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SINGLE BUNCH CURRENT DEPENDENT PHENOMENA IN CESR*

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Summary

Single bunch current dependent phenomena have been examined in CESR, the Cornell Electron Storage Ring. These measurements are described and their results compared with predictions using the broad band resonator model of vacuum chamber impedance. A transient anti-damping effect in the vertical plane has been observed. The influence of various machine parameters on this effect will be described and a possible mechanism suggested.

Introduction

CESR[1] has been in full operation since July, 1979 with experimental programs being carried on in its two interaction regions in the 4.7-5.5 GeV (beam) energy range. Since single bunch phenomena have not limited the high energy physics performance of CESR, emphasis has been placed instead on improving injection and luminosity. No active feedback systems are used in normal operation, although transverse feedback has been used briefly in an attempt to cure a multibunch instability which limited positron filling efficiency.[2] Maximum single bunch current is limited to 34 mA by a rise in pressure in the RF cavity, presumably caused by higher mode fields.

Until February 28, 1981, the storage ring has been running with only one 14-cell RF cavity operating at 500 MHz. All results reported are with one cavity. The measurements may be divided into four parts: 1) higher mode power loss resulting from the real part of the longitudinal wall impedance; 2) synchrotron frequency shift (imaginary part of longitudinal impedance); 3) transverse damping rates (real part, transverse impedance); and 4) transverse frequency shifts (imaginary part, transverse impedance). In addition, a transient anti-damping effect in the vertical plane has been investigated. We do not yet have a complete explanation of this phenomenon.

Broad Band Impedance

The total effect of the many cavities and discontinuities forming the inside of the storage ring vacuum chamber may be modeled by a single broad band resonator.[3] Its resonant frequency should be on the order of the cutoff frequency (for waveguide modes) corresponding to some characteristic dimension of the vacuum chamber. The exact resonant frequency (ω_r), Q, and shunt resistance (R_s) are varied to fit the experimental data.

Longitudinal Effects

The power loss by the beam includes a part linear with respect to current due to synchrotron radiation and a part quadratic in current due to the higher mode losses (HML). The quadratic part causes a shift in the synchronous phase. This shift was measured by injecting a small precursor bunch as a timing reference. Alternatively the difference between the forward and reflected RF power to the cavity was measured as a function of beam current. Subtracting the constant and linear parts of this difference, and correcting for the voltage induced in the fundamental mode of the cavity, leaves the quadratic term from which R may be calculated directly. Measurements were made at 5.5 GeV and 4.6 GeV. Machine parameters and results are shown in Table I. σ_s is the beam bunch length and K_{pm} is the loss parameter for parasitic modes.

Energy	5.5	4.6 GeV
$\sigma_{s\ I=0}$ (calculated)	2.34	1.74 cm
k_{pm} (pwr)	5.5	7.6 volts/picocoulomb
k_{pm} (phase shift)	4.3	6.6 volts/picocoulomb
R $(=\frac{W}{I^2})$	14	19.5 MΩ
R_s (res. shunt R)	4.2	3.7 kΩ

TABLE I = HML Parameters

The results are in good agreement with bench measurements[4] (at σ_s=2 cm) of vacuum chamber components and RF cavity (k_{pm}=1.7 and 5.3 respectively), and SUPERFISH computer calculations of cavity modes (k_{pm}=3.1). For a broad band resonator with ω_r=2.3 GHz and Q=1 the measurements give an effective shunt impedance of 4000Ω. This agrees with results obtained from transverse measurements.

The reactive part of the longitudinal broad band impedance causes a shift in the synchrotron frequencies. The sum of the incoherent shift and the coherent quadrupole mode shift may be measured by observing the longitudinal beam transfer function at approximately twice the synchrotron frequency. A dual channel FFT processor was used to make this measurement. The RF amplitude was modulated by narrow band noise centered around $2xf_s$ = 32 kHz. The response was detected by stretching and filtering the signal from a single button detector. In the absence of intra-bunch space charge effects and higher order radial modes, the small amplitude particle tune should be given by the high frequency "corner" in the phase response as shown in Fig. 1a. The results are plotted in Fig. 2 with additional parameters in Table II.

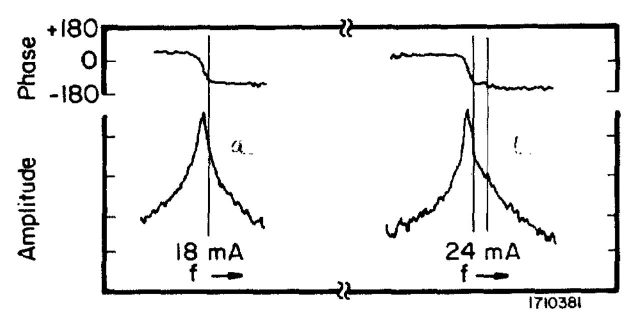

Fig. 1: Longitudinal Beam Transfer Function.

