COMPARISON BETWEEN THE SIMULATED AND MEASURED LUMINOSITY PERFORMANCE OF CESR[1]

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Abstract

In order to understand and optimize the luminosity of the Cornell Electron Storage Ring (CESR), a combined program of accelerator measurements and numerical simulation studies was undertaken during 1985 and early 1986. The results of the investigation of a number of particular subjects are reported: (1) Agreement between the simulated and measured beam current dependence of luminosity near the standard CESR operating point. (2) The effects on luminosity of chromaticity and the pattern of sextupole strengths. (3) The occurrence of asymmetric e+e- beam heights, "beam flipping", in both CESR and simulation results. (4) A tune plane scan performed with the simulation where a factor of two increase in luminosity was predicted at low vertical tune. CESR experiments revealed no such improvement due to the excitation of vertical coherent modes at multiples of the synchrotron frequency. Including single beam synchrobetatron coupling in an approximate manner improved agreement between the simulation and CESR.

Scope of Research

The luminosity at CESR is limited by the beam-beam interaction. Luminosity depends on the density of particles near the center of the horizontal and vertical Gaussian distributions, and this research is focussed only on quantities influencing luminosity, such as beam sizes and average trajectories. Particles with large amplitudes occur quite infrequently, and do not contribute significantly to the elementary particle production rate. The effects of these particles, such as beam lifetime and high energy physics detectors background rates, are important to the performance of storage rings, but ignored here.

CESR is oriented such that the two interaction regions are on the North and South sides of the ring. All results (either from simulations or CESR measurements) quoted here are for the South area. There is only one particle bunch per beam.

Simulation Programs

Two programs are used to simulate CESR. SYMP3 utilizes algorithms which fully express the transverse and longitudinal dependencies of the beam-beam interaction and which include machine arc nonlinearities up to second order in a symplectic manner[3]. The dominant nonlinearity in the CESR arcs are the 54 chromaticity correcting sextupoles. Previous research[4] has shown that a second order representation of the CESR arcs yields simulation results indistinguishable from results gained by including each sextupole exactly.

The program LINO contains a fast lookup-table/quadratic-interpolation algorithm for calculating beam-beam kicks, and simulates the arcs using linear transfer matrices. Chromaticity is included as an energy dependent tune modulation in the transfer matrix elements (which are calculated for each particle each turn). Though not as complete as SYMP3, LINO is used extensively during machine parameter scans since it executes approximately five times faster.

Both programs assume that the East and West CESR arcs are mirror symmetric. No coherent effects, except for the beam-beam effect and synchrobetatron coupling in the last section, are simulated in either program. The RF is assumed to be a linear restoring force. Radiation excitation and damping are added each turn to each test particle in order to establish the initial (noncolliding) horizontal and vertical emittances[5]. The beam-beam interaction is simulated at each collision point each turn by first calculating the beam centroids and rms sizes, and using this information to calculate the mean fields acting on each test particle[6]. For all quoted results 1000 test particles per beam were used. The approximate values of CESR parameters used by the simulations are listed below in Table 1.

Horizontal tune (Q_x)	9.4	
Vertical tune (Q_y)	9.3	
Synchrotron tune (Q_s)	0.05	
Horizontal β^*	1.0	meters
Vertical β^*	0.03	meters
Horizontal η^*	0.8	meters
Vertical η	0.0	meters
Horizontal emittance	0.2	mm-mrad
Vertical emittance	0.001	mm-mrad
Fractional energy spread	0.6×10^{-3}	
Bunch length (σ_τ)	0.022	meters
Rotation period (T_o)	2.5632	μsec
Beam energy (E)	5.2	GeV
Radiation energy loss	1.0	MeV/turn

Table 1: Approximate CESR parameter values

Results

Luminosity vs Beam Current

The first criterion by which the simulation programs were judged was their ability to predict the beam current dependence of CESR luminosity[7]. Figure 1 contains the SYMP3 prediction along with the CESR data measured a few days later. Due to short beam lifetimes the vertical tune of the prediction could not be attained. Nonetheless, the agreement is good. The disagreement between the two measures of CESR luminosity is consistent with estimated systematic errors, and should be remembered when viewing the remaining figures.

