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Synchro-Betatron Resonances Driven by the Beam-Beam Interaction

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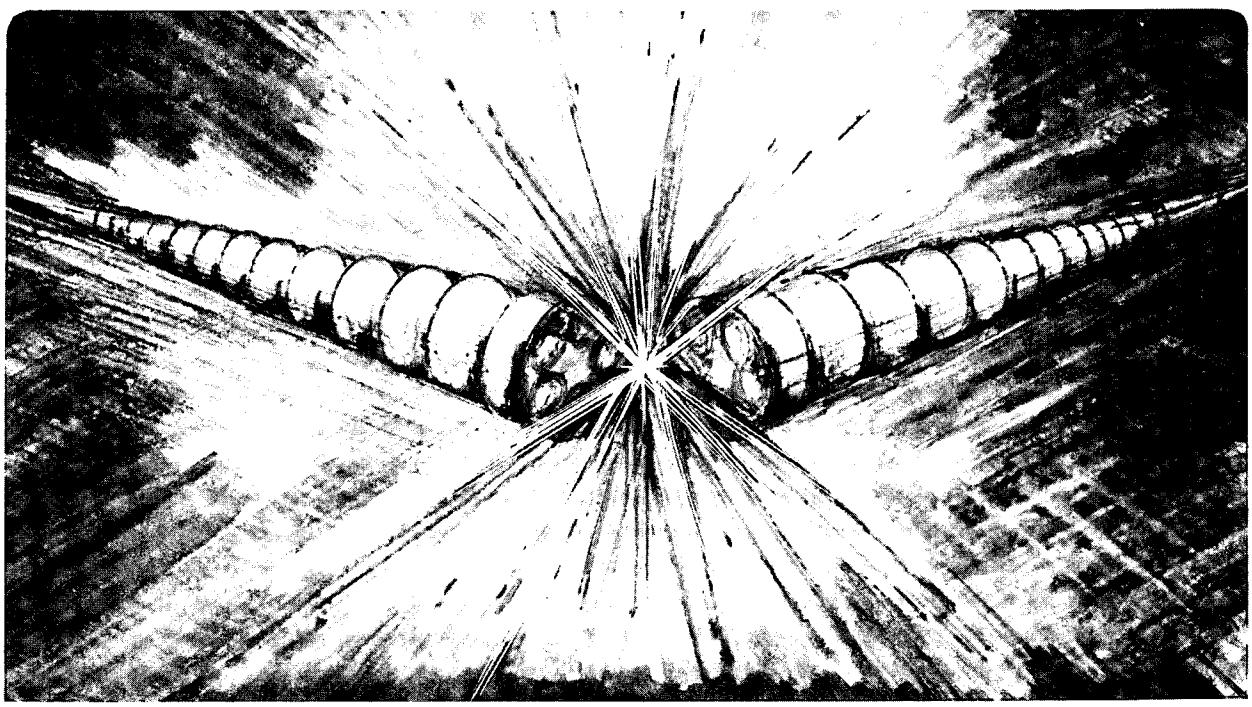

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SYNCHRO-BETATRON RESONANCES DRIVEN BY THE BEAM-BEAM INTERACTION*

(SUMMARY TALK)

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ABSTRACT

We present a selective summary of the discussions on beam-beam-driven synchrobetatron resonances at the 6th Advanced ICFA Beam Dynamics Workshop on the subject "Synchro-Betatron Resonances," held in Funchal (Madeira, Portugal), October 24–30, 1993.

Several beam-beam mechanisms were discussed that can drive synchro-betatron resonances (SBRs), such as nonzero dispersion at the interaction point (IP), longitudinal modulation of the IP, and nonzero crossing angle [1]. Since Steve Myers already gave a fairly comprehensive summary in his talks, I will focus on two topics only: crossing angle, and beam tail simulations.

Crossing-angle-driven SBRs were shown by Piwinski, around 1977, to limit the beam lifetime of DORIS-I, a two-ring collider with a vertical crossing angle [2]. The criterion was established then that the parameter $\Phi \equiv \phi\sigma_z/\sigma_y$, called the "normalized crossing angle," must be $\ll 1$ for the SBRs to be harmless. Here ϕ is half the crossing angle, σ_z is the rms bunch length and σ_y is the rms bunch height. In the particular case of DORIS-I, ϕ=12 mrad and Φ=0.6. Most of the current interest, particularly in colliders that are pushing the luminosity frontier, focuses on the possibility of a horizontal, rather than vertical, crossing angle. A recent experiment at CESR [3], summarized at this workshop by Chen, shows that there is little sign of performance degradation for horizontal crossing angles in the range -2.7 mrad $< \phi <$ $+2.7$ mrad. In this experiment, however, the normalized crossing angle was kept rather small: for ϕ=2.7 mrad, Φ reached the value 0.09 (in the horizontal-crossing case, of course, Φ is defined by $\Phi \equiv \phi\sigma_z/\sigma_x$ where σ_x is the rms bunch width). The observed lifetime limitation in this experiment is reasonably well

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understood from simulations and analytic calculations that identify the $5Q_x \pm Q_s$ SBRs of large-amplitude particles as being the resonances that determine the lifetime [4]. When these calculations are pushed to Φ=0.3, which is beyond the range of the experiment, no significant adverse effect on the lifetime is predicted.

