MEASUREMENT AND SIMULATION OF BEAM-BEAM EFFECTS IN THE WEAK/STRONG REGIME

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Abstract

In an effort to gain insight into the beam-beam interaction and its effect on beam distributions, we explored the weak/strong colliding-beam regime both experimentally and via simulation. In machine experiments the weak beam, because it is just a collection of test particles which do not perturb the strong beam, may be repeatedly sacrificed and replaced during the course of measurements. Diagnostic techniques which exploited this fact were developed. They allowed us to make beam-profile measurements in the core, the skirt, and the remote tails of the distribution. We describe these techniques and report on some beam distribution surveys performed on CESR. Results from a computer simulation designed to duplicate the weak/strong measurements are also presented. Simulation results overlapping with actual machine measurements are presently available only in the core and near-skirt regions.

Introduction

The luminosity of the Cornell Electron-Positron Storage Ring (CESR) is presently limited by the fact that, as the current is raised, the colliding-beam lifetimes deteriorate progressively; sudden loss of particles above some threshold is rarely seen. This fact suggests that the beam-beam limit is due to incoherent blowup rather than to a coherent beam-beam instability. Incoherent effects can be studied in the weak/strong regime, which offers several practical advantages. The results would be directly applicable to strong/strong conditions if the strong-beam profile were the same; we have however not achieved this degree of machine control so far.

Weak-beam vertical distributions were measured as a function of various machine parameters and strong-beam currents. The same conditions were also studied with a particle-tracking simulation. Interpretation of experimental data is difficult because only the overall properties of the beam are measured; the behavior of individual particles cannot be followed. This limits our information on the detailed mechanisms underlying the blowup phenomenon. In simulation, by contrast, individual particles can readily be tracked: selected parameters can then be varied to evaluate their influence. Evaluating such results with confidence requires that the adequacy of the computer model be established. We attempt to do this by comparing results from simulation and experiment where they overlap.

Because of the large difference between the weak and strong beam currents in the present study, many existing diagnostic instruments--designed to monitor colliding beams of approximately equal intensity--could not be used. Other techniques had to be developed. Because it was easy to replace the weak beam, destructive methods ("scrapers") were admissible for measuring its profile. These did not interfere with the strong beam, which is typically much smaller than the blown-up weak beam.

The machine experiments, scheduled between extended periods of routine machine operation, were made less invasive--and more repeatable--by restricting them to parameter ranges near the normal operating conditions. For best utilization of available time, data acquisition and machine adjustment was programmed under computer control.

Experimental Instrumentation

Data to be taken while the beams are in collision include, for the strong beam (e+), its current and characteristic size at the interaction point (IP); the profile is assumed to be gaussian. For the weak beam (e-) one needs to measure tunes, lifetime, and detailed distribution over the complete range of amplitudes up to the machine aperture. The absolute value of the weak-beam current is immaterial (provided it is small enough); measurement on a relative scale suffices to determine the lifetime.

Lattice-specific parameters, such as chromaticity, transverse coupling, and orbits, may be measured with only a single beam in the machine.

Currents and Lifetimes

Strong Beam The current of the strong beam was measured with the standard CESR current monitor, which uses a signal derived from capacitive pickup electrodes. The absolute calibration is thought to be accurate within about 10%.[1]

Weak Beam Two methods were used to monitor weak-beam current on a relative scale--one electrical (using a standard set of pickup electrodes), the other optical (using synchrotron light). Both achieve adequate rejection of the unwanted signal from the strong beam, which is typically one or two orders of magnitude more intense than the weak beam.

The electrodes for the electrical monitor are located where the strong bunch passes just after the weak bunch, allowing a time of almost one orbit revolution (2.56 μs) for overload recovery. A robust wide-band amplifier raises the gain of the system to suit the weak-beam signal. The strong-beam pulse massively overloads this amplifier, but a transistor clamp is timed to suppress the resulting output. The desired signal is digitized for the computer via an existing, slow (3Hz) channel, which limited the usefulness of the system to lifetimes longer than a few seconds.

