RECENT AND PLANNED IMPROVEMENTS OF CONVENTIONAL ELECTRON LINACS*

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I. Introduction

This paper reviews the status of existing and planned electron linacs. The progress on development of superconducting electron linacs is not discussed except for a few remarks on the SLAC conversion program study. Progress in the superconducting area is being reported in other papers[1,2,3] which are being presented to this conference. Because the SLAC accelerator is the largest existing electron machine and it is located at the authors' home institution, the main emphasis in this paper is given to reporting developments and plans at SLAC. The paper includes several recent ideas on the possible achievement of a somewhat higher duty cycle and/or higher energy from the SLAC accelerator by recirculation of the beam through the accelerator structure.

II. Status of Existing and Proposed Electron Linacs

In this section, the status and characteristics of a few of the operating and proposed electron linacs will be given. Actually achieved and projected performance data on 7 electron linacs is displayed in Table I. Unfortunately, it has not been possible to obtain complete information on all of the linacs listed. A few remarks on specific achievements and design characteristics are given below. The SLAC accelerator will be omitted from the discussion in this section since its status is covered more fully in later sections.

The ALS accelerator at Saclay began operation in 1968 and has established a laudable set of performance achievements. The maximum no-load energy is 640 MeV. Its beam pulse length (10 μsec) is longer than that of most other operating linacs. Even so, it has been possible to obtain beam currents as high as 61 mA peak without seeing any evidence of beam breakup phenomena. This good performance is attributable to the careful design of the accelerating structure. However, it is probably also aided by the focusing system which consists of solenoids from Section 1 to Section 18 and 11 quadrupole triplets from Section 19 to the end of Section 30. ALS has achieved an average beam power of 100 kW. New power tests will be run at the end of this year with the expectation of achieving a 250 kW beam. It has been possible to transmit 90% of the beam through 0.5% momentum-defining slits. The klystrons for ALS operate at repetition rates up to 2000 pps and with an 11 μsec pulse length. The rf average power output from each of these tubes is 65 kW. The 10 μsec electron beam pulse at the output of the accelerator is flat within 0.3%. The duty cycle of ALS is 1 to 2%. At 2% duty cycle the maximum no-load energy is 450 MeV.

The MIT accelerator is now under construction and is scheduled to begin operating in 1971. Its maximum no-load energy (430 MeV) will be somewhat less than that of ALS but its duty cycle at reduced energy will be as high as ~ 6% (5000 pps and 12 μsec pulse length). This accelerator

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will have a complement of 10 klystrons, each rated at 4 MW peak and 80 kW average power. The peak power must be reduced to ~1 MW at the maximum duty cycle. At 15 μsec pulse length, flat tops of ± 0.06% on modulator voltage pulses and ± 0.15% on rf power output pulses have already been achieved. The 400 kV gun injection system has been in operation for over 1000 hours and its performance has been excellent. Most of the accelerator sections have been manufactured. Extreme care has been taken to minimize the danger of beam breakup by building four different types of sections and by staggering them as a function of their HEM_{11} resonant frequencies.

The proposed Amsterdam accelerator will have a maximum no-load energy of 550 MeV and a duty cycle of 2.5 to 10%. In this machine, the maximum pulse repetition rate (2000 pps) is less than that of the MIT accelerator but the beam pulse length is considerably longer (~45 μsec). It is expected that a beam power up to 200 kW will be obtained. The accelerator will be provided with rf power by 12 klystrons, each having an average power capability of 100 kW. If achieved, this will be the highest average power per tube of any of the electron machines existing or proposed. At this date, the Amsterdam accelerator has not yet been authorized.

The 2.3 GeV Orsay accelerator is now the second highest energy electron linac (after SLAC). The length of this accelerator was approximately doubled in 1968 to its present length of 350 m. One of the important roles of this accelerator is to feed the 500 MeV ACO positron-electron storage ring.

The 2 GeV Kharkov accelerator began operation in 1965. Unfortunately, this machine has been troubled with beam breakup problems for a long time. Until recently, the peak beam current achieved was ~10 mA. During 1969, the addition of 4 radial slots 0.4 mm wide in the first section of the accelerator plus improved focusing resulted in an increase in the beam breakup threshold to ~15 mA. The slots were formed in the existing section by an electrical discharge milling technique using a long wire which passed through the section. Five different slot lengths were used in the section. The 4.5 meter section was removed and subdivided into lengths of ~1 meter for slotting purposes. From discussions at the 1969 Yerevan conference it was understood that work was underway on the slotting of 4 additional sections. We have not been able to learn what beam breakup results were obtained as a result of this additional slotting. The Kharkov accelerator has a relatively low beam duty cycle (6×10^{-5}). The pulse repetition rate is 50 pps and the beam pulse length is 1.3 μsec. RF power is provided by 50 - 20 MW klystrons. The average life of these tubes has been ~ 3000 hours although some have lived as long as 10,000 hours.

Three notable omissions from Table 1 are the 150 MeV linac at the National Bureau of Standards, the 450 MeV linac which serves as the injector for the storage ring "Adone" at Frascati and the 1.1 GeV Stanford accelerator. While complete details are not available on the first two machines, it is understood that neither has changed significantly in the past 2 years. The 1.1 GeV Stanford accelerator has been in operation since 1951. It is not being reported in detail here since it is scheduled to be shut down at the end of 1970 in order to make room for a new superconducting accelerator which will be installed at the same site. Design details and results achieved during the development phase of this program are presented in Ref. 1.

III. Recent Performance and Improvements

This section of the report deals exclusively with the SLAC accelerator. The two-mile machine has now been in operation for over four years. Activities concerned with the accelerator proper can be divided into three categories: improvements in beam performance (e.g., higher currents and energies), improvements in flexibility (e.g., better time multiplexing of beams with different characteristics) and improvements in efficiency and reliability (e.g., better klystrons and other components, improved preventive maintenance, more efficient control through centralization and computerization). All the work summarized in the next few paragraphs falls into one or more of these categories.

A. Higher Energies and Currents

The maximum no-load energy (22.1 GeV) of the accelerator is presently limited by the number of klystrons on-line (245 tubes) and their output power (~ 21 MW). Each klystron contributes about 90 MeV of energy. In practice, the maximum energy is lower (18 - 20 GeV) because of klystron maintenance and repairs, because of phase drifts and because of beam loading (~ 35 MeV/mA). (For methods of obtaining higher energies, see Section IV).

The maximum available current is limited by energy spectrum width, beam breakup and gun emission (for chopped beams only, see below). Spectrum broadening results from a wide variety of factors: transient beam loading, rf amplitude and phase variations, finite bunch width, etc. (See for example, Ref. 4, Chapters 6, 7, 8.) While the accelerator was originally designed for ~1% spectrum operation, increasingly higher resolution experiments often require 0.1 to 0.5% energy-defining slit widths. This results in lower and often less stable peak currents. Remedies presently under way include finer control of klystron timing delays and improvements in a device[5] called "gulch filler." This "gulch filler" makes it possible to add a short rf accelerating pulse of the correct amplitude, shape and timing which compensates for energy (and therefore analyzed current) deficiencies within the pulse.

The second factor limiting the current is beam breakup. The beam breakup remedial program has been described in many papers (e.g., see Ref. 5). Detuning or "dimpling" of the accelerator to shift the HEM_{11} resonance (4139.6 MHz) by 4, 2, or 0 MHz was completed in December 1969. It increased the beam breakup threshold to 76 mA at 17 GeV and 1.6 μsec pulse length. A final summary of the results is given in Fig. 1. Any further improvements will have to be obtained by increasing the quadrupole focusing strength near the end of the accelerator. It is expected that the pulsed quadrupoles (see below) which are gradually being added to complement the dc quadrupoles will increase the threshold at high energy up to about 80 mA. In practice, the currents used by typical experimenters rarely exceed 50 - 60 mA.

The third factor which in the past has limited the current under chopped beam conditions is gun emission. This factor will be discussed further in Section III. C below.

B. Multiple Interlaced Beam Operation

From the very beginning the accelerator was theoretically capable of supplying six interlaced beams of diverse energies and currents. The range in diversity, however, was and still is limited by the dc nature of the steering, focusing and other devices such as the beam loading delays. An optimum set of steering and focusing conditions for one beam may not be acceptable for another beam. For example, to obtain the highest possible beam breakup threshold, it is necessary to operate the quadrupoles at the maximum available strength compatible with the energy of the beam. The dc quadrupoles along the accelerator can be adjusted according to a rising profile or "taper" up to an equivalent maximum of 11 GeV. However, such a "taper" creates an energy stop-band for any other beam of lower energy. Thus, in practice, the accelerator is operated in either one of two regimes. If one or more of the several beams to be run at a given time is below 11 GeV, the quadrupole strength profile is set for the beam of lowest energy. The analyzed current transmitted beyond the energy-defining slits (for 0.2, 0.5, and 1.0% settings) as a function of energy is then as shown in the lower part of Fig. 2 (assuming the lowest energy beam is at 4.5 GeV). Conversely, if all beams have energies equal to or greater than 11 GeV, the quadrupole strength profile is set to its maximum allowable "taper" of 11 GeV. In this case, the obtainable analyzed currents are as shown in the upper part of Fig. 2.

In summary, the following rules of thumb can be used to predict the peak current that can be obtained for a 1.6 μsec pulse length:

Slit width	0.2%	≥ 0.5%
All beams above 11 GeV	25 - 30 mA	50 - 55 mA
One beam in the 5 GeV range	10 mA	18 - 25 mA

The handicap incurred by all beams in the presence of one low energy beam should gradually disappear over the next 18 months as pulsed quadrupoles and pulsed steering are installed on the machine between Sectors 10 and 30. Four of these devices which have already been described in Refs. 5 and 6, are now in operation and 16 more will be forthcoming. At present, these quadrupoles, three of which are located at the end of the accelerator, are used occasionally to adjust the beam spot size or angle into the beam switchyard on a pulse-to-pulse basis. Similarly, the fine control over klystron timing delay is also being instrumented so that in five selected sectors, it can be varied on a pulse-to-pulse basis. It will be shown in Section IV that these features will become indispensable when the SPEAR storage ring goes into operation.

C. Injector and Beam Chopper Improvements

For the past four years, the SLAC guns have proved to be extremely reliable and long-lived (over 10,000 hours life). Their only limitation has been encountered when chopped beams are interlaced with regular beams. This condition calls for extreme requirements, i.e., pulse-to-pulse gun control in the mA and ampere ranges. For this reason and in order to increase the reliability and serviceability of the gun modulator, it was decided over a year ago to install a second gun and gun modulator in the injector area (see Fig. 3). Thus, one of the two guns can have a higher perveance than the other and it can be used when extremely high rejection ratios (e.g., 1 bunch every 100 or 200 nsec) and high emission currents ($\geq$ 1A) are needed for time-of-flight experiments. The first off-axis gun was installed in March 1970. The design of the so-called "α-magnet" which causes the 50 - 80 kV beam to loop around and bend by 255° was very successful and has been operating essentially trouble-free. For the time being, this α-magnet is capable of operating only as a dc device; thus only one gun can operate at a time. By January 1971 it is expected that it will be replaced by a pulsed magnet and each gun will have its own modulator. Grid control will be effected by variable height cathode pulsers rather than by the present combination of fixed cathode pulsers and variable grid bias. The entire system will be adjustable on a pulse-to-pulse basis.

