SPEAR: STATUS AND IMPROVEMENT PROGRAM*

SPEAR Storage Ring Group†
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

Summary

Operating experience with the SLAC electron-positron storage ring over the past year is summarized. The control of several beam instabilities and the colliding beam performance over a wide operating range are described. The successful application of variable momentum dispersion to increase the beam size and luminosity is described. The improvement program to increase the energy to more than 4 GeV per beam is discussed and the results of testing the components of the new rf system are presented.

Introduction

The SLAC electron-positron colliding beam project SPEAR was completed in April, 1972. During the following year the operating characteristics of the ring were studied and, after approximately 20 weeks of testing, luminosities of greater than 10^{30} cm^{-2} sec^{-1} were attained in the operating-energy range, from 1.5 to 2.5 GeV per beam. Elementary particle experiments were installed in each of the two interaction regions, and since April, 1973 we have been routinely operating a high energy physics research program. The exciting results of this research program have already justified our efforts in the construction of SPEAR and encourage us in our next step of increasing the energy.

Every storage ring has incorporated in its design the lessons learned from earlier rings and is in itself a prototype for future higher energy rings. Although we have only begun to explore the characteristics and limitations of SPEAR we have already learned a great deal which has influenced the design of proposed electron-positron rings of higher energy, e.g., PEP.

General Description

In this section we summarize the salient features of the SPEAR project. Details of the design can be found elsewhere.[1,2] SPEAR is a single ring shown schematically 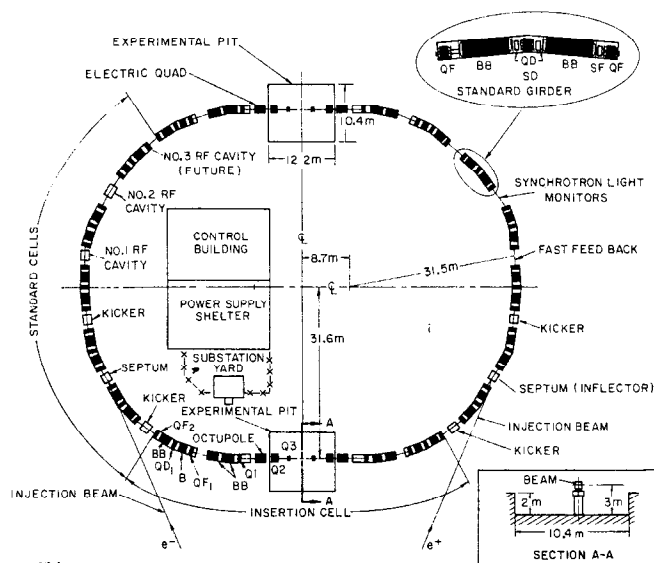in Fig. 1. Two arcs composed of standard modules connect two variable-dispersion, variable-beta, low-beta insertions. The lattice is extremely flexible in the choice of operating betatron tunes and in the choice of the momentum dispersion and beta values at the interaction points. The 51-MHz rf system operates on the 40th harmonic of the revolution frequency giving, in two accelerating cavities, a total voltage of 500 kV. This allows operation at present to 2.6 GeV.

Injection of positrons from the SLAC linac is accomplished using a septum magnet and two kicker magnets, with a duplicate system for electrons. The injection repetition rate is 20 pps and a typical accumulation rate is 20 mA/min (10^{11} particles/min) into a single bunch. Under optimum conditions we have achieved 120 mA/min (6×10^{11} particles/min) into a single bunch. Injection takes place into a standard configuration of betatron tune and other lattice parameters and at a fixed energy of 1.5 GeV. The two counter-rotating bunches are vertically separated, using electric plates, as they pass in the low-beta insertions. After injection the energy of the ring is adjusted to the desired value and the lattice changed to the appropriate values for high-luminosity operation.

