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OPERATING RESULTS FROM SPEAR*

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1. 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 that time, an active experimental high-energy physics program has begun in addition to a program of continued studies of accelerator physics. This paper discusses only the accelerator physics results as well as plans to increase the maximum operating energy of the ring. Some operating data have been presented previously.[1] This paper summarizes the operating experience to date.

SPEAR is a single ring composed of 36 rectangular zero-gradient bending magnets and 54 quadrupoles as 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,

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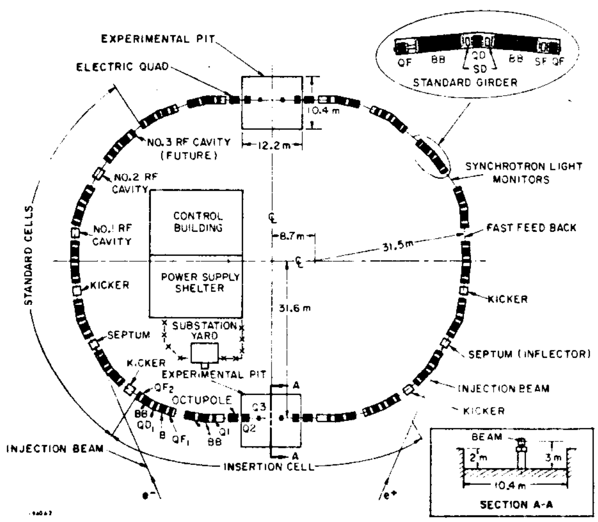

FIG. 1--Layout of SPEAR.

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 centers 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 cm to 5 cm per percent of momentum spread.

The design maximum operating energy of the ring is 2.7 GeV (limited by the available rf voltage) and the maximum design luminosity is $5\times10^{31}\text{cm}^{-2}\text{sec}^{-1}$ per interaction region at an energy of 2.3 GeV with 250 milliamperes of circulating current in each beam. The design 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 shifts are about 0.025. To reach design luminosity requires that the beam area be greatly increased over that naturally obtained 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 up to 3 mrad. The width of the beam can be controlled by varying the dispersion at the interaction points or by artificially exciting incoherent betatron oscillations in the beam.

2. Single-Particle Operation

The control of the magnets, as well as most of the other control and monitoring functions in SPEAR[2] is accomplished by an XDS Sigma-5 computer (48 K of core, 32-bit words, 1 μs cycle time), which also handles data logging and on-line analysis for the elementary-particle physics experimental program. In order to operate the ring, the operator specifies the energy, the two betatron frequencies, the two interaction-region betas and the dispersion at the interaction regions. These five parameters, along with three conditions matching the insertion to the ring cells, specify a "configuration" for which the necessary magnetic fields and power supply currents are calculated. The magnet power supplies can be changed together at the proper rate, arriving at a configuration without loss of a stored beam. It is possible to store and fetch the values of the power-supply currents which correspond to a desired configuration. Stored beams have been achieved over a wide range of configuration parameters with energies between 1.1 GeV to 2.7 GeV. Except for a small difference between the measured and calculated tunes, this procedure works well.

In order to measure and correct the closed orbit of a stored beam, the computer can scan a set of beam-positron-monitor electrodes and display the closed orbit. It is then possible to compute magnetic-field bumps to correct the closed orbit and display the new predicted orbit.[3] When the computed field bumps are used, the corrected orbit agrees with the predicted orbit. By this technique, the closed-orbit distortions all around the ring have been reduced to a few millimeters.

There exists a set of four skewed quadrupoles that can be powered in order to control the coupling between the vertical and horizontal beam motion, and hence to control the beam height. It is possible to achieve an aspect ratio (height-to-width ratio at equal beta values) between 0.05 to 1.

There are 52 sextupole magnets distributed throughout the lattice to control the chromaticity (variation of tune with energy). Measured chromaticities agree well with theory.

Injection energy is fixed at 1.5 GeV and the two-turn injection process consists of a pulse with two 10-nsec bursts of 1 to 5 mA, and a pulse rate of 20 pps dictated by the radiation damping time.

Injection rates of electrons up to 140 mA/min (average circulating current) have been obtained into a single electron bunch with positron rates being over one-fourth of the electron rate. The present kickers[4] contain ferrite cores inside the vacuum chamber and have produced unacceptable outgassing pressures at large beam currents due to inductive heating by the beam. These kickers will be replaced in the near future with an air-core design.