The capability of the beam chopping system (sometimes called BKO, for "beam knock-out") has been expanding steadily during the past year. A block diagram is shown in Fig. 4. Until about one year ago,[5] it consisted of two sets of deflecting plates, one resonant set driven at 40 MHz and the other, nonresonant, driven at a variable frequency between 5 and 20 MHz. The combination is capable of producing single bunches every 12.5 nsec and at various other multiples and intervals. The currents obtained are shown in Table 2. More recently, a fast grid pulser built for SLAC by E. G. &G. * has been added to the system. It is capable of producing bunch trains or bursts as short as 7 nsec, adjustably spaced. Up to three different spacings can be selected on a pulse-to-pulse basis. When used together with the 40 MHz system, it can produce single bunch trains. With a high perveance (~ 0.2 microperveance), 4.5 mA currents have been obtained with single bunch trains spaced 50 nsec apart.

D. Positron Production

The positron source in Sector 11 is used when an experimenter desires monoenergetic ($\leq$12 GeV) positrons. Two modes of positron operation are presently available. The first is used when positrons (or electrons) from the radiator are used exclusively. In this case the target (called "wheel" because it is made to rotate to prevent localized high temperatures) occludes the accelerator pipe completely. All impinging electron beams (with typical energies of the order of 6 GeV) are intercepted. The second mode, called the "flicking" mode, is used when the positron beams must be run interlaced with electron beams from the injector in Sector 0. In this regime the positron radiator is fixed but it only partially occludes the beam aperture (see Fig. 5) extending 1.5 mm beyond center. The beam aperture in the vicinity of the positron radiator is 17 mm in diameter and the beam is normally focused to about a 2 mm diameter at the radiator. Thus, it is not difficult to steer one beam pulse so that it hits the radiator at the center of the aperture, and to steer a second beam pulse, so that it misses the radiator and gets accelerated as an electron beam. It is expected that this "flicking mode" technique will be used to load the storage ring beams. (See Section IV. B.)

The positron yields presently attainable and expected in the future are shown in Fig. 6 as a function of the repetition rate. The decaying portions of the curves are due to the fact that above a certain repetition rate, the positron radiators are power limited.

E. Control Room Consolidation and Computer Control

For historical reasons, when SLAC was built, it was decided that the accelerator would be controlled from one control center ("CCR," the Central Control Room) and the beam switchyard from another ("DAB", the Data Assembly Building). After two years of operation and experience with two separate control rooms, the question was raised as to whether operating efficiency would be increased if the controls were to be centralized in one room. A long and fairly controversial study was carried out and it was concluded that the decision should be deferred in favor of better local instrumentation and control in both CCR and DAB and improved voice communication between them. It was also concluded that more experience was needed with the CCR and DAB control computers (a PDP-9 and SDS-925, respectively) before any consolidation could be contemplated, either technically, administratively or financially.

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More recently, after many of the above requirements had been fulfilled, the question was opened once again and it was decided that consolidation should now proceed. A plan was developed that will make it possible to control both the accelerator and the beam switchyard from the present DAB. The room will be called Main Control Room (see Fig. 7) and should become operational by about summer 1971. Most of the controls now located in the CCR and DAB will be left intact. To make the consolidation economically feasible, two features will be used:

a) Most of the signals from CCR to DAB and vice-versa will be transmitted through a computer link with a 10 kilobit/sec capacity. Only some of the beam guidance signals will be hard-wired.

b) The control surfaces for the CCR signals now to be located in the DAB will make use of a novel invention[7] called "touch panel" shown in Figs. 7 and 8. This touch panel consists of two elements: a TV screen for information display and an orthogonal array of surface wave collimated beams launched on the TV glass surface. The transmitters and receivers shown in Fig. 8 consist of piezoelectric ceramic transducers and lucite wedges cemented on the glass at regular intervals. Each intersection of two beams represents one "pushbutton" which can be actuated by applying direct finger pressure on the glass. Finger pressure attenuates the received signal by ~10 dB. The coordinates of this button are fed to the SDS-925 computer and used to perform a particular function; this function is generally related to the information displayed on the TV screen behind the button. Thus, both the display and the functions of the buttons can be reprogrammed at will by means of the proper software. Great flexibility and versatility are thus attained, making it possible to build a "library" of desirable panels, each of which can be called out by the operators when needed.

A prototype touch panel has recently been installed in the DAB and has operated successfully for more than two months. It is believed that once the basic hardware and software are developed, an additional panel can be programmed in approximately one week.

Referring back to Fig. 7, much of the present effort involves connecting inputs and outputs to the PDP-9 in CCR and preparing the link hardware. On the SDS-925, many of the beam switchyard signals are already available. Most of the effort ahead is in the software area. A system is being purchased from the Datadisk Corporation, Palo Alto, California, to interface the SDS-925 computer to 8 (expandable to 16) TV displays. An effort is also being made to facilitate programming by linking both computers to the IBM 360-91 available at SLAC and doing some of the printing and assembling on that machine.

F. Klystron Performance and Life

The SLAC accelerator has now been operating for about 4 years which is a sufficient period of time to allow a reasonably good assessment of the performance and life of the high power klystrons. The standard version of these tubes is rated at 21 MW peak, 22 kW average power output. The klystrons typically operate at a repetition rate of 360 pulses per second and a pulse length of 2.5 μsec.

Through June 30, 1970 a total of 4,527,500 klystron hours have been accumulated during somewhat more than 17 quarters of operation. The total number of failures through the same date was 289; thus, the cumulative mean-time-between-failures (MTBF) was ~15,700 hours. The mean age of all tubes which have failed was 5,650 hours. The cumulative MTBF has been roughly constant at around 15,000 hours for the past 3 years. On the other hand, the mean age of all failed tubes has increased from 1,060 to 5,650 hours during this same period and is continuing to rise at this time. Klystron operating statistics during the entire life of the accelerator are shown in Fig. 9. The age distribution of all the klystrons now in operation on the accelerator and the life distribution of all the failed tubes are shown in Fig. 10. It can be seen from the upper graph that somewhat more than 40% (107 tubes) of the tubes attached to the machine have operated more than 15,000 hours. About 5% of the tubes have operated more than 20,000 hours. On the other hand, the peak of the failure distribution occurs at a relatively low age: about 25% of the failed tubes have expired at an age of 1,000 hours or less.

As discussed in Section IV.A. the replacement of the 20 MW klystrons by higher power (30 MW) tubes is now underway. The replacement occurs as the existing tubes fail. Operating experience with the 30 MW tubes is still insufficient to allow a prediction of their life under these more elevated operating conditions.

IV. Future Plans and Possibilities

A. High Power Klystrons

As discussed in Section III.F, the SLAC 21 MW klystrons are being gradually replaced by 30 MW klystrons through the normal attrition process. At this date, 4 sectors comprising 32 klystron stations are now equipped with the higher power tubes. Basically, the increase in klystron power has been accomplished by means of the following actions: 1) the klystron efficiency has been increased from 38 - 40% to 42 - 44% by means of optimizing gun design, drift lengths and focusing conditions; and 2) the operating voltage has been increased from ~245 kV to ~265 kV. The existing modulators are capable of the higher power operation without modification. As the number of higher power klystrons attached to the accelerator gradually increases, the maximum energy capability of the accelerator will increase accordingly. When the accelerator is equipped with a full complement of 30 MW tubes 2 - 3 years from now, its maximum energy will have increased from the present maximum of about 22.1 GeV to about 25 GeV.

B. Injection into SPEAR

One of the major developments in the next 18 months at SLAC will be the inception of the SPEAR electron-positron storage ring.* The construction of this project will not only constitute a challenge[8] per se but it will also tax many of the existing linac systems involved in injecting the positron and electron beams to be stored. It is beyond the purpose of this paper to describe these in detail. Some of the essential elements are shown in Fig. 11. The goal is to store e^+ and e^- currents of about 0.5 amps each, which correspond to about 2×10^{12} particles of each sign. This would be an easy task if it were not for three constraints.

a) The SPEAR rf is 42 MHz; the harmonic number is 31, i.e., there are 31 buckets available around the ring which can be filled; actually, since only one ring will be built initially, beam-beam instabilities will dictate that it be possible to fill only a small number of buckets, perhaps one, two or three.** These buckets are 1/42 MHz or ~24 nsec apart; upon injection, each of them should be $< 120^{\circ}$ electrical or ~7-9 nsec long.

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* Final approval for construction of this ring has not yet been given but is expected shortly.

** During testing and in case the second ring should get built, this restriction will be lifted.

b) Because of the particular tune (5-1/4 betatron wavelengths per turn) that has been chosen, each bucket, before damping, would come back to the point of injection after 4 revolutions around the ring. Each bucket takes 730 nsec per revolution. In practice, this means that only 2 bucket-trains (spaced 730 nsec apart) can be injected per accelerator pulse (1.6 nsec). (See lower part of Fig. 11 where two 3-bucket trains have been shown as an example.)

c) After each injection pulse it is necessary to let the betatron and synchrotron oscillations damp out sufficiently before the kicker magnet can be turned on again. This damping time is 50 msec and corresponds to a filling rate of 20 pps.

The net result of these restrictions is that it may take about 5 minutes to fill the ring with positrons and slightly less for electrons (because these are available somewhat more copiously from the positron source).

Since the storage ring will need to be loaded quite often and on very short notice, it is expected that about 20 pps will have to be reserved at all times. Each beam will run at a low repetition rate with an energy of 1.5 GeV. Either the tuneup dump or the slit in beam line 15 will be used for energy analysis. The proper synchronization of the SPEAR rf and the injection chopping rate will probably be achieved by means of short synch pulses generated from the 42 MHz rf and sent to the injector via the drive line. Notice that in order to fill the same buckets on consecutive machine pulses, these synch pulses will be indispensable. As discussed in Section III. C, they will be used to trigger the E.G. & G. pulser. To make the SPEAR beams compatible with other beams, the positron source will be operated in the "flicking mode" (Section III. D). The pulsed quadrupoles and dipoles (see Section III. B) along the machine will be used to transmit the 1.5 GeV beams interlaced with other higher energy beams. All these problems will be very interesting to synchronize.

C. Upgrading of the Accelerator - Medium and Long-Range Plans and Possibilities

The gradual increase of the accelerator energy up to 25 GeV (see Section IV. A) and the inception of SPEAR (discussed in Section IV. B) constitute two of the medium-range plans of the laboratory. Certain other ideas for upgrading the duty cycle and the energy of the machine are under consideration. None of these ideas has progressed past the conceptual stage at this time.

1. Increased Duty Cycle. In the first and simplest of these schemes (see Recirculation Method 2 in Section IV. C. 4 below for discussion of another method of increasing duty cycle), the duty cycle of the accelerator is increased by a factor of two, but only at the expense of reducing the beam energy by a factor of $\sqrt{2}$. There are two variations of this method. In the first variation, the existing 6-ohm pulse forming network in the klystron modulator is split into two parts, each having a characteristic impedance of 12 ohms as shown schematically in Fig. 12. The task of splitting the network in this fashion is quite simple. The network is already divided in this manner because originally two thyratrons were needed to switch the network pulse current. At a later date, single thyratrons capable of handling the entire current became available and replaced the dual thyratrons. The basic network configuration was not changed at that time. For the present purposes a separate thyratron switch is again provided for each half of the network. The first thyratron is triggered to discharge the first half-network through the pulse transformer. This action provides a reduced (see below) voltage pulse to the klystrons. The klystron in turn produces an output rf pulse suitable for accelerating an electron beam pulse. At a time 1/720 sec later, the second thryratron is triggered to discharge the second half-network

through the pulse transformer. Thus, the maximum repetition rate of the accelerator has been effectively increased from 360 to 720 pulses per second. It would also be possible to provide trains of unequally spaced pulses, if desired. An extreme variation of this idea would consist of two successive pulses with no space between, giving in effect a single pulse of double length.

In the schemes just described the effective network impedance Z is twice as high as in the case where the two half-networks are switched simultaneously. Since the effective capacitance is one-half as high for one half-network as for two, the pulse length ($\tau = 2CZ$) is the same whether the half-networks are fired separately or simultaneously. The klystron beam voltage for each pulse (assuming a pulse network voltage of 41.6 kV) will be ~197 kV which will result in an rf power output of ~12 MW.