These lattice manipulations involve complex interrelations among the currents of eleven separate magnet systems and are much too difficult to accomplish under manual control. The control of the magnet system is accomplished by an XDS Sigma-5 computer. This computer system allows the operator to choose a wide range of values of tunes, betas, and dispersions and to vary any subset of these parameters while holding the other constant.[3] The computer handles most other instrumentation data-logging and control functions, e.g., closed-orbit measurement and control, and it also handles the data acquisition and on-line analysis of some of the physics experimental program.

Operating Experience

During this first year of routine running, SPEAR has operated on the SLAC schedule of 4- to 10-week running periods with similar maintenance and set-up periods. We have adopted a pattern of 5- to 6-day blocks of continuous operation for the research program with interruptions of 1 or 2 days for machine studies or equipment modification.

Figure 2 gives a breakdown of operating time during scheduled running for physics research over the past year. A typical fill takes of the order of 20 minutes with half the time being taken up by the lattice changes before and after injection. The beam lifetime is dominated in most cases by the beam-beam effect and varies from 2 to 8 hours. The luminosity decay rate is close to the beam-current decay rate as we operate in a region where the vertical beam size is greatly enlarged by the beam-beam effect and decreases as the beam current decays. In this region the luminosity is approximately proportional to current. The beams are maintained in collision for 2 to 4 hours before the injection cycle is repeated. We find that over a period of months the average luminosity delivered to the physics program is 25% of the peak achievable at the appropriate energy.

Two thirds of the SPEAR downtime occurred during an operating cycle when a vacuum loss led to contamination of approximately 30% of the ring, and necessitated an extensive bakeout to recover the required beam lifetimes and low backgrounds for the experimental program.

FIG. 1--Layout of SPEAR.

†M. Allen, W. Davies-White, N. Dean, G. Fischer, J. Harris, R. Helm, L. Karvonen, M. Lee, R. McConnell, R. Melen, P. Morton, J. M. Paterson, J. Rees, B. Richter, A. Sabersky, P. Wilson, J.-E. Augustin, M. Harold, M. Matera, H. Wiedemann.

BEAM AVAILABLE
57.8%

ACCELERATOR
DOWN
8.5%

RING DOWN
19.5%

FILLING
AND TUNE-UP
14.1%

FIG. 2

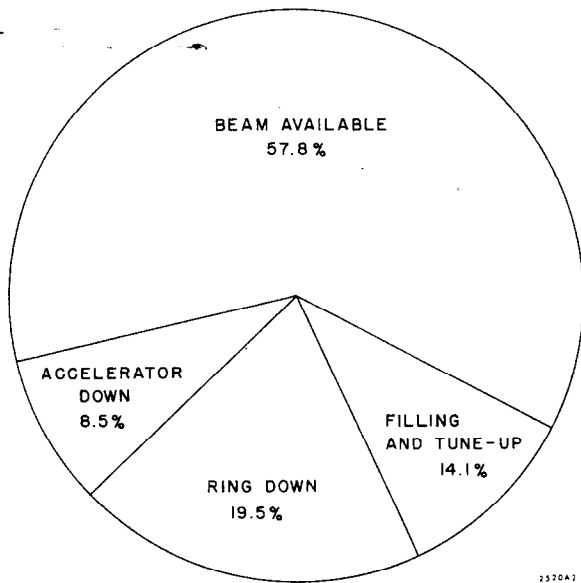FIG. 3—Measured vertical betatron tune versus peak circulating current.

During the year the Stanford Synchrotron Radiation Project has built a laboratory which will use the synchrotron radiation emanating from one point on the SPEAR orbit.[4] It is planned to have several experiments in the field of solid state physics, chemistry, and biology operating in the upcoming running period. A pilot project using the x-ray beam was successfully completed in March of this year.

Single-Beam Performance

Several single-beam instabilities have been observed in SPEAR. They have been controlled, and currents of greater than 200 mA (10^{12} particles) have been stored in a single bunch at the injection energy of 1.5 GeV. Taking bunch lengthening into account, this corresponds to a peak current within the bunch of approximately 55 amps.