One interaction region is surrounded by a four-meter-long axial detector solenoid with a central field of 4 kG. Reversed-field compensating solenoids are provided to adjust the integral of the axial field through the interaction region to zero. The effect of the detector solenoid upon single-particle motion has been studied. By powering the compensating solenoids and trimming the adjacent quadrupoles, it is possible to achieve tunes, beta values and aspect ratios equal to those achieved in the absence of the solenoid field. The magnetic-field bumps necessary to correct the closed orbit are different with the solenoid on, showing a slight misalignment of the solenoid; but with proper corrections, the injection rates and beam lifetimes are unaffected.

3. High-Current Single-Beam Effects

The first two instabilities observed were expected and correction had already been provided by equipment design. One was the coherent longitudinal dipole oscillation[5] of a single bunch that could become unstable by capacitively tuning the cavities; i.e., by making the resonance frequency of the cavities greater than the driving frequency. This oscillation can be stabilized either by inductively tuning the cavity or by applying an external phase feedback system.[6] The second expected instability was the head-tail[7] effect, wherein a transverse coherent instability occurs with one sign of the chromaticity. For SPEAR, the $p = 0$ mode, where the beam oscillates as a whole, limits the current below 1.5 mA for negative values of the chromaticity. This instability can be stabilized by having either a positive chromaticity or a transverse feedback system. In fact, we have found, as expected, that it is possible to introduce a fast damping of coherent oscillations for the longitudinal motion by proper detuning of the rf cavities and for the transverse motion by increasing the chromaticity. We have not yet identified any of the higher head-tail modes which might be there for positive chromaticities, but we have seen longitudinal quadrupole oscillations.[8] This oscillation can be eliminated by a slight change in the rf system; i.e., tuning, driving frequency or cavity voltage.

The next instability seen was due to a misfiring of one of the kickers and was caused by voltage pulses induced by the beam on the cathode of the thyratron modulator. A redesign of the modulator eliminated this problem.

We have observed an anomalous lengthening of the stored bunch under all conditions of energy and rf voltage, and also have observed a widening of the bunch at 1.5 GeV. Figure 2 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.[9]

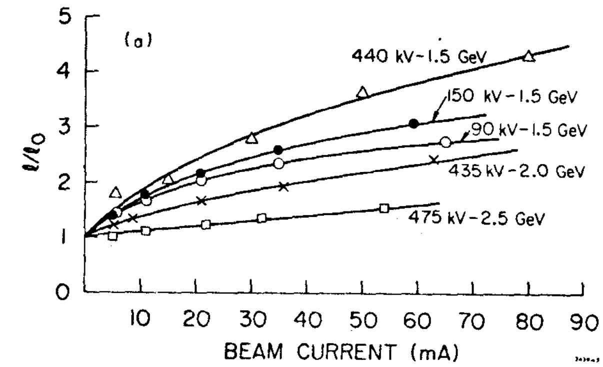

FIG. 2a--Fractional increase of bunch length vs beam current. The numbers of the curves give the rf voltage and beam energy.

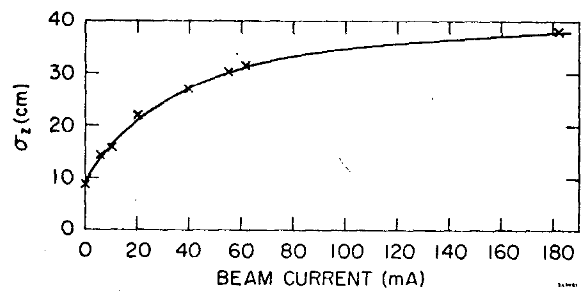

FIG. 2b--Bunch length (standard deviation) vs beam current at 1.5 GeV with rf voltage of 250 kV.

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-nsec 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 3 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.

