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THE SLAC ELECTRON–POSITRON COLLIDERS: PRESENT AND FUTURE*

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I. Introduction

The colliding-beam program at Stanford University began with the start of construction of the Princeton/Stanford 500 MeV electron–electron colliding-beam storage ring at the High-Energy Physics Laboratory in 1958. That machine is long gone, but the program of colliding-beam studies continues with the SLAC electron–positron colliders SPEAR (3.5 GeV per beam), PEP (15 GeV per beam), and the soon-to-be completed SLAC Linear Collider (50 GeV per beam). In this brief report I will discuss the accelerator developments we hope to pursue on these facilities in the future and also discuss our advanced accelerator R&D program and its goals.

II. SLC

Construction of the SLAC Linear Collider (SLC), the first of what we believe will be a new generation of electron–positron colliders, began in late 1983. We hope to begin the first colliding-beam trials around the end of this year. Dr. G. E. Fischer will give a paper at this conference on the SLC project, and so in this report I will remind you only briefly of what the SLC is and of some of its parameters. Figure 1 shows a schematic of the project. The SLC project includes an upgrade of the linac to 50 GeV, construction of two small storage rings near the injector (the damping rings) to produce the small-emittance e^+e^- beams required to reach the design luminosity at the collision point, the development of a positron source with a net yield of one positron per electron, the construction of about three kilometers of tunnels and magnets required to bring the beams to the collision point, the design and fabrication of very highly corrected beam transport and focusing systems to produce a micron sized spot at the collision point, and the construction of a large experimental hall to house the high-energy physics experiments. The main parameters of the facility are as follows:

E (c.m.)	100 GeV
Invariant Emittance	3×10^{-5} meters
σ_E/E (c.m.)	0.2%
σ_{r^*}	1.6 microns
n_b	7×10^{10}
$\mathcal{L}$ (design)	6×10^{30} cm^{-2}s^{-1}

I will leave the description of all of the interesting details to Dr. Fischer.

There are four major improvement projects already under way that will affect the performance of the SLC. Of these, two are necessary to achieve the design luminosity and two will give enhanced capability for experimental physics. The first of these improvements involves replacing the conventional iron quadrupoles in the final triplets before the interaction point with superconducting quadrupoles. The coils for these magnets are being fabricated for us by Fermilab, while we will build the dewars, cryogenic gear, etc. The substitution of these superconducting lenses for the present ones will allow a decrease of the interaction region beta function from one centimeter to 0.5 centimeter. The project is scheduled for completion in late 1988 or early 1989.

The second improvement project involves increasing the repetition rate of the linac from 120 Hz to 180 Hz. This improvement involves modifications to the AC and DC power distribution systems and the accelerator water cooling system. The job can be done incrementally with no extensive shutdown of the facility. This project requires special funds, and we would like to complete it in 1990 when more low-cost public power should be available to SLAC.

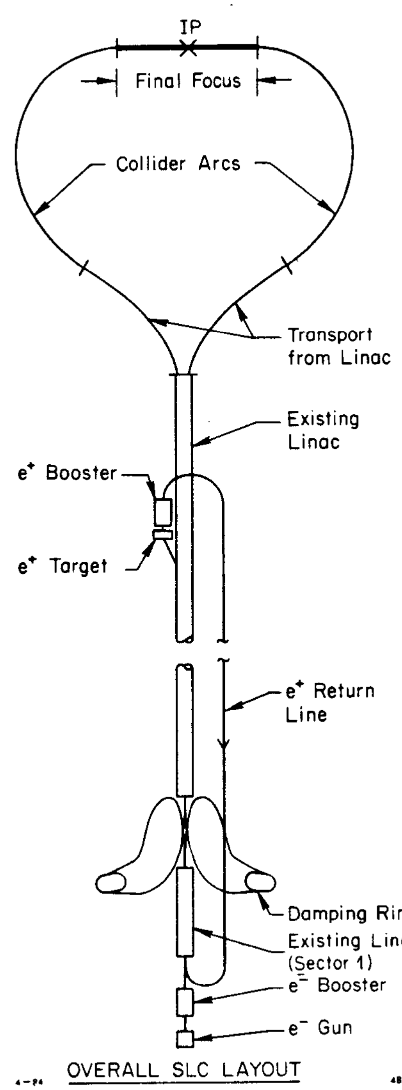

Fig. 1. Schematic of the SLC.