Since the klystron impedance varies as $V_K^{-1/2}$ where V_K is the klystron beam voltage, there is an impedance mismatch between the half-network impedance (12 ohms) and the klystron impedance (~7.8 ohms) referred to the primary side of the pulse transformer. A mismatch of this type means that there will be a positive backswing of the voltage pulse applied to the klystron during the 2.5 μsec period following the main pulse and additional negative and positive pulses of decreasing amplitudes during successive 2.5 μsec periods. These alternating pulses are undesirable and may cause instabilities or damage to the modulator components or to the klystron. It may be necessary to decrease the turns ratio of the pulse transformer from 12 to ~9.5 in order to obtain a good impedance match between the klystron and pulse transformer. This change would also result in a slight increase in the klystron beam voltage to ~201 kV. It would be desirable to provide a simple tap on the primary of the pulse transformer so that the turns ratio could easily be changed externally to satisfy the requirements of either normal 360 pps accelerator operation or 720 pps operation as described above.

Assuming that the double pulse operation described above proves feasible, the klystron power output in each pulse could be ~12 MW. The energy gain in the accelerator due to each klystron is $\sim 20\sqrt{P}$ MeV where P is the klystron output in MW. For P = 12 MW, the contribution of each klystron during each accelerator pulse would be ~69.3 MeV, or a total no-load energy gain of 16.6 GeV for 240 klystrons in operation.

In a second variation of this method one modulator supplies pulse power to two klystrons in parallel during each pulsing action. At a time 1/720 second later (or other time separation, if desired) an adjacent modulator supplies pulse power to the same two klystrons. In this variation it is not necessary to split the pulse forming network inside the modulator into 2 parts and to provide a second thyratron switching tube. The circuit arrangement is shown schematically in Fig. 13. The net energy gain for the two variations of this duty cycle doubling scheme is the same. In the second variation, it may also be desirable to provide taps on the primaries of the pulse transformers so that impedance matching can be accomplished. Variation 2 has an advantage over variation 1 in that an additional thyratron is not required in each modulator. It is also possible that, because the circuits associated with the generation of the two closely spaced pulses are separately housed in two different modulators, variation 2 will encounter fewer difficulties and instabilities stemming from pulse-to-pulse interactions than variation 1. However, in variation 2, an additional pulse cable is required to each klystron and an additional coaxial connector must be provided on each transformer tank.

2. Increased Beam Energy. In recent months, various particle physics experimental results obtained at SLAC have triggered renewed interest in the 25 - 40 GeV range. One of the "brute force" methods of increasing the energy is to double the number of klystrons (→ 28 GeV) or to quadruple it (→ 40 GeV). These schemes originally called Stage 1-1/2 and Stage 2 are straightforward but they are very costly. Another old idea which has recently been revived[9, 10] is that of recirculating and reaccelerating the beam. Several methods are presently being considered. All have one feature in common: a beam transport system with the correct optical properties. Figure 14 illustrates two possible configurations. The first or "racetrack" system (upper half of figure) consists of two 180° bends and one two-mile long separate return path. The second (lower half of figure) consists of two ~360° bends in the shape of "tear drops;" the return path can be installed in the accelerator housing.

The "racetrack" system requires half as many magnets and power supplies but necessitates a second tunnel, expanded real estate with additional utilities, vacuum system, monitors, beam guidance, etc. The "double tear drop" system, which seems more attractive, requires ~720° worth of bending magnets but can make use of the existing tunnel, the recirculating path being a small pipe parallel to the accelerator. (It has even been suggested that this pipe could be the accelerator itself, although this method would increase the transient beam-loading by 35 MeV/mA).

The optical requirements of the beam transport system depend on the method of reacceleration. Two recirculation methods are described below. In the first method, the present modulators are modified according to one of the two schemes described in C. 1 above so that they can produce two consecutive pulses (but at a lower voltage). However, in this case, the trigger system causes the pulses to be spaced ~20 μsec apart instead of 1/720 second as in the duty-cycle doubling scheme. The beam only recirculates once and the energy acquired on each pass is ~14 - 16 GeV for a total of 28 - 32 GeV. In the second method, the beam, after the first pass (15 - 20 GeV), is stored until 1/360th of a second (~2.8 msec) later, when the next rf pulse comes along and gives the beam an extra 20 GeV for a total of 35 - 40 GeV (Ref. 11).

If the beam recirculates only once, the transport system must be very close to isochronous to preserve the longitudinal phase space required by the rf accelerating wave. For multiple passes (~120), building a nearly isochronous system may prove impossible. The system might function much like a fixed energy synchrotron with a "make-up" rf section and with longitudinal phase stability. It remains to be seen whether such a transport system can be built and whether it can be matched into the accelerator for the last pass. As synchrotron designers know, the statistical nature of the synchrotron radiation causes transverse phase space broadening. Further work must be done to determine the damping and antidamping characteristics of the system. Whether the lattice would be of the A. G. or separated function type is not known at this time.

3. Recirculation Method 1. In this method, as noted above, the beam only recirculates once and thus only 3 transits of the beam along the accelerator length are required. The first of these transits is the usual accelerator passage in the forward direction through the accelerator structure. The second transit, which occurs after the beam is bent through 360° (or 180°) in the research area, is in the backward direction to return the beam to the injection end of the machine. This reverse transit can occur within the accelerator tube itself, within a separate tube located in the underground Accelerator Housing or in a tube located outside and parallel to

the Accelerator Housing (see Fig. 14). The third transit, which occurs after another 360° (or 180°) bend at the injector end, is a second acceleration passage through the accelerator. The second acceleration transit occurs approximately 20 μsec after the first acceleration transit. Thus, it is necessary to provide two pulses of rf power separated by ~20 μsec from each klystron. The no-load energy gain in the first accelerating transit is ~16.6 GeV as calculated in Section IV.C.1. Assuming that a beam current of 20 mA is accelerated during this transit, the energy loss due to beam loading is 0.70 GeV. The beam energy at the end of the first passage is thus 15.9 GeV. The energy loss due to radiation in a 360° bend at the target end of the accelerator is 0.11 GeV. Assuming that 5 mA are lost in this bend, the surviving 15 mA beam would lose 0.52 GeV due to excitation of the accelerator structure by the beam. Another energy loss of 0.10 mA GeV would occur in the 360° bend at the injector end of the accelerator. If another 5 mA of beam current is lost in the second bend, the remaining 10 mA beam will incur a further 0.35 GeV energy loss due to beam loading in the second acceleration passage. Thus, the net energy gain would amount to 16.6 - 0.70 - 0.11 - 0.52 - 0.10 + 16.6 - 0.35 = 31.4 GeV. For the same assumed current losses, the net energy gain would be roughly 0.6 GeV higher (~32.0 GeV) if the bends at the ends of the accelerator were 180° each and the beam were transported to the injector end through a tube located outside of the Accelerator Housing.

4. Recirculation Method 2 (Ref. 11). As indicated above, the second method would require no modification of the existing klystron-modulator system in that the beam would be accelerated once and then recirculated many times (~120) until the next rf pulse came long, ~2.8 msec later. On the other hand, the synchrotron radiation losses would have to be made up on a CW basis. The proposed idea is to put a superconducting linac section in the return loop or in one of the tear-drop loops. Estimates of power requirements are as follows.

The synchrotron radiation loss is given by[12]

$$U = 8.85 \times 10^{-32} \frac{V^4}{r} \text{ eV}/360^\circ \text{ turn}$$

where V is the beam energy in electron volts and r is the radius of curvature in meters. The power required depends on the current (i) which is being recirculated:

$$P = \frac{Uit}{T} = \frac{8.85 \times 10^{-32} \times V^4 it}{T r \cos\theta} \text{ watts}$$

where t is the SLAC pulse length (~1.5 μsec), T is the recirculation time (~20 μsec) and θ is the beam angle from crest. Assuming a bending radius of 50 m, and 5 mA recirculating current and $\theta = 0$, one obtains the requirements shown in Table 3.

The rf power figures in Table 3 assume that the electrons are riding on crest. For phase stability, these numbers would have to be increased by perhaps as much as 50%. Notice that because of the fourth-power dependence on V, the power requirements increase very rapidly with the first "pass" energy. Referring to some of the results given in Section IV.D, satisfying the power demand for a 15 GeV, 720° bend would require 4-6 20 kW klystrons and associated superconducting accelerator sections. Such a requirement would not seem unreasonable.

In this method, however, where rf power and energy spectrum width are at a premium, it would be impossible to use the two-mile accelerator itself as the return path. A second inexpensive pipe would be used. An alternate injector could be installed to simplify the "coexistence" problem of the high energy beam (on its last pass) with the low energy beam (just being injected).

As seen, even disregarding cost, several complicated problems would have to be solved before this method could be implemented. On the other hand, it would have the advantage that after the first pass (15 - 20 GeV), the system could be used as a beam stretcher with a 7% duty cycle. Another possibility to be contemplated would be to complete the circle in the BSY loop and use it as a storage ring.

It has been pointed out that both transport systems are suspiciously reminiscent of one or two electron synchrotrons. While this is partially true, it should also be pointed out that in contrast to a synchrotron, these loops operate at fixed field. It would not be straightforward to build a 360 pps synchrotron injector into the SLAC linac.

The advantages of recirculation method 1 over method 2 are: 1) only two additional one-way transits of the accelerator length are required instead of ~240 transits as required in method 1; 2) the superconducting accelerator section to make up for energy losses in the 360° bends at the end of the accelerator is not required; 3) fewer additional instrumentation and control circuits and devices are needed: 4) since only one transit in the backward direction is required, it may be feasible to use the accelerator itself as the transmission path; 5) the problems associated with minimizing beam loss and preserving isochronicity should be less; and 6) the overall cost should be less. The disadvantages of method 1 compared to method 2 are: 1) the net energy gain is somewhat lower; 2) the modulators and klystrons are operated in a new mode for which component life and reliability data are not available; and 3) it is not possible to obtain a "stretched" beam as in method 2.

In both recirculation methods, the beam breakup threshold will undoubtedly be reduced below the level obtained for a single acceleration passage. One might expect that the threshold would be lower for method 2 with many transits than for method 1 with only a single recirculation of the beam. The resistive wall effect and the excitation of higher order modes in the vacuum pipe may also cause beam transmission problems but these phenomena have not yet been studied in detail.

D. Conversion to Superconducting SLAC

A study of the feasibility of converting the two-mile SLAC accelerator to a superconducting machine has been carried out for the past 1-1/2 years.[13, 14] Design goals are a beam energy of 100 GeV and a duty cycle of 6%. Since the rf losses are proportional to the square of the energy gradient, higher duty cycles are possible at lower energies without increasing the capacity of the refrigeration system. For example, a 24% duty cycle should be achievable at a beam energy of 50 GeV and a 100% duty cycle at an energy of 25 GeV. The basic design parameters at the 100 GeV energy level are given in Table 4.

The feasibility study described in Ref. 13 has encompassed not only the accelerator structure itself but also the associated equipment and facilities which comprise a complete accelerator complex. In these studies, efforts have been made to select accelerator parameters which would utilize as many of the existing systems and facilities as possible without detracting from the scientific utility of the machine to a significant degree.

Studies of superconducting materials are now in progress at SLAC. The objectives of this program are to demonstrate the feasibility of obtaining an energy gradient of 33 MeV/m and to obtain sufficiently low surface resistance to permit operation at a 6% (or higher) duty cycle with a reasonable refrigeration system capacity. Although several materials including lead, technetium, and niobium have been investigated, the results obtained to date indicate that niobium is the optimum choice at this time. SLAC studies have been confined to structures fabricated from bulk or sheet niobium. Other techniques such as electroplating and vacuum evaporating may be investigated later.

