THE DEPENDENCE OF SINGLE PARTICLE STABILITY ON NET CHROMATICITY IN CESR, NEAR $Q_h = 9 + 1/3$

Stephen Peggs
Supercollider, URA Design Center*
c/o Lawrence Berkeley Laboratory, MS 90-4040
Berkeley, California 94720

INTRODUCTION

It was originally suggested on purely theoretical grounds that the synchrobetatron sidebands of non-linear resonances, caused by betatron tune modulation, could lead to chaos, or stochasticity[1,2,3]. This happens with both beam-beam and magnetic resonances, when the sidebands, which are typically as wide as the main resonance, overlap. The overlap criterion becomes more severe for lower frequency modulations. A real experiment with the "non linear lens" in the SPS was in semi-quantitative agreement with numerical experiments, and with the one dimensional theory[4,5,6]. The SPS experience with the beam-beam effect is also in reasonable quantitative agreement with numerical models, and one dimensional theory, although only a limited amount of real experimental data is available[7].

One source of low frequency tune modulation is power supply ripple, but with care this can be made negligible. A source which cannot usually be avoided, especially in electron storage rings, is the net chromaticity

1) $\chi = dQ/(dE/E)$

A particle with an energy oscillation amplitude n times the standard deviation, σ_E/E, has a tune modulation at the synchrotron frequency Q_s, with an amplitude of

2) $q = n(|\chi| \cdot \sigma_E/E)$

For CESR to reach high currents (and high luminosity) it is necessary to increase the net chromaticity to about 10.0 in both planes, in order to suppress head-tail instabilities. As shown in Table I, this causes a particle with a moderately large amplitude, $n \approx 3$, to have a tune modulation amplitude of $q \approx 0.02$, a comparatively large value, in the sense that synchrobetatron sidebands are expected to be significant within $\pm q$ of a non linear resonance, this defines an "effective" resonance width.

Dynamic aperture experiments made at CESR in April 84 are presented below, showing the importance of the net chromaticity. Experimental results are compared to tracking results from the code EVOL, with qualitative, or semi-quantitative, agreement. Possible experimental improvements are described, and final conclusions are drawn. Both real and numerical experiments show strong dependencies on the net chromaticity.

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QUANTITY	LABEL	NOMINAL VALUE
Tunes	Q_h	9.40
	Q_v	9.37
	Q_s	0.05
Energy spread	σ_E/E	6.4×10^{-4}
Emittance(metres)	ϵ	2.0×10^{-7}
Natural chromaticity	$\chi_{h\,nat}$	-20.3
	$\chi_{v\,nat}$	-42.0
Corrected chromaticity	$\chi_h \approx \chi_v$	10.0
Tune mod. amplitude	$q_h \approx q_v$	$n * 0.006$

Table I Nominal CESR parameters

THE EXPERIMENT

Preliminary measurements[8] of the off-resonance dynamic aperture as a function of net chromaticity were made at the nominal tunes, in order to compare two sextupole distribution schemes[9,10]. A single positron bunch of moderate current, around 10 milliamps, was used. The dynamic aperture was experimentally defined to be the displacement to which the beam must be kicked, by a vertical "pinger" operating at 30Hz, to lower the beam lifetime to 100 minutes. Individual measurements were quite slow to make, and were abandoned when their sensitivity to the tune was noticed - weak candidate resonances were $Q_v + 3Q_s = 9.5$, and $2Q_h - 2Q_v - Q_s = 0$.

It was decided instead to scan resonance structures in the tune plane, without using the vertical pinger, by simply and quickly measuring the "singles" rate of background events in the CLEO detector. Although this is not a direct dynamic aperture measurement, it is very flexible - structures with lifetimes very much less than 100 minutes can be visited, quantified, and avoided, in a total measurement time of three or four seconds. The background rates measured had a dynamic range of almost five decades, from 4 Hz to 100 kHz, above which the beam was lost very rapidly.

The two sextupole distributions behaved quite similarly in two dimensional scans near the working point, producing typical background rates of 50 Hz to 5.0 kHz when both net chromaticities were 6.0, with a single bunch current of 5.8 milliamps. One dimensional scans were then made across the $Q_h = 9 + 1/3$ resonance, with Q_v held fixed at 9.37 as illustrated in Figure 1, in order to

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study stronger features. Different net horizontal and vertical chromaticities, in the ranges $-2.0 < \chi_h < 8.0$ and $0.0 < \chi_v < 8.0$, were used[11]. It is this last experiment which is of most interest here.