The first instability observed in SPEAR was a transverse betatron instability. The thresholds for the horizontal and vertical modes were similar and were 0.5 mA. The behavior of this instability as a function of the chromaticity $[p(\delta\nu/\delta p)]$ is consistent with the theory of the barycentric mode 'head-tail' instability. The wake fields, which drive the beam, decay rapidly compared to the bunch separation in SPEAR, i.e., 20 nsec. When the lattice is adjusted to have positive chromaticity no instability is observed, but the wake fields then produce strong damping of coherent oscillations. This phenomenon has been studied and is discussed elsewhere in these proceedings.[5]

At higher currents, around 50 mA, a coherent vertical instability is again observed. A small increase in the chromaticity, to more positive values, raises the threshold to beyond 200 mA. A multi-bunch experiment shows that this is again a short wake-field effect as a second bunch, traveling 20 nsec behind an unstable bunch of higher current, is unaffected. The transverse coupling impedance of the beam to its surroundings leads to a tune shift for coherent oscillations. This has been measured and is shown in Fig. 3. The horizontal tune shift (not shown) is positive and five times smaller than the vertical. The magnitude of the tune shift is considerably larger than we would estimate from the
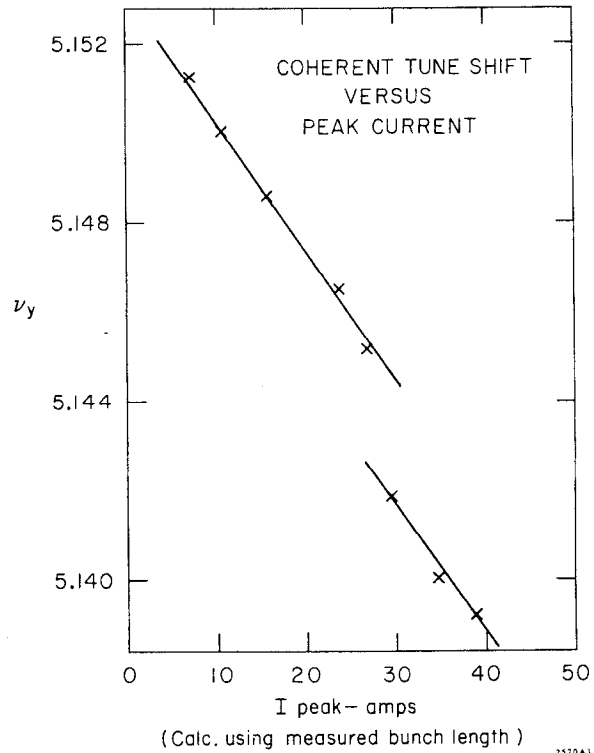
known impedances (e.g., the chamber walls and ferrite kicker magnets)[6] in the vacuum system and may be due to the many transverse cavity-mode oscillations which the beam is observed to excite in each of the 20 SPEAR straight sections.[7] The break in the curve in Fig. 3 indicates a region where the shape of the tune spread line is complex and wide, $\Delta\nu$ FWHM $\simeq 0.005$. At higher currents the tune spread line is again sharp. We do not understand this effect as yet, but it may be related to the vertical coherent instability which occurs at this current with appropriate chromaticity.

As has been reported previously, the phenomenon of bunch lengthening has been observed in SPEAR. Many measurements on this effect are reported elsewhere in these proceedings.[7] Briefly, it has been found that the ferrite injection kickers (now removed) made a significant contribution to the longitudinal coupling impedance and that many higher mode bunch-shape oscillations have been observed.

No intensity-dependent coherent phase instabilities (other than bunch lengthening!) have been observed. However, phase oscillations driven by higher order modes in the accelerating cavities and by rf system noise have been observed. They are controlled by either adjustment of the rf system or by phase feedback to the beam. Although not a single-beam effect, it is appropriate to include here the observation of coupled phase oscillations between counter-rotating bunches. Under certain operating conditions they have led to beam loss. The 0-mode oscillation, i.e., the bunches oscillating in phase, is strongly damped by the narrow-band phase feedback system, but the π-mode, out-of-phase oscillation, requires special treatment. Splitting the synchrotron oscillation frequencies of the bunches by a few per cent of the natural frequency completely removed these oscillations. The frequency splitting was achieved using a high-frequency cavity operating on the 122nd harmonic of the orbital frequency which was powered to give approximately 10 kV accelerating voltage.[8]

