equation, applying perturbation theory [9–14]. These comprehensive studies cover almost all aspects of the head-tail effect including mode coupling, various impedance models, chromaticity, and Landau damping. The simplified but effective mathematical model of the head-tail instability is based on the multimode analysis of the eigenvalue problem

$$\det[(\lambda - l)\,\mathbf{I} - \mathbf{M}] = 0\,, \tag{1}$$

where $\lambda = (\Omega - \omega_\beta)/\omega_s$, ω_β is the unperturbed betatron frequency, ω_s is the synchrotron frequency. The matrix elements are

$$M_{kk'} = I_b \frac{\beta}{2\nu_s E/e} \sum_{p=-\infty}^{\infty} Z_\perp(\omega') g_{lk}(\omega' - \omega_\xi) g_{lk'}(\omega' - \omega_\xi)\,, \tag{2}$$

where β is the average beta function, $\omega' = p\omega_0 + \omega_\beta + l\omega_s$, $\omega_\xi = \xi\omega_0/\alpha$ is the chromatic frequency. The functions characterizing oscillation modes of the Gaussian bunch are:

$$g_{lk}(\omega) = \frac{1}{\sqrt{2\pi k!(|l|+k)!}} \left(\frac{\omega\sigma_t}{\sqrt{2}}\right)^{|l|+2k} \exp\left(-\frac{\omega^2\sigma_t^2}{2}\right)\,. \tag{3}$$

Solving the eigenvalue problem for specific impedance and beam parameters, one can derive the intensity-dependent shift of complex oscillation frequencies for the head-tail modes.

The simplest case is the fast head-tail instability occurring with zero chromaticity if the beam current exceeds a certain threshold determined by the coupling of two modes. In the short bunch regime ($f_r\sigma_t < 1$, where f_r is the frequency of the broadband resonator representing the machine impedance and σ_t is the bunch length), where lepton machines tend to operate, these two modes are usually the azimuthal head-tail modes 0 and 1. The exponential growth of betatron oscillation results in the loss of the beam intensity down to the threshold value. The chromatic head-tail effect

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occurs if the chromaticity is not zero. In this case, there is no threshold beam intensity and some head-tail modes are unstable for any beam current. The coherent mode 0 is stable with positive chromaticity and unstable with negative chromaticity for machines operated above transition; again, this is usually the case for most lepton machines. The higher-order modes behave oppositely. The rising/damping rates decrease rapidly with the head-tail mode number, so the eigenmode analysis is quite efficient because only a few lowest modes are important.

TRANSVERSE FEEDBACK (DAMPER)

Transverse feedback systems (dampers) were proposed to cure the beam instabilities soon after they were observed. The idea is straightforward: coherent beam oscillations are measured by a beam position monitor (capacitive pickup, stripline) and the signal with proper amplification and phase shift is used to drive a high-voltage RF amplifier connected to a stripline kicker deflecting the beam to damp the oscillations. At VEPP-2, the transverse instability has been eliminated by feedback [5], this is likely one of the first published reports on the damper suppressing the head-tail instability. A detailed description of the transverse damper developed and commissioned at SPEAR-II is published in [15] including design principles, circuit analysis, and results of beam tests. For zero chromaticity, the SPEAR-II damper helped to increase the injected beam current by a factor of 5.

The dampers to suppress coherent instabilities have been then installed at other accelerators, e.g. SPS [16] and PETRA [17], and they were efficient to suppress coherent transverse instabilities as expected. However, it was not clear if the damper able to suppress the chromatic head-tail instability, which is a combination of coherent and incoherent oscillation modes and how the chromaticity affects the damper performance. Successful application of the damper to suppress the head-tail instability was experimentally demonstrated at PETRA [18]. Now almost all electron rings are equipped by bunch-by-bunch feedbacks [19], which are available as commercial products.

The mode-coupling theory of the fast head-tail (transverse mode coupling) instability was expanded including feedback [20]. The feedback term was added to the matrix equation (1) assuming the feedback system affects the only matrix element related to the coherent mode. The resistive feedback, which damps the center-of-mass oscillation, was already successfully used at several machines to suppress multi-bunch instabilities. In the case of the intra-bunch instability, the resistive feedback was considered inadequate, because the particle motion in the bunch is complicated and damping all modes by affecting the center of mass looks unfeasible. According to [20], the reactive feedback can increase the threshold beam current up to a factor of 4 and resistive feedback is completely ineffective as a cure for this instability.