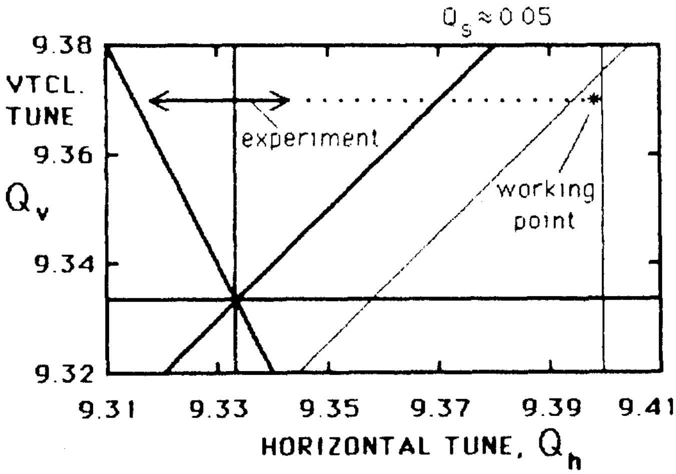

Figure 1 Tune location of the nominal CESR working point and the experiment.

EXPERIMENTAL RESULTS

Figure 1 shows the most deadly of all the features encountered, the resonance $2Q_h + Q_v = 28$, which consistently dumped the beam, regardless of the net chromaticities, usually in less than the background rate measurement time. The resonance occurs at the left of Figure 2, which plots the singles rate as a function of horizontal tune Q_h at net horizontal chromaticities of 0.0, 3.0, 6.0, and 7.0, with a constant net vertical chromaticity of $\chi_v = 1.0$.

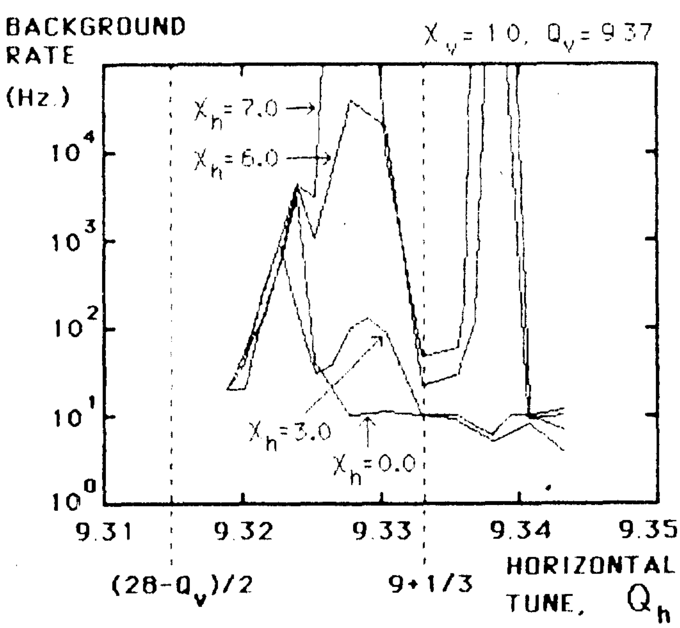

Figure2 Experimentally observed backround rate versus horizontal tune for various net horizontal chromaticities

At low net chromaticites the $Q_h = 9 + 1/3$ resonance can be crossed with impunity, with negligible background rates as low as 10 Hz. Tunes measured for this data were taken from the frequency peak observed on a spectrum analyser, which was usually self excited, but sometimes was driven. The single positron bunch current was small, usually in the range 5.0 to 10.0 milliamps. Where the curves imply backgrounds greater than 100kHz, the tune had to be 'jumped' across a resonance feature.

The exact interpretation of the features which arise on either side of $Q_h = 9 + 1/3$ as the horizontal chromaticity is increased is not at all clear. Synchrobetatron sidebands of significant strength should appear, according to the standard theory, in the range $9+1/3 - q < Q_h < 9+1/3 + q$, spaced by $Q_s/3$ and centered on the main resonance. Neither the spacing nor the location of the background peaks agree very well with their naive identification as synchrobetatron sidebands. However, the first sideband should appear when $q \approx Q_s/3$, which occurs at a chromaticity of $\chi_h \approx 6.0$ for a large amplitude particle with $n = 4$, in semi-quantitative agreement with the appearance of features in Figure 2.

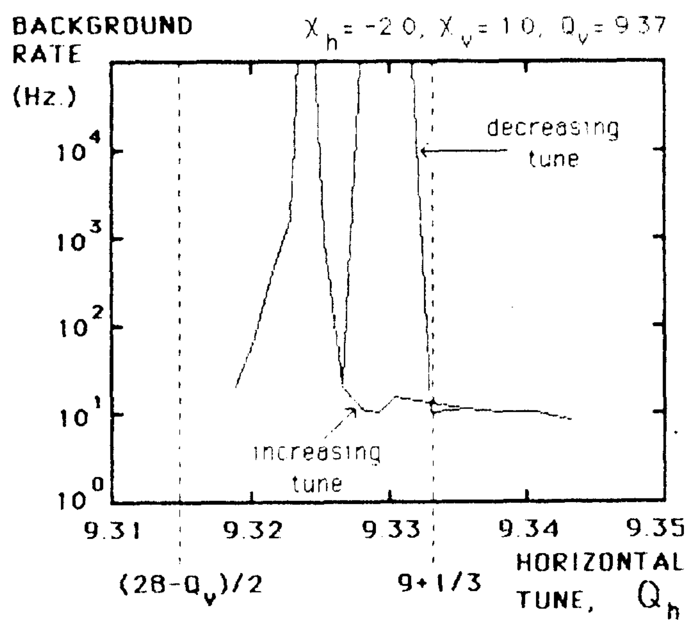

Figure 3 Hysteresis effect observed in background rate vs. horizontal tune, when $\chi_h = -2.0$

