Nearly Equal β^* at CESR *

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Abstract

Simulations [1] suggest that in e^+e^- storage rings collisions of round beams (equal emittances and equal β^*) can produce tune shifts of 0.1 and very large luminosities. Further simulations show the same large vertical tune shifts even with very different horizontal and vertical emittances. Using a special CESR lattice with $\beta_h^* = 32$ cm, $\beta_v^* = 20$ cm, and zero horizontal and vertical dispersion at the interaction point, we collided beams with horizontal emittance of 136 nm · rad and vertical emittance of about 9 nm · rad. There were experimental complications involving the damping partition numbers, a near miss at a parasitic crossing point, and small orbit offsets at the main collision point. We have done a detailed analysis of these complications and discuss their effects on the observed saturated tune shift of 0.045 ± 0.010.

Introduction

From January to March of 1990, the CESR operations group devoted 140 hours of machine studies to commissioning a lattice with nearly equal beta stars and colliding flat and fully coupled beams in that lattice. The original aim of this lattice was to investigate the beam beam performance of round beams (equal β^* and equal emittances) and to see if it matched the predictions of simulations. The simulations also predicted good beam beam performance for flat beams (equal β^* and horizontal emittance much larger than vertical emittance) and for fully coupled beams (equal β^* and equal emittances generated by operating on the coupling resonance). We began with the flat beam case, the simplest to achieve operationally, and had established its limits when we realized that this lattice was flawed by a separation scheme that made the damping partition numbers for the two beams very different. In view of this flaw, surprisingly good beam beam performance was seen for the flat beam collisions. But realizing that this flaw must be corrected we did not devote much effort to the coupled beam case or proceed to the round beam case. This paper reports our experimental results and analysis from this flawed lattice. A great deal of this analysis has focused on understanding the idiosyncrasies of the design lattice, particularly those of the separation scheme in the parasitic interaction region, delineating the differences between the lattice in the machine and the design lattice, and incorporating these differences and idiosyncrasies into the beam beam simulations.

The Lattice

CESR is an e^+e^- storage ring operating in the Υ energy region near a center of mass energy of 10 GeV. Our lattice for this experiment features β_h^*, β_v^* and η_h of 33 cm, 20 cm and 0 cm, respectfully, transverse tunes just above 9.75, synchrotron tune of .045, horizontal emittance of 1.36×10^{-7} m, bunch length of 1.9 cm and beam energy of 5.18 GeV (on the $\Upsilon(3S)$ resonance). The optics for half the ring are shown in figure 1. We show only half the ring since the design optics are mirror symmetric.

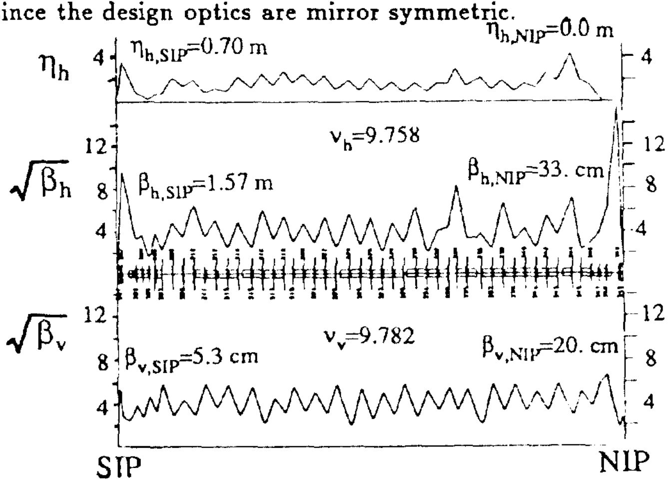

Figure 1. The lattice

All of the parameters mentioned above are for the north interaction point (NIP). The south interaction point (SIP) has very unequal beta stars. We found that the lattice appeared much more favorable if we did not configure the south interaction region for collisions, so we arranged to separate the beams horizontally through the south interaction region using the existing horizontal separators installed for multi bunch operation. These electrostatic separators are near detectors 8 and 91. The measured change in orbit produced by this separation scheme is shown in Figure 2. Since the optics at the two interaction points are very different, the separation scheme at the SIP is an integral part of the experiment.

