TRANSVERSE COUPLED BUNCH MODE GROWTH DUE TO PHOTOELECTRON TRAPPING IN THE CESR VACUUM CHAMBER

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Abstract

An anomalous damping or growth of transverse coupled bunch modes is 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 and disappears when the pumps are not powered. We show that this effect is due to 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. We have simulated this process numerically.

1 ANOMALOUS INSTABILITY

1.1 Distributed ion pumps

CESR contains distributed ion pumps (DIPs) in all of the bending magnets. A series of slots allows gas to flow from the beam chamber to the pump chamber. The slots also allow the DC electric field produced by the DIP anode to leak into the beam chamber. A numerical computation of the leakage field [1] shows that at the center of the beam chamber the dipole and quadrupole components of the electric field are 320 V/m and 2.1×10^4 V/m^2, respectively for an anode voltage of 7.3 kV. Higher-order multipole fields are also present. Distributed ion pumps in the CESR hard bend magnets have additional copper shields with offset slots, which shield the beam chamber from the DIP field.

1.2 Characteristics of the instability

An anomalous transverse coupled bunch instability ("anomalous antidamping") is observed in CESR [2]. Unlike an instability caused by the coupling impedance of the vacuum chamber, the growth rates and tune shifts are strongly nonlinear functions of beam current. The absolute value of the growth rate is largest at the intermediate currents encountered during CESR injection, and becomes dramatically smaller at higher currents. The growth rates are very reproducible for positrons, over a period of years, and do not depend on the residual gas pressure. The instability occurs for electrons as well as positrons, but is not as severe or as reproducible for electrons as it is for positrons.

The instability is much stronger in the horizontal than in the vertical direction. Coupled bunch modes at positive frequencies are damped; those at negative frequencies are antidamped (tend to grow). The absolute value of the growth rate is largest for the lowest frequency mode and decreases with mode frequency. The current at which the absolute value of the growth rate reaches its maximum value has a mild dependence on the number of bunches, unless the bunches are closely spaced, as shown in Table 1.

Table 1: Bunch current at maximum instability growth rate for different bunch patterns.

Number of trains	Bunches per train	Minimum bunch spacing	Bunch current at $\lvert\alpha_{max}\rvert$
1	1	2562 ns	7±1 mA
3	1	854 ns	7±1 mA
7	1	364 ns	6±1 mA
9	1	280 ns	4±0.5 mA
9	2	28 ns	2.3±0.3 mA
9	3	14 ns	2.0±0.3 mA

The instability "sees" two or three bunches which are spaced by 28 ns or less as a single bunch, and bunches spaced by 280 ns or more as separate. The anomalous instability is present only when the distributed ion pumps are powered [3]. It disappears quickly when the DIPs are turned off, with a time constant consistent with the discharge of the power supply filter capacitors, even though there is no rapid change in the residual gas pressure because of the continued gettering of the DIPs. The instability reappears immediately when the pumps are turned on. The growth rate is proportional to the number of DIPs (without copper shields) powered [4]. The DIPs with shields have no detectable effect on the beam. We have measured the growth rate of the $f_0 - f_h$ = 171 kHz coupled bunch mode (which has the largest growth rate) as a function of bunch current and DIP anode voltage [4]. We made measurements with eight and 35 DIPs under voltage control. The growth rate per DIP was found to be very nearly the same for eight and 35 pumps powered. At the full 7.4 kV anode voltage the growth rate per DIP was found to be the same for eight, 35, or all 141 unshielded pumps powered. In all cases the growth rate is approximately linear with DIP anode voltage.

2 INSTABILITY MODEL

2.1 Photoelectron trapping

We present the hypothesis [5,6] that slow electrons trapped in the CESR beam chamber are responsible for the anomalous instability. These electrons are produced through photoemission by synchrotron radiation striking the beam chamber walls and are trapped in the combined dipole magnetic field and electrostatic leakage field from the distributed ion pumps. The passage of the beam can capture or eject some of these photoelectrons. In this way the transverse position of the beam modulates the trapped charge density, which in turn produces a time-dependent force on the beam.