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The third project involves the development of a precision energy measuring capability for the SLC. The aim is to be able to measure the C.M. energy to 40 MeV on each SLC pulse. This allows an important improvement to the precision with which certain physical processes can be measured (Z^0 mass, for example). Present precision of energy measurement is about 300 MeV. The new system measures the bending angle of the beam in a special magnet, using synchrotron radiation to define the incoming and outgoing beam directions. The system is shown schematically in Fig. 2, and we hope to have it ready in mid-1987.

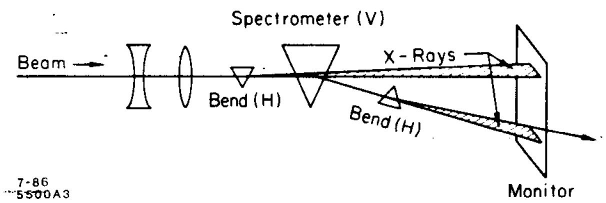

Fig. 2. Precision beam energy spectrometer for the SLC.

The fourth project is the production of a longitudinally polarized electron beam of sufficient intensity to produce full luminosity. The electron gun technology is the same as that used previously at SLAC to produce polarized beams for inelastic electron scattering. We expect the polarization to be about 45% with the first generation gun, and work on photocathodes that may allow the production of 80–90% polarization is also proceeding. The spin manipulations required to achieve longitudinal polarization at the collision point are complex: the electron spin is longitudinal at production and through acceleration to 1.2 GeV; it is rotated by a combination of bending magnets and a solenoid to the vertical direction for injection into the damping ring; on extraction from the damping ring it is pointed in the appropriate direction for reinjection into the linac by a combination of bending magnets and two solenoids; and finally, it undergoes $g-2$ precession in the collider arcs, ending up longitudinal at the interaction point. The gun is already on the linac ready for testing in the fall. We hope the full project will be ready in 1988 or 1989.

The design luminosity of the SLC as a function of energy is shown in Fig. 3. The curve has a broad maximum at about 6×10^{30} cm^{-2}s^{-1} at around 50 GeV per beam. At the design luminosity the production rate of Z_0 bosons at 94 GeV in the center of mass is approximately 800 per hour. Of course, since the SLC is a new kind of accelerator we may have new problems in tuning it up. We have set what I hope are realistic luminosity goals: the start of physics at a luminosity of about 10^{28} in the spring of 1987; a luminosity of about 10^{29} by the summer of 1987; a luminosity of 10^{30} by the summer of 1988; and the achievement of the design luminosity in 1990 when the power-system upgrade is complete. Of course it could go slower or it could even go faster. Linear colliders, unlike storage rings, have no hard luminosity limits from beam–beam tune shifts. For example, continued improvement in alignment reduces transverse wake field effects and allows larger charge per bunch in the linac and arcs, while more exotic final focus lenses can reduce the interaction region beta function. Both increase the luminosity, and thus it may be possible to go beyond the design value.

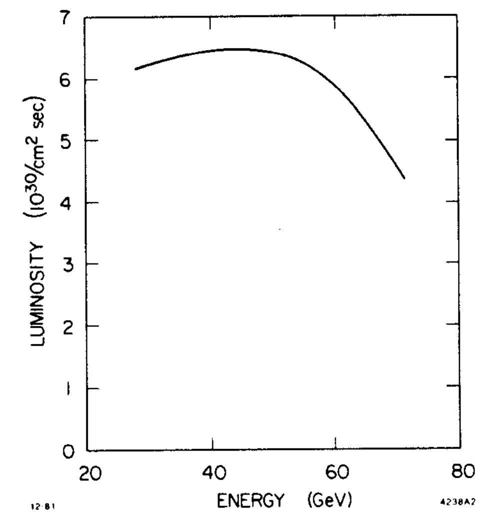

Fig. 3. SLC design luminosity versus beam energy.