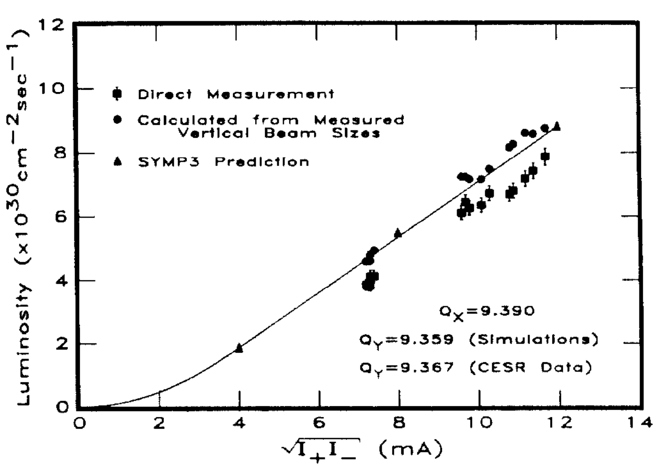

Figure 1: SYMP3 simulation prediction and CESR confirmation of the beam current dependence of the South interaction region luminosity.

Luminosity vs Chromaticity

It has been established at CESR that chromaticity (ξ = E/Q dQ/dE) has a profound influence on beam

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lifetimes and detector background rates, but its effect on luminosity was always clouded by background sensitivity of the luminosity monitors. With the introduction of a CCD visible light beam height monitor[8] this question can be answered. The SYMP3 predictions, along with the CESR data, again measured a few days later, are shown in figure 2.

When the horizontal and vertical tunes are not near a bad lifetime region the luminosity is independent of both horizontal and vertical chromaticity. Near a resonance, like the vertical third integer, the predicted luminosity varies by factors of three. Due to poor lifetime these predictions could not be tested.

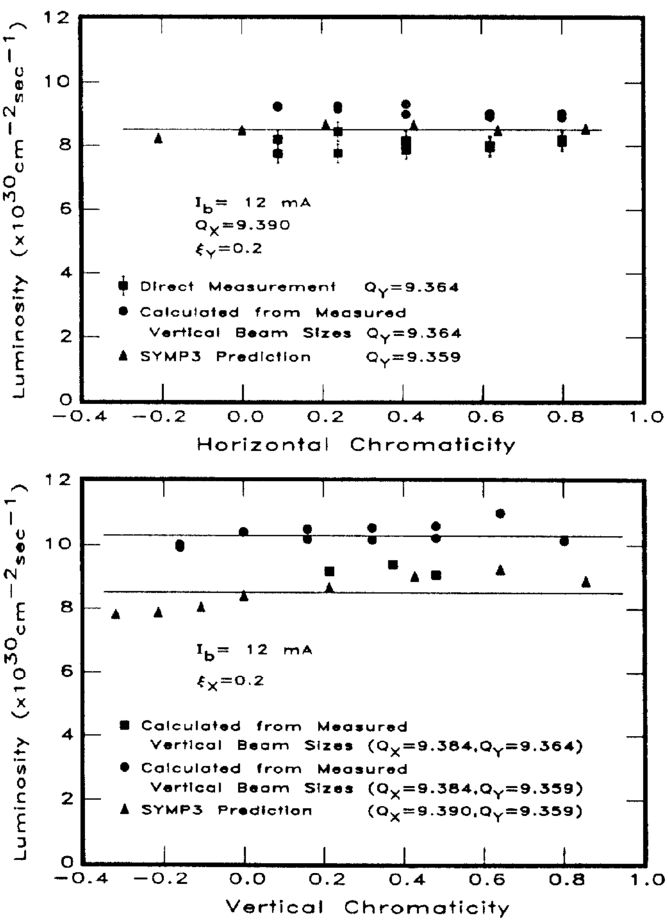

Figure 2: The dependence of luminosity on horizontal and vertical chromaticity. The prediction and CESR measurement tunes do not match exactly due to bad beam lifetime regions.

Luminosity vs Sextupole Distribution

CESR is normally run in multibunch mode[9], where the e+ and e- beams are electrostatically separated in the arcs. In order to keep tunes and interaction region lattice functions independent of the separation distance, a special sextupole distribution (K^4) was created. Previously, all horizontal compensating and all vertical compensating sextupoles were equally powered (Uniform). In either case, the chromaticities were adjusted to be slightly positive. Since the distribution of sextupole strengths in the K^4 lattice is quite broad, with a few very powerful sextupoles, a question was raised about the effect of sextupole distribution on luminosity. Figure 3 contains SYMP3 and LINO predictions of luminosity vs current, as well as the experimental CESR confirmation. The LINO data has been included to demonstrate the sensitivity of the results to the nonlinearity of the arcs.