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 the leakage field from the DIP slots confines the electrons vertically. The combination of the magnetic and electric fields acts as a Penning trap for electrons, much like the ion pump itself. Because of the horizontal dipole component of the pump leakage field, 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 meter magnets in a few milliseconds. Electrons are removed by interactions with the beam on a time scale of tens of microseconds [7], 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.

2.2 Numerical simulation

A numerical model of photoelectron trapping was produced to calculate the coupled bunch growth and tune shift [7]. In this model, we calculate the trajectories of electron macroparticles moving under the influence of the electric field of the distributed ion pumps, a bunched positron beam, and the space charge of the other photoelectrons. Only vertical motion of the electrons is allowed because of the strong dipole magnetic field. Electron macroparticle velocities and positions and the electric field in the chamber are updated each time step of 0.5 ns. If the trajectory of the macroparticle has taken it outside the chamber boundaries, it is removed. Secondary emission is modeled by injecting one or more macroparticles, depending on the secondary emission efficiency, which is a function of the incident macroparticle energy. During the beam passage, smaller time steps are used. In each of these small time steps, several photoelectron macroparticles are injected with a uniform distribution of velocities from zero to v_{max}, and all velocities, positions, and the electric field are updated.

There is considerable uncertainty in the value of the photoemission rate for the aluminum vacuum chamber. We have used a value which nearly reproduces the measured current dependence of the instability growth rate. This value is consistent with an extrapolation of the photoemission rate measured at DCI [8] to CESR parameters. The simulation physical parameters are summarized in Table 2.

Table 2: Simulation parameters.

Q_x	Fractional horizontal tune	≈ 0.5
T_0	Revolution period	2.562 μs
$\langle\beta_x\rangle$	Average β_x in DIPs	19 m
p	Beam momentum	5.3 GeV/c
L_{slot}	Total DIP slot length	408 m
R_{pe}	Photoemission rate	0.4 m^{-1}
v_{max}	Maximum photoelectron velocity	8×10^5 m/s

3 SIMULATION RESULTS

3.1 Trapped charge density

Figure 1 shows the the trapped electron charge density 10 ns after the passage of a leading bunch in the present CESR bunch pattern of 9 trains of 2 bunches, with bunches in a train separated by 28 ns. The pumping slots are to the left, and the beam is at the origin. The newly emitted photoelectrons are evident as bands at the top and bottom of the chamber. The space charge in this band is sufficient to drive the lagging electrons back into the chamber wall. The acceleration of the new photoelectrons by the DIP leakage field is significant on the left side of the chamber. At the extreme left, the photoelectrons have already crossed the chamber and have been lost. Photolectrons which have been slowed by the space charge of the leading photoelectrons may be trapped on low-amplitude trajectories. The passage of subsequent bunches will eventually eject these trapped electrons.

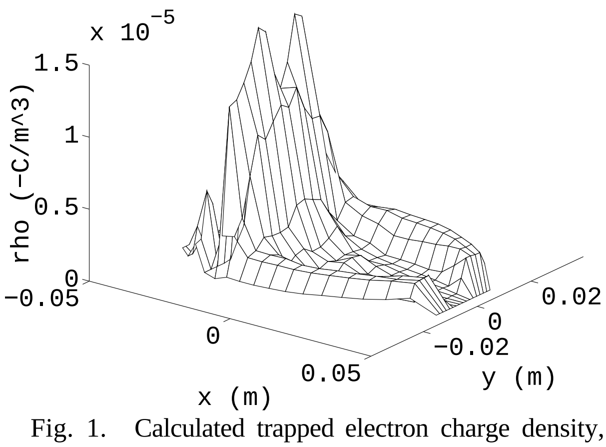

Fig. 1. Calculated trapped electron charge density, shown 10 ns after a bunch passage.

Although secondary emission is included in this calculation, it has been found to have a negligible effect on the trapped charge density.

3.2 *Current dependence of growth rate*

In the simulation the beam was moved horizontally at the tune frequency with an amplitude of 1 mm. The force on the beam at that frequency was used to calculate the growth rate of the lowest frequency coupled bunch mode. The growth rate for the 9×2 bunch pattern is shown in Fig. 2. The current dependence of the calculated growth rate is similar to that experimentally observed. The growth rate decreases at larger beam currents because the DIP potential well has been flattened out by the potential of the space charge. Because no further charge can be trapped, the force on the beam no longer varies significantly with time.