III. PEP and SPEAR

The largest of the SLAC electron-positron colliding-beam storage rings, PEP, began operation in 1980. It has run for physics exclusively at a center-of-mass energy of 29 GeV. The average luminosity is roughly 1–1.5 pb^{-1} per day. Significant advances in the PEP high energy physics experimental program require a large increase in the delivery luminosity, and so we have decided to implement a minibeta program. We are reducing the beta function at one interaction point to about four centimeters while increasing the beta function at the other interaction regions where the beams will remain separated. We expect a luminosity increase of a factor of three to five. At the same time the most sophisticated of the PEP detectors, the TPC, is also being improved to take advantage of the increased luminosity. Both PEP and the TPC should be ready in the spring of 1987 for tests of new systems. The first goal of the program is an integrated luminosity of about 3 fb^{-1}. We will review our options again at that time.

PEP will also be used by the synchrotron radiation community operating in a parasitic mode in parallel with the high-energy physics program. In this mode PEP is the world's brightest x-ray source by about a factor of ten. One synchrotron-light beam line is complete, a second is under construction, and two more are planned. In addition, tests have been made at 8 GeV in a special low-emittance configuration that is not compatible high-energy physics, but that approximately equals the emittance of the dedicated five to six GeV machines planned for Europe and the U.S. Funds are being sought for dedicated operation a few months per year in periods when the high-energy physics program does not normally run.

The nuclear-physics community has also begun to take an interest in PEP. Tests of gas-jet targets show that operation is completely compatible with high-energy physics when the luminosity in the beam–jet interaction is approximately 10^{33} cm^{-2}s^{-1}. A workshop will be held at SLAC next January to look at opportunities.

The SPEAR colliding-beam storage ring has been in operation since 1972, and remains an extremely productive physics research tool (11 papers appeared in refereed journals in the last 18 months). Running time on SPEAR is shared equally between high-energy physics and dedicated synchrotron-radiation experiments. The SPEAR high energy physics program will continue as long as the physics results are interesting. At present, no major improvements are planned.

IV. Advanced Accelerator R&D

The SLAC AARD program is mainly aimed at the theory and technology of linear colliders. Work goes on in the following areas:

1. Large Collider parameter studies and scaling laws
2. Linac beam dynamics
   (a) Longitudinal and transverse effects, and correcting schemes
   (b) Analytic and computer calculations
3. Damping Rings and low emittance sources
4. Beam–beam effects
   (a) Disruption
   (b) Beamstrahlung
   (c) Other quantum effects
5. Novel acceleration and focusing methods
   (a) Switched power schemes
   (b) Wake fields in plasmas
   (c) Wake fields in structures
   (d) Laser acceleration
   (e) Final focus design
6. RF breakdown limitations in structure
7. RF sources
   (a) Microwave tube theory using MASK and other programs
   (b) S-band lasertron (30 MW, 2.856 GHz)
   (c) X-band sheet-beam klystron (75–150 MW, 11.4 GHz)
   (d) Microlasertron (millimeter-wave generator)
8. Pulse compression techniques for peak power multiplication
9. Intermediate-size linear-collider design
10. RF superconductivity

This is much too long a list to cover in this brief review, and so I will comment on only a few of these items.

A. Beamstrahlung

The emission of synchrotron radiation in beam–beam collisions (beamstrahlung) imposes an important constraint on the design of linear colliders. Beamstrahlung affects both the mean energy and the energy spread in the beam–beam collision. The situation is illustrated in Fig. 4(a). An electron or positron in one beam of initial energy E_0 passes through the field generated by particles of the other beam and emits synchrotron radiation photons. The mean energy lost in synchrotron radiation is δ and the final energy after the collision is $E_0 - \delta$. Figure 4(b) shows schematically what happens to both the center-of-mass energy and energy spread for small δ, medium δ, and large δ. As delta increases, the mean center-of-mass energy is reduced and the energy spread increases. Obviously it is desirable that the mean center-of-mass energy be as high as practical, and that the energy spread be sufficiently small where "sufficiently" means that the constraint on center-of-mass energy, which is an important advantage over electron–positron colliding beams when compared to proton–proton colliding beams, not be lost. In practice we try to constrain δ to be less than about 0.3, which implies an RMS energy spread in the center of mass of about 10%.