Curve	A	B	C
Energy	5.5	5.5	4.6 GeV
$\sigma_{s\ I=0}$	2.34	1.74	1.74 cm
$f_{s\ I=0}$	16.6	12.7	18.5 kHz
Q_x	9.35	13.2	9.35
Q_z	9.15	12.1	9.15
Δf/2I (measured)	-8.6	-20	-26 Hz/mA
Δf/2I (calculated)	-22	7.6	11.1 Hz/mA

TABLE II - Parameters for Fig. 2

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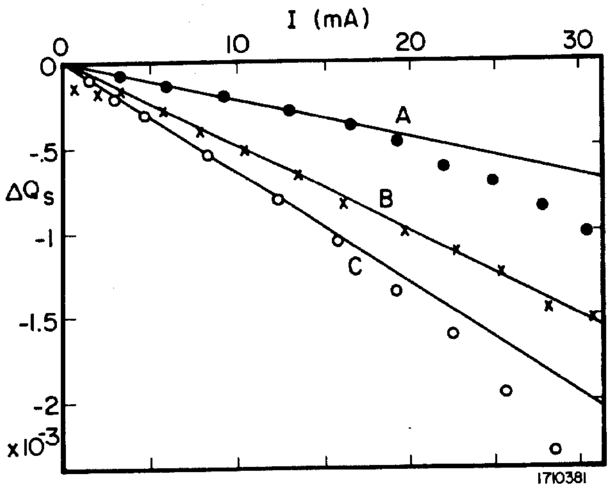

Fig. 2: Slewing of Synchrotron Tune with Current (one bunch)

The expected tune shift observed is calculated from Laclare.[5] As long as no tune shift is observed in the dipole (m=1) mode synchrotron oscillations we may assume that the incoherent tune shift, $\Delta\omega_s$, cancels the m=1 mode coherent shift. (This is strictly true only for rigid bunch motion.) The predicted observed shift is:

$$\frac{\Delta\omega_2}{2} = \frac{\Delta\omega_{2COH}}{2} - \Delta\omega_{1COH}$$

where $\Delta\omega_2$= full quadrupole mode observed shift, $\Delta\omega_{2COH}$= full quadrupole mode coherent shift, $\Delta\omega_{1COH}$=dipole mode coherent shift. Small changes in the choice of resonator frequency, ω_r, can raise or lower all three predicted shifts since the mode spectra lie close to ω_r. The disagreement in dependence on bunch length is not so easily resolved. Several possible explanations are offered:

1) A better calculation of the incoherent frequency shift, ω_s, must be done.
2) The modes of the bunch may be different when driven at the 500 MHz RF frequency from those calculated with a broad band impedance. (The presence of a 2nd mode is shown in Fig. 1b.)
3) Changing the beam position by 10mm in the RF cavity with a closed vertical bump can change the slope of the lines by 50%. While changing machine conditions a shift in beam position in the RF cavity could add on unexpected frequency shift.
4) A different distribution of resonators is more appropriate.

Transverse

The coherent damping time of the m=0 head-tail has been measured using a vertical pinger with a half sinusoid current pulse of approximately 2 revolution periods width. The reciprocal of the damping time has been plotted against current in Fig. 3. The intercept at zero current gives the theoretical radiation damping time of 22 ms. The head-tail damping rate is compatible with the model (Table 3).

The frequency shifts for the first three head-tail modes are shown in Fig. 4. These data were measured by scanning the appropriate parts of the spectrum while driving the beam transversly with a tracking generator. The relevant frequencies are:

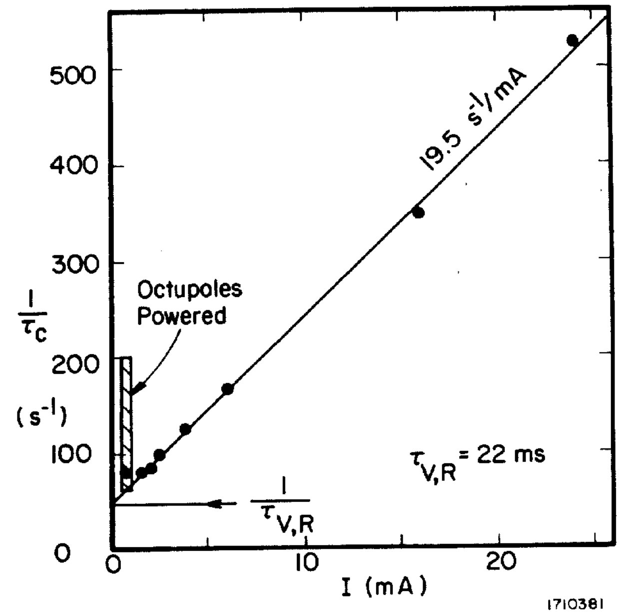

Fig. 3: Coherent Damping Factor. Single Bunch Current.