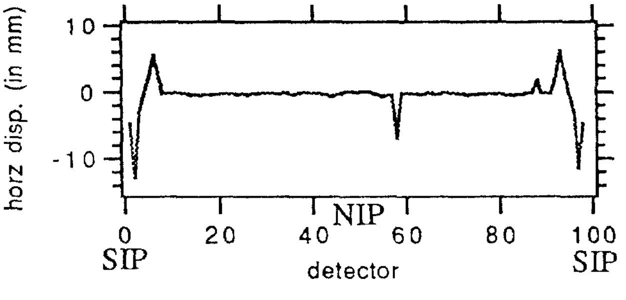

Figure 2 : Measured South Separation Bump for kick of ±0.43 mrad

The separation scheme complicated the experiment considerably. First the separation bump is not isochronous. Since the ring circumference is locked to a multiple of the RF wavelength, this causes a small energy difference between the electrons and the positrons.

The separators also significantly change the dispersion. Although the separators have a very weak first order effect on the dispersion, their second order effect is quite strong. That is, considering only the bend produced by the separators, the change in dispersion is very small. But there is a second order effect due to the local chromaticity, the change in the horizontal phase advance between the

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south separators due to a particle being slightly off energy. Since this phase advance is about 3π for an on energy particle, small changes in the phase advance will result in the south pretzel not closing and produce significant dispersion changes.

The major flaw is that the separation bump produces differences in the damping partition numbers. These differences lead to different horizontal emittances for the two beams. Sands [2] calculates the damping rates as

$$\alpha_x = (1-D)\,\frac{U_0}{2E_0T_0} \quad ; \quad \alpha_s = (2+D)\,\frac{U_0}{2E_0T_0} \qquad (1)$$

The vertical damping rate, α_y, does not depend on D which is defined as

$$D \equiv \frac{\oint \eta\left(G^3 + 2GK_1\right)ds}{\oint G^2 ds} \qquad (2)$$

where G is the inverse of the radius of curvature and K_1 is the quad strength in m^{-2}. The separation bump displaces the beam in all the quads within the bump. Thus they act as combined function magnets with inverse bending radius of $K_1 x_{sep}$, where x_{sep} is the displacement from centers of the quads.

Table 1 shows *calculated* parameters for the separator settings where colliding beam data were taken.

sep. kick	0.0 mrad	±0.16 mrad	±0.3 mrad
sep. volt	0.0 kV	±20. kV	± 37. kV
$(\Delta E/E_0)_+$	0.0	$-0.062e-3$	$-0.116e-3$
$(\Delta E/E_0)_-$	0.0	$0.060e-3$	$0.108e-3$
S_{sip}	0.0 mm	1.8 mm	3.3 mm
S_{sip}/σ_{x+}	0.0	2.9	5.4
S_{sip}/σ_{x-}	0.0	2.7	4.6
D_+	0.020	−0.19	−0.37
D_-	0.020	0.23	0.40
τ_{x+}	28.6 msec	23.6 msec	20.4 msec
τ_{x-}	28.6 msec	36.4 msec	47.1 msec
ϵ_{x+}	0.136 μm	0.109 μm	0.093 μm
ϵ_{x-}	0.136 μm	0.177 μm	0.234 μm
$(\sigma_E/E_0)_+$	$0.60e-3$	$0.63e-3$	$0.67e-3$
$(\sigma_E/E_0)_-$	$0.60e-3$	$0.57e-3$	$0.55e-3$
σ^*_{x+}	0.213 mm	0.190 mm	0.175 mm
σ^*_{x-}	0.213 mm	0.244 mm	0.281 mm
$\sigma_{z,CCD+}$	1.63 mm	1.54 mm	1.49 mm
$\sigma_{z,CCD-}$	1.69 mm	1.81 mm	1.97 mm

S_{sip} is the center to center separation.
The + and − subscripts indicate the calculated quantities for positrons and electrons respectfully.

Table 1 : Calculated Effects of the South Separation Bump

At the ±20. kV separator setting, the differences between the characteristics of the two beams are still fairly small, but the separation between the beams at the SIP is also small, and we are concerned that the near miss may strongly influence the beam beam dynamics. At the ±37. kV separator setting, there is sufficient separation so that we feel that we can neglect the near miss at the SIP, but there are now considerable differences between the two beams.

The dynamics of the near miss have all the nonlinearity of the head on beam beam interaction, but have less symmetry. To correctly account for its effects we must include it in the beam beam simulation.