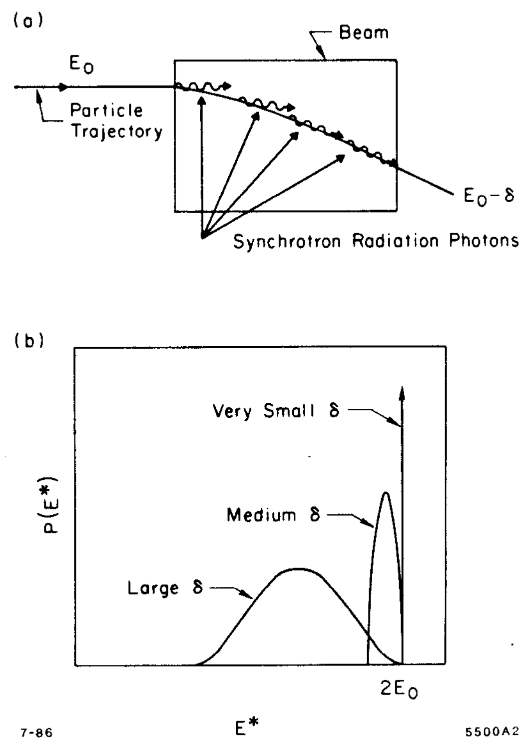

Fig. 4. (a) Emission of synchrotron radiation by an electron in the field of the other beam. (b) Energy distribution of the colliding beams in the center of mass system showing schematically the shift and broadening of the distribution as the single particle synchrotron loss increases.

The potential problem imposed by beamstrahlung was recognized in the first study of high-energy linear colliders,[1] and the design of machines was tailored to keep the beamstrahlung problem within bounds. The original goals in high-energy linear colliders were much more modest than they are now. In the late 1970s, we all thought that several hundred GeV in the center of mass was a very high energy, and our analysis of beamstrahlung was based on machines with center-of-mass energies less than one TeV. The energy lost in beamstrahlung was calculated from the classical synchrotron radiation formulas.

$$P(x) \propto E^4/R^2 f(x) \propto E^2 B^2 f(x) \tag{1}$$

$$x = E_\gamma / E_c \tag{2}$$

$$E_c \propto E^2 B \tag{3}$$

In these equations P is the power per unit photon energy, E is the beam energy, R is the radius of curvature of a particle in one beam in the field of the other beam, B is the effective field generated by one beam, x is the synchrotron photon energy measured in units of the so-called critical energy (E_c) and f is a universal function of the synchrotron photon energy measured in units of the critical energy. Even for a relatively low-energy machine like the SLC, B is megagauss, and with a beam energy of 50 GeV, E_c is about 300 MeV. However, in the SLC the mean energy loss δ is very small and beamstrahlung imposes no real constraint on the design of the machine.

For multi-TeV linear colliders it has become apparent that the classical synchrotron radiation formulas above can no longer apply. A combination of high energy and the requisite high luminosity moved us into a regime where the critical photon energy was greater than the beam energy, and simple conservation of energy tells us that no beam can radiate photons of higher energy than the beam itself.

Himel and Siegrist[2] and Noble,[3] at SLAC, looked into this problem and rediscovered the 1952 work of Sokolov, Klepikov, and Ternov (SKT).[4] This quantum-mechanical treatment of radiation in a field shows that the synchrotron radiation spectrum is to a good approximation simply cut off at the beam energy for E_c much greater than E_b (see Fig. 5). The transition between what has come to be called the classical and quantum mechanical regimes in synchrotron radiation is measured by the field strength B, compared to a reference field ($B_0 = 4.4 \times 10^{13}$ gauss) as follows.

$$\gamma B/B_o \ll 1 \qquad \text{Classical regime} \qquad (4a)$$

$$\gamma B/B_o \gg 1 \qquad \text{Quantum regime} \qquad (4b)$$

Himel and Siegrest used a simple analytic approximation to the SKT equation and rederived the beamstrahlung scaling laws for the quantum-mechanical regime. These are the scaling laws that have been used by SLAC physicists and others to derive the parameters of very-high-energy linear colliders.

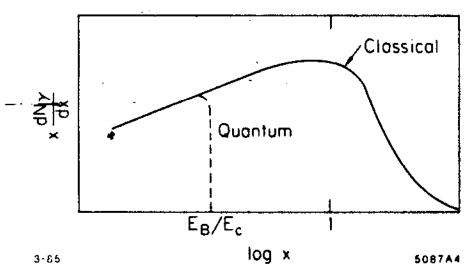

Fig. 5. The synchrotron radiation spectrum in the classical and quantum limits.

