"ANOMALOUS," NONLINEARLY CURRENT-DEPENDENT DAMPING IN CESR

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Summary

In multibunch operation of the e+e- storage ring CESR, a long-range interbunch coupling force reveals itself by causing coherent transverse instabilities. We measure the damping time constant of the beam's coherent response to shock excitation, using single beams of 1, 3, 5, 7, or 8 bunches of e+; frequency-selective observation of a pickup signal permits identification of the multibunch modes. The long-range force predominates at low frequencies, like the effect of a resistive wall impedance, but two orders of magnitude larger; it exhibits a strongly nonlinear current dependence. Because of this, and because the source of the coupling is as yet unknown, we call the damping "anomalous." The resulting multibunch instabilities can be controlled by use of head-tail damping (positive chromaticity) and narrowband feedback.

Introduction

To achieve higher luminosity, since 1983 the Cornell Electron Storage Ring (CESR) has been operated with multiple bunches in each beam [1]. Multibunch coherent horizontal instabilities are observed, fortunately only in an intermediate current range and not when the beams are actually colliding. However, these instabilities become more severe when the number of bunches is raised from 3 to 7 per beam. A program of diagnostic studies, focused principally on measuring the coherent damping time of various multibunch modes, has defined many aspects of the long-range coupling force responsible for the instability. The coupling is present even in single-bunch operation, but, at CESR's below-half-integer tune, it produces damping rather than antidamping. The effect is strongest in the horizontal plane, but some vertical force is also present. Longitudinal motion is not detectably involved, although some instabilities of the synchrotron oscillations--presumably controlled by the feedback loops within the RF system--have occasionally been seen.

This paper summarizes our experimental findings. A companion paper [2] shall provide more complete data and elaborate on the reasoning, establishing a phenomenological model for the long-range coupling force. The primary author's dissertation [3] treats multibunch instabilities and current-dependent phenomena in CESR more generally.

Coherent Damping Measurements

A small pickup electrode, sampling M similar, equally spaced bunches, yields frequency components Mpf_o [$p = 0,\pm1,\pm2,\ldots$], where f_o is the revolution frequency. The bunches can execute coherent oscillations with their progressive phase difference around the ring amounting to $2\pi\ell$ [$\ell = 0,1,\ldots,M-1$]. With the betatron frequency $f_\beta = (Q_\beta+q_\beta)f_o$ (we separate the integer part Q_β of the tune for convenience), a position-sensitive pickup then sees frequencies

$$f = [Mp+\ell+(Q_\beta+q_\beta)]f_o = nf_o + q_\beta f_o \qquad (1)$$
$$[n = Mp+\ell+Q_\beta] \ ,$$

i.e., sidebands lying $q_\beta f_o$ above a harmonic of f_o, provided n>0. For n<0, since experimentally we detect only $|f|$, we have $|f| = |n|f_o - q_\beta f_o$, a lower sideband. Different multibunch modes ℓ appear as different sidebands, permitting identification of the mode by frequency-selective detection of the pickup signal.

For diagnosis, coherent oscillations can be excited by externally applied beam deflections, either selectively by sinusoidal drive at the appropriate frequency $|f|$, or by a step function which excites all the modes at once. Because the step function drive ("pinger") does not require tuning to a precise frequency, most of our observations are made this way. The pulsed deflection lasts for about two turns and is repeated at a sufficiently low rate to permit complete recovery between events.

Figure 1 illustrates the beam response, at the lowest signal frequency $q_\beta f_o$, to such a stimulus. The detector (Tektronix 7L5 Spectrum Analyzer, operated in fixed-frequency mode) has logarithmic response; the slope of the displayed line determines the coherent damping time τ of the exponentially decaying component corresponding to the selected mode ℓ. For example, in CESR, $Q_\beta = 9$, and so with M = 3 bunches the signal of Figure 1 corresponds to mode $\ell = 0$. Of course, such measurements can be made only while the beam is stable (in all possible modes); under many conditions it is necessary to introduce some additional, overall damping (e.g., by use of positive chromaticity [4,5]) and to correct for this in interpreting the results.