Coupled betatron oscillations have also been studied and are reported elsewhere in these proceedings.[9]

Colliding-Beam Performance

SPEAR has operated for physics experiments with colliding beam at 0.1-GeV intervals, between 1.2 GeV and 2.6 GeV per beam. The luminosity which was achieved over this energy range is shown in Fig. 4. With an almost constant lattice configuration the luminosity increases rapidly
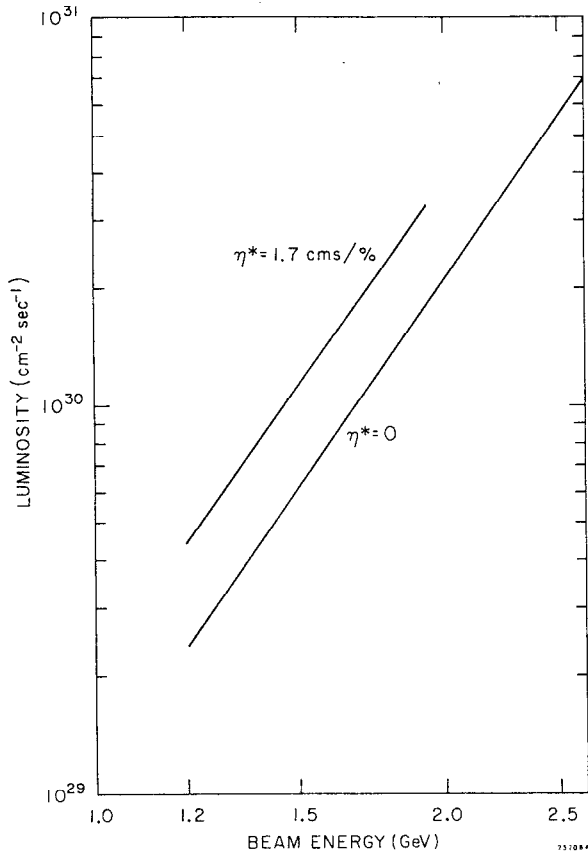

FIG. 4—Measured luminosity versus beam energy.

with energy, viz., $L \propto E^4$ and the beam current (equal beams) at maximum luminosity increases approximately as the cube of the energy. These dependences are what one would expect for an energy-independent small-amplitude tune-shift limit and a 'natural' beam width, determined by quantum excitation, increasing linearly with energy.

This simple model is, however, complicated by the fact that the bunch length in SPEAR is comparable to the value of the vertical betatron function at the interaction point and the bunch length is a function of both the beam energy and the beam current.[7] We have found that the highest luminosity and highest colliding currents are achieved when the value of the vertical beta function equals the standard deviation of the bunch length, i.e.,

$$\frac{\sigma_z}{\beta_y} \simeq 1, \quad \text{where } \beta_x >> \beta_y .$$

This means that at 1.5 GeV we operate with $\beta_y = 10$ cm and at 2.5 GeV $\beta_y = 20$ cm, and implies that the small-amplitude tune shift limit is higher at the higher energies. Calculations of the maximum tune shift can be done, using the

the measured luminosity and currents as input.

$$\Delta \nu_y = \frac{2 e r_e \beta_y L \ F(\Delta \nu, \nu)}{\gamma I [1 + (\sigma_y / \sigma_x)]} .$$

e is electronic charge,

r_e is classical electron radius,

γ is beam energy in units or rest mass.