Unfortunately, the situation is not as well understood as these calculations suggest. We were able to make some rough measurements of the horizontal beamsize and over the range of separator settings where we took colliding beam data, there was no appreciable change in the horizontal beamsize of either beam, in contrast to Table 1. This is not a standard measurement, so it may be flawed. All that we can conclude from the measurements is that the difference between the electron and positron beamsizes at the collision point is probably no more than (and may be less than) the calculated difference.

The final problem is that the beams have a small horizontal separation between the beam centers at the NIP. For the separator setting of ±0.16 mrad, this separation is $[78.-(6.8*I)]\ \mu\text{m} = [0.366-(0.032*I)]\sigma^*_{x,nom}$, where I is the current of the opposing beam in mA, and $\sigma^*_{x,nom}$ is the nominal, separator off, horizontal beamsize at the NIP of 213. μm. For the separator setting of ±0.30 mrad, this separation is $[81.-(3.0*I)]\ \mu\text{m} = [0.380-(0.014*I)]\sigma^*_{x,nom}$.

Several mechanisms contribute to this separation. The dominant mechanism is known locally as the sawtooth effect [2,3] and refers to the different orbits of the two beams due to their different energy histories when we are running with only 1 RF cavity. The other major effect is the beam beam kick given to the center of the bunch from the near miss at the SIP. These kicks appear as a horizontal displacement at the NIP. This gives the current dependent term above and is included naturally in the beam beam simulation. There are two more small effects. There is an offset at the NIP produced by errors in the separator settings and the phase advance between the separators and an offset from the *measured* non-zero dispersion at the NIP and the energy offset from the separators. The vertical displacement, and both crossing angles remain small at the NIP. With the exception of the SIP near miss kick, the separations between the beams at the NIP from the other effects are put into the beam beam simulation by hand.

Simulations

We will compare our data to a strong–strong, 3 dimensional simulation with linear arcs. Radiation fluctuations and damping are put in once per arc. The simulation was run for 30000 turns with 1000 particles and the parameters of the lattice. It includes the unequal damping partition numbers, the near miss in the south interaction region and the small separation between the beams at the NIP.

Tuning and Data Analysis

All of the useful colliding beam data were taken in two machine studies periods. The machine conditions during these two periods were sufficiently different so that we have plotted the results separately, however the beam beam performance is remarkably similar.

During the initial tune up at the beginning of each machine studies, we would horizontally and vertically close the south separation bump, as best we could. After this, the elements within that bump were not touched. In almost all the data shown, the tunes were within ±.003 of $\nu_h = 9.758$ and $\nu_v = 9.782$. While tuning, the ν_v was varied from about 9.76 to 9.80 and the ν_h varied from about 9.745 to 9.765. We used 2 sextupole families. The horizontal chromaticity, χ_h, was varied from about 1.0 to about 5.0, but was usually around 4.2. The vertical chromaticity, χ_v, was independently varied over about the same range and was usually about 1.9. Neither the luminosity nor the tune shift were strongly affected by either chromaticity. We begin each period with the machine globally decoupled, and then tuned skew quads for optimum performance, resulting in a small global coupling (a minimum separation of the tunes of about .01).

One feature seen during the experiment but not included in the simulations is the presence of several single beam resonances near our operating point. Chief among these was the resonance $\nu_h - \nu_v + \nu_s = 0$. We expect these to have some influence on the beam beam performance but we cannot predict how strong this influence will be.

Throughout the experiment, we observed a very strong flip flop effect above colliding currents of about 1.5 mA. In order to get the vertical beamsizes of the two beams approximately equal we found it necessary to artificially increase the vertical beamsizes using skew quads. This increased the vertical emittance from about 2.5 nm to about 9 nm. This strong flip flop effect was never observed in simulations. The beam beam limit was due to short electron lifetime when colliding more than 5 mA/beam.

Our main measure of beam beam performance is the vertical tune shift parameter. We calculate this in two different ways.

$$\xi_{CCD+} = \frac{N_- r_e \beta_v^*}{2\pi\gamma\sigma_{v-}^*\sigma_{h-}^*\left(1+\frac{\sigma_{v-}^*}{\sigma_{h-}^*}\right)} \tag{3}$$

$$\xi_{lum+} = \frac{2er_e}{\gamma}\frac{\beta_v^* L}{I_+}\sqrt{\frac{1}{2}\left[1+\left(\frac{\sigma_{v+}^*}{\sigma_{v-}^*}\right)^2\right]}\frac{1}{\left(1+\frac{\sigma_{v-}^*}{\sigma_{h-}^*}\right)} \tag{4}$$

The electron ξ are as the positron ξ but with + changed to − and vice versa. The σ_v^*'s are computed from the observed beamsizes at the synchrotron light monitors and the known ratio of β_v at the synchrotron light source point and at the NIP and the luminosity is measured with small angle Bhabha luminosity monitors. These calculations assume that the electron and positron beams have the horizontal beamsizes shown in Table 1.