The reactive feedback systems were proposed for LEP [21, 22] and PEP [23] to cure the fast head-tail instability. However, the experimental results from PEP [24] unexpectedly demonstrated that at high gain the resistive feedback provides a larger increase of the threshold current than the reactive feedback. The reactive feedback system proposed in [22] was implemented at the LEP collider resulting in a moderate increase of the threshold current [25].

A transverse feedback system with variable phase installed at the VEPP-4M electron-positron collider allowed testing efficiency of both reactive and resistive feedback with a small positive chromaticity [26]. As it was found, the optimum feedback phase is closer to zero (resistive feedback) than to 90° (reactive feedback), however, the dependence is not very strong.

A mathematical model of the head-tail instability has been developed on the basis of the multi-mode analysis of the eigenvalue problem [27, 28], chromaticity and feedback are taken into account. Starting from the continuum model and the Vlasov equation, the analysis of beam stability with feedback is reduced to a system of algebraic equations. Analysis of symmetric modes is efficient because only the lowest modes are essential. A theory of the head-tail instability caused by electron clouds has been developed using a similar approach [29]. As concluded in [27], the resistive feedback in combination with negative chromaticity can effectively damp the instability increasing the threshold beam current by a factor of 3 to 5 with relaxed tolerances of the feedback parameters. The same conclusion is made in the recent simulation studies of the damper efficiency for the Advanced Photon Source and LHC [30]: the resistive feedback is most effective with negative chromaticity. However, as shown in [28], high positive chromaticity can suppress the head-tail instability even without feedback.

EXPERIMENTAL RESULTS

The efficiency of the damper in combination with varied chromaticity was experimentally studied at several accelerator facilities. The results look quite contradictory. There are few experimental confirmations of the damper efficiency with negative chromaticity, theoretically predicted by the mode-coupling theory. However, other experiments show higher efficiency of the transverse feedback with positive chromaticity.

One of the first experiments was carried out at PETRA. It was noticed that for positive chromaticities close to zero the threshold currents increased by about 25% [18]. With the negative chromaticity of −4.5 and feedback on, the maximum bunch current was more than 6 mA, whereas it was limited to 0.3 mA without feedback [17].

The feedback performance with positive chromaticity varied up to high values was studied at ESRF [31]. The feedback gain required at low chromaticity to exceed 15 mA of the bunch current was reduced to almost zero at the increased chromaticity. For regular operations, the transverse instability limiting the single-bunch intensity is suppressed by increasing the vertical chromaticity to large positive values.

At ELETTRA [32], the dipole head-tail mode shift is quite large and increasing the chromaticity does not improve much the machine performance. A small improvement has been observed using the transverse multi-bunch feedback at positive chromaticity. With negative chromaticity and transverse feedback, the maximum stable current 50% beyond the 10 mA limit was achieved but could not be easily reproduced. Usually, the beam current saturates between 6 and 10 mA. Switching the feedback off causes the current always to drop below the threshold. Operating with negative chromaticity and transverse feedback in the single- or 4-bunch mode, the beam was very stable at all currents, unlike the operation at positive chromaticity.

On the basis of the theory [27, 28], a feedback system for suppression of transverse beam instability has been developed at the VEPP-4M electron-positron collider [33]. A special feature of this system is the simultaneous suppression of the oscillations of colliding electron and positron bunches using the same kickers and pickups. The feedback efficiency was studied experimentally with various vertical chromaticities. For the standard injection mode with the beam energy of 1845 MeV, vertical chromaticity $\xi_y = 4$, and horizontal chromaticity $\xi_x = 2$, the threshold beam current is about 5 mA. The feedback provides a reliable increase of the injected current by a factor of 3. Slowly decreasing the chromaticity leads to excitation of the instability and the beam loss down to 4.4 mA at $\xi_y = 1.4$. Increasing the chromaticity stabilizes the beam, at the vertical chromaticity $\xi_y = 6$ switching off the feedback does not cause a fast beam loss if there is no other perturbation. Further increase of positive chromaticity results in a more stable beam. With the negative vertical chromaticity $\xi_y = -8$, the injected beam current exceeding 10 mA was achieved. Switching off the feedback results in the beam loss down to 0.3-0.4 mA. So the relative increase of the beam current in comparison with the feedback off was large, however, the absolute injected beam current was lower than at the positive chromaticity.

