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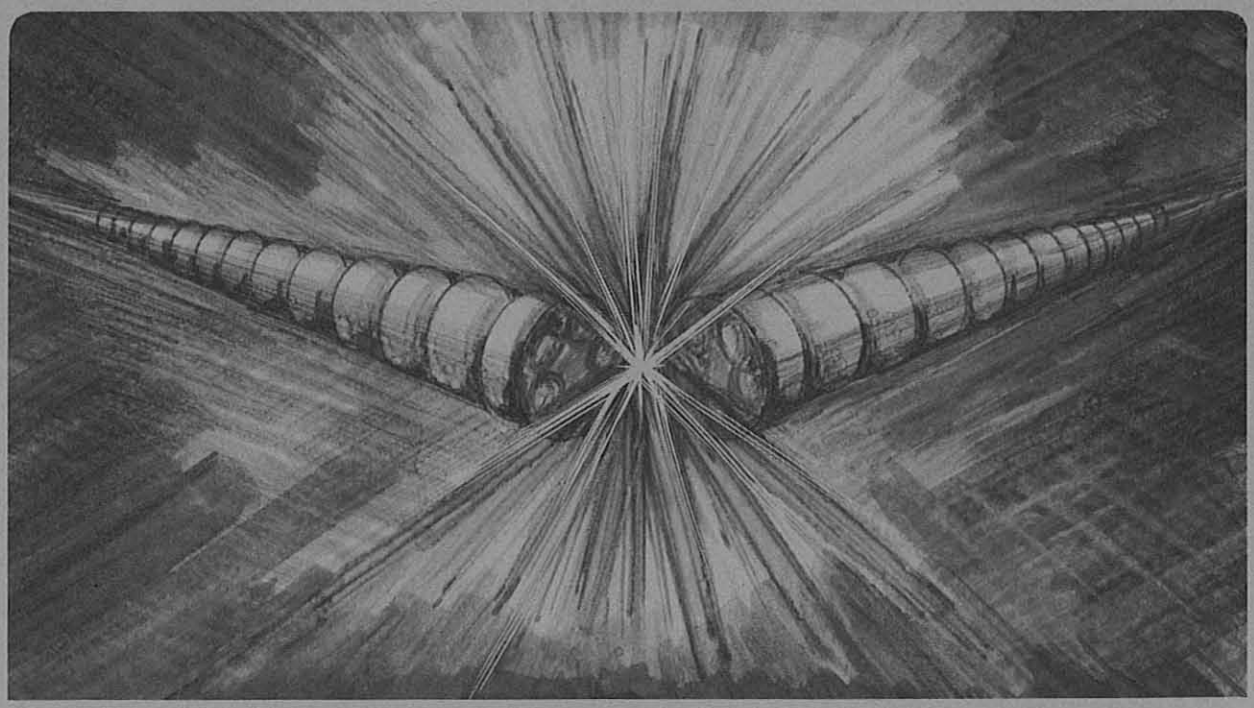

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AN INVESTIGATION OF COHERENT QUADRUPOLE BEAM-BEAM EFFECTS

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Abstract

We use a new simulation technique[1], that allows us to calculate the beam-beam kick from non-Gaussian beams, to discriminate between the predictions of two different theoretical models. Our results are in agreement with one of these models. We employ the simulation to better understand the nature of the coherent effects, and to explore their dependence on damping. We discuss the drawbacks in the other model and suggest improvements.

1 Introduction

One of the factors limiting the luminosity of e^+e^- storage ring colliders is the beam-beam interaction. There has been much speculation on the role of coherent (or collective) beam-beam effects as a mechanism for limiting the tune-shift parameter, but no consensus has been reached on this issue[2]. Coherent dipole motion, where the centroids of the two beams oscillate relative to each other, is commonly observed in operating storage rings, but there is no evidence that it affects luminosity. Such centroid motion is easily detected and could be removed with feedback. The potential for performance limitations comes from coherent effects that distort the beam shape.

2 Theoretical Models

These coherent *quadrupole* effects have been analyzed with two different types of models. In the nonlinear map (NM) models, of Hirata[3] and of Chao, Furman, and Ng[4], nonlinear maps for the colliding system are developed in the moments of the distributions and iterated on a computer to find the equilibrium solution. Here we consider only Hirata's model, because it is closer to the physics we wish to study. In earlier work Hirata starts with Gaussian beams and calculates the beam-beam kick using the formula of Bassetti and Erskine[5]. However the assumption that the beams keep their Gaussian form is inconsistent with the nonlinear nature of the kick. He finds *flip-flop* solutions, in which the beams maintain fixed but unequal sizes. Later attempts at including higher moments were in substantial agreement with the Gaussian calculation.

