PHOTOELECTRON TRAPPING MECHANISM FOR TRANSVERSE COUPLED BUNCH MODE GROWTH IN CESR*

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Abstract

An anomalous damping or growth of transverse coupled bunch modes has long been observed in CESR. The growth rates and tune shifts of these modes are a highly nonlinear function of current. The effect is associated with the operation of the distributed ion pumps, as it disappears when the pumps are not powered. We show that this effect can be explained by the presence of electrons trapped in the CESR chamber by the field of the dipole magnets and the electrostatic leakage field of the distributed ion pumps. Photoelectrons are introduced into the chamber by synchrotron radiation and can be ejected from the chamber by the passage of an e^+ or e^- bunch. The transverse position of the beam thus modulates the trapped photoelectron charge density, which in turn deflects the beam, creating growth or damping and a tune shift for each coupled bunch mode. Predictions of the dependence of growth rate and tune shift on bunch current, bunch pattern, and mode frequency by a numerical model of this process are in approximate agreement with observations.

I. INTRODUCTION

An anomalous horizontal coupled bunch instability [1] in CESR has growth rates and tune shifts which are nonlinear in beam current. It is strongest at the intermediate currents encountered during CESR injection, and becomes dramatically weaker at higher currents. It is present only when the distributed ion pumps are powered [2]. The absolute values of both the growth rate and tune shift are largest for the lowest frequency mode. They drop rapidly for higher frequency modes.

Here we present the hypothesis that slow electrons trapped in the CESR beam chamber are responsible. We show that photoelectrons from synchrotron radiation striking the beam chamber walls will be trapped in the combined dipole magnetic field and electrostatic leakage field from the distributed ion pumps, and calculate their interaction with the beam.

II. PHOTOELECTRON TRAPPING

Slow photoelectrons in the CESR chamber will be confined to very small orbits in the horizontal plane by the 0.2 T magnetic field of the CESR dipoles. The quadrupole component of electrostatic leakage field from the distributed ion pump slots, calculated to be 2.1×10^4 V/m^2 at the center of the beam chamber [3], confines the electrons vertically. Positive ions are expelled by this field. The combination of these fields acts as a Penning trap for electrons, much like the ion pump itself. Because there is a horizontal dipole component of the pump leakage field (320 V/m at the center of the beam chamber), the trapped electrons undergo an $\mathbf{E}\times\mathbf{B}$ drift down the length of the magnet, with a velocity of the order of 1.6×10^3 m/s. Thus a trapped electron is lost from the 6.5 m long magnets in about 2 ms. We will later show that electrons are removed by interactions with the beam on a far shorter time scale, so their drift velocity may be neglected. The cyclotron frequency of the trapped electrons is 5.6 GHz, so their cyclotron motion is unimportant at the frequencies of the coupled bunch modes. The vertical motion, with frequencies of the order of 10 MHz or less, dominates the dynamics.

In addition to producing photoelectrons through synchrotron radiation, the beam has an essential role in trapping the electrons. An electron which is emitted from the chamber wall will soon collide with the chamber unless perturbed by the time-dependent force provided by the beam. Electrons which are deflected by the beam opposite to their vertical velocities are trapped on orbits of lower amplitude. Other electrons are excited to higher amplitudes and may be lost in collisions with the beam chamber.

The magnitude of the impulse from the beam depends on the position of the beam relative to the trapped electrons. Thus the oscillating beam position modulates the trapped charge density, which in turn drives the transverse oscillation of the beam. Coupled bunch modes are damped, driven unstable, or shifted in tune, depending on the phase of the trapped charge density relative to the beam motion.

III. SIMULATION

A simplified numerical model of was produced to calculate the coupled bunch mode growth. In this model, we calculate the trajectories of photoelectrons moving under the influence of the electric field gradients of the distributed ion pumps, a bunched positron beam, and the other photoelectrons. Because several simplifying assumptions are used, the calculated growth rates and tune shifts should be regarded as estimates.