The effect of positive chromaticity stabilizing the transverse beam instabilities was studied theoretically [34] and experimentally [35] at NSLS-II. The instability threshold was calculated and measured as a function of chromaticity. The stabilizing effect of positive chromaticity was confirmed, the single-bunch threshold current of 0.95 mA was measured at zero chromaticity, 3.2 mA at the chromaticity $\xi_x = 5, \xi_y = 5$, and 6 mA at the chromaticity $\xi_x = 7, \xi_y = 7$. No significant effect on increasing the beam current was observed varying the chromaticity below 5.

Experimental studies of the feedback efficiency with high positive chromaticity were carried out at SOLEIL [36]. Without the feedback, the single-bunch beam current is about 2 mA with the vertical chromaticity varied from 0 to 3. At the vertical chromaticity of 3, a step-like increase of the beam current up to 8 mA was observed. Further increase of the vertical chromaticity results in almost linear growth of the beam current with the chromaticity, reaching 14 mA at $\xi_y = 5$. With the feedback on, the beam current is about 8 mA at $\xi_y = 0$; 10 mA at $\xi_y = 1$; and 16 mA at $\xi_y = 3$.

Measurements of single bunch instability thresholds were done at Diamond Light Source with the chromaticity varied from -2.5 to 2.5 [37]. It was found that changing the feedback phase from resistive to reactive and intermediate was helpful to maximize the achievable beam current. There is no unique phase that works best in all chromaticity regimes. A step-like increase of the beam current with the chromaticity was also observed with and without the feedback.

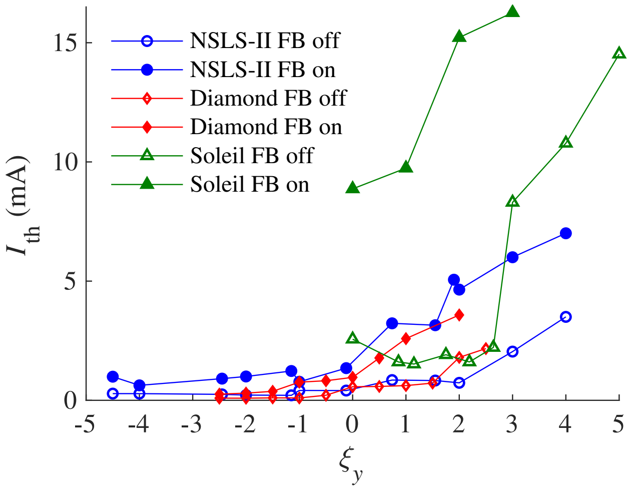

Figure 1: Measured single-bunch threshold current as a function of chromaticity, with and without feedback.

Fig. 1 shows a summary of the measured results discussed above. It looks like the threshold beam current is higher with the positive chromaticity, both with and without feedback. This is also consistent with the numerical simulation based on multi-particle tracking [33]. The bunch-by-bunch feedback systems installed at the synchrotron light sources are usually designed as narrow-band because the main purpose of these systems is to suppress the coupled-bunch instability. So the feedback acts on the center-of-mass motion only. A possible mechanism of the instability suppression discussed in [33] can result from the periodic energy exchange between the coherent and incoherent head-tail modes: the feedback is able to suppress the coherent fraction of oscillation, which always exists due to the chromatic decoherence/recoherence. Since the growth/damping rates of the head-tail modes strongly decrease with the mode number, it could be more effective to suppress the 0-th mode at positive chromaticity, when its decrement considerably exceeds the increments of higher modes. On the contrary, at negative chromaticity the higher modes are stable but the growth rate of the 0-th mode is large and much more powerful feedback is required, so the noise sensitivity is higher, which makes the beam unstable. A potential drawback of the high-chromaticity operations is a possible reduction of dynamic aperture and, therefore, the injection efficiency.

CONCLUSION

The transverse feedback (damper) is an effective way to suppress the head-tail instability, despite it is a combination of coherent and incoherent oscillation modes. The mode-coupling theory is now the most often used tool to describe beam dynamics with impedance and feedback. The calculations can be carried out with the impedance represented by a broad-band resonator model, resistive wall, and with the results of numerical wakefield simulations. Taking bunch lengthening into account is important for electron machines with short bunches. Positive chromaticity helps to increase the instability threshold even without feedback. Feedback in combination with negative chromaticity result in a significant relative increase of the instability threshold but the absolute accumulated beam current is lower. For electron storage rings, operation with negative chromaticity does not look practical, feedback in combination with positive chromaticity is more robust. The machine nonlinearity has a significant effect too, to simulate beam dynamics with the collective effects, feedbacks, chromaticity, and nonlinearity, multi-particle tracking with momentum-dependent and amplitude-dependent effects, is necessary.

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