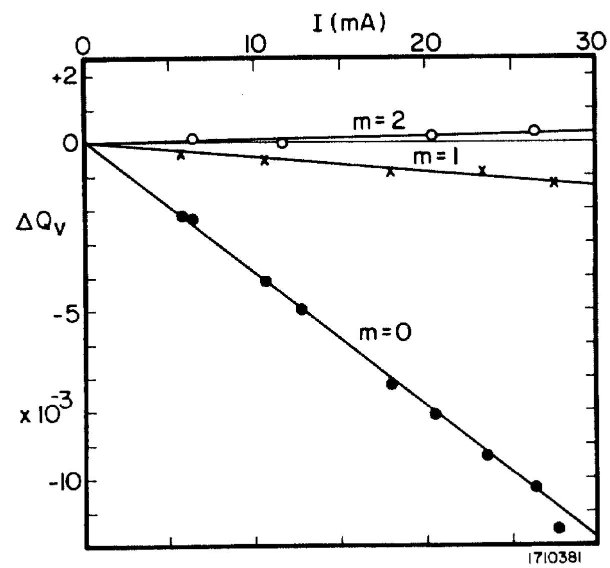

Fig. 4: Slewing of Vertical Betatron Tune with Beam Current (one bunch)

$$f = (1 \pm Q_\beta)\ f_o \pm m\ f_s$$

where m is the head-tail mode number, Q is the fractional part of the betatron tune, 1 is an integer, and f_o and f_s are the revolution and synchrotron frequencies.

The program BBI[6] was used to find the best fit to these transverse data. The result is listed below:

ω_r = 2.3 GHz x 2π
Q = 1
$Z_{\perp r}$= 240 kΩ/m

Mode m	$\frac{dQ}{dI}$ (mA^{-1})		γ^{-1} $(s^{-1}mA^{-1})$	
	Exp.	Model	Exp.	Model
0	-3.9×10^{-4}	-4×10^{-4}	-19.5	-37
1	-4.3×10^{-5}	-5.7×10^{-5}	-----	0.5
2	1×10^{-5}	1.7×10^{-5}		8

TABLE III - Vertical Betatron Parameters

Table 3 shows reasonable agreement between measurements and the broad band impedance model in the transverse plane. Using the approximate relation:[3]

$$Z_\perp(\omega) = \frac{2R}{b^2} \frac{Z_L(\omega)}{p}$$

and taking the effective vacuum chamber radius b=.025m, gives $\left|\frac{Z_L}{p}\right|_0 = 0.6\Omega$ or a shunt impedance $R_s = 3.53$ kΩ which compares favorably with the R_s in Table I.

Transient Anti-Damping

While making vertical aperture measurements using a resonant shaker, a current range was found where the apparent aperture dropped dramatically. After the vertical pinger magnet was installed the loss was seen to come 2 to 5 mS after the pinger fired, compared to 0 to 100 uS for "normal" loss. Looking at synchrotron radiation approximately 10σ vertically away from the beam with a photomultiplier tube and slit, one could see a coherent signal which peaked 2 to 5 mS after the pinger fired. Some results of changing machine parameters on the poor lifetime region are listed below:

1) This effect is confined to currents 1.5 mA $<I<$ 8 mA.
2) Increasing octupole strength lowers the lower threshold current.
3) Raising vertical sextupole strength (positive chromaticity) narrows the bad lifetime region.
4) A fixed tuned receiver looking at the betatron sideband (m=o) shows a current dependent periodic structure.
5) None of the effects above are seen if the pinger amplitude is lowered to about 1/2 that required to cause beam loss.

A possible explanation has been suggested by R. Meller.[7] He has shown that two oscillators in a non-conservative system with complex coupling coefficients can produce amplitudes greater than those with real coupling.

Conclusions

The behavior of single bunches in CESR is satisfactorily described by the broadband impedance model. The longitudinal frequency shift is the poorest fit; however, there are several possibilities for reconciliation. The vertical transient anti-damping, while interesting, does not seem to affect normal operation since it requires a very large coherent excitation to take place.

We would like to thank Jacque Gareyte for his valuable guidance in broad band impedance theory and for his help in setting up some of the measurements. He was of great service also in fitting the data to a resonator using BBI. We thank also Jean-Louis Laclare for discussions which have been very helpful in analyzing our observations.

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