The niobium material is first formed in cells or half-cells by either machining, electroshaping* or coining. The components are then joined together by electron beam welding. In order to minimize the possibility of obtaining excessive field emission or reaching the critical magnetic field at gradients below the design level, the welding passes are made from the inside of the cavity. This technique produces a smoother finish than can be obtained from an outside welding pass.

After fabrication, the cavities are processed by etching in an acid bath, vacuum firing at a temperature of 1600 - 2000°C, etching again, and then refiring at high temperature. The vacuum firing of the small X-band test cavities is accomplished by induction heating inside a quartz vacuum envelope.

The electron beam welder now in use at SLAC is a Hamilton-Standard 25 kW model. A rectangular vacuum chamber 5 ft wide, 5 ft high, and 9 ft long is nearing completion. This chamber will permit electron beam welding operations at a base pressure of 10^{-7} torr. A new furnace with a hot zone approximately 5 inches in diameter and 8-1/2 inches in length is being constructed. When this furnace is completed, S-band cavities and short S-band accelerator structures can be processed at temperatures up to 2000°C and at pressures of 10^{-9} torr.

Recent measurements at X-band and at a temperature of about 1.85°K in an electron beam welded TE_{011} cavity have given a Q of 3.4×10^9 and a rf magnetic breakdown field of ~700 gauss. Assuming that Q scales with frequency as $f^{-1.6}$, the value of Q at 2856 MHz would be $\sim 2.5 \times 10^{10}$. This is approximately a factor of 6 better than required for the two-mile accelerator conversion (see Table 4). However, the breakdown field must still be improved somewhat (to approximately 1000 gauss) to allow future accelerator operation at a gradient of 33 MeV/m. It is hoped that better processing techniques, improvement of cavity configuration, and perhaps the shift from a TE_{011} to a TM_{010} test cavity will result in further improvement in the magnetic breakdown field. Fields of approximately 1000 gauss have already been attained in TM X-band niobium cavities by Turneaure and Viet[15] at the Hansen Laboratories of Physics at Stanford University.

The optimum shapes of disk loaded accelerator structures have been studied at SLAC by Helm[2] and Herrmannsfeldt _et al._[3] with the aid of two different computer programs. The program used in the work discussed in Ref. 2 calculates the properties of traveling-wave linac structures employing a functional expansion of the fields rather than by using the mesh technique. The second program employed in the work described in Ref. 3 is a new Fortran version of the LALA[16, 17] program written at the Los Alamos Scientific Laboratory. The LASL program was originally written to study standing-wave structures and the results have to be somewhat modified for traveling-wave structures. These studies have attempted to optimize the various cavity parameters such as shunt impedance, Q, and r/Q. In addition, particular emphasis has been placed upon minimizing the ratios of peak-to-effective electric and magnetic fields since these quantities will determine the maximum gradient which can be sustained in the resulting accelerator

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*Trademark of Cincinnati Shaper Company.

structure. The result is obviously somewhat of a compromise and indicates that a cavity operating in the $2\pi/3$ mode and having a slight bulge in the disk tip and an elliptical cross section at the outer wall possesses the best overall characteristics. Such a structure having a peak-to-effective electric field ratio of 1.66 and a peak-magnetic-to-peak-electric field ratio of 31 G/(MeV/m) is described in more detail in Refs. 2 and 3.

In addition to the work already described, other investigations of superconducting structures are also being carried out at SLAC. These include topics such as: 1) breakdown fields and residual loss; 2) nonlinear effects at high field levels; 3) radiation damage effects; 4) field emission; 5) thermal conductivity of materials; and 6) cavity deformation due to rf fields. These studies are discussed in more detail in Ref. 14.

The investigations just listed are limited by available manpower and financial support. Furthermore, there is no assurance that all of the potential problems which will be encountered in operating superconducting accelerators have yet been identified. For these reasons, it has been decided to proceed, in parallel with the basic investigations, with the construction of a short test accelerator. This program is referred to as Project Leapfrog. Leapfrog differs from other superconducting accelerators being planned or fabricated elsewhere in that the accelerator structure is a constituent part of a traveling-wave resonant ring rather than being operated as a standing-wave device. This tentative design choice has been made not only for Leapfrog but also for the two-mile conversion study since it appears that the peak-to-effective field ratios in this structure are 20 to 30% lower than the equivalent values in a practical standing-wave accelerator. The Leapfrog accelerator structure is 52.5 cm (15 cavities) in length. In general, the rf and gradient characteristics of this small accelerator are similar to those already discussed in conjunction with the two-mile accelerator conversion. The Leapfrog accelerator is shown inside of its dewar assembly in Fig. 15. The dewar is approximately 2 ft in diameter and 5 ft high. The thickness of the S-band cavity walls will be ~0.100 inches. The rectangular waveguide return loop will be fabricated from 1/8 in thick niobium sheet. Leapfrog is being designed for a gradient of 33 MeV/m. For a power input of ~860 W from the klystron, the circulating power at rated beam current (48 μA) will be 30 MW. The design loaded energy is 17.2 MeV. On a schedule basis, Leapfrog is divided into 2 stages. In Stage 1, the accelerator will be tested with rf power only (without a beam) to check the capability of obtaining the design gradient and to determine the feasibility of phasing and matching the feedback loop. This stage should be complete by the end of calendar year 1970. In Stage 2, the accelerator will be placed in a new horizontal dewar and operated with an electron beam.

Cost estimates[13,14] (based on 1969 prices) of converting the two-mile accelerator to a superconducting version range from $67 M to $79 M, the exact cost depending upon the final feasibility of various design alternates. The above figures include a 25% contingency and are based upon an operating frequency of 2856 MHz.

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TABLE 1

SELECTED CHARACTERISTICS OF SEVEN ELECTRON LINACS

CHARACTERISTIC	SACLAY (ALS)	MIT[6]	AMSTERDAM (EVA)	AMSTERDAM (Proposed)	ORSAY	KHARKOV	SLAC
General							
Date of first operation	1968	1971	—	Not yet authorized	1960, 1968(14)	1965	1966
Total length (m)	185	180	7	200	350	240	~3000
$V_{max(i=0)}$(MeV)	640	430	95	550	2300	2000	22, 100
V(MeV) and I(mA) for typical operation	500/30	400/8.4	90/50	500/10	2100/60	1980/10	20, 000/40
ΔV/Δi (MeV/mA)	2.75	3	0.08	—	3	1.3	35
Duty cycle (%)	1 - 2(1)	1.8 - 5.6(9)	0.07	2.5 - 10(12)	0.025	0.006	0.06
Beam pulse length (max) (μsec)	10	14	3.5	45	1.7	1.3	1.6
Pulse repetition rate (max) (pps)	1000 - 2000(1)	5000	200	2000	50 - 150(15)	50	360
Frequency (MHz) and operating mode	2999/2π/3	2856/2π/3	2856/2π/3	2856/2π/3	2998/(π/2)/approx. const. grad.	2797/(π/2)/ const. imp.	2856 (2π/3) const. grad.
Electron Current							
i_p (max. unanalyzed) (mA)	61	40(5)	600	(< 200 kW Aver. beam power)	200	15	77
i_p (Δp/p = ± 0.5%) (mA)	61	—	≤ 50	(100%)	—	—	55
i_p (Δp/p = ± 0.25%) (mA)	55	10	≤ 50	(80%)	—	—	50
i_p (BBU limit; unanalyzed) (mA)	Not reached	50(6)	Not observed	—	—	15	77
Focusing system	Solenoids & quad triplets	Solenoids & quads	Quad doublet	Quad doublets	Solenoids & quads	—	Pulsed and dc quad doublets
HEM_{11} mode freq. (MHz)	Not observed	—	Not observed	—	Not observed	—	4140
Beam Power							
Pk. beam power (unanalyzed) (MW)	25	—	29	—	—	—	~1000
Aver. beam power (unanalyzed) (kW)	100(2)	60(10)	7	≤ 200 kW	—	—	~ 600
Injector							
Gun type	Triode	Tetrode	Diode	—	Diode	Diode	Spherical triode
Cathode type	Tungsten filament	Impregnated	Carbonized thoriated tung.	—	Tungsten	Tantalum	Oxide
Perveance ($A\ V^{-3/2} \times 10^{-6}$)	10^{-2}	10^{-3}	10^{-1}	—	—	—	1 and 2×10^{-1}
Gun voltage (kV)	40	400 (nominal)	130	(High)	60 - 120	80	50 - 80
Grid voltage (V)	800 - 1600	2500 (nominal)	—	—	—	—	-100 to +700
Injection current (max) (mA)	400	200	4000	—	3500	300	—
Injection current (min) (μA)	<10	<10	—	—	—	—	≤ 10^{-4}

(continued)

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Table 1 (cont'd.)

CHARACTERISTIC	SACLAY (ALS)	MIT[6]	AMSTERDAM (EVA)	AMSTERDAM (Proposed)	ORSAY	KHARKOV	SLAC
Chopped Beam Capability	None	None	None	None	None	None	—
Chopping frequencies (MHz)	—	—	—	—	—	—	40 and 10 - 20
i_{pk} obtained (mA)	—	—	—	—	—	—	~12(7)
BBU threshold current (mA)	—	—	—	—	—	—	~12(7)
Positron Beams	—	None	None	None	—	—	—
e^- energy incident on radiator (MeV)	85	—	—	—	200 - 600(15)	—	6000
e^- current (aver) incident on radiator (μA)	300	—	—	—	24 - 32	—	20
e^+ energy (max) (MeV)	480	—	—	—	250 - 1800(15)	1200	12, 000
e^+ pk. current (unanalyzed) (μA)	36	—	—	—	30 - 70	~7	2400
Yield (e^+/e^-) for $(\Delta p/p)_{e^+} = \pm 0.5\%$	—	—	—	—	10^{-4}	4×10^{-4}	2×10^{-2}
e^+ pk. current ($\Delta p/p = 1\%$) (μA)	22	—	—	—	10 - 25	—	1200
Length e^- accel. path (m)	28	—	—	—	—	—	1000
Length e^+ accel. path (m)	160	—	—	—	—	—	2000
Phase Space (2-Dimensional)							
At injector output (e^-) (MeV/c) (cm)	—	$10^{-3}\,\pi$(11)	—	—	—	—	$10^{-3}\,\pi$
At end of accel. (e^-) (MeV/c) (cm)	$1.7\,\pi \times 10^{-2}$	$5 \times 10^{-3}\,\pi$(11)	—	—	—	—	$10^{-1}\,\pi$
At end of accel. (e^+) (MeV/c) (cm)	—	—	—	—	—	—	$3 \times 10^{-1}\,\pi$
Klystron Data							
Number of klystrons	15	10	2	12	38	50	245
Pk. power per tube (MW)	2 - 4(3)	1 - 4(16)	21 - 25	1 - 4(13)	20 - 25	20	21
Aver. power per tube (kW)	65	80	20	100	—	—	22
RF pulse length (μsec)	11	15	4	50	2.2	—	2.5
Cumulative MTBF(4) (hrs)	—	—	6000	—	—	—	~15, 000
Klystron life (hrs.)	>4000	—	—	—	—	~3000	>12, 000
Klystron cost ($)	~30, 000	~22, 000	8500	—	—	—	8300 and 9350(8)

Notes:

1. At 2% duty cycle, $V_{max(i=0)} = 450$ MeV.
2. 250 kW expected later.
3. 2 MW at 2000 pps, 4 MW at 1000 pps.
4. No. of kly. hrs. since beginning of operation ÷ No. of kly. failures since beginning of operation.
5. At pulse length ≤ 10 μsec.
6. Predicted results.
7. With 25 nsec burst spacing, i.e., 1 bunch accepted out of every 72.
8. Two separate contracts in 1963 and 1965; magnets are included in cost.
9. 1.8% at 400 MeV; 5.6% at 200 MeV.
10. At 400 MeV.
11. Design objectives
12. 2.5% at 500 MeV; 10% at 250 MeV.
13. 1 MW at 10% duty cycle; 4 MW at 2.5% duty cycle.
14. Machine built in 2 stages.
15. Because of the two stages of construction, machine can be operated in a wide variety of modes.
16. 1 MW at 1.8% duty cycle; 4 MW at 5.6% duty cycle.

