OPERATING RESULTS FROM SPEAR*

SPEAR Storage Ring Group**

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Abstract

Initial operating experience with the SLAC electron-positron storage ring SPEAR is described. A luminosity of 1.2×10^{31} cm^{-2} sec^{-1} has been achieved and two-beam interaction effects are described. A single-beam coherent instability, which can be suppressed either by control of the ring chromaticity or by feedback, has been observed. Current-dependent bunch lengthening and widening have been observed, and experiments indicate that these phenomena may be associated with an increase in the energy spread of the beam. Procedures to increase the luminosity to the design value are discussed. Plans to increase the maximum beam energy of SPEAR to 4.5 GeV are described.

Introduction

The SLAC electron-positron colliding beam project SPEAR was completed, and stable colliding beams were achieved in April, 1972 after a construction period of approximately 20 months. Since the completion of the project we have had 20 weeks of testing time and during that period we have attained a luminosity (yield per unit cross section per unit time) of $\mathscr{L} = 1.2 \times 10^{31}$ cm^{-2} sec^{-1}. SPEAR has achieved sufficient luminosity to make feasible an exciting set of elementary particle experiments, and this program is scheduled to begin in March of this year. This paper discusses our experience with SPEAR since its completion, as well as our plans to increase the maximum operating energy of the ring.

Our understanding of colliding beam devices has an impact beyond those of us who are interested in electron-positron collisions, for in the past few years — especially since the turn-on of the ISR — more attention has been given to the possibility of achieving enormous center-of-mass energies through the use of colliding beam techniques. To make the colliding beam techniques useful to study elementary particle physics, high luminosities must be achieved and this in turn requires that we understand the limitations on the performance of colliding beam devices. SPEAR may be considered in a sense as a test vehicle for the colliding beam devices of the future, for we have incorporated in its design those structural features, devices, and procedures which experience with Soviet, Italian, French, and American colliding beam projects has indicated could contribute to the achievement of high luminosity. In brief, some of our observations agree quantitatively with predictions (effect of low-beta on the two-beam incoherent instability, for example); some of our observations agree qualitatively with predictions (the effect of sextupoles on single-beam coherent instabilities, for example); and some of our observations are not now understood (the dependence of bunch length on current, for example).

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General Description

In this section we summarize the salient features of the SPEAR project. More details are available elsewhere.[1]

SPEAR is a single ring composed of n=0 bending magnets and quadrupoles to provide focusing — it is shown schematically in Fig. 1. Two arcs composed of standard modules connect two variable-dispersion, low-beta insertions. The RF system runs on the 40th harmonic of the orbit frequency. In operation only one out of the forty possible bunches of electrons and positrons is filled so that the electron and positron beams, which circulate in a common aluminum vacuum chamber, collide only at the center of the two low-beta insertions. These low-beta insertions are designed to achieve high luminosity in the face of the incoherent two-beam instability which has been the limit on the beam-beam interaction rate in all electron colliding beam devices built to date. The tune of the ring is variable from 5 to 5.5; the vertical beta function and horizontal beta function at the interaction points are variable from 5 cm to 50 cm and 1 m to 8 m, respectively; and the dispersion at the interaction point can be varied from 0 to 5 cm per percent of momentum spread.

The maximum operating energy of the ring is 2.8 GeV (limited by the available RF voltage) and the maximum design luminosity is 7×10^{31} cm^{-2} sec^{-1} at an energy of 2.3 GeV and 250 milliamperes circulating beam current. The luminosity drops to 10^{31} at an energy of about 2.8 GeV and also at an energy of about 1 GeV. These luminosities assume that the luminosity is limited by the incoherent two-beam instability and that the corresponding tune shift is about 0.025. To reach design luminosity requires that the beam area be greatly increased over that which obtains in the configuration into which we inject (corresponding to zero dispersion at the interaction region). We can control the effective beam height either by introduction of external horizontal-vertical betatron coupling or by introducing a small crossing angle of up to 3 mrad. The width of the beam can be controlled by varying the dispersion of the lattice or by artificially exciting incoherent betatron oscillations. In practice, we must inject with the two beams separated at the interaction point; build up to currents far above the incoherent two-beam limit which would apply if the beams were colliding in the injection configuration; change the coupling, beta functions and dispersion with the beam stored; change the energy to the design operating energy and only then bring the beams into interaction.