We divide the beam chamber into slices along the x direction from the pump slots to the center of the chamber. In each time increment δt:

1. a photoelectron macroparticle is started in each x slice at $y = y_{wall}$ with vertical velocity $v_y = 0$;
2. the electric field gradient $\partial E_y/\partial y$ is calculated for each x slice;
3. y and v_y are updated for each macroparticle using the calculated $\partial E_y/\partial y$; and
4. any macroparticle for which $y \geq y_{wall}$ is removed.

No horizontal motion of the macroparticle is allowed because of the strong vertical magnetic field. An approximate model is used for the field gradients in which $\partial E_y/\partial y$ falls off as the square of the distance from the distributed pump slots and the beam, and the effect of the photoelectron macroparticles is to screen the field due to the pump slots. The beam position x_{beam} is made to

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oscillate sinusoidally with amplitude 4 mm. The constants used in the simulation are listed in Table 1.

Table 1: Simulation physical constants

y_{wall}	Beam chamber half-height	20 mm
x_{center}	Position of center of chamber	45.2 mm
Q_x	Horizontal tune	$\approx$ 10.5
T_0	Revolution period	2.56 μs
$\overline{\beta}_x$	Average β in dipole magnets	19 m
p	Beam momentum	5.3 GeV/c
L_{slot}	Total pump slot length	408 m
q_{slot}	Eff. slot linear charge density	4.79 nC/m
R_{pe}	Photoemission rate	0.92 m^{-1}

All of the physical constants used in the simulation are based on measured quantities except R_{pe}, the photoelectron charge injected per unit time, length, and beam current. No attempt was made to calculate or directly measure this quantity. It was treated as a free parameter, and was adjusted so that the maximum growth rate for the 7 bunch pattern occurred 5 mA as experimentally observed. It was then held fixed at this value for all simulations. No other free parameters were used, and no other changes of any sort were made to the original numerical model to bring it in closer agreement with experimental observations.

IV. SIMULATION RESULTS

A. Time dependence of trapped charge density

The calculated photoelectron charge density as a function of time for the 7 bunch pattern is shown in Fig. 1. The horizontal scale is in units of $\delta t = 1.4$ ns. The abrupt loss of trapped charge following each bunch passage is clearly seen, as is the slow variation due to the horizontal beam oscillation.

The reason that the instability growth rate falls off rapidly at higher beam currents is apparent from these plots. The rate at which photoelectrons are injected into the beam chamber is proportional to the synchrotron radiation flux, which is in turn proportional to the beam current. When the average photoelectron charge density is sufficient to completely screen the pump leakage field, no more electrons can be trapped. The charge density reaches an approximately constant level, extinguishing the variation needed to drive the beam.

The trapped photoelectron density depends strongly on the details of the bunch pattern. The effect of a very small gap in the bunch pattern can be seen in the sudden drop every turn (1830 increments) in Fig. 1b (the interval between bunches 7 and 1 is 378 ns as opposed to 364 ns for all other bunches). The characteristic recovery time of the photoelectron charge is of the order of 50 ns, as shown in Fig. 2, where the data of Fig. 1c are plotted on a finer time scale.

B. Current dependence of growth rate and tune shift

The growth rates α_x and tune shifts $\delta\omega_x$ for the 7 bunch pattern are shown in Figs. 3 and 4. We also simulated 9 trains of two bunches each, with a 28 ns interval between bunches. Because the recovery time of the photoelectron charge is longer than the interval between bunches, the bunches within a train act coherently. The current at which the growth rate peaks is half that of the 7 bunch case.