In the Vlasov-equation (VE) model, of Chao and Ruth[6], and of Dikansky and Pestrikov[7], the phase-space distributions of the two beams influence each other, and modes develop in phase-space. The stability of these modes is analyzed using the linearized Vlasov equation, assuming small perturbations from equilibrium. Their results are characterized by the appearance of even-order coherent resonances, leading to period-n beam-size oscillations. The widths of these resonances, i.e. the range of beam-current over which these coherent effects occur, are *finite*, and there are sharp thresholds for their onset. However there remain questions about some of the assumptions that go into the theory, as well as about the effects of including radiation and Landau damping.

3 Simulation Technique and Results

Recently we developed a simulation program[1] to explore the consequences to coherent beam-beam dynamics of being able to calculate fields from non-Gaussian beam-distributions. The program is strong-strong and two-dimensional (there is no longitudinal dynamics). Radiation damping and quantum excitation effects are put in once a turn and at one point in the ring. The beam-beam algorithm is general, making no assumption about the beam-distribution; the test particles are cast onto a polar grid and their net electric field is calculated[8]. The beams start out round and, though they are not constrained to remain so, the algorithm fails if the beam-

profiles develop substantial eccentricity; in the results presented below this never happened. Typical parameters are given in Table 1.

Table 1: Typical parameters used in the simulations

Energy (E_0)	5.3 GeV
Revolution Period (T_0)	2.56 μsec
Transverse Emittances ($\epsilon_x = \epsilon_y$)	1×10^{-7}m
Amplitude Functions ($\beta_x^* = \beta_y^*$)	3 cm
Betatron Tunes ($Q_x = Q_y$)	0.67
Damping Decrement (δ)	1×10^{-3}
Current (I)	35 mA
Nominal Beam-Beam Parameter (ξ_0)	0.1225
Number of test particles	10000

The results of the simulation are summarized in Figure 1. Essentially, they are in agreement with the VE model: at tunes close to resonant values we find the dynamics determined by even-order coherent resonances of finite width, leading to period-n oscillations in the beam sizes. The magnitude of that width is a function of the distance away from the nominal resonant value. A careful search for odd-order resonances was fruitless. At other tunes the beams have equal sizes and there is no evidence of coherent motion – in particular there was no flip-flop motion.

For the sixth-order resonance the period-3, anti correlated nature of the beam-size oscillations is shown in Figure 2. A closer examination of the beam-distribution is illuminating. On a particular turn one beam has a dense core while the other is hollow (and therefore non-Gaussian), forming a halo around the first. On the next turn the beams have comparable sizes, while on the third turn the first beam is hollow and the second dense. This three-fold pattern repeats indefinitely. For the eighth-order resonance there were similar period-4 oscillations.

We emphasize that the appearance of these higher-order coherent resonances is a direct consequence of the general field calculation; these resonances are *not* observed with multi-particle simulations that assume Gaussian distributions in calculating the field.

Dependence on Damping: The simulation permits us to go beyond the limitations of the VE model and consider the influence of radiation damping and fluctuation on the strengths of these resonances. The degree of damping is usually measured by the *damping decrement* δ – the average fractional energy emitted by a particle, in one turn, as synchrotron radiation. We find that the strength of a given resonance *decreases* as δ is increased. Further, the eighth-order resonance of Fig. 1 disappeared at a higher damping of $\delta = 1 \times 10^{-4}$.

The effects of damping are evinced in another way, in Fig 1, where the extrapolated widths of the resonances can be seen to go to zero before reaching the resonant tune. This is unlike the predictions of the VE model (where the widths are zero only at the resonant tune) and is a consequence of Landau damping amongst the particles being strong enough to suppress the outbreak of coherent oscillations.