These lattice manipulations involve complex interrelations among the currents of eleven separate magnet systems and are much too difficult to be accomplished manually in any reasonable time. The control of the magnets, as well as most of the other control and monitoring functions in SPEAR, is accomplished by an XDS Sigma-5 computer (48 K of core, 32-bit words, 1 μs cycle time) which will also handle data logging and on-line analysis for the elementary-particle physics experimental program. This computer system allows the storage ring operator to choose any values of tunes, betas, and dispersions and to vary any subset of these parameters while holding the others constant.

SPEAR is equipped with a variety of devices to control beam instabilities. These include sextupole magnets to control the variation of tune with energy, electric quadrupoles to separate the betatron frequencies of the electron-positron beams, octupole magnets to provide variable Landau damping and a fast servosystem which works independently on the electron and positron beams to control coherent betatron instabilities.

Operating Experience

Single Beam

The studies of beam behavior have been carried out at beam energies of 1.5 GeV to 2.7 GeV. Injection rates of up to 70 milliamperes per minute (average circulating current) have been obtained into a single electron bunch with positron filling rates being two to three times lower. Injection energy is fixed at 1.5 GeV; the injection pulse rate is 20 pps dictated by radiation damping time; and a typical injection pulse is one to two milliamperes in height and 10 ns long.

Initially, uncorrected distortions of the equilibrium orbit caused by imperfections in the magnet fields and misalignment were measured to be as large as 1.4 cm in the radial coordinate and 0.7 cm in the vertical coordinate. Each of the bending magnets is provided with a small correcting winding. Three of these were chosen by analysis of the distortion data and powered to reduce the largest radial distortion to a few millimeters. The vertical distortions were also reduced to a few millimeters by means of correcting windings in the interaction-region quadrupoles.

A beam instability has been observed which is partially consistent with the expected behavior of the head-tail effect,[2] wherein a transverse coherent instability is expected, depending on the chromaticity of the lattice and where the lowest mode involves motion of the center of charge. The chromaticity of the beam is controlled by a system of sextupoles distributed around the ring, three to a cell. Also provided is a wide-band transverse feedback system for damping coherent bunch center-of-charge motion. This system acts independently on electrons and positrons and on radial and vertical motion. It has a risetime of 12 ns and can produce decay times (e^{-1}) as short as 3 ms for 1 mA average beam.

A series of experiments carried out to study the chromaticity-dependent instability is summarized in Table 1.

TABLE 1

Chromaticity-Dependent Instability Thresholds

$p\frac{\partial\nu_x}{\partial p}$	$p\frac{\partial\nu_y}{\partial p}$	Threshold Current (mA)	Loss	Feedback System
-1.05	-1.05	1.4	Vertical	off
-1.05	+1.05	1.5	Radial	off
+1.05	-1.05	1.6	Vertical	off
-1.05	-1.05	> 60.0	Radial	on
+1.05	+1.05	>104.0	Radial	off

(The momentum-compaction coefficient during these experiments was 0.042.) We may interpret these results with reference to the head-tail effect by assuming that the driving forces in both radial and vertical coordinates have signs such that the barycentric mode (in which all particles in the bunch move together) is unstable when the chromaticity is negative and that all the other modes are therefore stable. The feedback system is capable of stabilizing the barycentric mode up to a current of 60 mA, where a breakdown of one of the injection magnet modulators causes the loss of the beam. (This breakdown is caused by a voltage pulse induced by the beam on the cathode of the thyratron modulator. A high-frequency filter raised this threshold to 104 mA, but we have not repeated this experiment since the filter was installed.) With both chromaticities positive, the barycentric mode should be stable and the higher modes should be unstable. We see no sign of any instability up to a current of 104 mA (again limited by the injection modulator).

We have observed a lengthening of the stored bunch under all conditions of energy and RF voltage, and have also observed a widening of the bunch at 1.5 GeV. Figure 2 shows the measured dependence of the length of a single bunch as a function of circulating current at various RF-accelerating voltages and beam energies. Figure 3a shows the ratio of the measured bunch length to the calculated zero-current bunch length. The measurements were made with a photodiode which is expected to introduce only negligible instrumental broadening of the signal. The curves are fits to the data by eye. The measurements of Fig. 2 were taken with two RF cavities in the storage ring. Previously a measurement had been made with one RF cavity at 1.5 GeV and 150 kV of accelerating voltage, which gave the same results for these conditions as the two-cavity measurements.

