PERFORMANCE OF THE CEA AS AN e^+e^- STORAGE RING*

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Summary

The Cambridge Electron Accelerator (CEA) has been devoted solely to electron-positron colliding-beam physics since 1970. By early 1972 an operational system had been developed with a peak luminosity of $2 \times 10^{28}\ cm^{-2}sec^{-1}$. An experiment observing e^+e^-, $\gamma\gamma$, $\mu^+\mu^-$, and hadron events was then completed at a beam energy of 2 + 2 GeV and an integrated luminosity of $1.12 \times 10^{34}\ cm^{-2}$. Since then, many improvements have been made to increase the average luminosity and to permit operation at higher energy. A cryogenic pumping system has been installed close to the interaction region resulting in a significant pressure drop and reduction in background in the luminosity counters. A final experiment is now in progress at a center-of-mass energy of 2.5 + 2.5 GeV, after which the colliding beam physics program will be terminated because higher luminosity is available from the Stanford storage ring SPEAR.

Introduction

This is a National Accelerator Conference final report on the CEA bypass colliding-beam program. The progress of this program has been detailed in conference reports and CEAL reports over the years starting with the original concept[1, 2, 3] of converting a strong-focussing high-energy electron synchrotron into a colliding-beam storage ring.

The essential parts of this program have been the following developments:

1. Low-beta insertion (bypass)[4] to enhance luminosity and provide a long straight section for experiments.
2. Damping system[5] to counteract radiation anti-damping of radial betatron oscillations in the normal AG structure.
3. Installation of a positron linac.
4. Multicycle injection and accumulation system[6, 7] to reach large stored currents.
5. Electrostatic separation system[8]
6. Ceramic vacuum chamber system,[9] new pumps, new foreline system, and bakeout system to reach a base pressure of ∿ 4×10^{-9} Torr, an operating pressure of ∿ 1×10^{-8} Torr, and beam lifetime in excess of 1 hour.
7. Fast switching system (ultraflector)[10] to divert the beam into the bypass.
8. Devices to raise the threshold for betatron and synchrotron instabilities[11,12,13] (sextupoles, Landau cavity, high harmonic cavity).

In addition, many other technical developments were required such as:

1) A synchronizer timing system[14] to insure proper orbit filling of electrons and positrons and proper timing of ultraflectors and other devices.

2) A pinhole camera[15] using synchrotron radiation x-rays to measure beam size.

3) A programmable beam bump[16] to move the beam into and out of the damping magnet at high energy during cycling and also to maintain adequate damping during the transition to storage, and during storage.

Other developments have been described in recent progress reports[17, 18]

(1) A fiber mover to measure beam size and overlap at the interaction point.

(2) A linac and injection control system that allows rapid switching from positron to electron injection.

(3) A low shunt-impedance rf system to reduce beam cavity interaction.

All of this work culminated in a successful experiment,[19] which ended in early August 1972. Typically the peak luminosity at the start of a run was ∿ $0.8 \times 10^{28}\ cm^{-2}sec^{-1}$. The best average luminosity during a 12-hour run was $0.4 \times 10^{28}\ cm^{-2}sec^{-1}$. The integrated luminosity over the run was $1.12 \times 10^{34}\ cm^{-2}$. About 500 events were observed (e^+e^-, $\gamma\gamma$, $\mu\mu$, and multi-hadrons) and the predictions of quantum electrodynamics were confirmed at the highest colliding beam energy yet reported (E_{cm} = 4 GeV). An unexpectedly large number of multi-hadron events were observed extending similar observations made at Frascati[20] and giving impetus to efforts to extend the observations to even higher energy. The higher energy experiment (E_{cm} = 5 GeV) is now in progress.

Experience with the Vacuum System

Background rates in the luminosity counters improved significantly during the run. This is due to the cleanup of surfaces struck by synchrotron radiation and the consequent decrease in bypass pressure with continuous running. The bypass was not let up to air during the entire experimental run. The base pressure, in the absence of beam, was $< 5 \times 10^{-11}$ to 4×10^{-10} Torr. Early in the run the gauges would show an increase in pressure of ∿ $2 - 3 \times 10^{-9}$ Torr when 6 - 8 mA at 2 GeV was put into the bypass. At the end of the run, after a total of ∿ 2 A-hrs of beam in the bypass, these pressure rises were a factor of 5 - 10 lower.

Preparations for Experiment at E_{cm} = 5.0 GeV

A. New 4-Inch-Bore Quadrupoles

The need for better fields at large radii led to the replacement of six original 3-inch quadrupoles with an equal number of 4-inch quadrupoles. $B_r(\theta)$ was measured with a flag coil and Fourier-analyzed for multipole harmonic content. The method used was easy, fast, and accurate.[21] The measurements showed that the 12- and 20-pole components were excessive (See Table 1).

Table 1
n-pole/quadrupole (percent) at r = 1.85"

Multipole Number	Uncorrected	After Shimming
12	0.80	0.13
20	0.90	0.10
28	0.17	1.0

Three shims per pole were used to correct 12- and 20-pole at the expense of 28-pole. Results given by Halbach[22] greatly facilitated the shimming process.