Because of the inherent directionality of synchrotron radiation, the weak beam can be monitored by its light without interference from the strong beam. The light is viewed by a photomultiplier. The output signal, smoothed by a low-pass filter, is tracked by a transient digitizer at a sampling frequency of 500Hz. Lifetimes as short as 100 ms can be measured.

Tunes

Only the strong beam's betatron tunes were monitored continuously; weak-beam tunes were deduced by applying two corrections to the values: (1) Adjust for the coherent tune shift of the strong beam, typically $dQ_h/dI = -1.7\times10^{-3}$mA and $dQ_v/dI = -6.3\times10^{-4}$mA. (2) Allow for a systematic tune difference between e^+ and e^-. This difference arises in part from the opposite energy histories of the two beams around the ring, and varies with the relative adjustment of the two RF cavities. The other part is so far unexplained; however, it can be readily measured by storing, in quick succession, beams of opposite sign in an undisturbed lattice. When the RF cavities are adjusted to make the vertical tunes equal, the horizontal tune difference is $\Delta Q^+ - \Delta Q^- = 4.6\times10^{-3}$.

Measurement of Core Sizes

The core sizes of both beams (weak and strong) in a guide-field dipole were measured by imaging their visible synchrotron radiation onto separate CCD light detectors.[2] The system has a known calibration. The measured beam size is projected back to the IP via the known lattice functions; in conjunction with the measured beam currents this yields a luminosity estimate which was found to be within 10-20% of the value displayed by the CESR luminosity monitor. Because of dark current, spurious reflections in the vacuum chamber, and the limited dynamic range of the CCD, the core-profile measurements are considered reliable only within about 2σ of

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beam center. Profile curves were digitized at 10 Hz; however, at very low intensity the CCD scan rate could drop to 1 Hz.

Measurement of the Skirt and Tails of the Distribution

The outlying particle distribution may be deduced from the added particle loss rate, $\alpha_s = 1/\tau_s$, produced by a movable vertical obstacle (thick scraper).[3] Assuming the distribution in amplitude, F(r), is not perturbed by the scraper,

$$F(r) = \frac{\tau_d}{r^2 \tau_s(r)}$$

where τ_d (= 22 ms in CESR) is the transverse damping time.

We verified that the insertion of the scraper did not significantly perturb the strong-beam orbit or weak-beam tunes (wake-field effects).

Scans

Three types of scans were used to measure the weak-beam distribution as a function of various parameters. During the course of these scans all information was stored in a computer file for later analysis; this also included supervisory strong-beam data (monitoring its current and core size), tune information, and such subsidiary indicators as the background counting rate in the CLEO detector.

(1) Fixed Scraper/Variable Tune The scraper was inserted to a known depth; for a selected strong-beam current, a tune scan was made (Q_h, Q_s fixed; Q_v varied) and the resulting weak-beam core size and lifetime were recorded.

(2) Fixed Tune/Stepwise Insertion of Scraper At a selected tune point, the weak-beam tail distribution was measured by monitoring relatively long scraper-induced lifetimes (> 2s). The scraper was inserted in steps, being held at each position until a satisfactory lifetime measurement had been obtained. This (slow) method used the electrical weak-beam current monitor.

(3) Fixed Tune/Fast-Moving Scraper To penetrate into the skirt of the beam distribution, nearer the core, shorter lifetimes (down to 100 ms) were induced. The scraper was driven into the beam as fast as possible (5mm/s). Weak-beam current and scraper position, as a function of time, were recorded by a transient digitizer. The synchrotron-light current monitor was used.

Numerical Simulation

The numerical simulation used a version of the strong/strong program LINO,[4] modified for the weak/strong situation. This speeded up execution by a factor of about 3.5. LINO is a fully 3-dimensional tracking code and includes quantum excitation and damping. The beam-beam kick, impulse-like, is that of a 2-dimensional bigaussian charge distribution,[5] with the kick displaced longitudinally as appropriate. Code segments have been added specifically to model the results of experimental scraper lifetime runs.