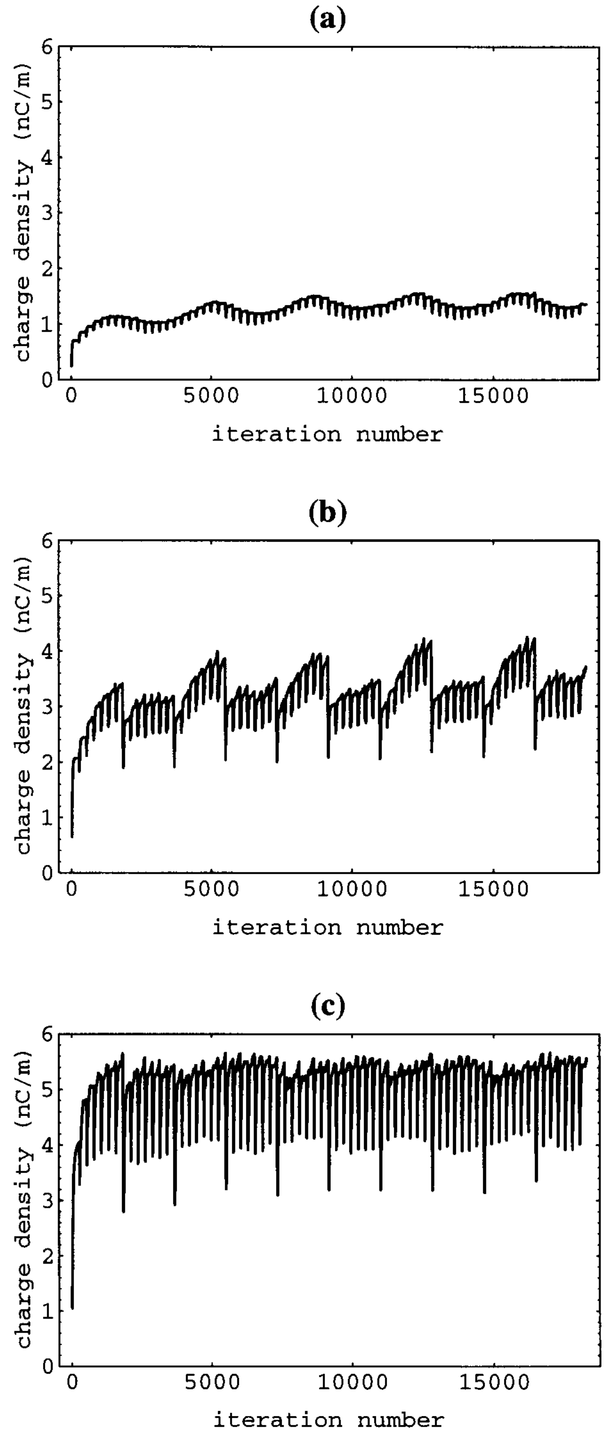

Figure. 1. Photoelectron linear charge density vs. time. The horizontal scale is in units of the 1.4 ns simulation increment. The total time is 10 CESR revolutions. The beam is moving horizontally with frequency $f_0/2$. Beam currents are: (a) 3; (b) 5; and (c) 6 mA/bunch.

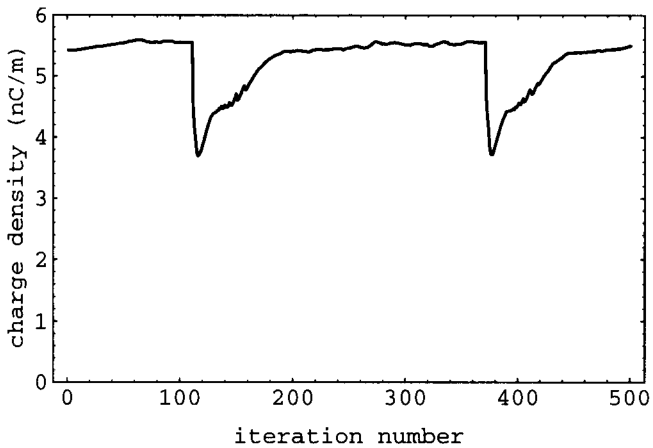

Figure. 2. Photoelectron linear charge density vs. time in units of 1.4 ns (data of Fig. 1c plotted on a finer scale).