To further investigate these phenomena we have done two experiments using more than one bunch in the ring. In the first of these experiments the length of one bunch was measured as a function of current in a bunch ahead of the one being measured (20-ns time separation). No change in length of the constant-current bunch was observed, indicating that the fields responsible for the lengthening are local fields. We also simultaneously measured at low RF voltage the "quantum" lifetime of a low-current (short, narrow) bunch and of a high current (long, wide) bunch. The high-current bunch has a shorter lifetime. Figure 3b shows the energy spread calculated from the measured lifetime and the standard quantum lifetime equation.

We have also measured the bunch width and find a clear increase in width with current at 1.5 GeV. At 2.0 GeV the width increase is statistically marginal, and no effect within the errors is observed at 2.5 GeV. We find at 1.5 GeV that, within the errors, the increase in energy spread derived from the increase in width is consistent with that derived from the lifetime data, assuming either that the synchrotron width or the total width is increased.

While the energy spread in the beam has not been measured directly, the consistency of the width and "quantum lifetime" measurements make it reasonable to assume that the energy spread is, indeed, a function of current. If so, the plots of Fig. 3a and 3b indicate that there must be two effects operating to increase the bunch length — these two effects having different dependences on beam energy.

As explained previously, the SPEAR beams need a larger effective interaction area to obtain design luminosity than the area which results from natural beam size with zero dispersion at the interaction region; and one method of obtaining a greater width is to adjust the lattice to produce a large dispersion at the interaction region (high-η^*). The injection rate into the high-η^* configuration is much lower than that into the zero-η^* configuration, so we must fill the ring in the zero-η^* configuration. The computer program to guide this parameter variation allows the operator to choose set points for the five optical parameters ν_x, ν_y, β_x^*, β_y^*, η^*, and then carry the ring lattice to that condition from wherever it happens to be. This system works well, and we have been able to vary the dispersion from 0 to 6 meters with the beam stored. However, for a given set of tunes and β_y^*, there are certain combinations of β_x^* and η^* which are unreachable due to power-supply limitations.

We have also enlarged the beam by a quasi-stochastic process, using a fast pulsed magnet triggered by a noise generator, together with our octupole magnet system. The beam is given a small coherent kick ($\leq$ natural beam size) with the pulsed magnet, and the nonlinearities provided by the octupole system spread the relative phases of particles with various betatron amplitudes. A typical result is shown in Fig. 4. A quasi-stochastic system is required for SPEAR because the beams must be enlarged before being brought into interaction and remain enlarged on being brought into interaction, in spite of the enormous change in betatron frequency spread caused by the beam-beam interaction.

Double Beam

The colliding beam performance of SPEAR with natural beam size and zero dispersion at the interaction region has been better than expected. Figure 5 shows the measured luminosities at beam energies from 1.5 to 2.6 GeV. The largest luminosity measured was 1.25×10^{31} at an energy of 2.6 GeV and a current of about 25 mA in each beam. The maximum luminosity appears to be proportional to the fourth power of the energy, while the beam current (equal beams) at the maximum luminosity is proportional to the cube of the energy. These energy dependences are to be expected if the beam-beam interaction is limited at an energy-independent, small-amplitude tune shift.

The parameter which relates the beam strength to the tune shift is given by:

$$\Delta = \frac{KI\beta}{EA} \quad ,$$

where K is a constant, I is the bunch current, β is the unperturbed β of the lattice, E is the beam energy, and A is the area of the interacting beams. Quantum fluctuations in the synchrotron radiation make A proportional to E^2 for constant coupling, which in turn makes I proportional to E^3 for constant Δ and the luminosity proportional to E^4.

Figure 6 shows the detailed dependence of the luminosity on beam current for various values of the vertical tune. While the luminosity at low beam current is independent of tune and is proportional to i^2, at high current, the luminosity depends weakly on current and is strongly dependent on the vertical betatron frequency. The real tune shift per interaction region computed from the specific luminosity and corrected for finite bunch length, ranges from about 0.03 at $\nu_y = 5.189$, to about 0.08 at $\nu_y = 5.100$. It is interesting to note that for all of these curves, the vertical tune plus twice the real tune shift (2 interactions per turn) equals 5.25. (Wiedemann will speak in more detail about these results at the beam dynamics session.) As the limiting current is approached, the beams become enlarged vertically and, at the limit, the lifetime of one of the beams becomes short and it decays away.

To increase the luminosity above that already attained with natural beam sizes, we must enlarge the beams. We have not yet done much work with either the high-dispersion or quasi-stochastic beam enlargement. One test made with a dispersion of about 1.5 cm/% which should have increased the luminosity by about a factor of two for the same tune shift, resulted in a lower luminosity than for zero dispersion. These experiments will have to be done over a greater range of dispersion before any conclusions can be drawn.

