BEAM DYNAMICS IN HIGH LUMINOSITY e^+e^- FACTORIES

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Abstract

The e^+e^- factories achieve their high luminosity by storing a large current in many bunches. A number of collective effects, some of them new, strongly influence the dynamics of the beams in this very high current regime. Backgrounds of electrons (due to multipacting or photoemission) cause collective instabilities and emittance dilution. Heavy beam loading and ion clearing gaps in the bunch pattern have a strong effect on the longitudinal dynamics. The large number of bunches in the factories requires crossing angle collisions in some machines, coupling the longitudinal and transverse dynamics. Parasitic collisions are present, wigglers may be used to manipulate the emittance and radiation damping rates, and the electron and positron beams in asymmetric B-factories have unequal parameters. We review the wealth of recent beam dynamics observations made at the e^+e^- factories.

1 INTRODUCTION

High luminosity e^+e^- "factories" produce large samples of high-energy physics data to search for rare particle decays or to make precision measurements. All of them achieve a high luminosity by storing a large current in many bunches. The operating e^+e^- storage ring colliders which use this strategy are: DAΦNE (INFN Frascati); CESR (Cornell University); KEKB (KEK); and PEP-II (SLAC). Several important characteristics of each collider are listed in Table 1.

Table 1: Characteristics of Operating e^+e^- Factories

Parameter	DAΦNE	CESR	KEKB	PEP-II
E_+/E_- (GeV)	0.51/0.51	5.3/5.3	3.5/8.0	3.1/9.0
$N_{bunches}$	48	45/45	1154/ 1154	692/692
I_{beam} (mA)	1000/ 1000	356/329	885/ 748	1492/ 800
β^*_V (cm)	4.5/4.5	2.1/2.1	0.65/0.7	1.25/ 1.25
β^*_H (cm)	450/450	100/100	59/63	50/50
ξ_V	0.0015/ 0.0015	0.07/ 0.07	0.045/ 0.028	0.055/ 0.028
ξ_H	0.02 to 0.025/ 0.02 to 0.025	0.028/ 0.028	0.072/ 0.050	0.069/ 0.059
θ_{cross} (mrad)	±12.5	±2.3	±11	<0.1
L (10^{33}cm^{-2}s^{-1})	0.029	1.3	4.04	3.3

Collective beam dynamics effects tend to be important for the e^+e^- factories because of their large total current. These include long-range wake field instabilities, instabilities due to electron backgrounds, and perturbations to the longitudinal dynamics from heavy beam loading and ion clearing gaps. Several single-particle effects are related to the large number of bunches. There are long-range interactions between the beams where they share the same beam chamber. Some of the factories require the beams to cross each other at a small angle, generating synchro-betatron coupling. The asymmetric B-factories have unequal parameters for the two rings, which can potentially influence the beam dynamics. Low energy rings may use wigglers to influence the damping rate and emittance, introducing additional magnetic nonlinearity. In this paper we review the observations of each of these effects.

2 BEAM LOADING

The heavy beam loading produced by the large average current in the e^+e^- factories, together with the long gap in the bunch pattern required for ion clearing, produce a significant transient in the equilibrium rf phase of the bunches. In PEP-II, for example, a difference in the rf phase of positrons relative to electrons, which varies from bunch to bunch, has been measured [1]. This difference of several degrees slightly shifts the bunch collision point away from the point of minimum β_y and may have an effect on the luminosity. Steps are being taken to reduce this phase difference in PEP-II.

3 ELECTRON BACKGROUNDS

The interaction of the beam with an electron cloud in the beam chamber is a relatively recently explained collective effect [2,3,4]. Electrons transit the beam chamber and are stopped at the chamber walls in a time of order 10 ns, so electron cloud effects are usually important in machines with many closely spaced bunches, such as the e^+e^- factories. Electron cloud effects are observed in CESR, KEKB, and PEP-II, but have not yet been observed in DAΦNE.

3.1 Instability Mechanism

Slow electrons can be ejected from the beam chamber by synchrotron radiation photons, residual gas ionization (a small effect in the e^+e^- factories), or by secondary emission. In the secondary emission process the primary electrons already present in the chamber are driven by the electric field of the beam into the chamber with sufficient kinetic energy to generate secondary electrons. Hence, this is a type of multipacting process.