An example of the parameters of a very-high-energy machine, compared to those of the SLC, that I have used in the past[5] is given in Table I. Achieving some of the parameters in the table for the 10-TeV machine with a luminosity of 10^{34} will be a formidable technical challenge, for we will have to make multi-megawatt beams with radii at the beam–beam collision point measured in tens of angstroms.

Linear colliders are still in their infancy, and we keep learning more about them as we think more deeply about the problems. This is a continuing process, and I regret to say that we may not be finished yet with the beamstrahlung problem. The SKT formulation is derived for a smooth field, and the field seen by a particle in one beam on passing through the other beam *may not be smooth.*

Table I. Parameters of some 10 TeV (c.m.) linear colliders compared to the parameters of the SLC. The c.m. energy spread, σ_{E^*}/E^*, is the contribution of beamstrahlung only.

MACHINE	L.L.C.			SLC
E^* (TeV)	10			0.1
$\mathcal{L}$ ($cm^{-2}s^{-1}$)	10^{34}			6×10^{30}
σ_{E^*}/E^* (%)	10			0.04
β^* (cm)	0.1			0.5
D	0.1			1.0
P (MW)	1	3	10	0.16
f (Hz)	3000	9000	30,000	180
N (e^+ or e^-)	4.1×10^8	4.1×10^8	4.1×10^8	5×10^{10}
ϵ_N (M)	4×10^{-9}	1.2×10^{-8}	4×10^{-8}	3×10^{-5}
σ_{r_o} (micron)	6.4×10^{-4}	1.1×10^{-3}	2×10^{-3}	1.5
σ_z (mm)	3.4×10^{-4}	1×10^{-3}	3.4×10^{-3}	1.5

To see whether a field is smooth, *or not*, consider a cylinder of electrons moving with energy γ (rest mass units) having a length $2\sigma_z$ and radius σ_r. In the ultrarelativistic limit the field produced by one particle in a beam is significant only within an angle given by $1/\gamma$ transverse to the direction of motion. For a particle in the beam on the axis this means that the field is appreciable only over a longitudinal distance given by σ_r/γ. If the total number of particles in this length is much greater than one, then the field is smooth and the SKT formulas surely apply. If the total number of particles in the distance is much less than one then the field is not smooth, and I am not yet sure of what the radiation formulas should be. For the SLC and our very-high-energy machines the number of particles in this critical distance n_c is given by

$$n_c = \frac{N\sigma_r}{2\sigma_z\gamma} = \begin{cases} 2 \times 10^2 & \text{(SLC)} \\ 2 \times 10^{-2} & \text{(LLC)} \end{cases} \qquad (5)$$

Radiation in a "lumpy" field like that of the LLC is a very complex problem. Naively, one expects that since radiation (classically) is proportional to the square of the acceleration and the RMS acceleration is much larger in the lumpy field than in the smooth field, the radiation will be enhanced. This, however, is not a classical problem. Blankenbecler and Drell at SLAC have been working for some time on this problem and may to have solved it. They are preparing a paper that will appear soon. We may soon have to impose some new constraints on the design of our very-high-energy linear colliders.

B. Stability Requirements

In the construction of practical very-high-energy machines we are concerned about keeping both the capital and operating costs down, and so there is much interest in high-gradient acceleration which can perhaps lower the length associated costs of a big machine. Many people are working on new techniques such as laser acceleration, plasma acceleration, wake field acceleration, etc. In theory, these techniques can give accelerator gradients that some have estimated to range from hundreds of MeV per meter to GeV per meter. Indeed, a gradient of about one GeV per meter has been demonstrated in a plasma accelerator,[6] though for a length of only a few millimeters. While there is much promise in these new techniques there are concerns as well, particularly about energy efficiency. I would like to add another concern which I believe to be at least as important as the efficiency concern—that of stability.