The term $[1 + (\sigma_y / \sigma_x)]$ can be calculated from the luminosity and current, on the assumption that σ_x is unaffected by the beam-beam effect. To an accuracy of 10% in σ_x, this is consistent with our observations. The correction term $F(\Delta \nu, \nu)$ represents the perturbation to the lattice from the optical tune shift and, for the case of $\sigma_z / \beta_y \leq 1$ and $\nu_y \geq 0.1$, deviates from unity by no more than 10%. The value of $\Delta \nu_x$ can be calculated in a similar fashion. The calculated maximum tune shifts for a variety of lattice configurations and energies have been analyzed, and we find that the maximum $\Delta \nu_y$ is 0.025 ± 0.005 per interaction at 1.5 GeV and 0.035 ± 0.005 per interaction at 2.5 GeV. The complex dependence of luminosity and therefore $\Delta \nu$ on betatron tune at a fixed energy makes definitive analysis difficult, but we might say that the data suggest a trend. The calculated $\Delta \nu_x$ is greater than the $\Delta \nu_y$ and can be as large as 0.06 per interaction in some configurations.

The complex nature of this problem and its importance in our understanding of the beam-beam limit has led us to attempt to measure directly the tune spread in colliding beams with the smallest perturbations possible to the interacting system of particles. The technique is still in development, but begins to show encouraging results. It is reported elsewhere in these proceedings.[10]

To increase the luminosity at the lower energies we must find a technique for enlarging the beam width at the interaction point. The beam height can be controlled by x-y coupling. However, in practice we find that the beam-beam effect enlarges the vertical size, maintaining an approximately constant particle density over a large range of current. The effective vertical height can also be controlled using small vertical crossing angles. SPEAR is equipped with the necessary electrostatic plates, but we have found that with the present bunch length and betatron function we cannot attain as high a luminosity using a crossing angle as with head-on collisions. It will be interesting to see whether this is still true in SPEAR II with its much shorter bunch lengths. (See below.)

When SPEAR was constructed, two techniques for beam enlargement were considered. One technique was a quasi-stochastic process, where a fast kicker magnet gave coherent kicks to the beam whose amplitudes were small compared to the beam size. Random application of these perturbations and the decoherence from the nonlinearities of the ring or from the other beam should lead to an enlarged beam. This technique worked well with single beams or with colliding beams of low current density. As the colliding currents were increased, the small amount of residual coherence led to instability, and independent control of the two beam sizes became impossible. No improvement in luminosity was achieved with this technique.

The other technique of beam enlargement is the introduction of momentum dispersion $\eta *$ at the interaction point.[1] As mentioned above, the complex lattice changes occur after injection with the beams stored. This proved troublesome at first until improvements in both hardware and software were made. Even now, we have explored only a small fraction of the lattice options which are available. During the past year the use of $\eta * = 1.7$ m (i.e., 1.7 cm per percent) became routine to increase the luminosity at the lower

energies. The luminosities obtained by this technique are also shown in Fig. 4.

A new technique of beam enlargement has been investigated recently and tested on SPEAR. This technique of 'mismatched η' is the subject of a separate paper in these proceedings,[11] and will not be discussed here in detail. The principle is that by allowing large variations in momentum dispersion through the standard lattice cells, while maintaining a constant average, one increases the natural betatron emittance given by quantum excitation and damping. Figure 5 shows the η function through one quadrant of SPEAR for two cases: matched-η with a non-zero η^* at the interaction region and a mismatched-η with $\eta^* = 0$ at the interaction region. These configurations give almost identical effective beam sizes, and the luminosities and currents agree with prediction. At a constant energy, the normal lattice $\eta^* = 0$, the $\eta^* = 1.7$ m and the 'mismatched η' give a constant ratio of maximum luminosity to current and therefore a constant maximum tune shift.
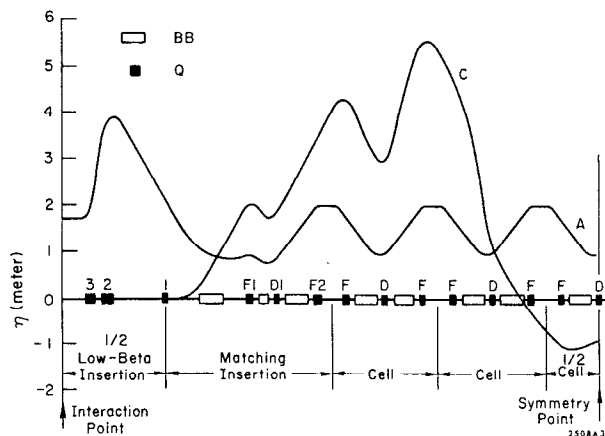
FIG. 5--Two lattice configurations used to increase the beam size at the interaction point
A 'Matched η' with $\eta^* = 1.7$ m
C 'Mismatched η' with $\eta^* = 0$.