Ordinary Runs

A simulation (usually at conditions equivalent to some previous machine experiment) tracked an ensemble of 1000 particles until equilibrium was reached. This occurred in 2-3 damping times (20,000-30,000 turns). Tracking then continued until the desired accuracy for the statistical properties of the ensemble and for the lifetimes as a function of aperture were reached.

Special Runs

To investigate individual particle dynamics, selected large-amplitude particles could be retraced and followed in detail. Also, simulations could examine machine parameters impossible to achieve in practice; or they could be applied to specialized starting distributions, highlighting a particular region of phase space.

Ring Distribution[6] The 1000 particles all start with the same vertical amplitude; their horizontal amplitudes are distributed over a certain range. (The phases in both planes are distributed uniformly.) In addition, all particles are started with the same longitudinal amplitude and phase. This distribution is tracked for a short period of time (usually < one damping time) and then displayed in the horizontal/vertical amplitude plane. The plots show the flow direction of particles in this space, indicating relationships between the amplitude-dependent, shifted tunes and thus identifying possible underlying resonances.

Results

Comparison of Experiment and Simulation

Results from a type-1 scan (Qv = 9.366 to 9.405) are shown in Fig.1. The vertical and horizontal linear tune shifts induced per collision were $\xi_h = 0.019$ and $\xi_v = 0.026$. The nominal weak-beam horizontal and synchrotron tunes were Qh = 9.413 and Qs = 0.062. There were two equally spaced collisions per machine revolution. Also shown in Fig.1 are the results from a simulation using identical parameters. Though the two curves are not identical, the location of the bumps they exhibit appear to correspond except for a small frequency offset. When the horizontal and/or synchrotron tune is varied, the bumps move on both curves in the same manner. This tracking between experiment and simulation suggests that the process underlying the beam blowup has been correctly modeled.

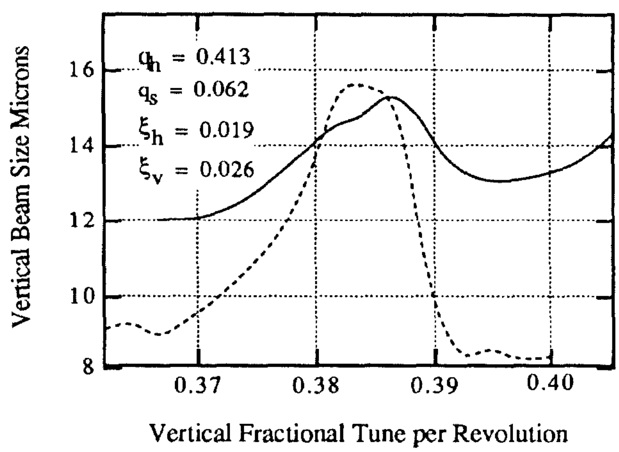

Fig. 1: Weak-beam core size vs. vertical tune. The solid line is experimental data; the dashed is simulation.

For the same strong- and weak-beam parameters, type-2 and -3 scans were also made at various fixed vertical tunes, yielding distribution data for much of the beam profile. In the corresponding simulations, beam density distributions could of course be obtained directly by appropriate binning. However, to check whether the deep insertion of a scraper would falsify results by producing a non-equilibrium profile, the experimental procedure was duplicated in the simulation and the distribution was derived from the particle loss rates. No significant scraper-induced error was seen.

A example comparing experiment and simulated distributions is shown in Fig. 2. Again, even though exact agreement was not found, the results from tune point to tune point tracked very well, once more suggesting that the simulation adequately accounted for the underlying process driving the particles to large amplitudes.