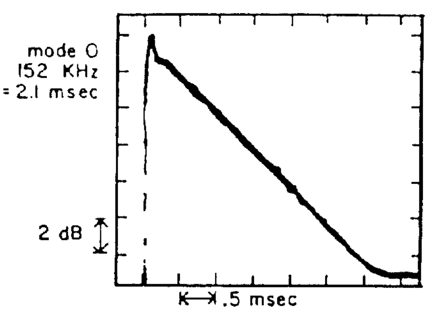

Fig. 1: Shock Excitation Response at $f=q_\beta f_o$
Receiver bandwidth = 10 kHz.

The damping rate, $1/\tau$, results from all mechanisms (e.g., radiation, head-tail, Landau damping) acting on individual bunches, plus the effect of the long-range force here being studied. If this force is due to an impedance Z_T, a given multibunch mode ℓ excites Z_T at all angular frequencies, $\omega = 2\pi f$, associated with ℓ by equation (1); the net contribution is obtained by summing over this group of frequencies to give

$$\frac{1}{\tau_{M\ell}} = \frac{ecf_o}{2\omega_\beta E_o} MI \sum_{p=-\infty}^{\infty} \mathrm{Re}\ Z_T(\omega) \qquad (2)$$

[E_o = beam energy, I = current/bunch]. Upper and lower sidebands, in order of increasing $|\omega|$, arise alternately from f>0 and f<0. Because $\mathrm{Re}\ Z_T(\omega) = \mathrm{sgn}(\omega)\ \mathrm{Re}\ Z_T(|\omega|)$, these sidebands make alternate positive and negative contributions in equation (2). For example, the resistive wall impedance [6],

$$Z_T(\omega) = \frac{c^2}{\pi b^3 f_o} \sqrt{\frac{\mu_o \rho}{2|\omega|}} \, [\mathrm{sgn}(\omega) - i] \, , \qquad (3)$$

for a chamber of radius b and resistivity ρ, leads to terms in equation (2) as shown (for q_β=.4) in Figure 2. With M=3, modes ℓ=0 and ℓ=1 are stabilized, while ℓ=2 is destabilized (its leading term, the lower sideband at $f_o - q_\beta f_o$, is negative).

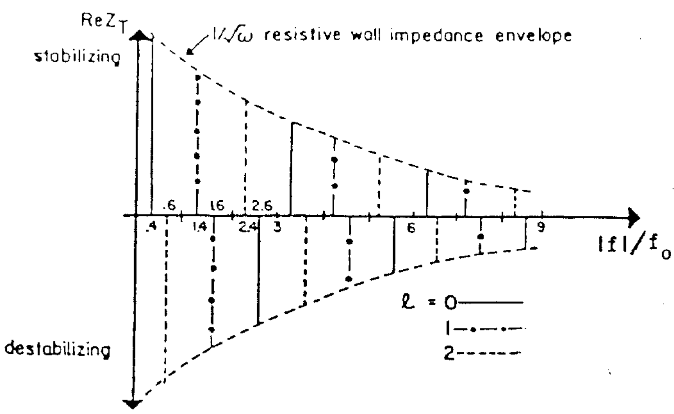

Fig. 2: Multibunch Mode Spectrum for M=3 Bunches.

As illustrated in Figure 3, our results for the long-range coupling force resemble the resistive wall effect qualitatively, in that alternate modes are stabilized and destabilized. However, the current dependence is grossly nonlinear, and the general magnitude of the damping rates is about 10^2 times the result of the impedance in equation (3) for an aluminum chamber. The data presented in Figure 3 were taken at positive chromaticity [ξ_H = $(df_H/f_o)/(dE/E_o)$]; the associated head-tail damping has been subtracted off to obtain the plotted results.

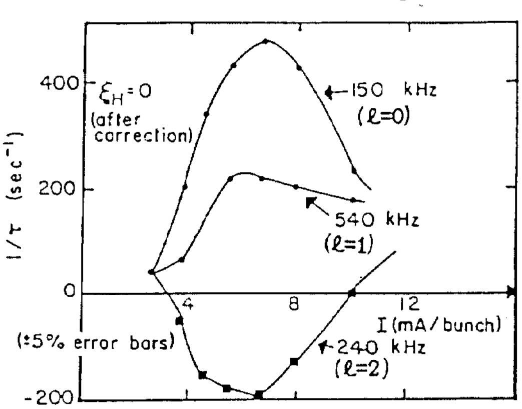

Fig. 3: Multibunch Coherent Damping for M=3 Bunches.