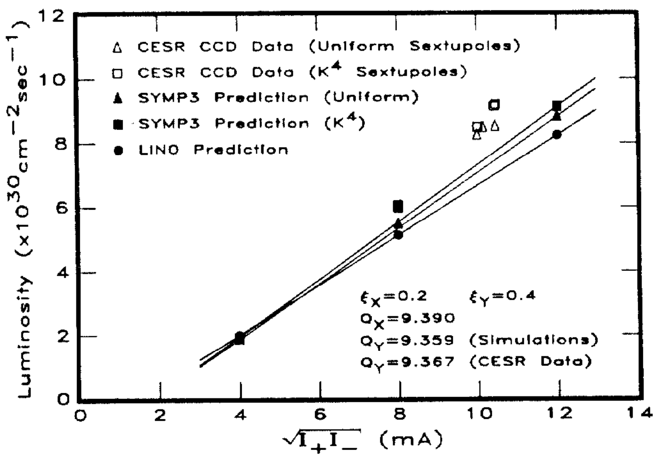

Figure 3: Prediction and CESR verification of the dependence of luminosity on sextupole distribution.

Beam Flipping

The phenomena where the two colliding beams develop different beam heights is referred to as the "flip-flop" effect[10]. The phrase was coined because of the hysteretic nature of the flipped state. A systematic study of this phenomena[11] concentrated on the effect of horizontal dispersion (η) at the interaction region coupled with a small horizontal beam separation. Figure 4 contains a simulation prediction and CESR verification of the e- beam height as a function of interaction region separation (at both the North and South detector areas) for the standard horizontal interaction region dispersion of 0.8 meters.

At lower beam currents (4 ma), or for zero horizontal dispersion, both LINO and CESR results display beam heights independent of horizontal separation. Also, with a interaction region dispersion of 0.8 meters and a horizontal offset of $0.3\sigma_X$, the LINO predicted and measured beam flipping are a strong function of vertical tune for currents above 10 ma.

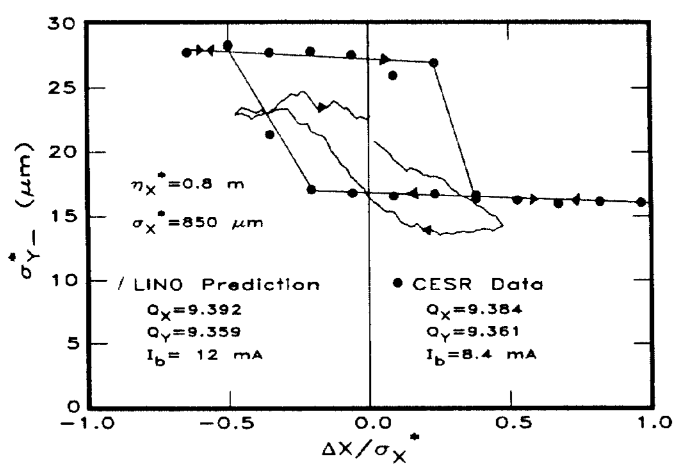

Figure 4: LINO prediction and CESR verification of the dependence of the electron beam height on horizontal beam separation at the interaction regions.

Synchrobetatron Resonances

At low vertical tune LINO predicted a factor of two improvement in CESR luminosity. The measured luminosity and the tune of an observed vertical coherent mode (called the π-mode here) are plotted in figure 5 as a function of beam current. The apparent vertical π-mode tune never crossed over the resonance

$Q_y - nQ_s = 9$. As the vertical betatron tune was raised, luminosity decreased and the beam lifetimes dropped rapidly. Therefore, the maximum vertical tune spread was constrained to be less than the synchrotron tune. Through single beam studies the vertical electrostatic separator plates (used to keep the beams separated at the interaction regions during injection) were identified as candidates for the source of the coupling between the vertical and synchrotron oscillation planes[12]. Using the wakefield coupling

$$\Delta y' = A\, I_b \exp(-[\tau-\tau_w]^2/2\sigma_w^2)$$

suggested by the computer program DBCI[13], where σ_w=90 ps, τ_w=65 ps, and A=0.01 rad/A (set by single beam measurements and simulations), the LINO prediction changed dramatically. The DBCI prediction for A, assuming a beam offset (Y) of 1 cm and a peak vertical transverse wakefield (W_{perp}) of 8×10^{13} N/C^2, is

$$A = W_{perp} Y\, T_o/E = 4\times10^{-4} \text{ rad/A}$$

Figure 6 is a comparison between the vertical tune dependence of luminosity with and without this synchrobetatron coupling mechanism. Note that agreement between LINO and CESR has been improved qualitatively, though the required vertical offset of 25 cm for A = 0.01 rad/A is clearly unrealistic.