The charge distribution of the electron cloud responds to the position of a passing bunch. In turn, the electric field of the electron cloud perturbs subsequent bunches,

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creating a bunch-to-bunch coupling which can drive transverse multi-bunch instabilities. The multi-bunch instability is broadband, involving many modes. The electron cloud can also couple the head of a bunch to its tail, creating a single-bunch head-tail instability (which, however, requires the presence of many bunches in the machine to generate the electron cloud) [5]. The electron cloud couples most strongly to a positively charged beam, because the space charge of a negative beam repels the electron cloud.

3.2 Control of the Instabilities

Instabilities generated by electron backgrounds may be suppressed by reducing the emission of photoelectrons or secondary electrons, by using gaps in the bunch pattern, by using weak magnetic fields to keep the electrons away from the beam, or by using broadband transverse beam feedback to damp the instabilities. All of the e^+e^- factories use broadband transverse feedback systems to damp multi-bunch instabilities [6,7,8,9]. The PEP-II LER chamber is coated with TiN, a material with a low secondary emission coefficient, to reduce multipacting [10]. The straight sections of the PEP-II LER chamber have been wrapped with wire to create a 30 gauss solenoidal magnetic field [11]. C-yoke permanent magnets had been installed on the KEKB LER chamber where synchrotron radiation strikes the chamber, but these did not improve the electron cloud effect for closely spaced bunches. Solenoids have been installed around the KEKB LER chamber [12]. Bunch-by-bunch luminosity measurements in PEP-II indicate that the electron cloud in the LER has a significant effect by about the tenth bunch in a train, but the effect disappears after a short gap in the bunch pattern. PEP-II currently operates with a 20 bunch train, in which every fourth rf bucket is filled, followed by a 4 bunch gap [13].

3.3 Observations of Electron Cloud Effects

A number of effects of the electron cloud have been observed in the e^+e^- factories. These include:

- A sudden transition from beam stability to beam loss when the bunch spacing is decreased. For example, the CESR positron beam is stable against electron cloud instability for trains with • 8 ns spacing, but unstable for 2, 4, or 6 ns spacing. This observation is exactly consistent with a numerical simulation of the electron cloud effect in CESR [14].
- A rapid increase in vertical positron beam size with positron beam current. This effect on beam size was measured in KEKB [15] and PEP-II [11].
- A rapid increase in vacuum pressure with positron beam current. A sharp threshold in vacuum pressure is observed in the PEP-II LER at approximately 500 mA total current, indicating the onset of multipacting [11]. A similar increase in pressure is observed in KEKB [16].
- Suppression of these effects when weak solenoids are present in the straight sections. This suppression has been observed in both PEP-II and KEKB and continues to improve as the coverage with solenoids improves.
- An increase in beam size for later bunches in a train. This dependence of beam size on bunch number was measured directly at KEKB with a gated camera [15], and indirectly at PEP-II with bunch-by-bunch luminosity measurements [11, 13].
- An increase in the vertical beam size of the last positron bunch in a train as the current in the last bunch is increased was measured at KEKB and indicates a single bunch instability caused by the presence of the electron cloud set up by previous bunches.

In addition, at several machines other than e^+e^- factories the kinetic energy spectrum and time structure of the background electrons has been measured by direct detection [17,18,19].

At KEKB the pressure in the vacuum chamber was deliberately increased by a factor of 100 to 1000 with no observable change in beam size, indicating that ions are not involved in the observed beam size increase.

4 BEAM-BEAM PERFORMANCE

The beam-beam performance in e^+e^- factories may be influenced by the unequal energies of the colliding beams in the asymmetric B-factories, by the difference in transverse tune of the beams, by the crossing angle used in some colliders, and by magnetic nonlinearities and errors. We examine each of these in turn.

4.1 Unequal energy beams

The asymmetric B-factories have unequal energy beams. The B mesons they produce have a boosted center of mass in the lab frame, which allows the time dependence of their decay to be measured. To make the beam-beam interaction appear the same to both beams, some parameters (for example, beam dimensions or damping times) should be made equal for the electron and positron beams and others (for example, beam current) should be made unequal. In both PEP-II and KEKB these *energy transparency* conditions are violated, as it was found that exact energy transparency is not necessary for good operation.