We have kept factors in both ξ_{CCD} and ξ_{lum} that are usually neglected for flat beams. The aspect ratio term $[1 + (\sigma_{v-}/\sigma_{h-})]$ may differ from 1 because our $\beta_v^* \approx \beta_h^*$ and we intentionally increased the vertical emittance to ameliorate a strong flip flop effect. For some data points this term is as large as 1.2. The other term, the one containing σ_{v+}/σ_{v-}, is a flip-flop term. This says that if the beams are in a flip-flop state, where one beam is vertically very blown up and the other beam is very collapsed, the overlap of the 2 beams at the interaction point is reduced and there is a loss of luminosity.

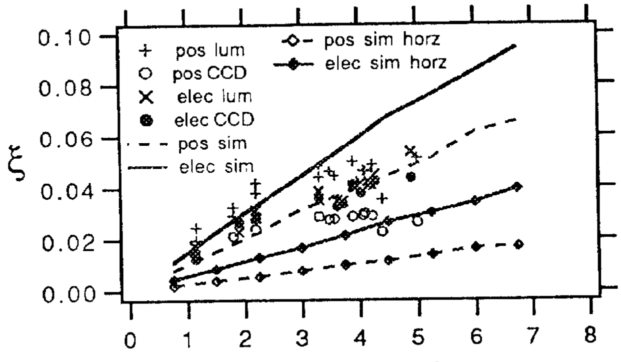

Figure 3 : Data and Simulations : ξ with separators at ±0.30 mrad

Data show that for either separator kick, the vertical tune shift saturates at about 0.045±0.010. The agreement between ξ_{lum+} and ξ_{CCD+} is not good.

We ran simulations with various effects included : the near miss at the SIP, unequal damping, unequal emittances, synchrotron oscillations, and the horizontal offset at the NIP. In the ideal case, $\xi_v > 0.08$ were reached. We believe that such high tune shifts were possible because the beam beam interaction is effectively one dimensional in this case. Simulation runs for separator kicks of ±0.16 mrad showed that the unequal damping and unequal emittance individually or together had little effect. The results from the simulation runs including all effects are shown in Figures 3 and 4. These results are substantially different from the ideal case. For the separator kick of ±0.16 mrad, the behavior of the vertical tune shifts seen in the simulation and the data are in qualitative agreement, both show saturation. However the simulation shows this occuring at a value of the tune shift 0.01 to 0.02 higher than the data. Also in the simulation both the horizontal and the vertical tune shift saturate due to the horizontal beamsize increasing with current. The saturation of the vertical tune shift in the data is due to the vertical beamsize increasing with current and the horizontal beamsize is *assumed* not to change. For the separator kick of 0.30 mrad, the simulation and the data do not agree. The simulation shows no saturation of the vertical tune shift whereas the data again show saturation at about 0.045.

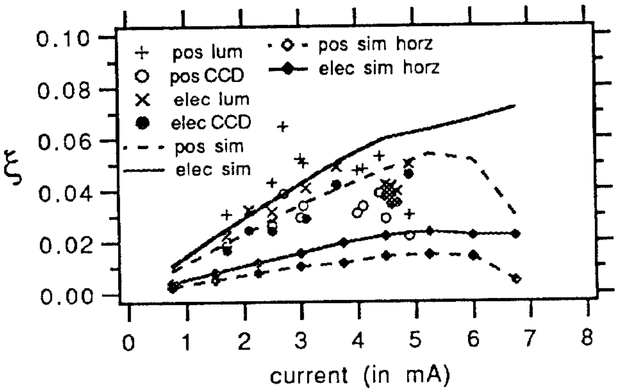

Figure 4 : Data and Simulations : ξ with separators at ±0.16 mrad

Conclusions

We do not have overall agreement between the simulations and the experiment, however both are complex with many important details that must be included to reach our current understanding.

Acknowledgements

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