In summary, the following table gives some typical SPEAR parameters which have been used over the past year.

TABLE I

	Colliding	Injection
Beam Energy	1.2 — 2.6 GeV	1.5 GeV
Max. Beam Current (single bunch)	45 mA × 45 mA (2.25×10^{11} particles)	> 200 mA (> 10^{12} particles)
Max. Luminosity	7×10^{30} cm^{-2}sec^{-1}	
Vertical Tune	5.10 - 5.13	5.15
Horizontal Tune	5.12 - 5.16	5.22
Vertical Beta Function at I.R.	0.1 - 0.2 m	0.1 m
Horizontal Beta Function at I.R.	1.0 - 4.5 m	1.1 m
Momentum Dispersion at I.R.	0 - 1.7 cm/%	0

SPEAR II (Improvement Program)

The design of SPEAR incorporated the possibility of an eventual increase in maximum operating energy to between 4.0 and 4.5 GeV, limited by magnet saturation. To accomplish this goal, we need a substantial increase in rf and magnet power and vacuum improvements to handle the increased synchrotron-radiation load. We started on this improvement program 14 months ago and we will complete the installation of the equipment this summer. Testing of SPEAR II is planned for the SLAC operating cycle this fall

and physics experiments are scheduled to begin at the higher energy in January, 1975.

RF System

The rf problems associated with the energy increase are considerable. A particle in SPEAR at 4.5 GeV loses 2.8 MeV per turn and still higher voltages are required to maintain an adequate quantum lifetime. Both the shunt impedance per unit length and the available straight-section length make it impractical to achieve these voltages at the present frequency of 50 MHz.

An analysis of cost versus frequency for a new rf system to meet the above constraints, gave a broad optimum around 300 MHz, and we selected 358 MHz (the 280th harmonic of the orbital frequency) for the new design. An accelerating system was designed around a cavity similar to that of the Los Alamos proton linac. A group of five π-mode, slot-coupled cavities is built into a single accelerator structure which matches the 3-meter straight-section length in SPEAR. Four such accelerators are being built.

One of the accelerators is shown in Fig. 6. They are machined from aluminum which has many cost and mechanical advantages over copper. One disadvantage of aluminum
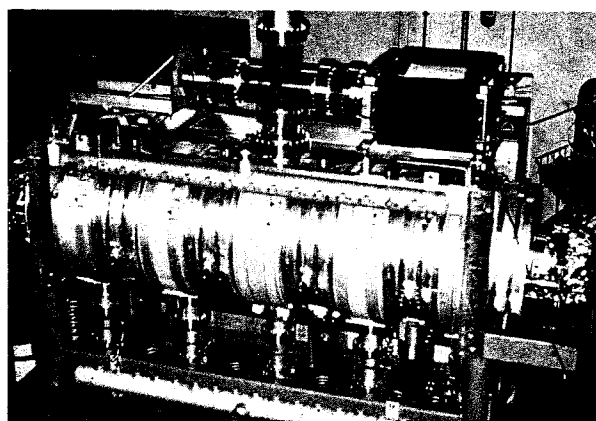
FIG. 6--Photograph of one of the four SPEAR II accelerator structures.

is that aluminum oxide has a high secondary-emission coefficient which can lead to multipactoring. This was overcome by coating the inside surfaces of the cavity with a few-hundred-angstrom layer of titanium nitride. The first accelerator section has been satisfactorily tested to its design limit of 75 kW of wall losses. The measured shunt impedance is 17.5 megohms per accelerator ($P = V^2/2R$) and this gives a transit-time-corrected accelerating voltage of 1.6 MV per accelerator. The four-accelerator rf system will therefore be capable of giving in excess of 6 MeV/turn to the beam.