Asymmetric energies may or may not significantly affect beam-beam performance. The maximum vertical beam-beam parameter ξ_v in CESR is 0.07. The maximum ξ_v in PEP-II is 0.055 for e^+ and 0.028 for e^-, and the maximum ξ_v in KEKB is 0.045 for e^+ and 0.028 for e^-. These differences between the symmetric energy CESR and asymmetric energy PEP-II and KEKB may not be significant, as the CESR value was obtained only after a lengthy program of error correction and tuning.

4.2 Differential tunes

DAΦNE, CESR and KEKB obtain their best operating conditions with slightly different vertical and horizontal tunes for the two beams [20]. The tune difference is of the order of 0.01. In PEP-II the tunes are (ν_H, ν_V) = (38.65, 36.58) for e^+ and (ν_H, ν_V) = (24.57, 23.64) for e^-. Note that the fractional parts of the PEP-II vertical and horizontal tunes are exchanged (approximately) for the two beams. In PEP-II it is found that equal tunes result in a 50% reduction in luminosity. This behavior does not have a full explanation at present.

4.3 Crossing angle collisions

To avoid multiple collisions in the interaction region, DAΦNE, CESR, and KEKB have orbits for the two beams that cross at a horizontal angle at the interaction point. There are two consequences of crossing angle collisions. First, the beam-beam force acquires a different dependence on the longitudinal position of the particle which experiences the force. That is, additional synchro-betatron resonances may become significant. Second, for bunches of fixed size and charge, the lack of perfect geometrical overlap reduces the luminosity. However, the beam-beam parameters ξ_V and ξ_H are also reduced and, if the same value of the beam-beam parameters can be achieved as in head-on collisions, there may be no luminosity reduction.

The departure from perfect geometrical overlap is characterized by a *normalized crossing angle* $\theta_{cross}\sigma_L/\sigma^*_H$. The values of the crossing angle parameters for the e^+e^- factories are listed in Table 2.

Table 2: Horizontal Crossing Angle Parameters

Parameter	**DAΦNE**	**CESR**	**KEKB**	**PEP-II**
θ_{cross} (mrad)	±12.5	±2.3	±11	<0.1
σ^*_H (mm)	2.1	0.46	0.103/0.123	0.147
σ_L (mm)	30	18.0	6	12
$\theta_{cross}\sigma_L/\sigma^*_H$	±0.18	±0.090	±0.58	<0.008

Experiments in which the crossing angle is varied to determine the dependence of luminosity on crossing angle are difficult. In machines designed for a large crossing angle with separate chambers for the two beams the crossing angle cannot be varied all the way to zero. In CESR, which has a single vacuum chamber for both beams, an experiment was done in which the normalized crossing angle was varied from zero to nearly ±0.1. The aperture of the vacuum chamber prohibited larger values of the crossing angle. It was found that the luminosity did not significantly drop until the crossing angle was near this maximum value. This drop in luminosity may well have been due to magnetic errors encountered at the large orbit displacement.

An indication of the effect of the crossing angle is provided by a comparison of ξ_V = 0.045 (e^+) in KEKB, which has a very large normalized crossing angle, with ξ_V = 0.055 (e^+) in PEP-II, which has a nearly zero crossing angle. The similarity of ξ_V for these colliders demonstrates that a large normalized crossing angle is not necessarily dangerous. Beam-beam simulations of KEKB indicate that a large crossing angle is has little effect on beam-beam performance if the synchrotron tune is small, but that head-on collisions or crab-crossing collisions should provide some improvement in luminosity.