Figure 3 shows the hysteresis observed when the net horizontal chromaticity was $\chi_h = -2.0$, in contrast to the data shown in Figure 2, which closely reproduced whether the tune was increasing or decreasing. When the beam was hysteretically self excited, separate spots of light were seen on a synchrotron light monitor, an effect seen at other storage rings[12]. Presumably the tune increased with amplitude, so that as Q_h was lowered positrons trapped in the three resonance islands were moved to higher amplitudes, where they were more prone to loss.

TRACKING RESULTS

Numerical searches for the dynamic aperture were made with EVOL[7], using the real sextupole distribution. Twelve or fifteen particles, with initial amplitudes distributed around a phase ellipse with a beam aspect ratio of 8 to 1, were tracked for 240 synchrotron periods of 37/2 turns, or until one of them was lost. The initial amplitude was gradually reduced until all of the particles were stable, at what was called the dynamic aperture.

Figure 4 records the dynamic aperture over a tune range of $9.33 < Q_h < 9.35$, for different tune modulation amplitudes q, the same in both transverse planes. As q is increased from 0.0 to 0.01, the minimum dynamic aperture is reduced from 5.0σ to 1.6σ, always occurring just above $Q_h = 9+1/3$. This q range corresponds to a chromaticity range of $0.0 < |\chi| < 5.0$ for a particle with $n \approx 3$, a moderately large energy amplitude.

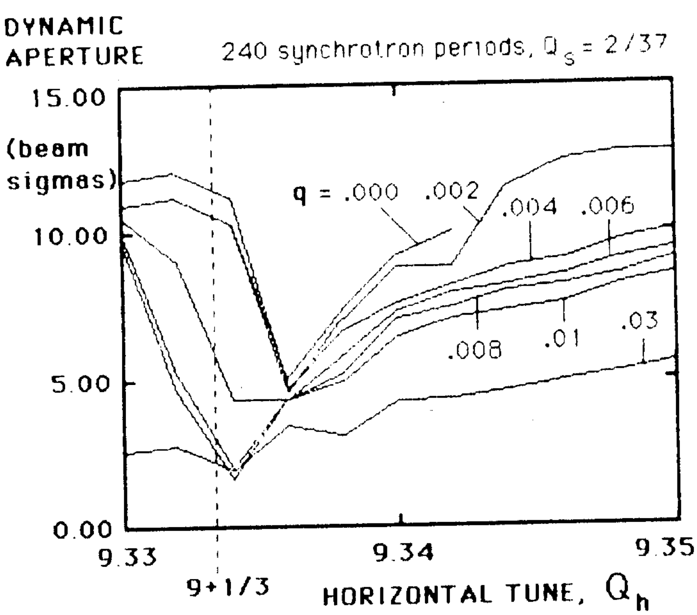

Figure 4 Tracking measurements of dynamic aperture for various tune modulation amplitudes, q.

CONCLUSIONS

The tracking results shown in Figure 4 are in qualitative, or semi-quantitative, agreement with the real experimental results shown in Figure 3. Many remaining questions about the specific comparison of tracking and experiment could be addressed in an improved analysis, given time. For example, the tracking analysis would be improved by looking at the hysteresis effect, and at mid-plane symmetry violations driving the $2Q_h + Q_v = 28$ resonance. An improved experiment would compare the effects of small, equal and opposite net chromaticities, which cause the same tune modulation amplitude and require only slightly different sextupole strengths.

Comparison is also necessary with theory. One advantage of experiments near the 1/3 resonance is that dynamic aperture predictions based on first order perturbation theory are likely to be correct. In contrast, the off-resonance dynamic aperture is generally governed by high order cross terms between chromaticity correction sextupoles, which are usually the only strong non-linearities present. This is particularly true at the working point, which is chosen for its stability. The SSC may be an exception to this rule, since unavoidable high order multipole errors in the superconducting dipoles could cause single resonance excitation to dominate the dynamic aperture, "near" to any operating point.

What is unequivocally clear and important is that the net chromaticity is a key variable in tracking programs and in real life. Tracking studies for any future accelerator must include tune modulation effects. This is particularly true for high current electron rings where the net chromaticity must be large, in order to combat head-tail instabilities.

Acknowledgements

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