Measurements of Synchro-Betatron Coupling by an RF Cavity in CESR*

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Abstract·

Results of measurements of synchro-betatron coupling from an RF cavity in CESR are presented. Measurements of transverse kicks given to the beam by parasitic deflecting modes in the RF cavity are shown along with a comparison to theoretical predictions.

I. INTRODUCTION

Synchro-betatron resonances in storage rings define the "ground rules" for choosing operating points in tune space. The performance of large storage rings, with high synchrotron tune and large charge per bunch, is often limited by these resonances, particularly where an energy ramp must be made between injection and colliding beam conditions.

In the most general case, synchro-betatron resonances are excited when:

$$p\,Q_x + q\,Q_z + r\,Q_s = n \qquad (1)$$

where p,q,r,and n are integers and $Q_{x,y,z}$ are horizontal, vertical, and longitudinal tune numbers.

There are several mechanisms for coupling longitudinal to transverse motion. Of these, two have been clearly identified in existing machines [1-4]: coupling by the beam-beam effect and by dispersion or deflecting fields in cavity-like structures. Here we will discuss only coupling by RF cavities in single beam conditions.

II. COUPLING BY AN RF CAVITY

A. Dispersion in Cavities

The presence of dispersion in a circular accelerator will cause the equilibrium orbit to make a step displacement if a particle's energy is suddenly changed as happens in an accelerating cavity. In a time varying field the change in energy will depend on the position of a particle in a bunch, resulting in coupling from the longitudinal dimension to the appropriate transverse plane. A similar argument may be made for the derivative of dispersion with respect to the longitudinal coordinate and an angular kick in the transverse plane. The "cavity" need not be an accelerating cavity, but can be any discontinuity in the smoothness of the vacuum chamber wall where fields may be excited by passing bunches. Analytic analyses for this mechanism are given in references [5,6].

B. Deflecting Modes in RF Cavities

Nearly all RF cavities have higher modes which may be excited by passing bunches. Many of these modes have a variation of longitudinal field across the cavity aperture which results in transverse forces on the particles. These modes may be driven by a beam passing off center with respect to the mode center.[7] Since they exert a time dependent transverse kick on the particles, coupling from longitudinal to transverse dimensions follows. This coupling remains an incoherent effect while its strength is proportional to bunch current.

III. OBSERVATIONS IN CESR

A. CESR Configuration

CESR is a 768 m circumference electron-positron storage ring operating between 4.7 and 6 GeV beam energy. At 5 GeV radiation loss is 1 MeV/turn. Either one or two 14-cell 500 MHz RF cavities[8] were installed for these tests. Their locations are symmetric about the South interaction region. High Energy Physics running optics in CESR have a large horizontal dispersion (1.5-2.5 m) at the RF cavity locations due to restrictions on beam emittance. Next to the location of each RF cavity is a horizontal electrostatic separator which also has parasitic RF modes. Its effect is ignored in our analysis.

During these experiments the beam energy was between 5.2 and 5.3 GeV. Unless otherwise stated, a single bunch of positrons was used.

The synchrotron tune was .049 and betatron tunes varied around two separate operating points, one at Q_x=9.44, Q_y=9.36, and the second at Q_x=8.56, Q_y=9.64.

B. Measurements

Most of the measurements were made using the program "SCAN" which records the following data while stepping the betatron tunes in a 2-dimension pattern by changing quadrupole currents in two uniform families: 1) Vertical beam size as measured by a CCD array upon which the visible synchrotron light is imaged; 2) beam current; and 3) the counting rate of a scintillator-photomultiplier device placed about 0.5 m downstream of a movable vertical scraper. The scraper normally was placed halfway between the chamber wall and beam centerline.

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Since the normal operating tunes of CESR are far from integer values, the synchro-betatron satellite resonances of integer tunes:

$$Q_x + r\,Q_s = n \qquad (2)$$

are not readily observable.

IV. Experimental Results

A. *Current Dependent Deflection of the Beam*

While the synchro-betatron coupling from deflecting modes in the cavity is determined by $dV_\perp/ds$, where $V_\perp$ is the deflecting voltage and s is the longitudinal coordinate, there is an average voltage the bunch sees, $\langle V_\perp \rangle$, which gives a dipole kick to the beam proportional to current. This was measured by analyzing differences of orbits taken at 1 and 10 mA to determine the kick at the cavity. The results are shown in Figure 1.