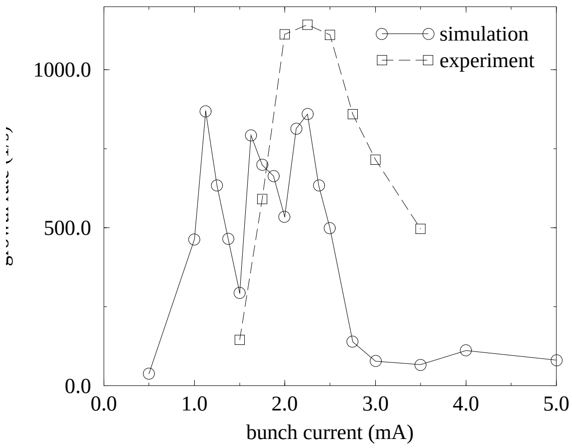

Fig. 2. Calculated and observed growth rate vs. bunch current for the lowest frequency mode.

3.3 *Variation of bunch pattern*

Because the transit time of the photoelectrons across the chamber is shorter than the bunch train spacing in CESR but longer than the bunch spacing in B-factories, the behavior of the photoelectrons in B-factories with closely spaced bunches may be very different than that observed in CESR. In both the simulation and in observations of CESR, the instability vanishes when the DIPs are turned off, because the electrons move freely out of the chamber before the next bunch arrives. However, for bunch spacings less than 8 ns, the simulation shows that the trapped charge density is large and nearly independent of DIP voltage.

4 CURES

There are several ways in which the effects of the anomalous instability can be suppressed. Transverse feedback has been successfully used to stabilize the beam against this instability [9,10]. The presence of a gap in the bunch pattern has been used during positron injection to reduce the growth rate. Because the growth rate is proportional to the DIP anode voltage, we are currently modifying the DIP power supplies to produce a remotely controlled voltage.

The shields installed in the hard bend pump chambers completely suppress the anomalous instability. It is possible to fit similar shields into all of the CESR DIPs, although this is the most costly and time-consuming solution. The combination of reduced DIP anode voltage and transverse feedback is expected to be more than sufficient to stabilize any bunch pattern planned for the CESR upgrade.

5 CONCLUSIONS

We have demonstrated that the anomalous instability in CESR can be explained by the trapping of photoelectrons in the combined magnetic field of the bending magnets and electrostatic leakage field of the distributed ion pumps. Our numerical simulation successfully describes the qualitativefeatures of the observed instability. Secondary emission is found to have a negligible effect in the simulation. For the closely spaced bunches of B-factories a high density of photoelectrons is present in the chamber even in the absence of the DIP leakage field. By a combination of reduced DIP anode voltage and transverse feedback, we can adequately suppress the instability in CESR.

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REFERENCES

[1] D. Sagan and J.J. Welch, Cornell LNS report CBN 92-1 (1992).
[2] L.E. Sakazaki, R.M. Littauer, R.H. Siemann and R.M. Talman, IEEE Trans. Nuc. Sci. **32** (1985) 2353.
[3] R. Littauer, Cornell LNS report CLNS 88/847 (1988).
[4] D.L. Hartill, T. Holmquist, J.T. Rogers, and D.C. Sagan, Cornell LNS report CBN 95-3 (1995).
[5] J.T. Rogers, Cornell LNS report CBN 95-2 (1995).
[6] J.T. Rogers, Proc. 1995 Particle Accel. Conf., Dallas, Texas, USA (1995) 3052.
[7] T. Holmquist, "A Model of the Nonlinear Coupled Bunch Instability in the Cornell Electron Storage Ring", M.S. Thesis, Cornell University (1996).
[8] O. Gröbner *et al.*, J. Vac. Sci. Technol. **A7**, (1989) 223.
[9] R. Littauer, Cornell LNS report CON 87-19 (1987).
[10] J.T. Rogers, *et al.*, Proc. 1995 Particle Accel. Conf., Dallas, Texas, USA (1995) 2426.