In the linear collider example shown in Table I, beams with transverse dimensions measured in tens of angstroms must collide with each other, and this is only possible if the random component of transverse momentum given the beam in the acceleration cycle is small enough. A rough limit on how small is "small enough" can be set by requiring that at the end of the accelerator the displacement of successive accelerator bunches in phase space be less than the transverse dimensions of the bunch itself in phase space. A crude estimate of the limit can be made by assuming an accelerator of N independent stages with a focusing lattice of constant β. In this simplified machine, the stability requirement is satisfied if the ratio of the random component of transverse momentum per stage (ΔP_t) to the energy gained per stage (ΔP_L) is limited to

$$\Delta P_t/\Delta P_L \leq (\epsilon_n/\beta\Delta\gamma_L)^{1/2} \tag{6}$$

where ϵ_n is the invariant emittance of the bunch and $\Delta\gamma_L$ is the energy gain per stage in electron rest mass units. To get a numerical limit we take ϵ_n about 10^{-7} meters, β from 10–100 meters, $\Delta\gamma_L$ of 100–1000 per stage, and find that

$$\Delta P_t/\Delta P_L \leq 10^{-5} - 10^{-6} \tag{7}$$

This is a very restrictive requirement that may not be achievable for laser, plasma, or wake field accelerators. All high efficiency lasers are multimode lasers and the mode pattern does not reproduce from pulse to pulse. Plasma accelerators must have extremely uniform plasma density. Wakefield schemes must have very uniform driving beams. Personally, I doubt that these exotic schemes can be made stable enough and as of now I believe that two-beam high-Q systems like linacs and klystrons, linacs and free electron lasers, linacs and relativistic klystrons, etc., offer the best chance of making practical high gradient devices.

C. Breakdown Limits

Since we believe that the most promise for future colliders is in some kind of resonant linac structure, it is important to determine the limits to accelerating fields that can be reached in such structures. Loew and colleagues at SLAC and at Varian Associates have been measuring the breakdown limit as a function of rf frequency for pulses in the microsecond range. Their results to-date are shown in Fig. 6. They have achieved surface fields of 300 megavolts per meter at 3 GHz and about 450 megavolts per meter at 5 GHz. The breakdown limit at these two frequencies follows the standard heuristic frequency to the 7/8 power formula. The results at 9 GHz fall considerably below this curve, but these are very preliminary results, and the experimenters believe the problem is in the coupler rather than in the cavity. They intend to continue these important experiments to see if the frequency to the 7/8 law continues to

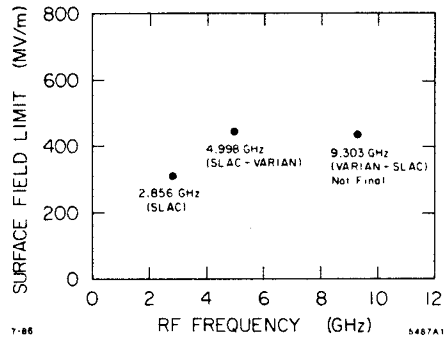

Fig. 6. Breakdown limits for copper surfaces as a function of RF frequency. The data at 9 GHz in preliminary.

apply up to at least 9 GHz. The maximum acceleration gradient implied by these breakdown fields is about one-half the breakdown limit for structures like SLAC.

D. Power Sources

Future high-energy linear colliders will require efficient, low-cost sources of RF power for, as the examples shown in Table I illustrate, the power in the beam alone is very large. There are many approaches to this problem being pursued at laboratories around the world. At SLAC we are working on a device called the The Lasertron. Basically, it is a photodiode illuminated by an RF-modulated laser with the anode replaced by an RF cavity structure to extract energy at the laser modulation frequency. The advantage of this approach over the conventional klystron lies in its simplicity and potential high efficiency. Photocathodes can easily be run at ten times the current density that can be obtained from thermionic cathodes. Using an RF-modulated laser as a driver, the beam is produced bunched at the cathode, eliminating the complex bunching sections of conventional klystrons. The efficiency is potentially high because these devices can easily be run at very high voltage, in contrast to conventional klystrons where the bunching efficiency decreases as the beam voltage increases.

At SLAC our first large-scale proof-of-principle tube is nearing completion. This device is designed to produce 30 megawatts of S-band power in a one microsecond pulse with an efficiency of approximately 70%. A schematic of the device is shown in Fig. 7. The Lasertron itself is complete and is undergoing high-voltage tests. The RF-modulated laser will delivered this fall and we hope to begin RF testing by the end of the year. If this project is successful, our next step will probably be a 200 megawatt, 1 microsecond tube which could be used on the SLAC linac, replacing a klystron and SLED cavity system with a potential significant saving in power.