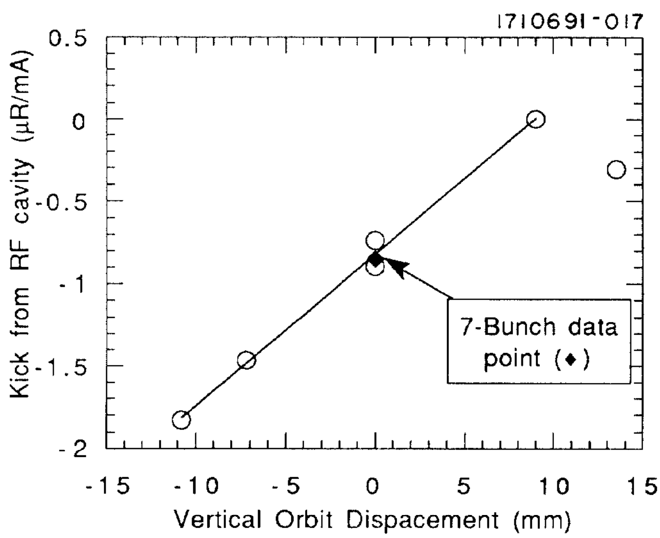

Figure 1 - Kick angle per mA beam current given to the beam by RF cavity deflecting modes as a function of beam position in the cavity.

The cavity cells are, on the average, obviously displaced from the nominal beam centerline. This was confirmed by measuring the average offset in a spare cavity's cell positions, compared to the vacuum flange positions, to be around 12 mm. This displacement is a result of the tuning technique used in the construction of the cavity.

The expected beam deflection may be easily calculated if the transverse wakefield function is known:

$$\frac{\Delta x'}{\Delta I_{(1\ mA)}} = \langle W_\perp \rangle \frac{e\, q_{(1\ mA)}\, \Delta x}{E_0} \qquad (3)$$

where $\Delta x'$ is the transverse kick, $\langle W_\perp \rangle$ the average of the transverse wake function over the bunch, e the electron charge, q(1 mA) the charge of a 1 mA bunch, Δx the transverse beam displacement from the "center" of the modes, and E_0 is the beam energy. A calculation[9] of the transverse wake using DBCI gives $\langle W_\perp \rangle = 7\times10^{12}$ NT/coulomb^2 which yields 0.47 µrad/mA for a 10 mm offset from the modes' center. The measured value of ≈ 1 µrad/ mA is in reasonable agreement.

In order to assess whether this deflection is due to long range wakes the same measurement was done using 7 bunches. There is no enhancement of the transverse kick, indicating the effect is short range (see Figure 1).

B. *Effect s on Resonance Structure*

Beam Position in Cavity - Tune plane scans were made around tunes Q_x=9.44, Q_y=9.36 for different displacements of the beam in a single cavity in CESR. Qualitative results are shown in Figure 2. Satellites of the coupling resonance are particularly visible in CESR. The $3Q_y$-Q_s= 28 resonance is clearly driven by the beam passing through the RF cavity off center since it vanishes when the beam is bumped to a position shown above to be approximately centered on the cell modes (c.f. 2d, 2e). The influence of the $2Q_x$+ $2Q_s$= 19 resonance on the vertical beam size is not understood. The 4th order resonance, $3Q_x$-Q_y=19 is apparently aggravated by the beam bumps in the cavity, possibly due to octupole components in the cavity fields or the steering magnets themselves. The structure of the beam loss map (Fig. 2c) is quite different than the vertical beam size map (Fig. 2b). Intersections of resonance lines are usually the most prominent features in the beam loss maps and the frequencies are shifted somewhat compared to the vertical size tune plane plots.

Dispersion in Cavity - Several attempts were made to see any change to resonance strengths due to a large horizontal dispersion in the RF cavity. Optics with zero dispersion were compared with normal (2 m dispersion) optics. Two cavities operating symmetrically with a horizontal betatron phase advance of 3π between them (one cavity will cancel the orbit distortion caused by the other) were compared with single cavity operation. Neither experiment demonstrated any reduction of the observed resonances when the effect of dispersion in the cavity(s) was reduced.

Current Dependence - Most of the synchro-betatron resonances are current dependent. Figure 3 shows scans across two resonances, $-Q_x$+ $2Q_y$- $2Q_s$= 1 and $2Q_x$ - $2Q_s$= 19 at beam currents of 7 and 15 mA. The change in blow up factor (ratio of on-resonance beam size to off-resonance beam size) was 1.6 for the first resonance compared with the current ratio of 2.1. No change in the $2Q_x$ - $2Q_s$= 19 signal was seen.

Chromaticity - The horizontal chromaticity was changed to determine whether tune modulation was responsible for the resonance's visibility. The vertical blow up on the $-Q_x$+ $2Q_y$- $2Q_s$= 1 resonance was found to decrease by about 25% when horizontal chromaticity was raised from 0 to +6 (dQ/(dP/P)). The $3Q_x$- Q_y= 18 blow up remained about the same, and the $2Q_x$ - $2Q_s$= 19 resonance's visibility increased slightly. These varying responses suggest that the chromaticity function should be examined for harmful harmonics.

