
A COMPUTER SIMULATION STUDY OF e+e- STORAGE RING PERFORMANCE AS A FUNCTION OF SEXTUPOLE DISTRIBUTION

G. P. Jackson and R. H. Siemann
Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, N.Y. 14853

Abstract

Operational experience at CESR has shown that sextupoles are important factors in the observed beam-beam behavior. A computer program to simulate colliding beam dynamics in e+e- storage rings has been written. The first version of the program which does not incorporate sextupoles shows some of the characteristics measured in various machines in the past. The focus of the present work is the understanding of the effects of sextupoles on these results. To do this thin sextupoles are added in two ways. The first employs a linear-transfer/nonlinear-kick algorithm for each lattice cell. The second method is to create a symplectic second-order transfer map for the entire machine. While the first method is exact, it is slow for machine lattices with many sextupoles. The luminosities, beam sizes, and tune shifts from these programs are compared. In addition, the shapes of the time-averaged transverse distributions are studied.

Motivation

The maximum attainable luminosity at the Cornell Electron Storage Ring (CESR) is limited by the beam-beam interaction. One must either understand or model this interaction in order to optimize luminosity, since direct searches using machine time are both expensive and difficult to interpret. In the past many authors have done calculations of beam-beam effects within a restricted framework of assumptions. In order to develop a realistic (albeit empirical) understanding of machine performance, we have started to model CESR using computer simulations. The results quoted in this paper are derived from simulations which do not track synchrotron oscillations. Our purpose, for the results being reported, is to understand transverse beam-beam and sextupole effects before expanding the scope of the research to include motion in longitudinal phase space.

Programs

A program with three algorithms for describing the passage of the beams through the CESR arcs was written. In order to understand the transverse effects of sextupole nonlinearities, the first algorithm simply uses a linear transfer matrix to map 1000 test particles per bunch (one bunch e+ and one bunch e- ) through the arc. In all three algorithms no linear terms couple horizontal and vertical oscillations. Thin sextupoles are included in two different ways. The exact method involved modeling each of the two CESR arcs by 38 linear matrices separated by 37 nonlinear thin sextupole kicks. The third algorithm is a fast but approximate second order one turn mapping, where emittance changes due to expansion truncations are eliminated through symplecticification. Sextupole strengths are used which result in zero chromaticity in CESR.

This simulation presumes that the beams interact in only one of the two CESR interaction regions due to program running time limitations. The beam-beam interaction is accomplished each turn by first calculating the beam centroids and rms sizes, and then using this information to determine the transverse kicks received by each test particle. The bunch positions and sizes are output each turn. In addition, the test particle positions are binned and accumulated in 1000 turn intervals.

Radiation excitation and damping are added to each test particle each turn in order to maintain the initial (noncolliding) horizontal and vertical emittances. Since there are no energy oscillations the contribution to the horizontal beam size from horizontal off-energy function at the interaction region is replaced by additional betatron emittance. Each of the three CESR arc mapping algorithms were used in scans of machine behavior vs. beam current, where the two beams had equal currents. No other parameters were varied in the data set presented in this paper. The CESR parameters used by the simulation listed below in Table 1.

Table 1: CESR parameters used to produce the results quoted in this paper.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation period (T_0)</td>
<td>2.5632 usec</td>
</tr>
<tr>
<td>Beam energy (E_b)</td>
<td>5.3 GeV</td>
</tr>
<tr>
<td>Horizontal emittance (e_H)</td>
<td>0.01 mm-mrad</td>
</tr>
<tr>
<td>Vertical emittance (e_V)</td>
<td>0.002 mm-mrad</td>
</tr>
<tr>
<td>Radiation energy loss (U)</td>
<td>1.0 MeV</td>
</tr>
<tr>
<td>Horizontal tune (Q_H)</td>
<td>3.247 cm</td>
</tr>
<tr>
<td>Vertical tune (Q_V)</td>
<td>9.395 cm</td>
</tr>
<tr>
<td>Vertical tune (Q_V')</td>
<td>9.371 cm</td>
</tr>
</tbody>
</table>

Figure 1: Vertical centroid position vs. turn number for one of the 18 mA bunches. Sextupoles do not modify this behavior.