At this workshop Hirata [5] presented results for large horizontal crossing angles which show that, as the angle increases, beam blowup peaks at Φ~0.5 and then *decreases* rather quickly for larger angles. The results are based on a based on a 6-D symplectic code whose key ingredient is a Lorentz boost to the frame of reference where the bunches collide head-on, but are tilted. The motivation is to analyze, by means of simulations, the crossing angle case with the same degree of detail as the head-on case. Thick lens effects during the beam-beam collision are taken into account by dividing up the bunches into several slices. The machine is described by a linear transport matrix, and damping and noise are put in the usual way for this type of model. Hirata presented weak-strong simulation results in the soft-gaussian approximation as a function of ϕ, for machine parameters like those contemplated for the KEK B factory, and for a "very good" working point determined from a tune scan at ϕ=0. The results show that the beam blowup factor peaks at Φ~0.5, then comes back down to unity. The heuristic explanation is that, as ϕ increases the beam overlap during the collision becomes smaller, hence the beam-beam interaction becomes weaker, hence it ceases to cause beam blowup. Even if there were no beam blowup at all, the luminosity would decrease as ϕ increases due to the falling geometrical overlap factor. However, it turns out that beam blowup disappears at a faster rate than the geometrical overlap factor decreases; the net result is that, in the region $0.5 \lesssim \Phi \lesssim 1$, the luminosity *increases* (though it always stays below its value for ϕ=0), and then decreases monotonically for Φ>1. For the particular set of parameters chosen, Φ=1 translates into ϕ=5 mrad, at which point the luminosity is ~50% of its head-on value.

So, what has been gained? Generally speaking, a crossing angle is an attractive option to consider in two-ring high-luminosity colliders: compared to the head-on case, a crossing angle tends to simplify beam separation, to reduce the strength of the parasitic collisions, to make the optics of the two rings more decoupled, and to ease the shielding of the detector. Therefore, if one could pack more bunches in the beam (by at least a factor of 2 in this particular example), one could recover or exceed the head-on luminosity. If, in addition, one could then use crab crossing to straighten the bunches and thus recover the beam overlap, the luminosity would, of course, be even larger. If one cannot add significantly more bunches in the beam than the head-on situation allows, this scheme does not make practical sense. Of course, if one packs too many bunches in the beam, the bunch spacing becomes so short that some of the advantages mentioned above could be diluted or eliminated, and some new disadvantages could appear, such as a more difficult design of common IR quads, and a possibly enhanced chance of multibunch instabilities. The welcome surprise from Hirata's calculation is that beam blowup disappears so quickly as the crossing angle increases beyond a certain value. The much more difficult question of beam lifetime at large crossing angles was not addressed in the talk. Nevertheless, the results presented will likely attract the interest of high-luminosity "factory" designers.

An outstanding challenge for beam-beam simulations is the prediction of the beam tail distribution. The overwhelming majority of particles are in the beam core, and thus determine the instantaneous (or short-time-average) luminosity; the time scale of the relevant physics is the damping time. If the dynamic aperture is adequate, machine nonlinearities are generally not

expected to play an important role due to the relative smallness of the typical particle amplitudes. Thus simulations for a few damping times generally yield a stable answer for the core distribution, provided the beam-beam parameter is not too large. On the other hand, the few particles at the tail of the distribution determine the beam lifetime. By definition, the amplitudes of these particles are large, hence machine nonlinearities are generally expected to be important. Thus the physics of the beam tails is much more complicated [6]. Possible mechanisms that drive particles to large amplitudes are resonance overlap, diffusion and resonance streaming. Although there is not a uniquely-defined time scale, experience suggests that it is on the order of 100's to 1000's of damping times. Since the tail particles are so rare, and since the time scale is so long, the conventional tracking method is virtually hopeless with present-day computers, since most of the CPU time is spent tracking the vast majority of "uninteresting" particles in the core. Chen [7] presented results for tail simulations based on a novel algorithm by Irwin [8] which emphasizes the tail particles over those at the core. Roughly speaking, the algorithm divides the amplitude space into several layers separated by dynamically-determined boundaries. The code successively tracks the particles within each layer, during which step the code "learns" the flux pattern through the outer boundary. This knowledge is then used in the tracking of the next layer, thus ensuring the continuity of the density and the flux. Obviously, the desired accuracy of the final distribution determines how many particles and boundaries are used, and how many turns one must track. By emphasizing the rare particles, the code achieves large speed-up factors relative to the brute-force method. Typically 1000 particles per layer and three layers were used in the cases presented, resulting in speed-up factors of 50–100 over the conventional algorithm. A comparison of a set of results obtained from this code with those from brute-force tracking for the same conditions showed impressive agreement. Other checks showed that there is little sensitivity to the boundaries. Particles streaming along expected SBR lines are clearly seen in the density distribution of the beam tails, and their location agree well with analytic calculations of these resonance lines. The code has been applied for the case of PEP-II parameters in order to establish a preliminary estimate of the beam lifetime for a given aperture. The results, which included the effects from the parasitic collisions, indicate more than adequate lifetime. Effects from lattice nonlinearities, however, are included so far in a simplified way, such as an amplitude-dependent tune. A developmental goal for the short-term future is to include nonlinearities in a more realistic fashion, for example by means of a nonlinear transfer map. Although comparisons with experiment are presently lacking, it seems clear that this code shows great promise of becoming a standard tool in beam-beam studies.

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