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A SINGLE BEAM MULTIBUNCH INSTABILITY AT CESR*

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Summary

A transverse coupled bunch instability has been observed in the Cornell Electron Storage Ring CESR[1] for both positrons and electrons. This instability shows strong horizontal or vertical coherent signals but very weak longitudinal signals. Positron injection, which requires sixty-one uniformly spaced bunches in CESR, was originally restricted by the enlarged effective horizontal beam size resulting from this instability. Although several cures have been discovered, only external octupoles provide a sufficient increase in the threshold and are compatible with injection. The theory for coupled bunch motion correctly predicts the instability threshold assuming that the driving mechanism is a 1140 MHz parasitic resonance in the RF cavity. Changes in the threshold with tune and octupole field strength are also correctly predicted.

Observations

The coupled bunch instability is easily observed on a transverse beam position detector or on a synchrotron radiation monitor. Above threshold a self-excited horizontal or vertical betatron oscillation is observed depending upon the CESR lattice. There is a definite phase relationship between adjacent oscillating bunches. For example, in the horizontal plane the bunch displacements repeat after approximately 2.7 revolutions corresponding to the fractional part of Q_h. The growth rate of the instability just above threshold is a few tens of milliseconds. Since a single bunch is stable to very high currents, the number of bunches was varied to determine the memory time of the driving mechanism. The current threshold for the radial instability with 61, 30, and 15 uniformly spaced bunches is about 5.3 mA total current at 5.5 GeV with the intrinsic octupole moment cancelled by external octupoles. For seven or fewer bunches the threshold is much higher indicating that the memory time is 200-300 nsec. Although the radial instability is most often seen, the vertical instability has been seen at about the same threshold but with seven bunches or with sixty-one bunches in a special injection lattice with low η_{RF}.

Many attempts have been made to increase the threshold. External octupoles were most successful, increasing the threshold a factor of five. A large radial orbit distortion produced by a single horizontal correction coil or a -7 KHz shift of the 500 MHz RF frequency raised the threshold but neither allowed injection. A single channel transverse feedback was only partially successful in raising the threshold. Changes in the chromaticity, the fractional part of the tune, the RF overvoltage, and η at the RF cavity and at the intersection point had little effect. A radial tune change from 9.38 to 13.19 increased the horizontal current threshold from 5.3 to 8. mA. The threshold did not change after the separator tanks were installed.

Comparison with Theory

The frequency of a coupled bunch mode n from a theory by Sacherer[2] for bunched beam instabilities is $kF +/- (n-q)f_o$, where f_o is the revolution frequency (390 kHz), $F \cong 61 f_o$ for 61 uniformly spaced bunches, q is the fractional part of the tune, and k is an integer. From observations in CESR near 1.785 GHz, n takes on values of 2,3,4, and 1 in order of decreasing strength. Feedback was applied to the n = 2 frequency successfully suppressing that mode, but the other modes increased in strength. The mode spectrum remained in this new state after the removal of the feedback until it resumed its original distribution when perturbed by a pulsed magnet.

The growth rate τ of an instability is calculated by Laclare.[3] A narrow band impedance for CESR is assumed where the frequency involved is ω_n. For dipole oscillations

$$\frac{1}{\tau} = \frac{cIZ_\perp F_o'(\chi-\omega_n\tau_L)}{4\pi QE}$$

where c is the speed of light, I the average beam current, $Z_\perp$ the real part of the transverse impedance, Q the tune, E the beam energy, ω_n the mode frequency, and τ_L the bunch length. $\chi = 2\pi Q\xi f_o\tau_L/\alpha$ where $\xi = (dQ/Q)/(dE/E)$ is the chromaticity and α is the momentum compaction. F_o' is a function calculated by Laclare[2] and is of order unity. The threshold is reached when τ equals the transverse radiation damping time (23 msec in CESR at 5.5 GeV).

The resistive wall impedance is not adequate to explain the CESR observations. This impedance is largest at low frequencies suggesting that n = 1 should dominate. The resistivity and dimensions of the vacuum chamber gives a $Z_\perp$ which when used in Eqn. (1) results in a threshold 50 to 100 times higher than observed. Finally, since the vertical dimension of the vacuum chamber is about half the radial dimension a vertical instability threshold should be much lower than the horizontal threshold, but the two thresholds are about equal.

There are many transverse deflecting modes in the CESR RF cavity[4]. The thresholds can be adequately explained by a TM_{111} resonance at about 1140 MHz. This mode has a loaded Q of about 1415 and a $Z_\perp$ of 14.6 M Ωm^{-1}. This impedance is quite narrow and only covers a few revolution harmonics which agrees with observations. For E = 5.5 GeV, Q = 9.38, $\omega_n/2\pi$ = 1140 MHz, τ_L = 100 psec, and $F_o'(\omega_n\tau_L) = 0.72$, and assuming that only one half of the fourteen cells in the 4.2 m long RF cavity contribute to $Z_\perp$, Eqn. (1) gives the current threshold to be 8.5 mA, remarkably close to the observed 5.3 mA. The vertical instability threshold is approximately the same as the radial threshold, which can be explained by the roughly equal orthogonal modes at 1140 MHz in the cavity. The frequency and loaded Q of this resonance give a decay time of the beam induced fields not inconsistent with the observed memory time.

The tune Q is proportional to the growth rate as is seen in Eqn. (1). During machine studies the horizontal tune was changed from 9.38 to 13.19 and an increase in the threshold from 5.3 to 8 mA resulted. Again there is good agreement. The chromaticity enters Eqn. (1) in F_o'. With α = 0.0128 for CESR at 5.5 GeV, $\chi = 0.18\ \xi$. Even for changes of $\Delta\xi$= 1, F_o' changes very little and thus the growth rate is insensitive to ξ, as observed.

The instability threshold has been increased by more than a factor of five using Landau damping from external octupole magnets. Only two symmetrically

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located octupoles are required, each producing a field of 38 T m^{-3} per ampere and being 39 cm long. The natural octupole field in CESR is compensated by one ampere in these two magnets. The linear increase in the threshold of 2.2 mA per octupole ampere is consistent with that calculated from an octupole induced betatron and momentum tune spread[5]. The calculation is a simple extension of that in Ref. 6. The observed increase in the threshold is slightly asymmetric with respect to the octupole polarity. This can be attributed to the bias on the tune spread due to momentum from the expected curvature in the horizontal chromaticity. In the present injection lattice, instabilities in the vertical plane are preferentially damped over those in the horizontal plane because of a relatively large tune spread from the large curvature of the vertical chromaticity. An injection lattice change was made which lowered β_H and η at the octupole magnets and reduced ε_H. This change reduced the threshold shift per octupole ampere by a factor of four. The calculated change[5] agrees with the observations.

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