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TABLE 2

CHOPPED BEAM CAPABILITY OF THE CHOPPING SYSTEM (17 GeV)

Chopper Frequency	Burst Spacing	Max. Average Pulse Current through 1% Slits
40 MHz	12.5 nsec (single bunch/burst)	~ 10 mA
40 + 20 MHz	25 nsec (single bunch/burst)	~ 8 mA
40 + 20 MHz	25 nsec (several bunches/burst)	~ 12 mA
40 + 10 MHz	50 nsec (single bunch/burst)	~ 2.5 mA
40 + 6.6 MHz	75 nsec (single bunch/burst)	~ 2 mA
6.6 + 20 MHz (continuously variable)	75 - 25 nsec (several bunches/burst)	1 - 15 mA (gun limited)
40 + 10 MHz + pulsed steering bias	100 nsec (single bunch/burst)	~ 1 mA
40 + 10 MHz + ≤ 50 nsec pulse on gun	one bunch (~ 10 psec long)	$\sim 10^9$ electrons

TABLE 3

POWER REQUIREMENTS FOR SUPERCONDUCTING LINAC "MAKE-UP" SECTION ASSUMING 50 m RADIUS AND 5 mA BEAM RIDING ON CREST

Energy after first pass (GeV)	15	20
Magnetic field required (kG)	10	13.3
Synchrotron radiation energy loss (MeV)		
per 360° bend	90	285
per 720° bend	180	570
RF power requirements (kW)		
for 360° bend	34	107
for 720° bend	68	214

TABLE 4

PARAMETERS OF A TWO-MILE 100 GeV SUPERCONDUCTING ACCELERATOR*

Operating frequency	2856 MHz
Length	3000 m
$\bar{r}$	1.72×10^{13} Ω/m
Q	4.0×10^{9}
Loaded energy (max)	100 GeV
Duty cycle	1/16
Peak beam current	48 μA
Average beam current	3μA
Peak beam power	4.8 MW
Average beam power	0.3 MW
Number of klystrons	240
Peak power per klystron	20 kW
Average power per klystron	1.25 kW
Type of rf structure	TW with rf feedback loop
Number of accelerator sections	480
Length of accelerator section	20 ft
Filling time (to 63.2%)	18 msec
Power dissipated in accelerator	12,000 W (4.0 W/m)
Pulse length (rf)	0.25 sec
Pulse length (beam)	0.24 sec
Time off between rf pulses	3.75 sec
Accelerator attenuation factor (τ)	37.0×10^{-7} nepers
Feedback attenuation factor (γ)	3.7×10^{-7} nepers
Bridge ratio (g)	0.546×10^{4}
Circulating power P_0 at η_{max}	54.6 MW

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[*] The values of parameters in this table are based upon operation at 100 GeV.

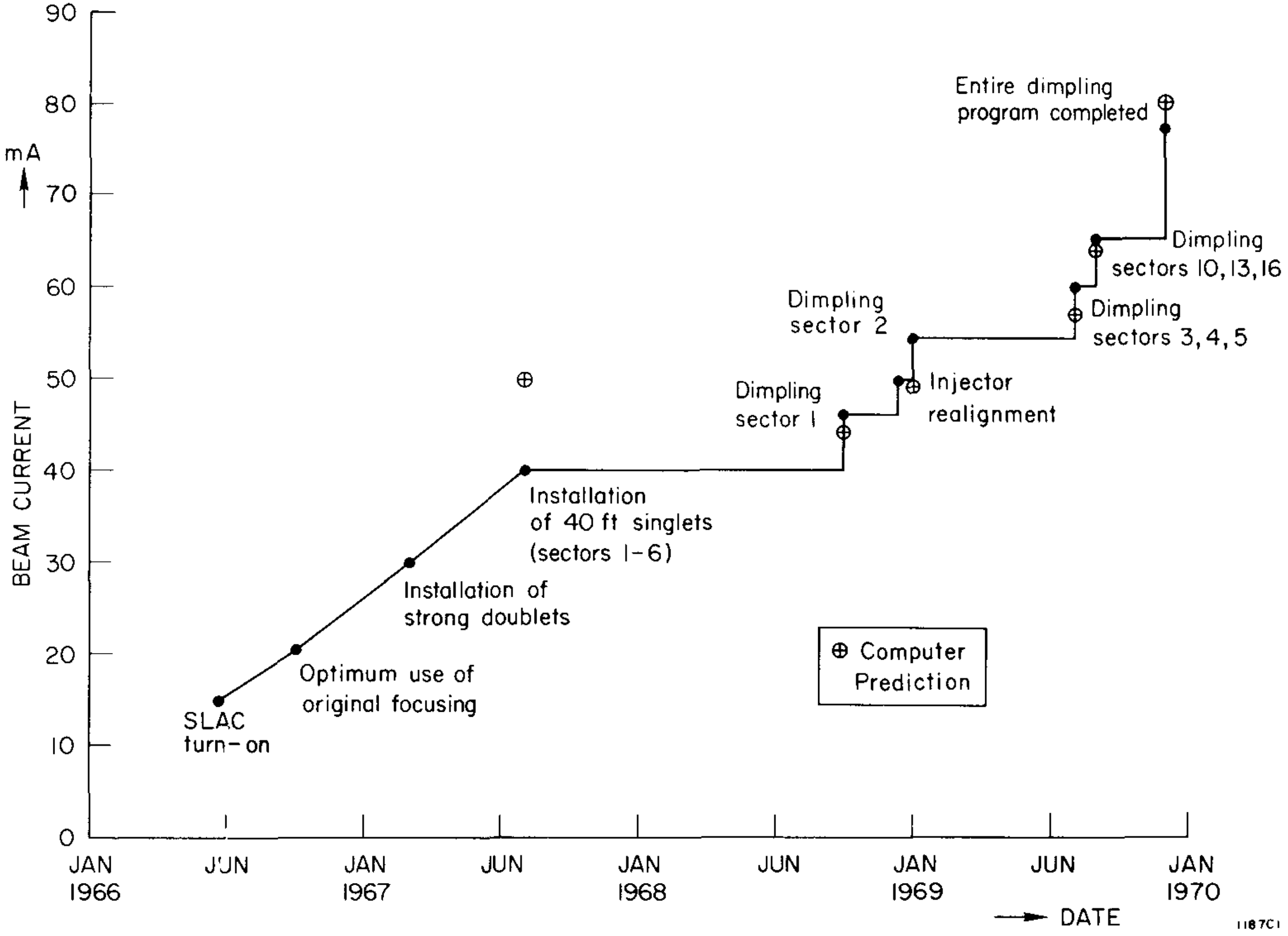


FIG. 1--Improvement of beam breakup threshold at SLAC as a function of calendar time (at 17 GeV and 1.6 μsec pulse length).

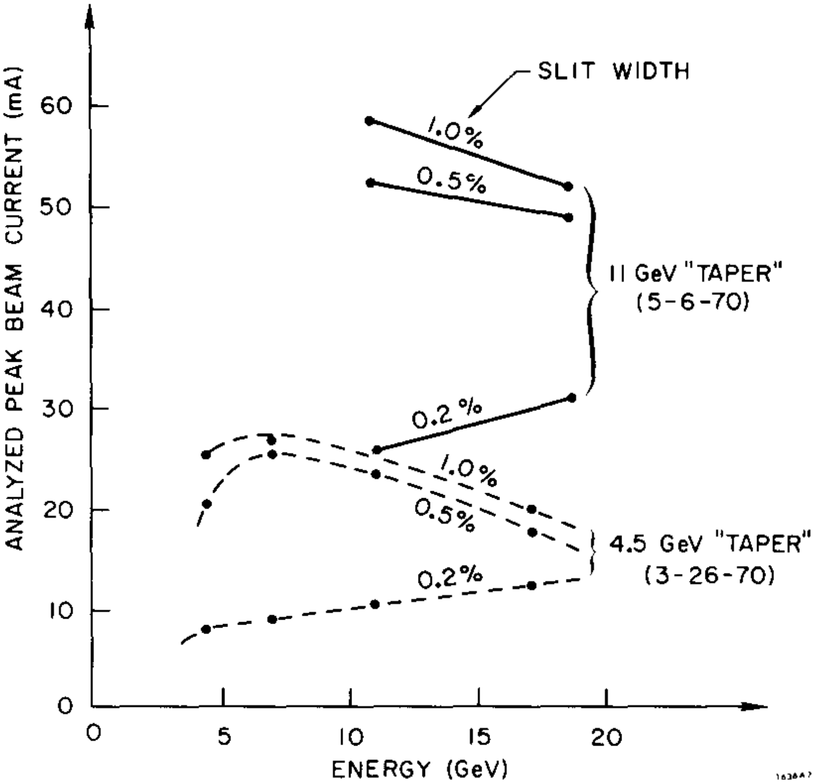


FIG. 2--Analyzed peak beam current vs. energy for three slit widths and two quadrupole tapers.

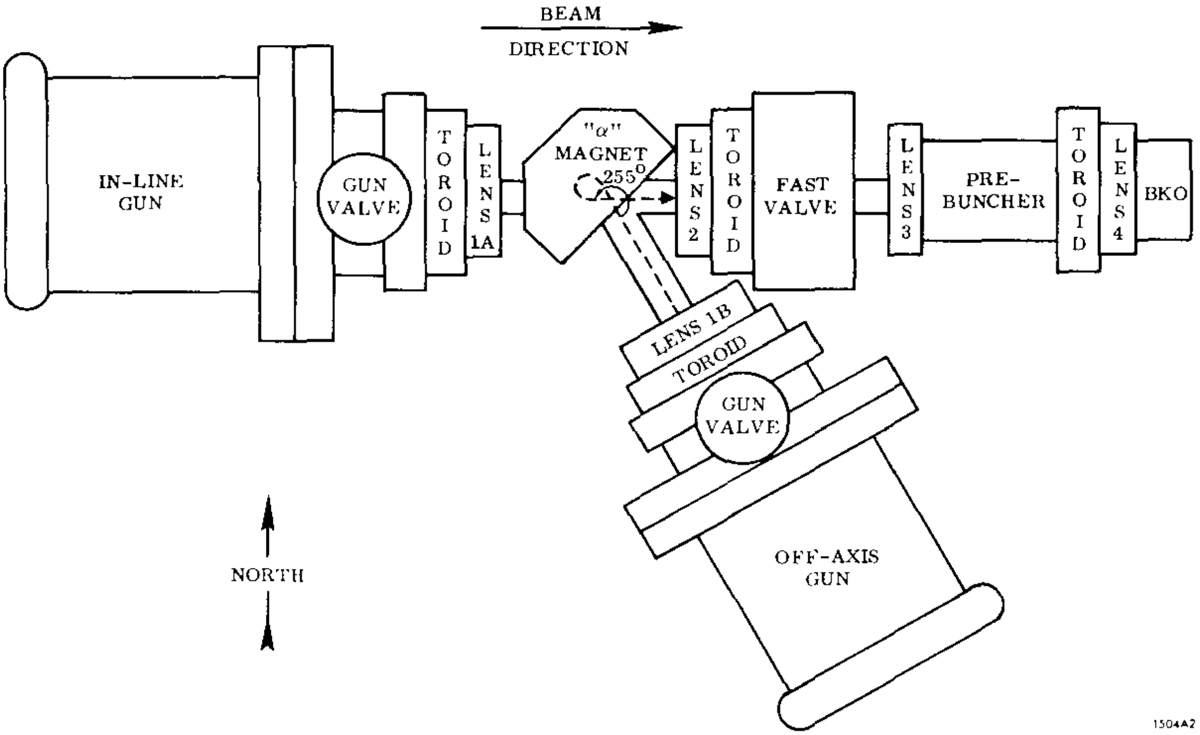


FIG. 3--Two gun assembly, plan view.