There has been designed and developed at SLAC a 125-kW cw klystron and its associated power supplies. One klystron will feed each accelerator. The klystron is shown in Fig. 7. The first of the four klystrons has been tested to 125 kW cw into a dummy load and to 75 kW into an accelerator section. The klystrons operate at 41 kV with an efficiency of 50 to 55% as predicted by the design calculations. The assembly and testing program of this 500-kW rf system is under way and the system will be installed in SPEAR during July and August of this year.

A higher-frequency single cavity at 475 MHz is also being built and will be powered to 30 kW by an existing 50-kW transmitter. This system will be capable of splitting the synchrotron oscillation frequencies of the two counter-rotating bunches by 10% of the unperturbed frequency.
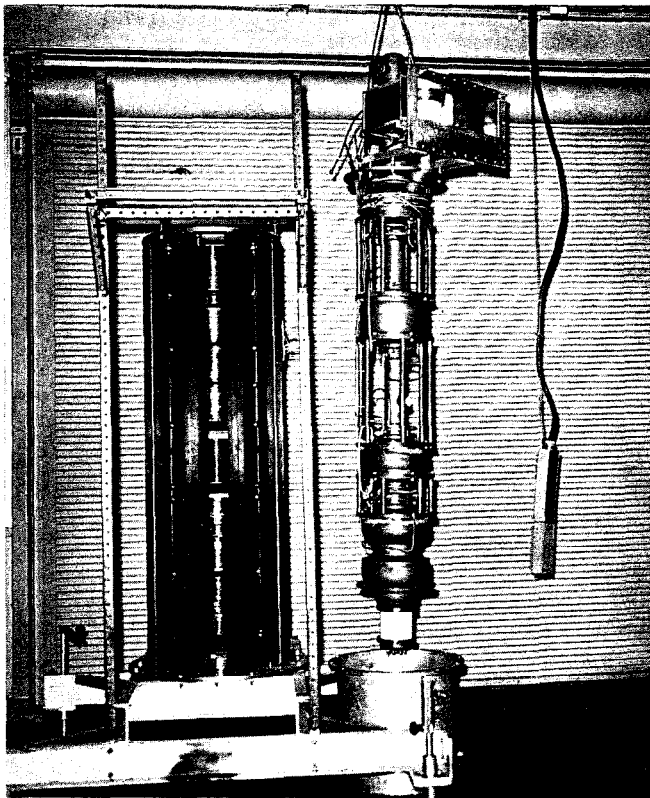
FIG. 7--Photograph of a SPEAR II, 125-kW cw klystron.

Magnet System

The only change to the magnet system itself is an increase in the water-cooling capacity. Most of this work has been completed. The additional 2.5 MW of dc power is obtained by adding a new power supply to the existing complement of power supplies and by a rearrangement in the utilization of these supplies. Although there is considerable work remaining, it involves no new technology. These changes will be made during July and August of this year.

Vacuum

To maintain good beam lifetime in the face of up to 300 kW of synchrotron radiation being deposited into the vacuum system, greater pumping capacity has been added to the SPEAR straight sections and interaction regions. The average pressure in the arcs was 6×10^{-11} torr/mA at 1.5 GeV and it increases approximately linearly with energy. The distributed ion pumps inside the bending-magnet chambers have adequate speed but the straight-section pumps have been increased from 100 ℓ/s to 400 ℓ/s.

The four ferrite injector kicker magnets absorbed considerable power[7] from the beam at high currents raising the pressures locally to the 10^{-7} torr range. These kickers have now been removed and replaced with an open-coil design.

Expected Performance

The single-beam performance is difficult to predict as we will be increasing the peak current densities because of the seven-fold increase in rf frequency. SPEAR's arsenal of beam-control devices and its flexibility may be needed to control instabilities and accumulate the high currents which we will be capable of colliding at the high energy. To maintain the present injection rates into a much shorter bunch,

a new high-current, short-pulse gun is being developed for SLAC. An intriguing possibility lies in the fact that the fast coherent damping that we observe[5] may allow a faster injection repetition rate than the 20 pps, which is determined by the radiation damping at 1.5 GeV. Some tests of this indicated a possible 50% improvement in injection rate.