V. Conclusions

In this brief report I have summarized the SLAC program. Our principal concerns at the moment are to complete the SLC and bring it into operation, both for experimental high energy physics research and for linear collider development studies. We hope that the machine will be operating in the spring of 1987.

I believe that the future of electron-positron colliding beam physics, and indeed the future of accelerator-based high energy physics depends on the development of linear colliders of very

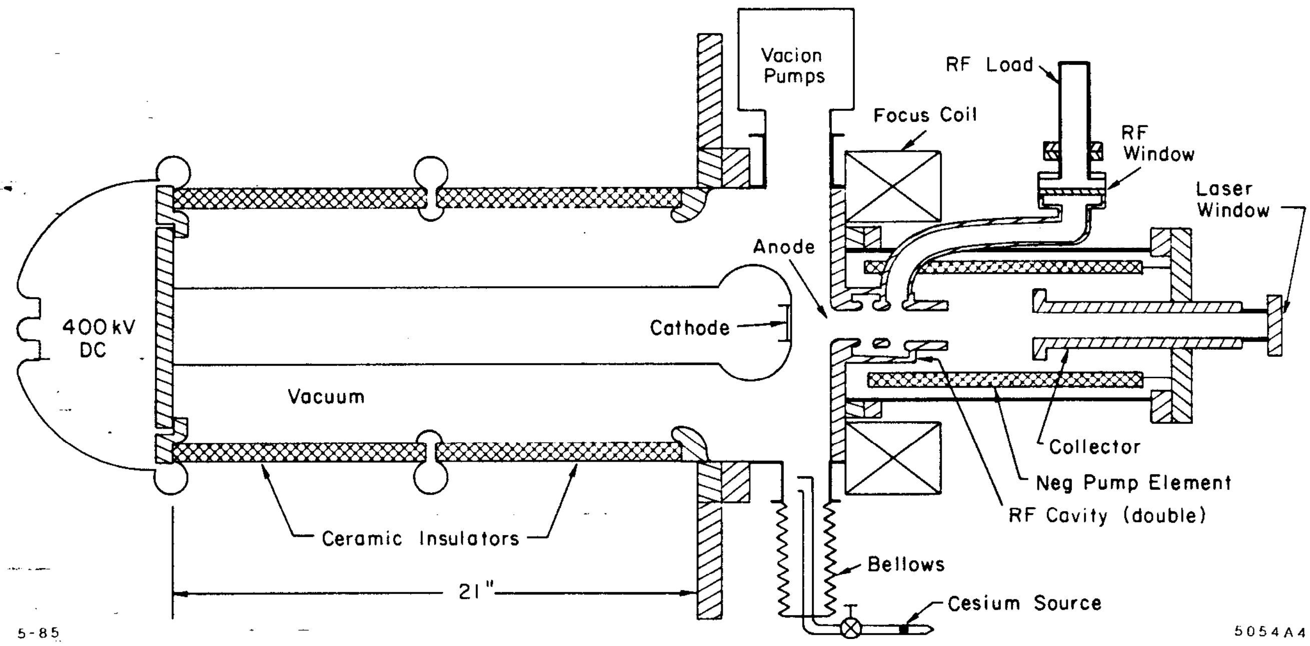

Fig. 7. Schematic of the SLAC 30 MW S-band lasertron.

high energy. Clearly, multi-TeV devices require a very large step from the parameters of the SLC. I believe that the step is too large to be made in a single stride, and thus that a machine with a center of mass energy someplace between .5 and 1.5 TeV will be required. Fortunately, such a project would be more than just a demonstration of accelerator technology because our present state of understanding of high energy physics indicates that we would expect new phenomenon to occur in this energy region. Machines as expensive as this next linear collider will have to be require both a scientific and a technological rationale. The program of advanced accelerator development at SLAC is aimed at producing the design for such a machine in about five years. There is great interest in a machine of this size in Europe, Japan, and the Soviet Union as well. I ~~hope~~ that two accelerator conferences from now there will be a talk on a 1 TeV electron-positron linear collider in the conference section on "Projects Under Construction."

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