B. New Vacuum Pipe in Quadrupoles - Cryogenic Pump

A square vacuum pipe for the four-inch quadrupoles has been fabricated to maximize the pneumatic conductance and to provide space for additional devices, namely: electrostatic plates, remotely movable horizontal and vertical calipers, a water-cooled tube for absorption of synchrotron radiation, and a tube carrying cold helium gas for cryopumping. The cold gas is supplied by a 15 HP Philips Stirling cycle refrigerator with a capacity of 50 watts at 20°K. The cryopumping tube has 1300 cm^2 of surface and when operating at $\sim$ 20°K reduces the base pressure in the interaction region from $\sim 3 \times 10^{-9}$ to $< 3 \times 10^{-10}$ Torr with 6 - 8 mA of beam at 2.5 GeV. This results in a reduction of background rates in the luminosity counters by a factor of about 3. This improved signal-to-noise ratio has allowed clean measurements and optimization of the luminosity, and has proven to be one of the most significant improvements over the first experimental run.

C. Improvement to Electrostatic Plate System

The electrostatic separation system in the synchrotron was redesigned with a more uniform distribution of plates resulting in an increase in the minimum separation of the two beams by a factor of 1.8 for the same maximum separation. The main result has been an increase of the beam-beam interaction limit from 6 mA to 12 mA during e^- injection.

D. Computer Monitoring System

A 128-channel multiplex system is used to monitor critical parameters, actuating an alarm for any change outside of tolerance. The system utilizes a Dymec 240/C DVM and an XDS92 computer. The computer also processes and displays the beam lifetime.

E. Injection Energy Increase

By raising the peak power levels in the linac modulators, injection energy for both electrons and positrons was increased by 15%, thereby reducing single-beam instabilities and beam-beam interactions.

F. Improvements to Sextupole System

Thirty distributed sextupoles correct for chromaticities which would otherwise range from 0 to -25 in both planes. The current in the sextupoles is programmed to keep the chromaticity positive and close to zero at all times: during cycling, transition to storage, and bypass operation. This has raised the threshold of betatron instabilities to a level above our normal operating beam intensities.

Properties of the Beams

With the aid of a computer program, several different tunes of the bypass were used and evaluated. Limits were found on the maximum values that the beta function (β) could assume at certain quadrupoles in the bypass. By May 1972 a tune was developed which held the values of β within these limits, while minimizing the values of β and the momentum vector at the interaction point. This tune was used for the first run (E_{cm} = 4 GeV) and the present run (E_{cm} = 5 GeV). The values of the horizontal and vertical beta functions at the interaction point are 5 cm and 30 cm respectively, resulting in a beam cross-section of 0.16 x 0.1 mm^2. The maximum value that the beta functions assume in the quadrupoles adjacent to the interaction point is 48 m. At other (weaker) quadrupoles β = 76 m. Within 20%, the beta functions are unchanged in the synchrotron itself, where the average is 7.3 m.

Sum and difference resonances and their satellites up to sixth order are observed to affect beam lifetime. At the operating point of $\nu_h = 7.29$, $\nu_v = 6.82$, the tuning plateau has a width of $\Delta\nu = 0.025$. Most of these resonances are due to nonlinearities in the damping system and the bypass quadrupoles. The strength of a resonance[17] is proportional to $w^{n-1} \beta^{n+1}$, where w is the average beam size and n is the order of the nonlinearity. Since beam size increases linearly with energy, nonlinear resonances have imposed a 2.5-GeV upper limit on the energy for reliable operation.

Cross coupling of horizontal betatron oscillations into the vertical plane constitute a major limitation on the luminosity that can be obtained. The CEA operates far from the "space charge limit" for crossing beams and would benefit from a decrease in vertical beam size. Several skew magnetic and electrostatic quadrupoles in the bypass and the synchrotron are used to minimize vertical beam size at the interaction point. In addition, two quadrupoles on either side of the interaction point can be remotely rotated. However, the main contribution to the cross-coupling comes from beam separation in the distributed sextupole system, causing vertical components of the momentum vector as well as coupled betatron motion. As a result, there is some quantum excitation in the vertical plane, which we cannot correct with our limited number of electrostatic skew quadrupoles. The average ratio of horizontal to vertical beam size in the synchrotron is about 4 which is a factor of 5 worse than can be obtained without electrostatic separation.

Performance During Run at E_{cm} = 5 GeV

Tuning the bypass is greatly facilitated through the use of horizontal and vertical calipers located at the quadrupoles on either side of the interaction point. Beam sizes and positions can be measured and the beam crossing angle determined.

The carbon fiber at the interaction region[17] is used regularly to check vertical beam size and coincidence.

Luminosity is measured using double bremsstrahlung rates and is monitored continuously in the Control Room. Using a shower counter threshold of about 0.05 E_{max}, counting rates are 1 to 3 per second, permitting optimization of luminosity during a run. Operators have become adept at making small variations in bypass parameters to maximize the double-bremsstrahlung rates.

Typically, it takes 4 to 5 minutes to fill the synchrotron with 6 - 7 mA of positrons (limited by phase instabilities),[13] followed by rapid filling to about 8 mA of electrons.

After transition to storage (~ 1 minute) and switching into the bypass, 4 - 6 mA in each beam remain.

At the time of this writing (Feb. 28, 1973) the experimental run is in its early stages and performance is improving. Each beam has a lifetime of about 2400 sec and thus the luminosity lifetime is 20 minutes. The beams are allowed to collide and data is taken for about 20 minutes after which the cycle is repeated. Typically, the average luminosity during such a cycle is $\geq 10^{28} cm^{-2} s^{-1}$. (The peak luminosity that has been measured is 3×10^{28} $cm^{-2} sec^{-1}$.)

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