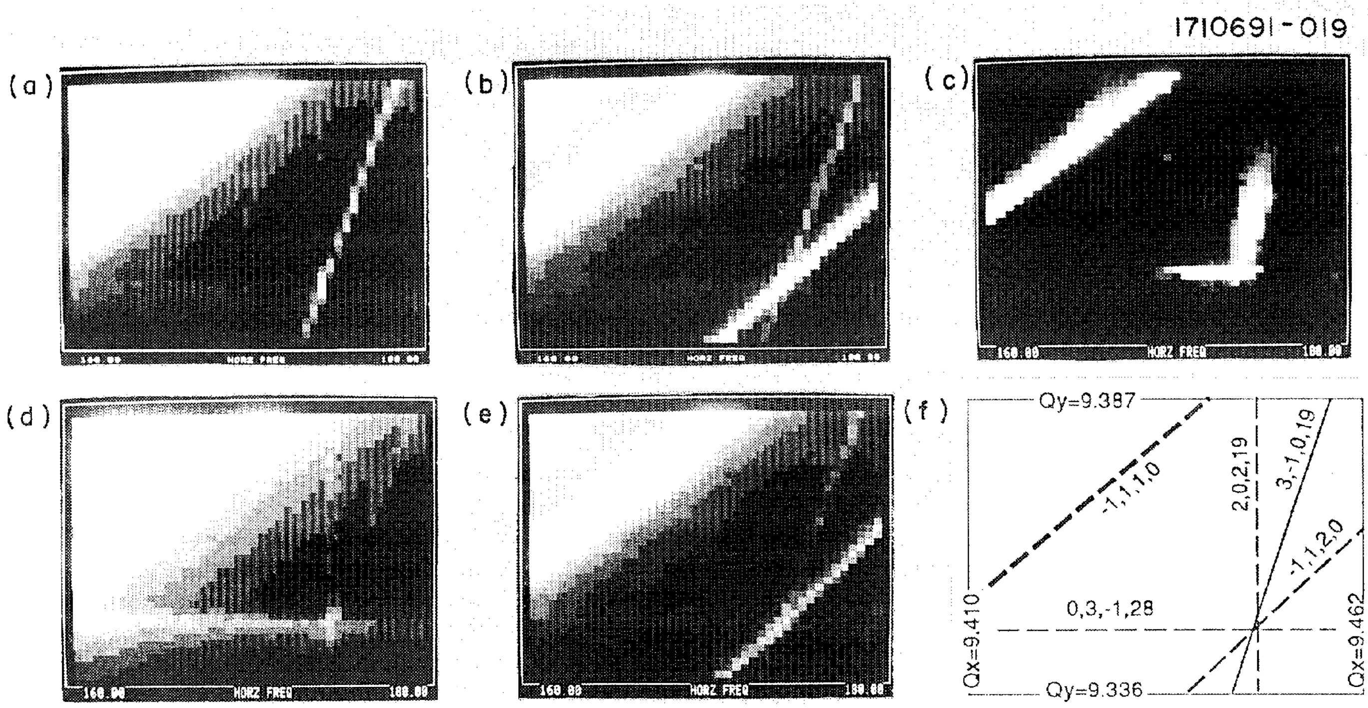

Figure 2 - Tune plane scans for different beam positions in the CESR RF cavity (vertical beam size except 2c). a) +10 mm horizontal (radially out); b) -10 mm horizontal c) same as 2b except beam loss rate plotted; d) no displacement in cavity; e) +9 mm vertical displacement; f) tune plane map identifying resonances - the 4 numbers are p,q,r, and n in equation (1).

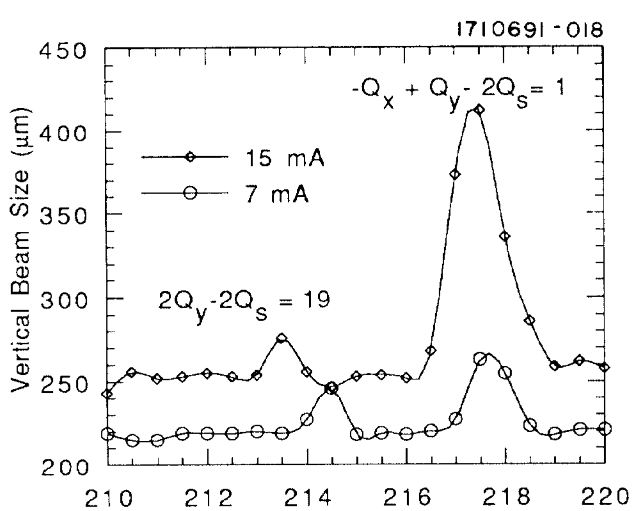

Figure 3 - Resonance response to varying beam current. Vertical tune was 256 kHz, or Q_y= 9.658.

V. CONCLUSIONS

The synchro-betatron resonances encountered in CESR operation are not related to integer tunes, making quantitative analysis difficult. They are strongly affected by closed orbit bumps in the RF cavity. A measurement of the strength of the parasitic deflecting modes using the kick imparted to the beam is in reasonable agreement with a computer calculation of the transverse wake function. Further work is needed.

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