To determine the frequency region over which Z_T is important, we measure $\tau_{M\ell}$ for various modes, with M = 1, 3, 5, 7, or 8 bunches. For q_β = .4 we find that the most strongly damped mode is always the one associated with the lowest frequency, $q_\beta f_o$, regardless of the required value of ℓ. The other modes show damping rates consistent with a Re $Z_T(\omega)$ decreasing as $|\omega|$ rises, perhaps somewhat more slowly than the example of Figure 2. When the sequence of upper and lower sidebands is reversed by making q_β = .6, the long-range part of the damping also approximately inverts (Figure 4). For q_β = .2 the damping associated with the lowest sideband frequency, $q_\beta f_o$ = 80 kHz, increases by about a factor of 2.4, relative to Figure 4, as expected for a Z_T whose envelope continues to grow as $|f|$ goes to zero.

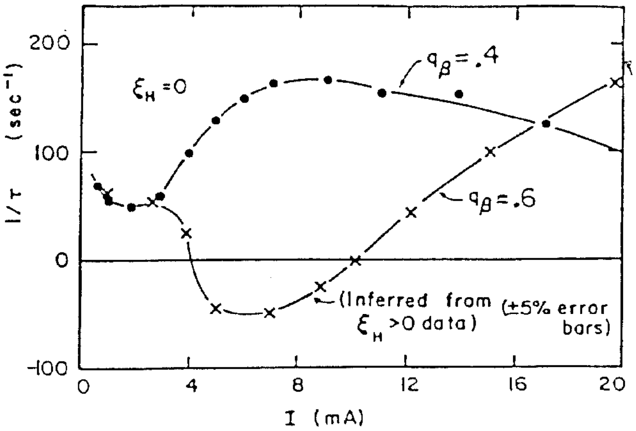

Fig. 4: Single-Bunch Coherent Damping, Q_β = 9.

Comparison of Figures 3 and 4 shows that the onset of the anomalous damping occurs at roughly 3 mA per bunch for the single-bunch (M=1) and three-bunch (M=3) cases. The magnitudes of the coherent damping peaks, on the other hand, scale relatively with the product of the total beam current and a transverse impedance sum, as expressed by equation (2). This dependence of onset approximately on current per bunch (I) and magnitude on total beam current (MI) has also been verified with seven bunches (M=7).

All this points to a long-range coupling impedance Z_T which peaks at low frequency. Any alternative model, relying on a narrow high-frequency resonance in Z_T, would require this resonance to be placed very precisely adjacent to a selected harmonic of f_o, the lowest possible being 840 f_o (= 1x3x5x7x8 f_o). The numerology of picking a high harmonic which happens always to be associated with the lowest frequency sideband, for all values of M explored, is far-fetched. Such a resonance would moreover need to be extremely stable in order not occasionally to favor another mode, or even to move to the wrong side of the harmonic and thus to antidamp at the lowest frequency.

Related Diagnostic Experiments

Because the resistive wall impedance of the aluminum vacuum chamber fails to account for the magnitude of the observed damping rates, much effort has gone into attempting to implicate local elements within CESR:

a. RF cavity: two cavities vs. one, different cavities, disabling of amplitude and phase feedback loops, variation of RF amplitude (modifying the bunch length), displacing the orbit within the cavity;

b. horizontal separator plates: disconnecting supply cables, impedance modification by attaching inductances;

c. ceramic sections (with thin metallic coating): shorting coils on various magnetic elements in those sections, removing ferrite, wrapping ceramic with copper foil, turning off transductor power supply.

None of these modifications significantly altered the measured damping rates. In view of the low-frequency peaking of Z_T, short elements (other than ferrites) are, in any event, unlikely contributors. (Also, bench measurements and calculations for ferrites fail to yield sufficiently large fields for our need.)

The damping of vertical betatron oscillations also shows anomalous behavior, but on a much smaller scale ($\Delta(1/\tau)$ < 50 sec^{-1}). No coupling of coherent horizontal betatron motion to synchrotron oscillations could be detected. Electron beams also show anomalous behavior, but much less reproducibly, and generally not leading to actual instability. We attribute this to the capture of ions by electron beams and have consequently focused our attention on positron beams.