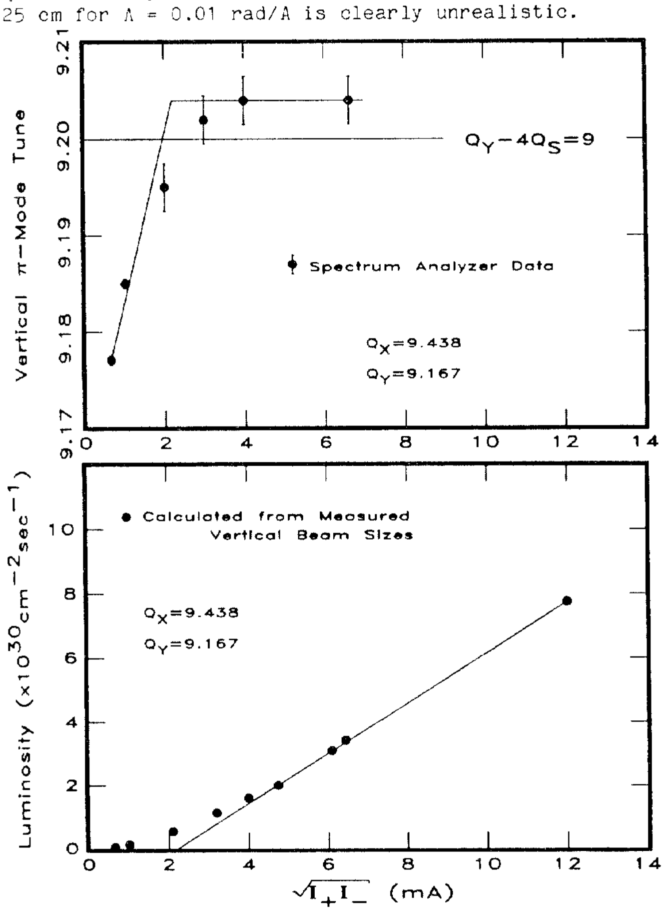

Figure 5: CESR luminosity and vertical π-mode tune as a function of beam current at a low vertical tune.

Conclusions

A pair of simulation programs now exist which accurately predict CESR performance. Agreement over a number of parameter scans and the discovery of previously unsuspected phenomena demonstrate the usefulness of this coupled simulation/measurement approach to experimental e+e- luminosity research.

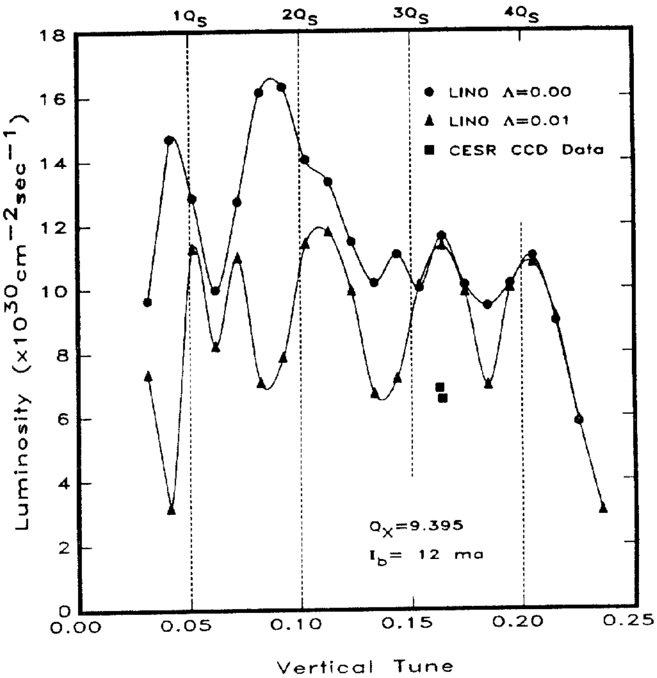

Figure 6: Comparison between the LINO luminosity predictions with and without synchrobetatron coupling. CESR data has also been included. In fairness to the measured data, it should be pointed out that no optimization of the luminosity took place under these conditions.

References

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