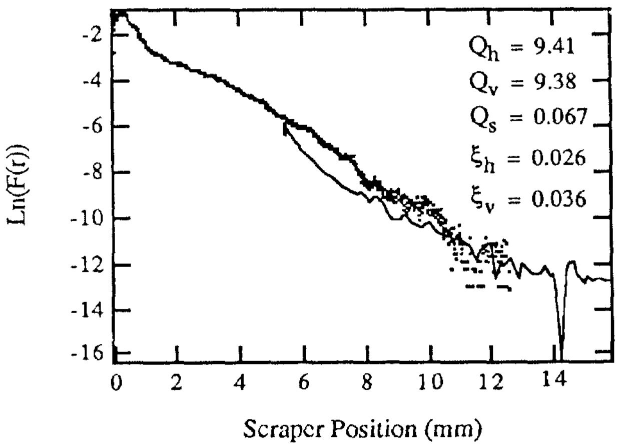

Fig. 2: Logarithm of the distribution F(r) vs. scraper position from the center of the beam. The dots are simulated data. The solid line is the distribution function reconstructed from the scraper induced lifetime measurements. For this particular case the synchrotron light monitor was accurate out to about the 2mm point, leaving a gap between 2mm and 5.2mm which we were not able to experimentally explore.

Mechanism Responsible for Enhanced Blowup

A ring distribution was run for 1/50 of a damping time, with tunes set where the beam profiles, in experiment and simulation, showed greatly enhanced tails. Several parameters were modified in turn in an attempt to identify a key mechanism in the blowup (Fig.3). The only parameter which produced any significant change in the resultant distribution was bunch length. For zero length, the rapid blowup of vertical amplitude disappeared almost entirely (Fig.4). We conclude that the synchrobetatron resonance, $2Q_h - 2Q_v = Q_s$, is involved; longitudinal oscillation of the effective beam-beam kick, at Q_s, modulates the vertical tune. This effect is emphasized if β varies rapidly near the nominal IP, i.e., when the bunch length becomes comparable to β^*.

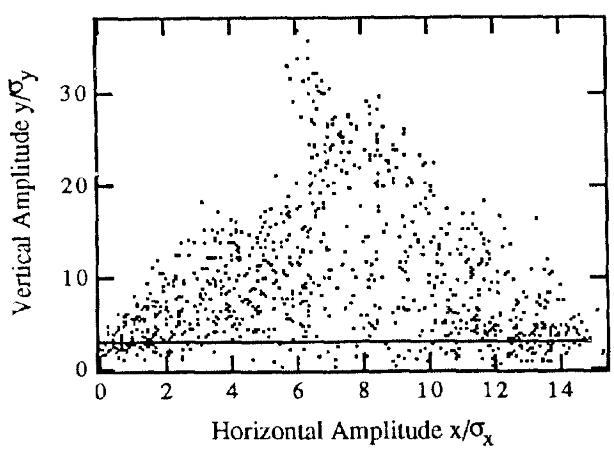

Fig. 3: Ring distribution simulation run with particles initially at amplitudes $3\sigma_v$, $0\text{-}15\sigma_h$, and $2\sigma_s$ (3.64cm which is to be compared to $\beta_v^* = 1.5$cm). The solid line is the initial distribution; the dots are the final particle positions. The tunes were $Q_h = 9.410$, $Q_v = 9.380$, and $Q_s = 0.062$. The tune shifts per collision were $\xi_h = 0.025$ and $\xi_v = 0.038$. Only 400 machine turns were tracked.

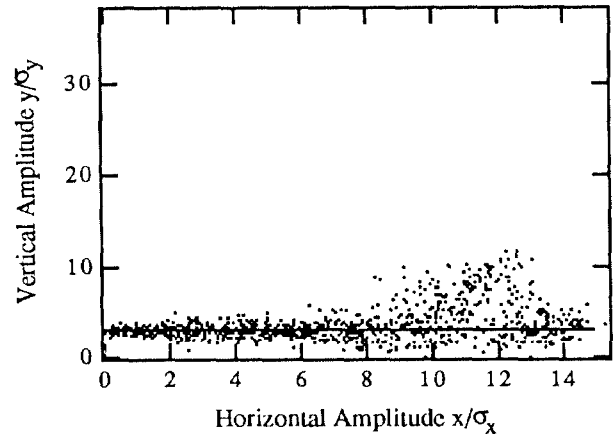

Fig. 4: Identical run to fig. 3 except the longitudinal amplitude of the particles was held to zero. Energy oscillations, chromaticity and horizontal dispersion at the IP are still present.

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