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Figure 2: Vertical beam size vs. turn number for the same data set shown in Figure 1. Sextupoles enhance the overshoot at the arrow. The horizontal line is the initial (zero current) equilibrium size.

1 occurs at approximately the same current at which the vertical and horizontal \( n \)-mode (\( e^+e^- \) antisymmetric oscillation) frequencies overlap. Note that the sudden increase in beam size shown in Figure 2 (at the arrow) coincides with the precipitous amplitude growth.

Phenomena with these characteristics have been observed on CESR. At the end of a normal high energy physics run we raised the vertical machine tune until the vertical and horizontal \( n \)-modes began to overlap. The peak observed on a spectrum analyzer connected to vertically sensitive beam buttons showed a increase in oscillation amplitude. This condition was very sensitive to the machine horizontal/vertical coupling.

Luminosity

The remainder of the paper is a discussion of the dependence of equilibrium conditions on beam current and the treatment of sextupoles. The most important of these conditions is the luminosity, which is plotted vs current for each arc calculation method in Figure 3. The numbers are derived from the beam size and centroid information. Also plotted in Figure 3 are actual CESR luminosities scaled up by 26\% using damping decrement scaling laws to compensate for the missing interaction region.

It should be noted that the maximum current in CESR is determined by a lifetime limit associated with the vertical aperture. There is no way to simulate this limit since the loss of just one particle in 10,000 turns (which represents 10's of hours of VAX780 CPU time) would yield a 25 second beam lifetime.

Frequency Spectrum

The \( n \)-mode frequencies, measured by performing a fast Fourier transform on the turn-by-turn difference in \( e^+e^- \) coherent position, are shown in Figure 4.

Superimposed on this plot is the linear beam-beam tune shift expected from the luminosity. The effect of sextupoles is not clearly determined.

Beam Sizes, Betas, and Emittances

At the symmetry point half way through the beam-beam lens exists the condition \( B' = 0 \). In this case

\[
\sigma_i^2 = \epsilon_i \delta_i, \quad \sigma_i' = \frac{\epsilon_i}{\delta_i}, \quad i=x,y
\]

This information is plotted in Figure 5. Note that the data, along with the luminosity and \( n \)-mode frequencies, agree qualitatively with measurements made on a number of \( e^+e^- \) machines.

Beam Profiles

Figure 6 shows the vertical and horizontal time averaged 18 mA beam profiles with fitted Gaussian curves. The vertical profile is independent of arc algorithm. Note that a Gaussian profile does not accurately describe the bunch shape, even at small
amplitudes. On the other hand, the horizontal space charge density is well described by a Gaussian profile, except that sextupole treatment does affect the bunch shape in the distribution wings beyond 30. Vertical non-Gaussian tails are sometimes seen, but these extensions beyond the Gaussian beam shape are quite tune dependent and smaller than expected."

Conclusions

Within the framework of assumptions used in the simulations, sextupoles do not seem to affect machine performance to the extent expected from measurements on the real machines. Although we get qualitative agreement with most e+e- machines, precise quantitative agreement has not yet been attained. In addition, the method of approximating CESR arcs by a symplectic second order mapping is in very good agreement with the exact thin sextupole algorithm.

Future Plans

We are upgrading the simulation to include longitudinal oscillations and energy dependence of various machine functions. This will allow to include more of the physics at work in CESR. Running with various values of chromaticity (a variable known to affect luminosity) will also be possible.

In addition, a more general beam-beam force equation is being investigated. At present, only coherent dipole oscillations have been included in the beam-beam force. Comparisons of our simulation with CESR when scanning vertical tune has indicated that this model may be insufficient under many normal operating conditions.

Figure 5: Beam sizes, betas, and emittances vs current and sextupole treatment.

Figure 6: Vertical and horizontal beam profiles for a run using the exact sextupole algorithm. The bumps on the horizontal distribution occur with sextupoles in the lattice (using either algorithm).

References

[1] Review articles containing references to the original works are:


S. Myers, Lectures at US/CERN Sardinia 1985 Accelerator School