4.4 Nonlinearities and errors

CESR is longest-running of the e^+e^- colliders considered here and provides a good case study of a long-term program to improve beam-beam performance. The history of the vertical beam-beam parameter in CESR can be summarized as:

- Head-on collisions, 2 interaction points: ξ_V • 0.02
- Head-on collisions, 1 interaction point: ξ_V • 0.04
- First 7-bunch crossing angle collisions: ξ_V • 0.03
- First 9-bunch crossing angle collisions: ξ_V • 0.023
- Present 45-bunch crossing angle collisions: ξ_V • 0.07

In going from two interaction points to one, the beam-beam parameter (per interaction point) doubled. In going to 7-bunch collisions and then to 9-bunch collisions with a crossing angle, the effect of the large orbit displacement in and near the interaction region severely limited the beam-beam parameter. At present, CESR operates with 9 trains of 5 bunches each with a ξ_V that is three times as large as it was in the first 9-bunch collisions, even though the number of parasitic beam-beam interactions has increased. The improvement in ξ_V is due to:

- elimination of multipoles in the wigglers used for producing synchrotron radiation;
- improvement in operating point;
- reduction of the higher multipole fields of the sextupole magnets by altering the pole tips;
- improvement in the measurement and correction of betatron phase, local coupling, dispersion, and interaction point parameters (*e.g.*, α^* and β^*);
- improvement in the distribution of sextupole magnet strengths;
- survey and alignment of quadrupole and dipole magnet rolls;
- rewiring of dipole magnet backleg windings to eliminate a skew sextupole moment.

Careful attention to the closed orbit, coupling, β function errors, operating point, interaction point errors and multipole errors has resulted in a large increase in the beam-beam performance. CESR shows the typical behavior of a ξ_V that increases with current up to a maximum value, after which it no longer increases (see

Figure 1 below) [21]. There is some evidence that ξ_v has reached its limiting value for the present choice of CESR operating parameters. A strong-strong beam-beam simulation [22] using a linear single-turn map to represent the storage ring arcs predicts the observed luminosity almost exactly.

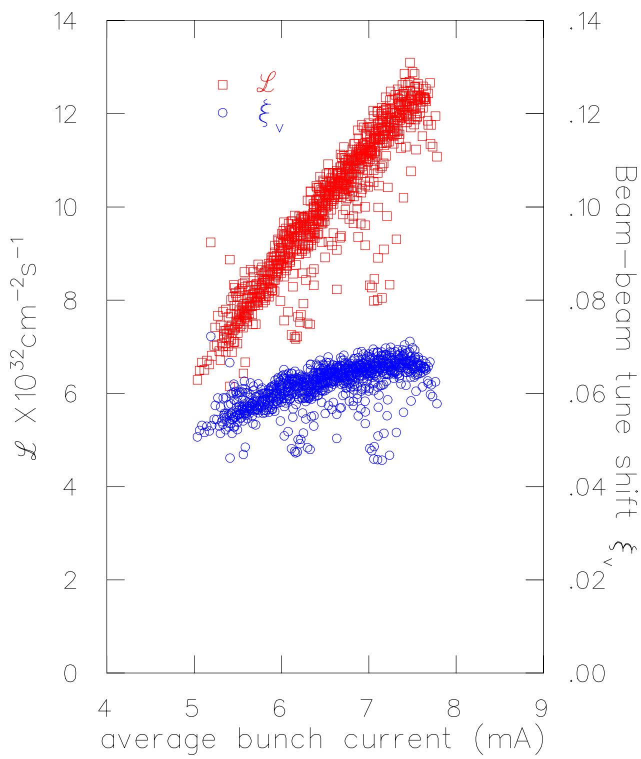

Figure 1. Observed luminosity and vertical beam-beam parameter *vs.* bunch current in CESR.

DAΦNE makes use of wigglers for the control of synchrotron radiation emission. These wigglers have been found to produce a chromaticity which is nonlinear in the momentum deviation as well as a tune shift which depends on horizontal position [23, 24]. This tune shift has been measured using the decoherence of a kicked beam as well as with static orbit bumps and is found to be quadratic in horizontal position. The octupole-like behavior of the tune shift is understood to be due to a decupole component of the wiggler magnetic field sampled by the beam as it moves from side to side of the wiggler. New optics with a smaller β function in the wigglers is found to increase the single-bunch luminosity. Octupole magnets are being installed in DAΦNE to provide tuning of the octupole content of the optics.