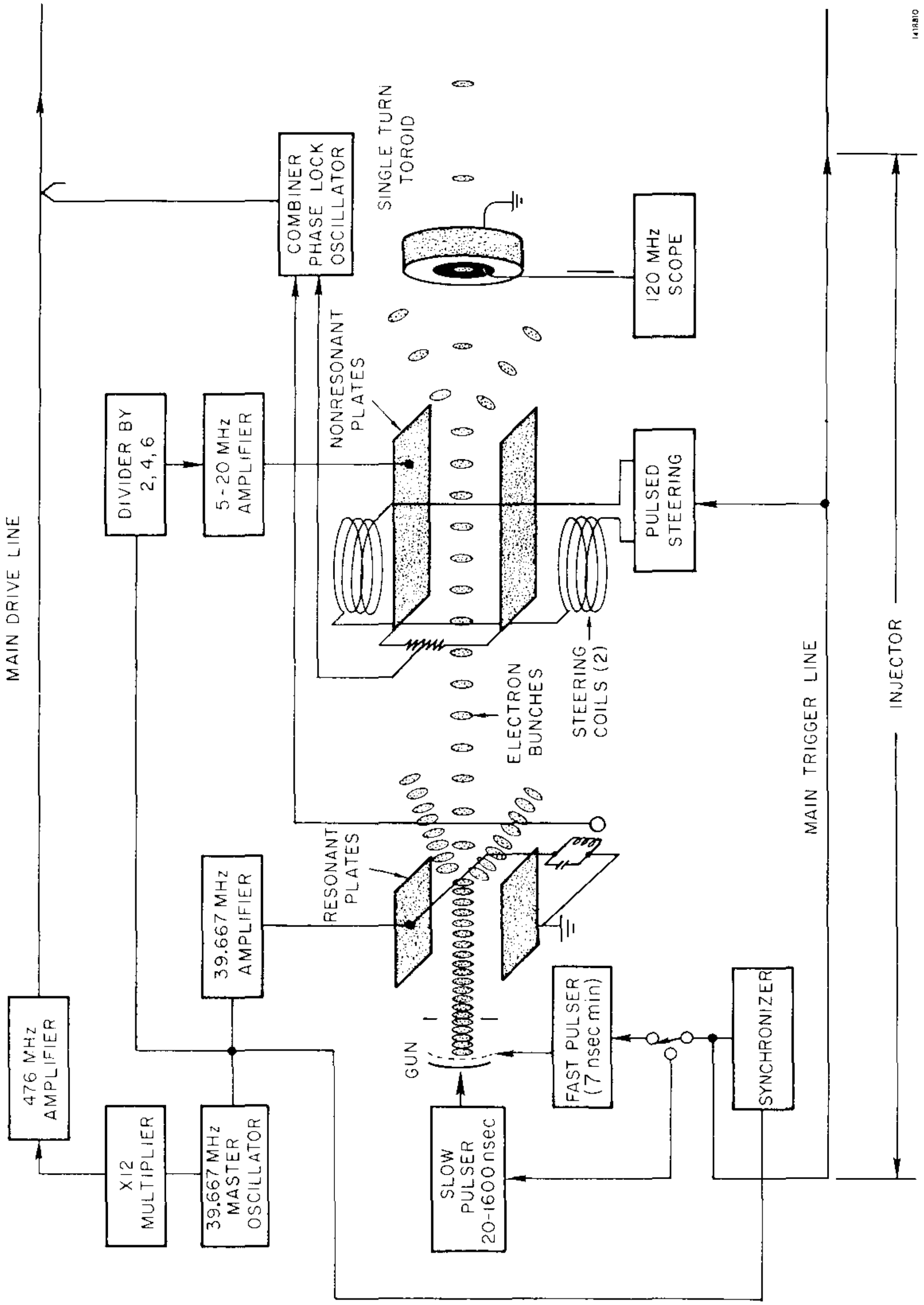


FIG. 4--Block diagram of chopped beam system.

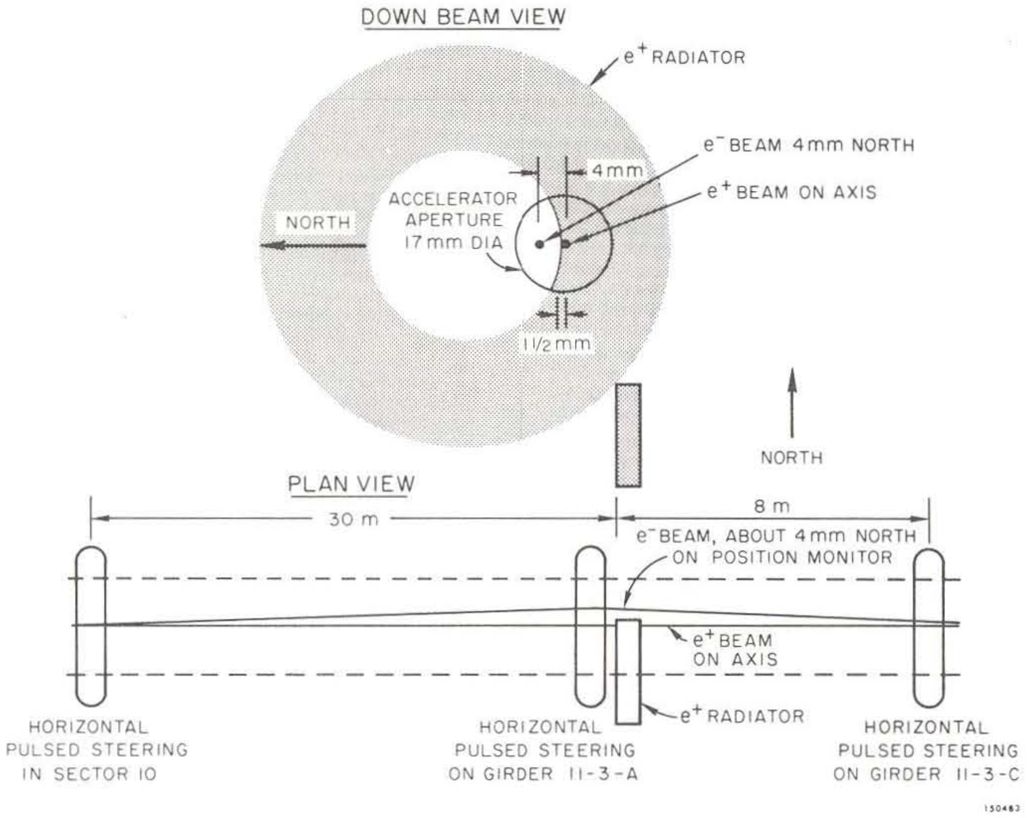


FIG. 5--Flicking beam, e^+ - e^- operation.

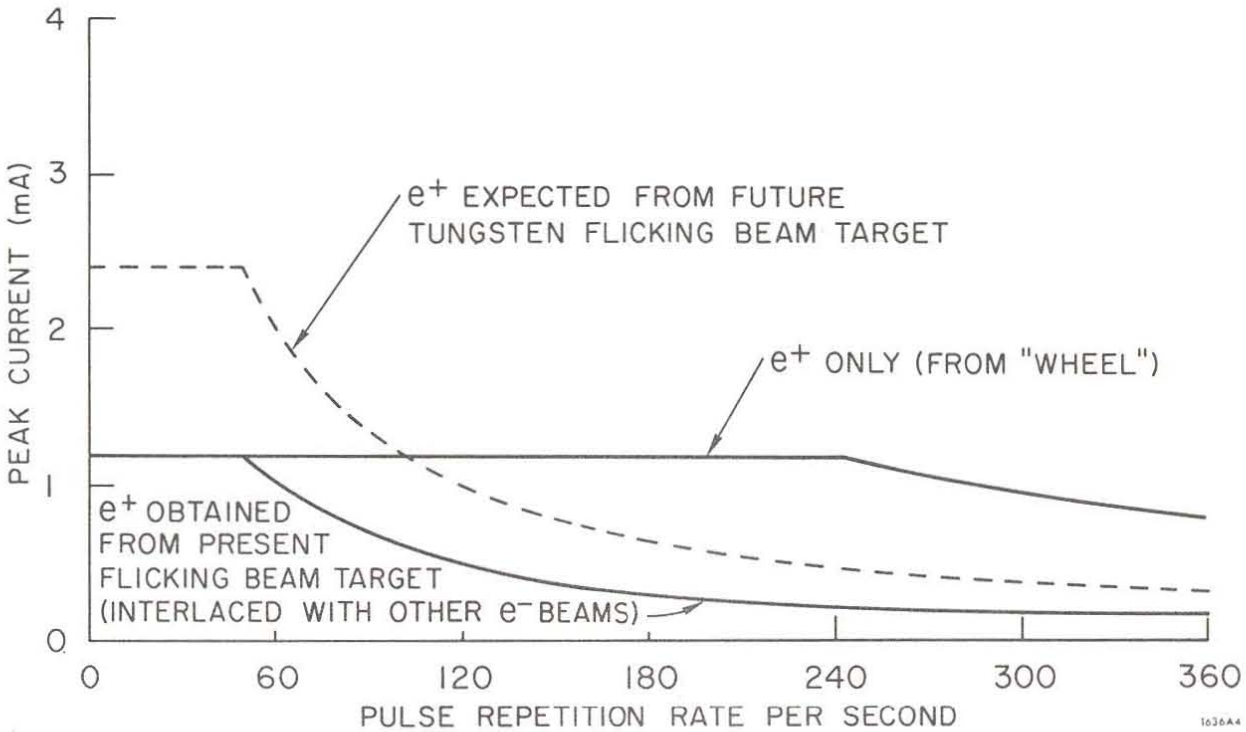


FIG. 6--Positron current in a 1% spectrum at ~8 GeV.

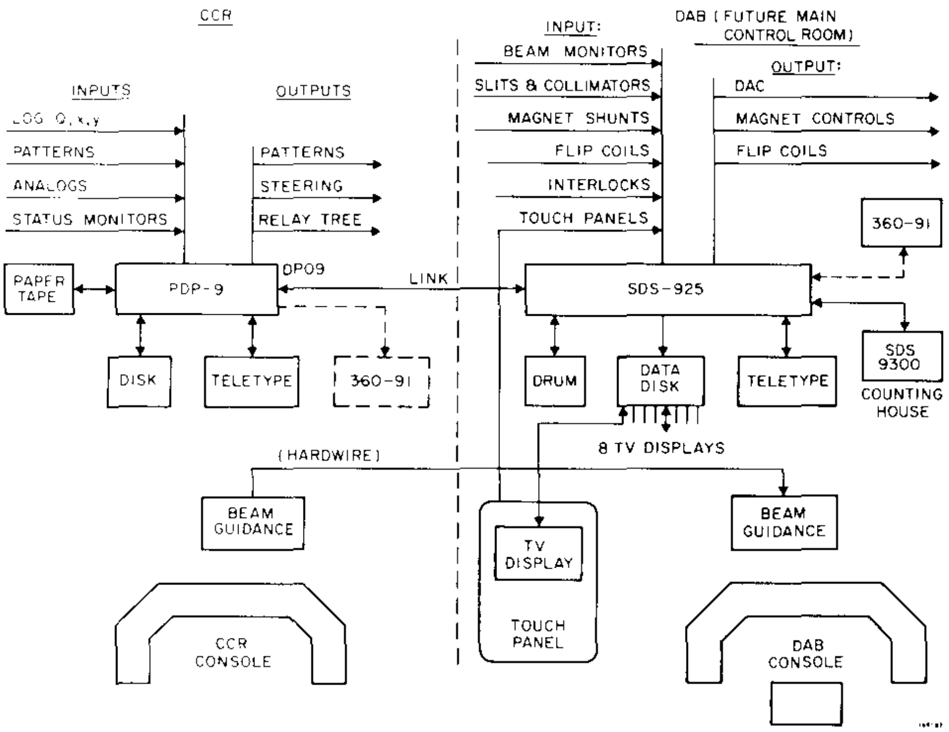


FIG. 7--Schematic diagram of control room consolidation through computer link.