We have had more success with the stochastic system and, using crude apparatus, have increased the beam size by about 1.5 to 2 and observed a 50% increase in luminosity. It was necessary to obtain a good beam lifetime, to use the electric quadrupoles to separate the tunes of the electron and positron beams.

SPEAR Improvement Program

The initial design of SPEAR incorporated the possibility of an eventual increase in both the maximum operating energy of the ring and the RF power available. We have begun both of these projects. The goals of the improvement program are to increase the maximum operating energy from the present 2.8 GeV to 4.5 GeV each beam, and to increase the RF power from 160 kW to 500 kW. The results of these two improvements are a luminosity versus energy curve, which is illustrated in Fig. 5. We have again assumed the luminosity to be limited by the incoherent two-beam instability with tune shift $\Delta\nu = 0.025$ and an aperture limit given by the present size of the vacuum chamber. At energies above about 3 GeV the luminosity is limited by the available RF power.

The maximum operating energy of 4.5 GeV is determined by saturation in the magnets. The increase in the peak magnetic field is a relatively simple project which requires the addition of about 2.5 MW of dc power to the existing complement of power supplies. This is straightforward and we will not discuss this part of the project further.

The RF problems associated with the energy increase are much more formidable. The RF voltage required to make up for synchrotron losses goes from approximately 420 kV per turn at the present maximum energy of 2.8 GeV to about 2.8 MeV per turn at 4.5 GeV. Still higher voltages are required to achieve a reasonable quantum lifetime. Both the shunt impedance per unit length of our present RF cavity system and the available straight-section length make it entirely impractical to achieve these voltages at the present frequency of 50 Mc.

We have conducted a study of cost versus frequency for a new RF system constrained by the available straight-section length and find a broad cost minimum at about a frequency of 300 MHz. We have selected a frequency of 358 Mc (280th harmonic) and plan to use a set of RF cavities patterned on those used in the Los Alamos proton linac. We are developing a cw, 125-kW klystron at SLAC for powering the new system. Four of these klystrons are required, each feeding a straight section containing a module consisting of 5 Los Alamos-type cavities.

The improvement program should be completed by summer 1974.

References

1. SLAC Storage Ring Group, Proceedings of 8th International Conference on High-Energy Accelerators, CERN, 1971 (European Organization for Nuclear Research, Geneva, 1971), p. 145.
2. C. Pellegrini, Nuovo Cimento, Series 10, 64A, 447 (1969).

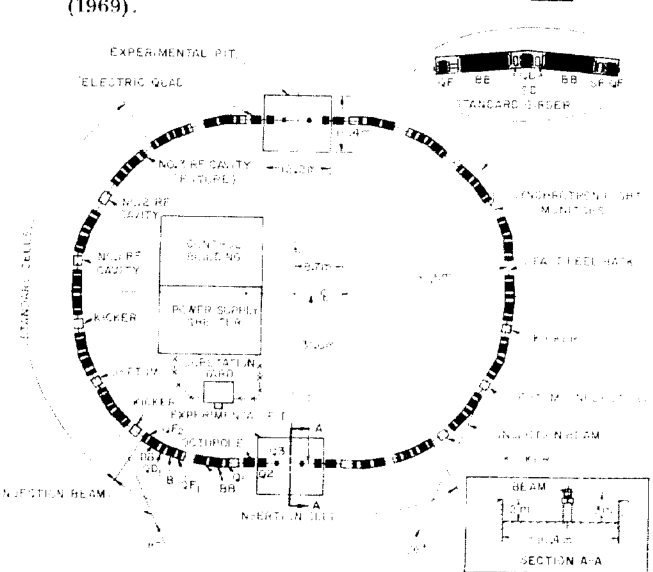

FIG. 1--Layout of SPEAR.

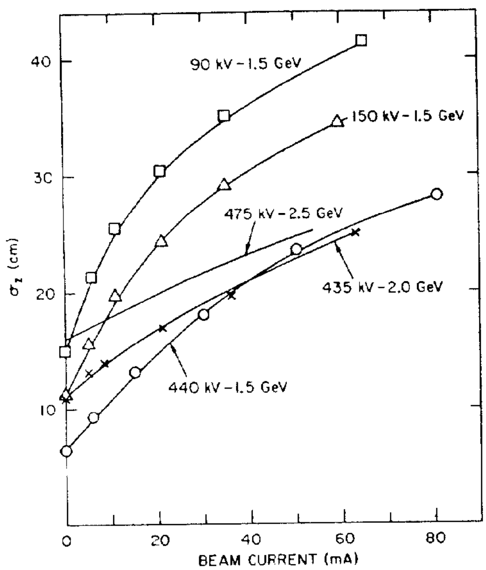

FIG. 2--Bunch length (standard deviation) vs beam current for various values of RF-accelerating voltage and circulating-beam energy.