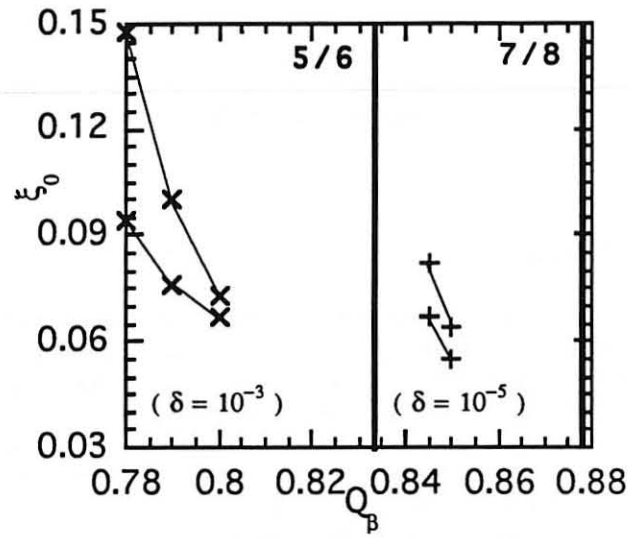

Figure 1: Onset and offset values of ξ_0 as a function of Q_β for the sixth-order (crosses) and eighth-order (plusses) resonances. In each case the region of coherent motion is between the lines. The resonance tunes are indicated by solid vertical lines. Note the difference in the damping decrement δ for the two cases.

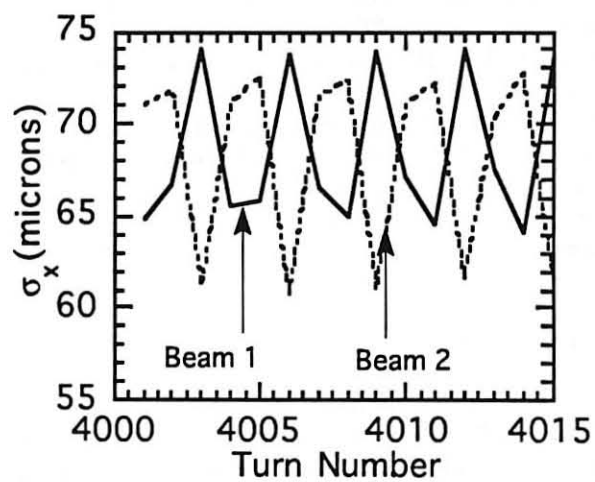

Figure 2: rms beam-size as a function of turn-number, for $Q_\beta = 0.79, \xi_0 = 0.13$, and $\delta = 1 \times 10^{-3}$. The period-3, anti-correlated nature of the size variations is evident.

4 Discussion

Some features of these resonances are worth emphasizing. Firstly, their signature is a rapid, turn-to-turn variation in the beam-size. Since most existing beam-size detectors are not sensitive to such swift variations, these resonances would not have been detected, and an increase in average beam-size would have been mistaken as being due to incoherent phenomena. We urge a closer search for these resonances.

As mentioned earlier, the equilibrium beam distribution is strongly non-Gaussian, with a substantial decrease in the overlap between the two beams — and consequently in the tune-shift parameter and luminosity of the collider. On the other hand, the strong dependence of the strength of these resonances on damping suggests that for machines with large damping, such as the heavy-quark factories under design, these resonances can easily be avoided.

The non-Gaussian nature of the beam distribution also explains why the NM model is unsuccessful. Since it assumes Gaussian distributions and directly tracks second moments instead of individual test particles, it is inherently incapable of finding these period-n solutions. The VE model, on the other hand, explicitly assumes harmonic perturbations in the phase-space density, and hence effectively allows for non-Gaussian shapes. The close correspondence between the simulation results and the predictions of the VE is indicative of the importance of allowing the beams to relax into non-Gaussian modes.

To compare with, and better understand, the results of the NM model, we performed a simulation that constrains the beams to remain round and assumes a Gaussian distribution in calculating the beam-beam kick. We found that the equilibrium solutions were flip-flop ones – though near the quarter-integer resonance there were transient period-2 solutions. We thus find that by suitably constraining the dynamics it is possible to change the relative strengths of various fixed-point solutions, and affect the final outcome.

Nonetheless, it needs to be stressed that if one allows for the non-Gaussian nature of real particle distributions in the calculation of the beam-beam force, then the period-n solutions predicted by the VE model are the dominant solutions, and are therefore the ones most likely to affect beam performance in storage rings.

5 Conclusions

Our simulations confirm the validity of the VE model and affirm the existence of period-n fixed-point solutions. Our study of the influence of damping on these resonances shows that for colliders with large damping, resonances beyond sixth-order will not be present. We find that the drawback with the NM model lies not in the technique, but in the assumption of Gaussian beams. We therefore suggest an extension of this technique to allow the distribution to take on non-Gaussian shapes.

Of course, our results are for nearly-round beams and e^+e^- colliders operate with flat beams. In Ref. [7] the authors find the same kind of resonances for flat beams. At present we are in the process of developing a technique that can handle non-Gaussian distributions and elliptic beam-profiles, and should soon be able to check their predictions.

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