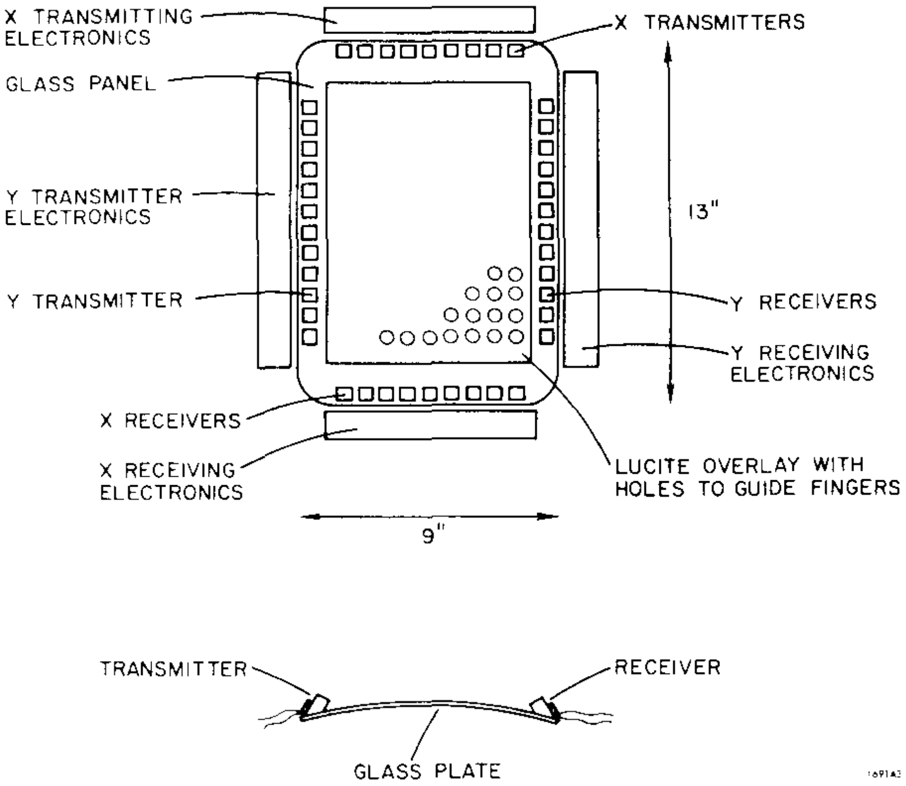


FIG. 8--Touch panel using TV display.

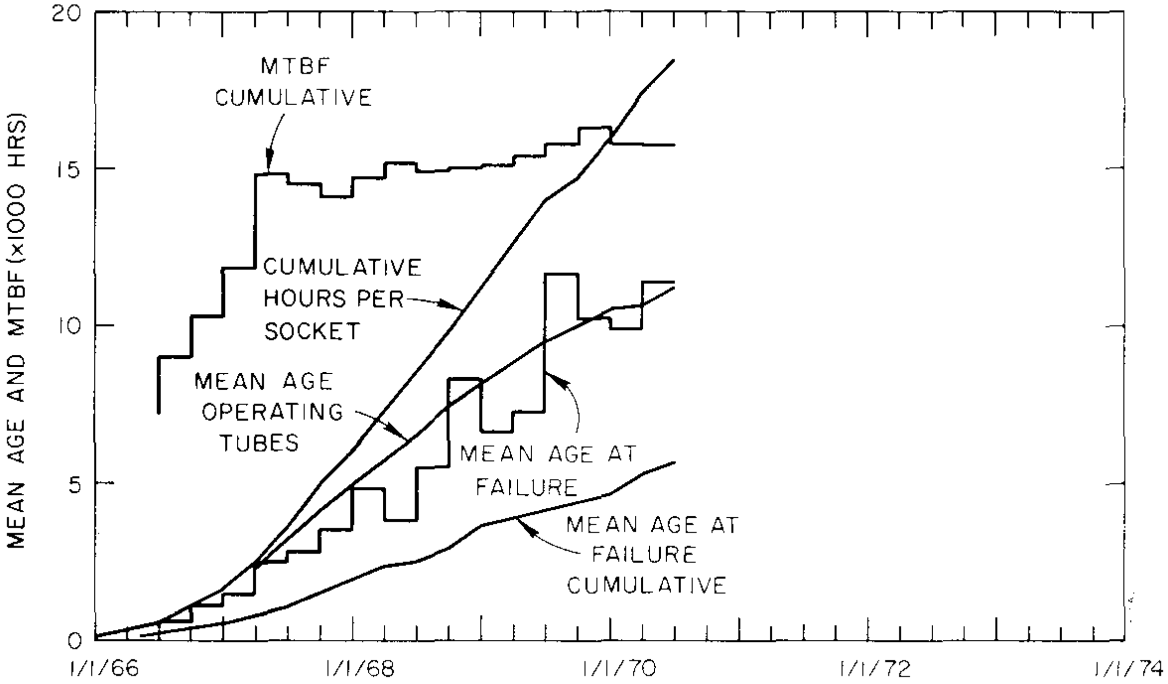


FIG. 9--Klystron operations statistics.

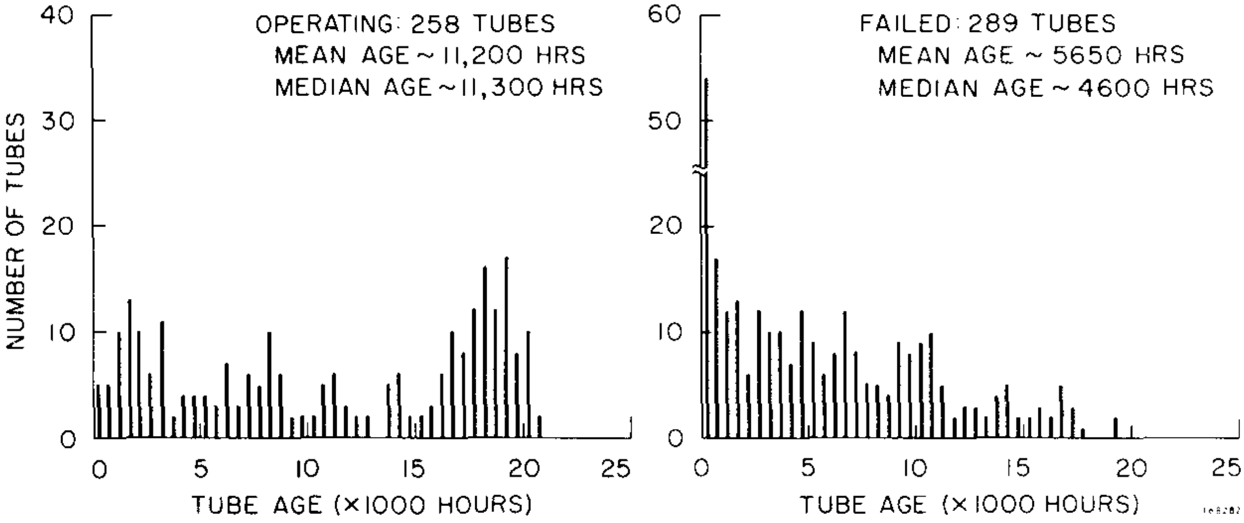


FIG. 10--Klystron age and failure distributions.

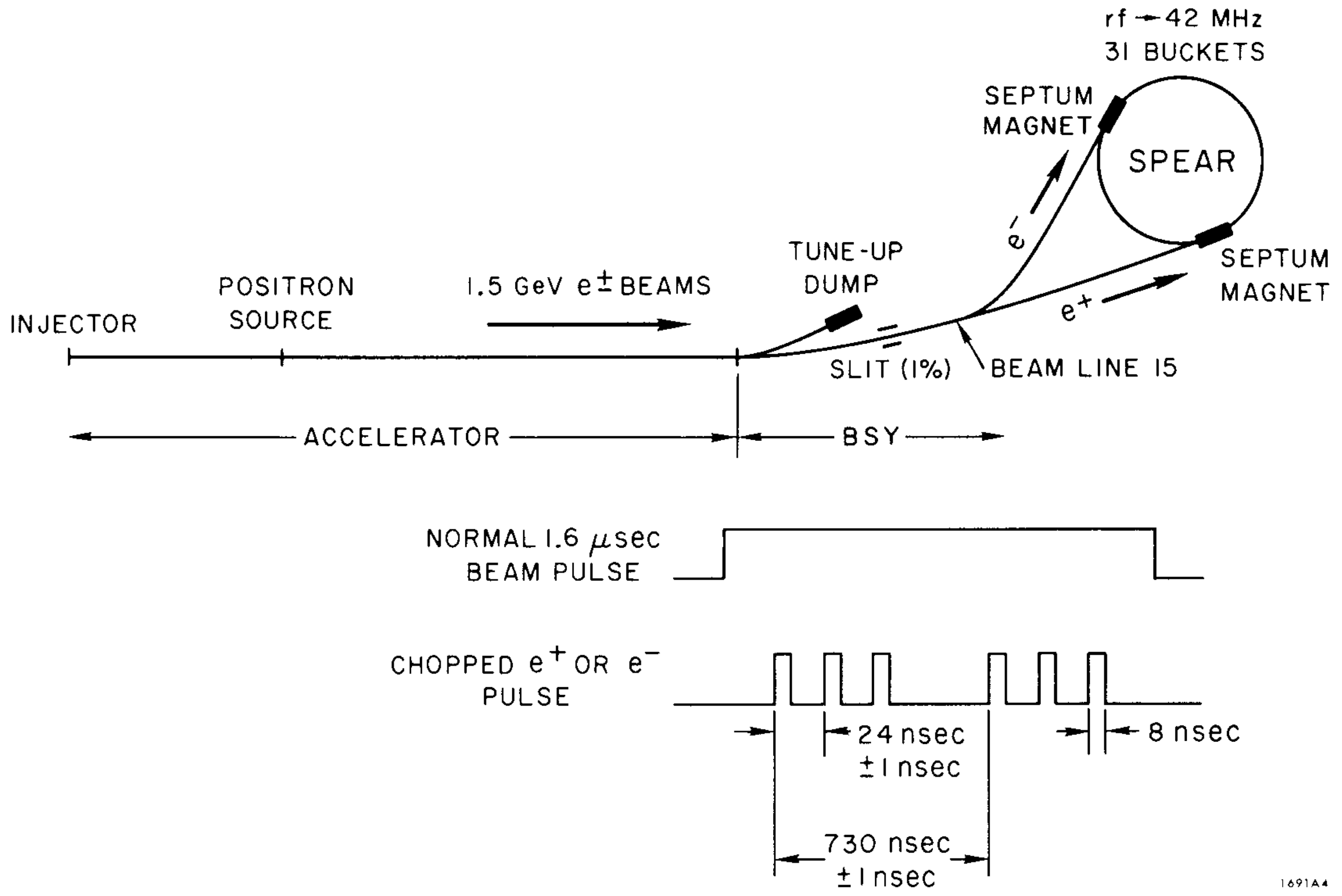


FIG. 11--Simplified diagram of injection into SPEAR.