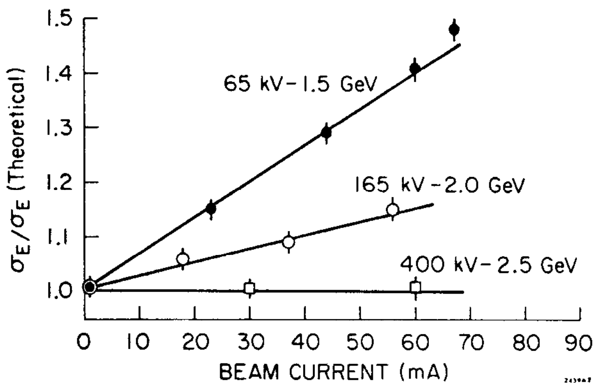

FIG. 3--Fractional increase of energy spread derived from the quantum lifetime formula. The numbers of the curves give the rf voltage and beam energy.

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 Figs. 2 and 3 indicate that there must be two effects operating to increase the bunch length — these two effects having different dependences on beam energy.

Under certain conditions, we observe beam loss due to large vertical oscillations at single-bunch currents of about 60 mA. It is possible to suppress these oscillations by lowering the rf cavity voltage and by increasing the vertical chromaticity. At the present time, we have stored over 220 mA in a single bunch.

Essentially, all of the high-current single-beam phenomena depend upon the current per bunch as has been verified by operating with more than one bunch in the machine. The only exception to this is that with two high-current bunches of the same beam, it is possible to excite longitudinal oscillations in the pi mode. This mode is unaffected by the phase feedback system, which damps only the barycentric mode. A separate feedback system is being constructed to damp the pi mode.

4. Two-Beam

There are two methods of achieving two countercirculating stored beams in SPEAR. One method is to inject the second beam such that it is colliding head-on with the stored beam during injection. This method has its obvious restriction in that it is impossible to achieve stored currents exceeding the incoherent two-beam limit in the injection configuration. Because the higher values of luminosity do not occur in the injection configuration, it is desirable to use a second method of two-beam injection. The orbits of the two beams are separated vertically at the interaction points by applying voltage to four sets of electric plates in the ring. It is then possible to inject a second beam, separated vertically, in the presence of a stored beam current that exceeds the incoherent two-beam limit. The high-voltage electric plate system is capable of applying a 50-kV potential difference on the separation plates, producing a beam-beam separation of 1 mm at the injection regions. We have found that separated beams behave as two coupled oscillators so that, for sufficiently large stored beams, coherent betatron oscillations of the incoming beam can produce large coupled coherent oscillations of the first beam. This problem can be ameliorated by: increasing the beam-beam separation, changing the kicker timing, or powering electric quadrupoles to separate the betatron frequencies of the beams. By use of these methods, it is possible to store two separated beams of 50 mA each.

The colliding-beam performance of SPEAR with natural beam size and zero dispersion at the interaction region has been better than expected. Figure 4 shows the measured luminosities for various beam energies between 1.3 to 2.6 GeV. Because of the anomalous bunch length, the higher luminosities occur for values of the vertical beta function at the interaction point greater than the design value of 5 cm. The highest luminosity measured to date is about $0.85 \times 10^{31}/\mathrm{cm}^2$ sec at an energy of 2.5 GeV and currents of 40 mA, using a vertical beta function of 20 cm. The maximum measured luminosities show that the real tune shifts per interaction region computed from the specific luminosity is greater than 0.08 as compared with the design value of 0.025. The maximum luminosity appears to 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 with natural beam size if the beam-beam interaction is limited by an energy-independent, small-amplitude tune shift.

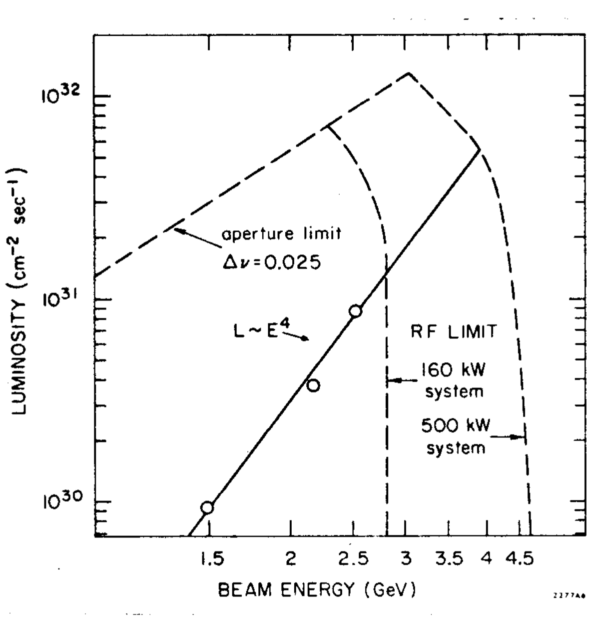

FIG. 4--Luminosity vs energy. The dashed lines show the design limits for both the present rf system, and for the new 500 kW system now under construction. The open circles are measured values.