5 LONG RANGE BEAM-BEAM INTERACTIONS

A long-range beam-beam interaction (LRBBI) occurs where beams share the same vacuum chamber. In colliders that use separate chambers for both beams, parasitic collisions and LRBBI occur only in the interaction region. The LRBBI can result in particle loss if a significant number of large-amplitude particles in one beam are near the core of the other. For beams with larger separation, the main effect of the LRBBI is to cause closed orbit errors and tune shifts.

5.1 Perturbation to Optics

The long-range beam-beam interaction causes closed orbit errors and tune shifts. If the bunches are non-uniformly spaced, which is true for all e^+e^- factories because of ion-clearing gaps, electron cloud clearing gaps, or other reasons, then the orbit displacements and tune shifts are different for different bunches. Significant vertical kicks are possible for beams that are normally in the same horizontal plane because of the vertical displacement of the beams in the interaction region caused by the detector solenoid. The calculated differential displacement of the beams at the interaction point and tune shifts due to the LRBBI in CESR are shown in Figure 2 [25]. These are in rough qualitative agreement with observations made using the beam-beam deflection, the position information recorded by the transverse feedback system, and luminosity monitored by the CLEO detector [26]. Most of the effect is due to the close parasitic crossings in the interaction region, even though most of the parasitic crossings occur outside this region. The differential vertical displacements at the interaction point are of the order of 20% of the vertical beam size, and appear to have a significant effect on luminosity.

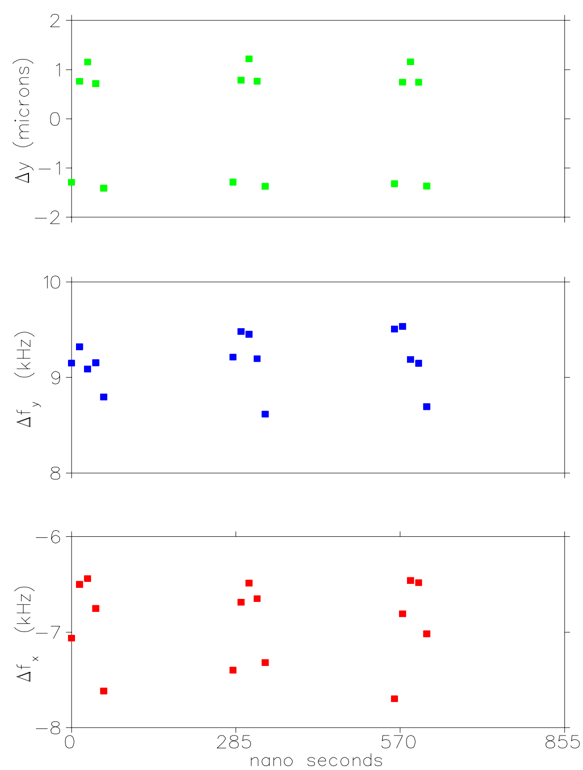

Figure 2. Calculated differential vertical orbit displacement and vertical and horizontal tune shifts caused by the long-range beam-beam interaction in CESR.

5.2 Compensation of LRBBI

The long-range beam-beam interaction causes orbit errors that can be corrected with steering magnets and tune shifts that can be corrected with quadrupole magnets. The residual differences in closed orbit between bunches needs to be corrected by a time-dependent element. In CESR the vertical bunch-by-bunch feedback system has also been used as a feed-forward system to correct the differential vertical displacement at the interaction point [27]. The compensation has been partially successful in increasing the luminosity of the collisions between bunches with differential vertical displacements. A radio-frequency quadrupole to correct the residual differential tune shifts in CESR is under development.

6 SUMMARY

- Beam dynamics in the e^+e^- factories is distinguished by effects which occur when many bunches are used to achieve a large total current.
- Careful attention to impedances in the new high-current machines has kept them under control. Electron cloud effects have become the bigger challenge for PEP-II and KEKB.
- The details of the beam-beam interaction still need exploration. Why are unequal tunes beneficial? Is a large crossing angle completely benign, or is crab crossing needed?
- The long-range beam-beam interaction creates significant bunch-to-bunch differences in orbit and tune. This is an important effect for the single-chamber CESR and will be an increasingly important effect for the other colliders when more buckets are populated.

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