The coherent betatron tune shifts, related to Im Z_T but also containing short-range effects, indicate some nonlinear behavior also. This behavior appears to be correlated with the anomalous damping and sits on top of the main linear tune shifts (e.g$_+$, about 200 Hz peak-to-peak "ripple" on top of $\Delta f_H/\Delta I$ = - 80 Hz/mA for horizontal betatron motion of positrons). The e- tune shift curve does not exhibit as much nonlinearity as the e+ curve (Figure 5).

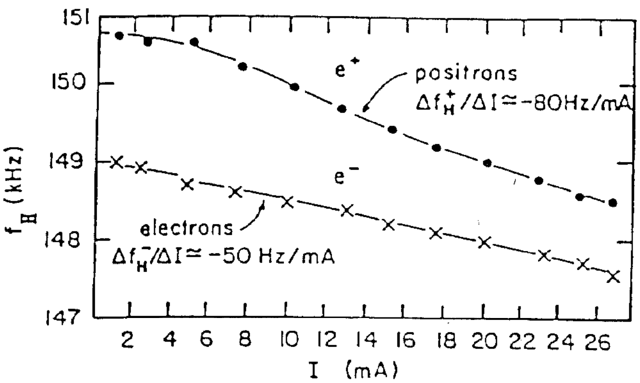

Fig. 5: Single-Bunch Horizontal Tune Shift.

Relation of "Anomalous" Damping to Known Types of Damping

The "anomalous" damping observed in CESR has the following characteristics: nonlinearly current-dependent, long-range (capable of coupling bunches together), low-frequency (greater effect on modes associated with lower frequencies), broadband (not critically dependent on betatron tune), and gives exponentially decaying shock excitation response.

In contrast,

1. Radiation damping (about 45 sec^{-1} in CESR) is independent of beam current.
2. Head-tail damping (contributing $b_H \xi_H I$ to $1/\tau$, where b_H = (7 ± 2)/(mA sec) in CESR) depends on short-range wake fields.
3. Landau damping [7,8] is capable of showing a strongly nonlinear current dependence (e.g., with an applied octupole field in CESR). However, it does not exhibit the long-range wake field characteristics of: (a) stability inversion upon tune reflection about the half-integer, and (b) differential stability effects on the various multibunch modes. Generally, too, the Landau damping "decoherence" response decays non-exponentially.
4. Tune plane coupling resonances, of course, give strongly tune-dependent effects over narrow tune regions.
5. Resistive wall damping, though long-range, low-frequency, and broadband, is linear in beam current and quantitatively (both for the thick-walled aluminum vacuum chamber and the thin-walled kovar-coated ceramic sections) at least two orders of magnitude too small to account for the anomalous damping. The expected damping is .3 sec^{-1} at 8 mA, compared to the observed value of 100 to 150 sec^{-1}.
6. Other beam-wall damping (e.g., from the RF cavity or horizontal separator plates) is high-frequency and narrowband.

Therefore, the above known types of transverse damping do not account for the multibunch instability-related damping we observe.

Cure of Multibunch Instabilities

Though the cause of the anomalous long-range coupling is unknown, the multibunch instability nevertheless may be cured. In multibunch operation of CESR with three bunches, additional head-tail damping through increased horizontal chromaticity is sufficient to counteract the instability so that injection can proceed past the worst, middle-current regime from about 5 mA to 8 mA per bunch. With seven bunches, since the instability is stronger, active feedback at the most unstable multibunch mode frequency of $(1-q_\beta)f_0$ = 240 kHz is used along with elevated chromaticity to cure the instability.

Conclusion

Multibunch instabilities having "anomalous," nonlinearly current-dependent damping of horizontal betatron oscillations as their signature have been observed in CESR. The associated long-range interbunch coupling force behaves qualitatively like a resistive wall impedance but has the large magnitude and strong current dependence that might be expected from a Landau damping mechanism. However, no successful "first principles" mechanism, capable of accounting for the anomalous damping, has yet been discovered. Also, all experimental attempts to implicate local elements of the beam environment as the underlying cause have yielded null results. We are challenged to identify the physical source of the coupler, and to account for the nonlinearity.

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