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

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

where K is a constant, I is the bunch current, β is the unperturbed β of the lattice at the interaction point, E is the beam energy, and A is the effective area of the interacting beams. The luminosity $\mathscr{L}$ is defined by

$$\mathscr{L} = K_1 \frac{I^2}{A}$$

which gives, for the luminosity, in terms of the tune shift,

$$\mathscr{L} = K_2 \frac{\Delta^2 E^2}{\beta^2} A \; .$$

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.

To increase the luminosity above that already attained with natural beam sizes, it is necessary to enlarge the beam area. We have tried a quasi-stochastic beam enlargement of giving each beam separately constant dipole kicks at a random times. This has been successful in the enlargement of both beams when they are separated, but is only moderately successful when the beams are colliding. The method that presently appears the most promising is to introduce dispersion at the interaction point. With this method, it has been possible to increase the luminosity at 1.5 GeV by a factor of 2 to 3. Operationally, there is a problem in that often a coherent longitudinal oscillation in the pi-mode occurs which is unaffected by the phase feedback system. It is sometimes possible to prevent the occurrence of this oscillation by powering the electric quadrupoles which are situated at a point with dispersion, although the electric quadrupoles produce a fractional difference in the synchrotron frequencies of the order of 10^{-3}. We have several possible methods of damping these phase oscillations and we hope to have these operational in the near future. One such method is to split the synchrotron frequencies by the use of an rf cavity operating at a higher harmonic of the revolution frequency.[10]

This cavity is presently installed in the ring and is capable of operating at the 120, 121 or 122 harmonic.

The problems that presently limit the maximum luminosity are: bunch lengthening, which prevents us from taking full advantage of possible lower values of the vertical beta function at the interaction points at high energies, and the pi-mode phase oscillations that prevent us from using the high-dispersion method of beam enlargement at lower energies.

5. 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. 4. 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 370 kV per turn at the present maximum energy of 2.7 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 MHz.

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 MHz (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 which is on schedule should be completed by the end of the summer 1974.

References

1. SPEAR Storage Ring Group, "Operating Results from SPEAR," IEEE Trans. Nucl. Sci., Vol. NS-20, No. 3, June 1973.
2. A.M. Boyarski, et al., "Automatic Control Program for SPEAR," IEEE Trans. Nucl. Sci., Vol. NS-20, No. 3, p. 580, June 1973.
3. A.S. King, et al., "Closed Orbit Correction in SPEAR," IEEE Trans. Nucl. Sci., Vol. NS-20, No. 3, p. 898, June 1973.
4. SPEAR Storage Ring Group, "The SLAC Storage Ring Project: SPEAR," VIII Int. Conf. on High Energy Accel., p. 145, CERN (1971).
5. K.W. Robinson, "Stability of Beam in Radiofrequency Systems," Report No. CEAL-1010, Cambridge Electron Accelerator, Cambridge, Mass. (Feb. 1964).
6. M.J. Lee, "Beam RF Cavity Stability with Feedback Control in a Circular Accelerator," IEEE Trans. Nucl. Sci., Vol. NS-18, No. 3, p. 1086, June 1971.
7. C. Pellegrini, Nuovo Cimento, Series 10, 64A (1969).
8. F.J. Sacherer, "A Longitudinal Stability Criterion for Bunched Beams," IEEE Trans. Nucl. Sci., Vol. NS-20, No. 3, June 1973.
9. A.P. Sabersky, "Monitoring the Beams in SPEAR with Synchrotron Light," IEEE Trans. Nucl. Sci., Vol. NS-20, No. 3, p. 638, June 1973.
10. M.A. Allen, et al., "Synchrotron Frequency Splitting in the SLAC Storage Ring," IEEE Trans. Nucl. Sci., Vol. NS-18, No. 3, p. 1084, June 1971.