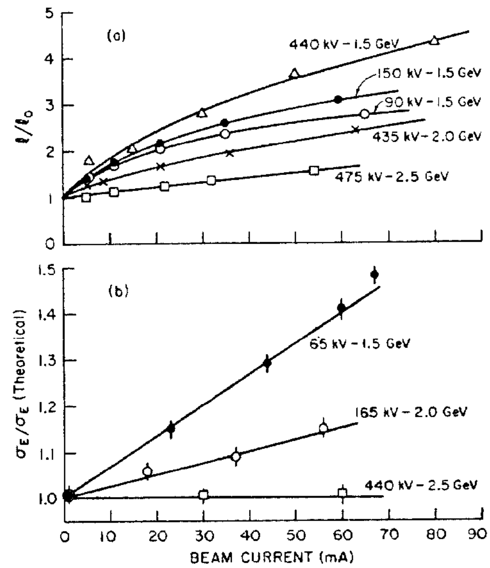

FIG. 3--Fraction increase vs beam current of (a) bunch length and (b) energy spread derived from the quantum lifetime formula. The numbers of the curves give the RF voltage and beam energy.

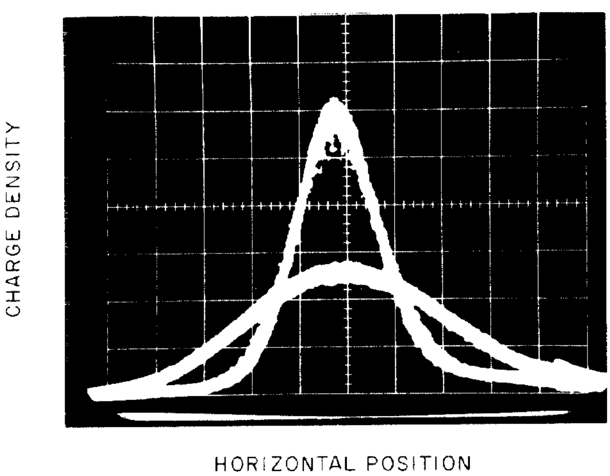

FIG. 4--Horizontal beam profile with (wide curve) and without (narrow curve) the betatron exciter.

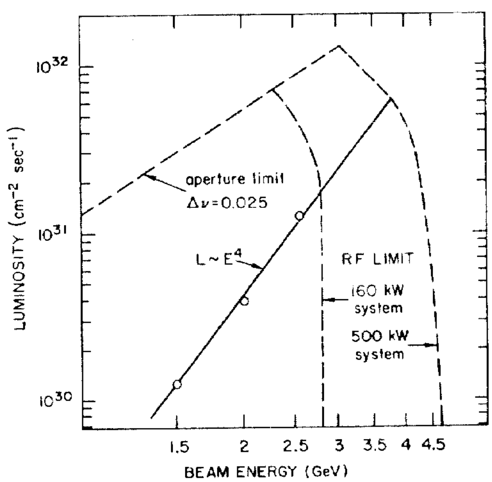

FIG. 5--Luminosity vs energy. The dashed lines show the design limits for both the present RF system, and for the new 500 kW system now under construction. The open circles are measured values.

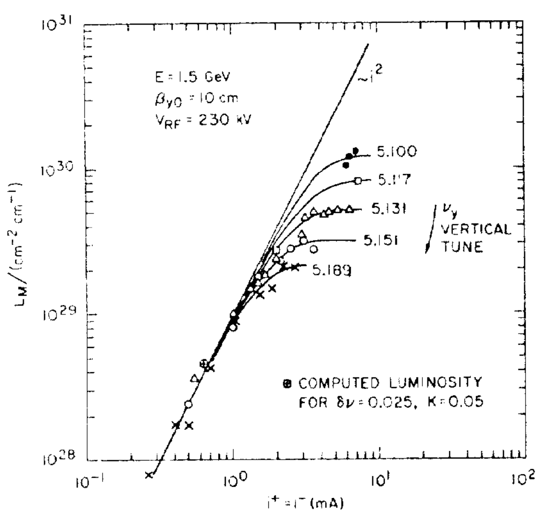

FIG. 6--Luminosity vs beam current for various values of the vertical tune.