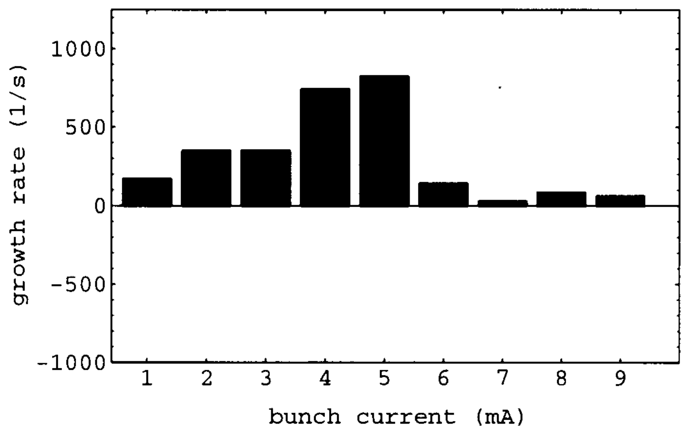

Figure. 3. Growth rate vs. bunch current.

C. Frequency dependence of growth rate and tune shift

To determine the dependence of the growth rate and tune shift on the coupled-bunch frequency we followed the same procedure for coupled bunch modes with frequencies of $f_0/2$, $3f_0/2$, and $5f_0/2$, where f_0 = 390 kHz is the CESR revolution frequency. We used the 7 bunch pattern with 3 mA/bunch. The results are shown in Table 2. The magnitude of both the growth rate and tune shift fall off rapidly with increasing frequency, in qualitative agreement with observation.

Table 2: Frequency dependence of α_x and $\delta\omega_x$

Mode frequency	α_x (s^{-1})	$\delta\omega_x/2\pi$ (Hz)
$f_0/2$	291.1	78.2
$3f_0/2$	-37.8	0.7
$5f_0/2$	2.2	2.0

V. CONCLUSIONS

The photoelectron trapping model successfully describes the qualitative features of the observed instability. The numerical model provides estimates of growth rates which are in approximate agreement with observations in spite of a number of simplifying assumptions. For example, the calculated growth rate

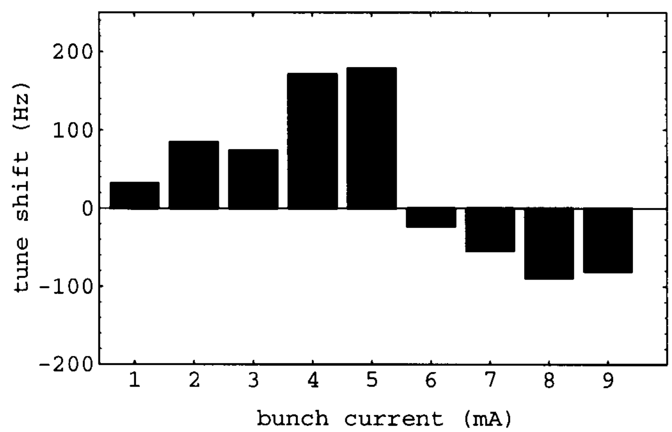

Figure. 4. Tune shift vs. bunch current.

for the 7 bunch pattern at 4 mA/bunch is 740 s^{-1}, while the observed rate is 520 s^{-1} [1]. The numerical model reproduces the observed behavior of the tune shift, which changes sign at the same current at which the growth rate starts to diminish, and predicts that the magnitude of the growth rate falls rapidly with frequency.

It has been observed that the $m = 1$ vertical head-tail mode is stabilized by the operation of the distributed ion pumps [2]. We note that the peak of the frequency spectrum for this mode occurs at approximately 2.4 GHz, with substantial spectral density at the 5.6 GHz cyclotron frequency of the trapped photoelectrons. The photoelectrons may be damping this mode by absorbing energy from the head-tail mode before being lost by collision with the chamber.

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