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

S. V. Milton and R. M. Litauer
Wilson Laboratory, Cornell University, Ithaca, New York 14853

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 near to the threshold current of about 120 mA. 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%.

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 used to suppress the resulting output. The desired signal is digitized for the computer via an existing, slow (3 Hz) 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 500 Hz. 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/dI = -1.7 x 10^-3 mA and dQ/dI = -6.3 x 10^-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 ∆Q = 4.6 x 10^-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. 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 low 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
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, \( \alpha_p = \frac{1}{\tau_p} \), produced by a movable vertical obstacle (thick scraper).\(^3\) Assuming the distribution in amplitude, \( F(r) \), is not perturbed by the scraper,

\[
F(r) = \frac{\tau_d}{\tau_p} F(r_0)
\]

where \( \tau_d = 22 \text{ ms} \) 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.

- **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.

- **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 (\( > 2 \tau \)). 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.

- **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 (5 mm/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 LIN0,\(^4\) modified for the weak/strong situation. This speeded up execution by a factor of about 3.5.

**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.

**Results**

**Comparison of Experiment and Simulation**

Results from a type-1 scan (\( Q_v = 9.366 \) 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 \( Q_h = 9.413 \) and \( Q_s = 0.062 \). 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.](image-url)
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 synchrotron 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 $\beta$ varies rapidly near the nominal IP, i.e., when the bunch length becomes comparable to $\beta^*$.  

**ACKNOWLEDGEMENTS**

We wish to thank the CESR machine group and accelerator operators for all their help and support.

Work supported by the National Science Foundation and the Center for Theory and Simulation in Science and Engineering, which manages the computer resources of the Cornell National Supercomputer Facility for the National Science Foundation.

1. Private Discussion with D. Rice.
6. Developed during private conversations with J. Irwin.