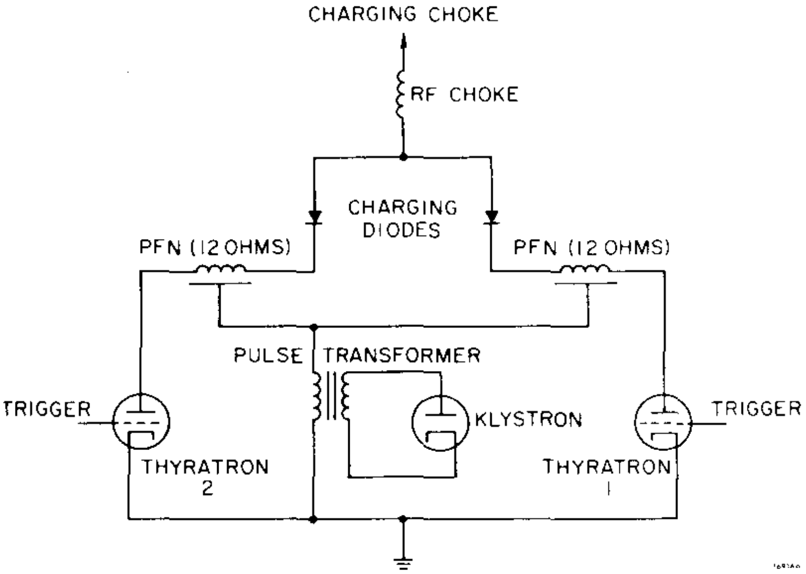


FIG. 12--Modulator-klystron connections in beam recirculation method 2.

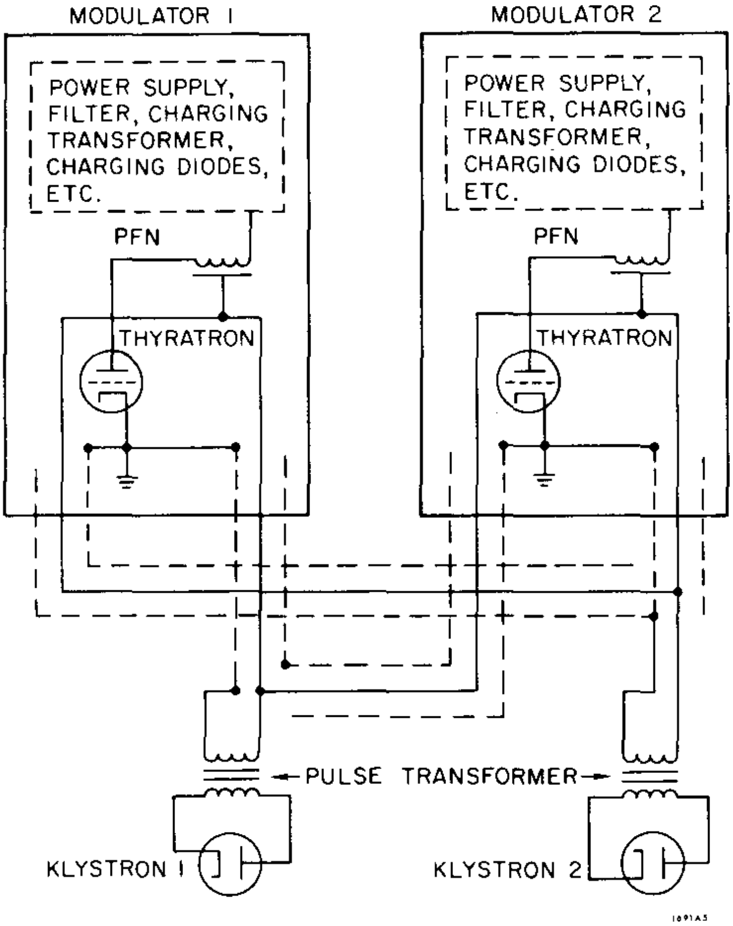
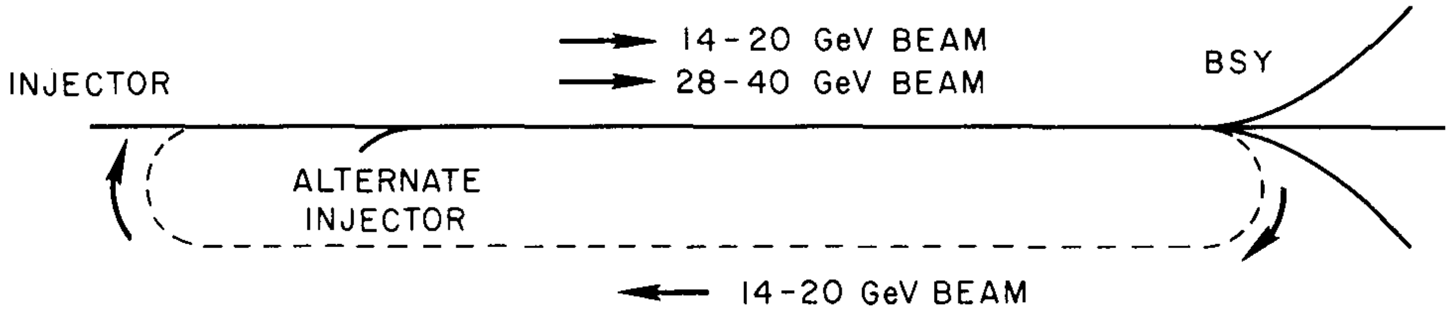
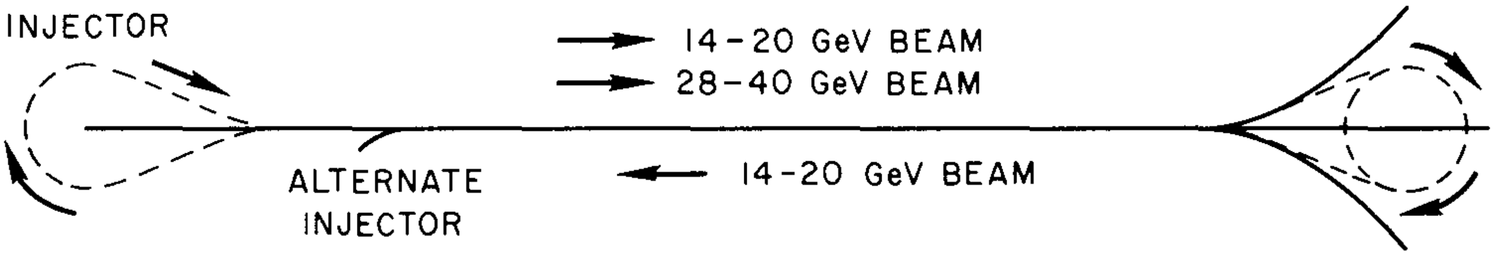


FIG. 13--Modulator-klystron connections in beam recirculation method 3.



a) "RACETRACK" SYSTEM



b) "DOUBLE TEAR-DROP" SYSTEM

FIG. 14--Possible beam transport systems to recirculate the SLAC beam.

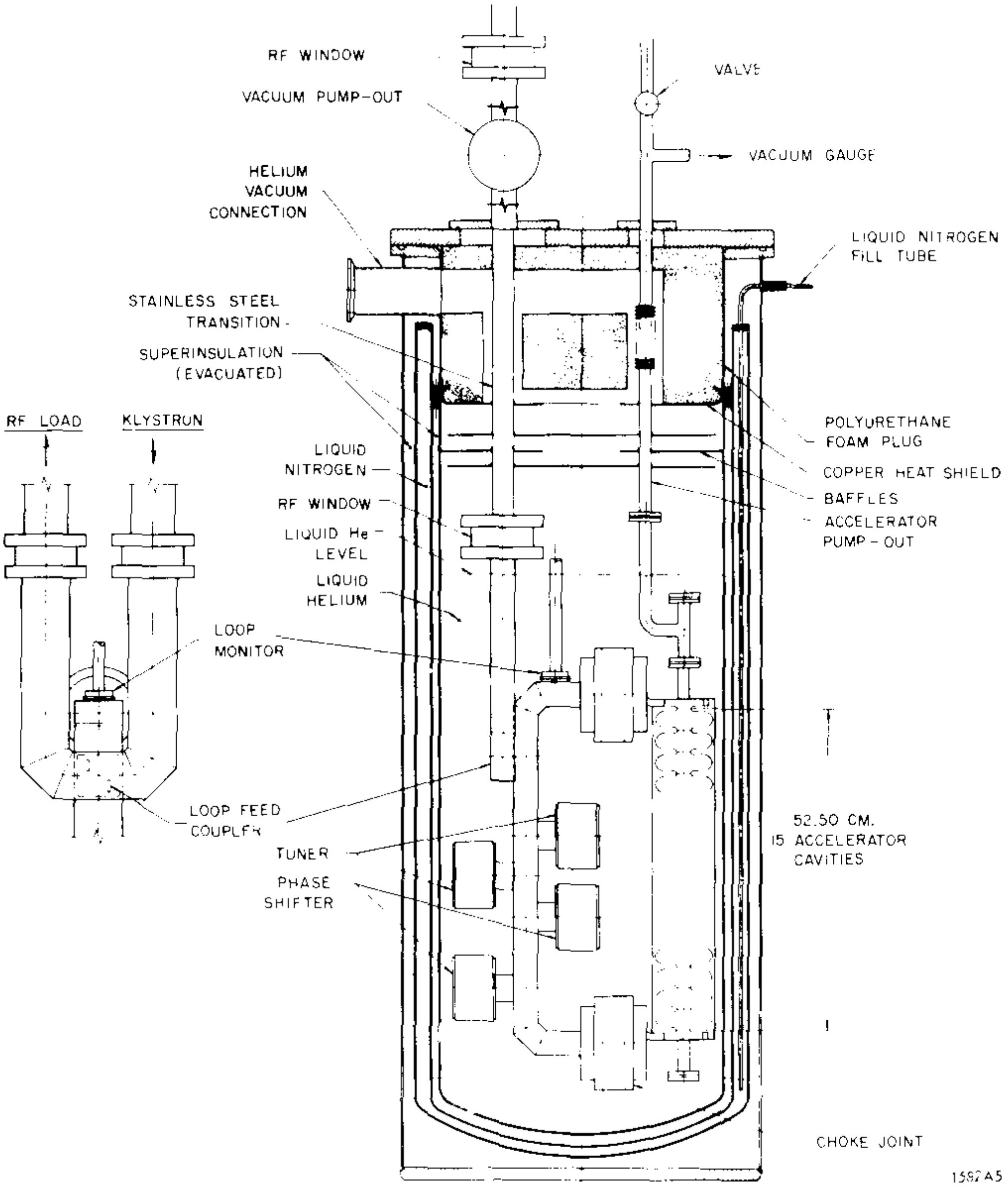


FIG. 15--Dewar assembly for the Leapfrog test accelerator.

DISCUSSION

P. R. Tunnicliffe (AECL): How much power is there in the Leapfrog and how much in the recirculation?

G. A. Loew (SLAC): We will use approximately a kilowatt in Leapfrog, but that depends on whether there is a beam in it or not. The recirculating power will be about 30 megawatts, i.e., if we achieve the Q's and if we don't reach the quenching fields that would quench the whole thing.

B. Cork (ANL): Are there any special requirements in order to make the system synchronous with a radiofrequency separator?

G. A. Loew: We have thought about that but first of all we have to try and design the system with just an accelerator. If it then turns out that we can't solve the isochronous problem without it, there is a way of helping with a separator, but hopefully we won't need that. We hope to do without a separator.