The two-beam performance is easier to predict ignoring any single-beam limitations. We believe that the luminosity will continue to increase as E^4 and the current as E^3 up to approximately 3.8 GeV. At that point the rf power to the beams equals 300 kW, and beyond that we will be rf-limited. The luminosity should peak at around 3 to 4×10^{31} cm^{-2}sec^{-1} at 3.8 GeV. The extrapolation from the present performance is shown in Fig. 8 (cf. Fig. 4). We eagerly await the opportunity to study this new regime of SPEAR operation and of elementary particle physics.
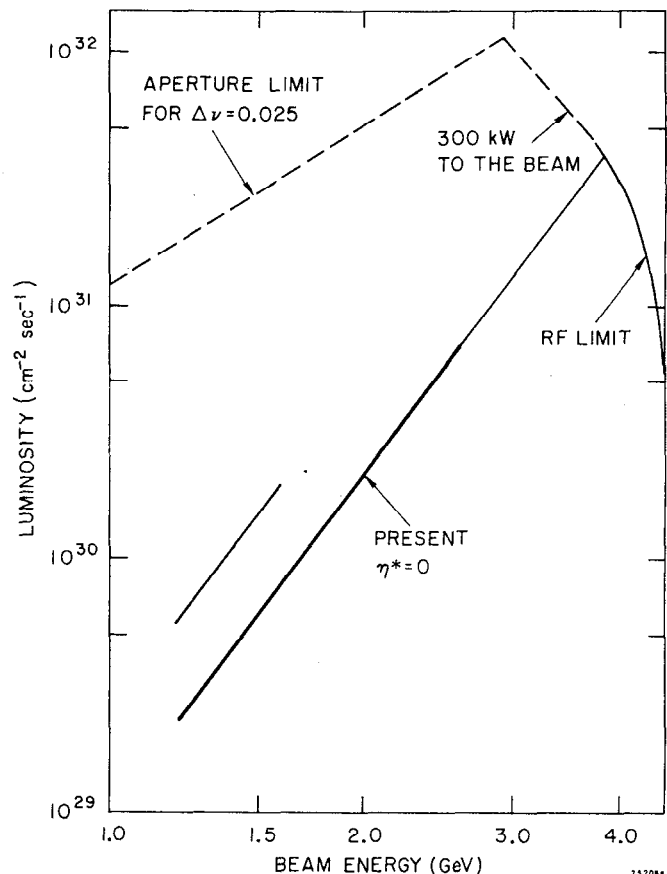

FIG. 8--Operating region of luminosity and energy in SPEAR II.

References

1. Stanford Linear Accelerator Center Storage Ring Group, Proceedings of the 8th International Conference on High Energy Accelerators, CERN 1971, p. 145.
2. SPEAR Storage Ring Group, Proceedings of the 1973 Accelerator Conference on Accelerator Engineering and Technology, IEEE Transactions, Vol. 1 NS-20, p. 752.
3. Boyarski et al., Automatic Control Program for SPEAR Proceedings of 1973 Accelerator Conference on

Accelerator Engineering and Technology, IEEE Trans. NS-20, 580 (1973).

4. H. Winick, Stanford Synchrotron Radiation Project, these Proceedings.

5. SPEAR Group, Fast Damping in SPEAR, these Proceedings.

6. G. Fischer, Miscellaneous Single-Beam Observations, SPEAR-173 (1974, unpublished).

7. M. Allen et al., Observations on Bunch Lengthening in SPEAR, these Proceedings.

8. M. Allen et al., Operation of the SPEAR RF System, IEEE Trans. on Nucl. Sci. NS-20, 373 (1973).

9. SPEAR Group, Beam-Beam Coupling in SPEAR, these Proceedings.

10. A. Sabersky, Direct Measurement of Beam-Beam Tune Spread in SPEAR, these proceedings.

11. R. Helm et al., Beam Enlargement by Mismatching the Energy Dispersion Function, these Proceedings.