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TWO-MILE SUPERCONDUCTING ACCELERATOR STUDY*

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I. Introduction

This report summarizes the present status of a continuing study to explore the feasibility of converting the present SLAC 20 GeV two-mile accelerator to a 100 GeV superconducting machine. The conversion would also result in an increase in duty cycle from 6×10^{-4} to 6×10^{-2}.

It should be noted that no authorization for conversion of the SLAC accelerator exists at this time and no specific date for submission of a proposal has been set. Also, it should be pointed out that the technical feasibility of a long, high-gradient superconducting accelerator has not yet been fully demonstrated. So far, only a short (about 2 feet) superconducting accelerator fabricated by plating lead on a copper substrate has been operated successfully with a stable beam at the Hansen Laboratories, Stanford University. However, Q values and maximum magnetic fields and energy gradients approaching those expected theoretically (and approximately equal to the corresponding design values used in this report) have been obtained at the Hansen Laboratories in test cavities fabricated from niobium. While these successful developments are very encouraging, much work, some of a fundamental nature, must yet be completed before the technical basis of the conversion of the SLAC accelerator can be considered to be firmly established.

As to the fundamental design parameters for the planned accelerator, there is a wide variety of choice. For reasons of economy, efforts are being made to use as many of the existing machine facilities as possible. Within these general limitations, the parameters of the new machine have been optimized to achieve minimal cost while maximizing scientific utility.

II. High Energy Physics Objectives

Several new areas of high energy physics would be opened by electron and photon beams with a good duty cycle and energies up to 100 GeV. In the 30 to 40 GeV range, it would be possible to analyze the detailed structure of the electro- and photoproduction reactions. The high duty cycle would make it possible to use tagged photons to perform accurate missing mass spectroscopy. Polarized photons, produced by either crystal bremsstrahlung or laser back-scattering of the electron beam, could be used to determine the parity of the channels contributing to the reaction. These studies, which would reveal the basic properties of electromagnetic interactions, could be undertaken together with studies of hadron reactions, thereby greatly increasing the understanding of the entire subject.

There is even greater interest in studies of electromagnetic interactions at energies up to the 100 GeV region. Exploratory studies at such energies would be possible at reduced duty cycle by the detection of single scattered particles. The experiments would include two-body elastic reactions and a continuation of the photoproduction and inelastic electron scattering now being done at 20 GeV. These initial explorations of the 100 GeV region would be used to determine the interest in more detailed studies of the many-body final states. Such interest is expected to be high in light of the present SLAC experimental program of such single particle detection.

The superconducting electron accelerator would also generate intense beams of hadrons which would complement the program of the 200 GeV NAL accelerator. Especially interesting is the neutral K meson beam which would be free of the background contamination of neutrons which are present at a proton accelerator. New particle searches and tests of quantum electrodynamics with muon beams would also be part of the hadron program.

III. Basic Accelerator Parameters

A tentative set of basic parameters is shown in Table 1. The energy goal of 100 GeV requires a

TABLE 1
PARAMETERS OF A TWO-MILE 100 GEV SUPERCONDUCTING ACCELERATOR AT TWO FREQUENCIES*

Parameter	f = 1428 MHz	f = 2856 MHz
Length	3000 m	3000 m
$\bar{r}$	$3.44 \times 10^{13}\ \Omega/m$	$1.72 \times 10^{13}\ \Omega/m$
Q	16×10^9	4.0×10^9
Loaded Energy (max)	100 GeV	100 GeV
Duty Cycle	1/16	1/16
Peak Beam Current	48 μA	48 μA
Average Beam Current	3 μA	3 μA
Peak Beam Power	4.8 MW	4.8 MW
Average Beam Power	0.3 MW	0.3 MW
Number of Klystrons	240	240
Peak Power per Klystron	20 kW	20 kW
Average Power per Klystron	1.25 kW	1.25 kW
Type of rf Structure	TW with rf feedback loop	TW with rf feedback loop
No. of Accelerator Sections	480	480
Length of Accelerator Section	20 ft	20 ft
Filling time (to 63.2%)	72 msec	18 msec
Power Dissipated in Accelerator	6000 W (2.0 W/m)	12000 W (4.0 W/m)
Pulse Length (rf)	1.00 sec	0.25 sec
Pulse Length (beam)	0.95 sec	0.24 sec
Time Off Between rf Pulses	15.0 sec	3.75 sec
Accelerator Attenuation Factor (τ)	4.62×10^{-7}	37.0×10^{-7}
Feedback Attenuation Factor (γ)	0.462×10^{-7}	3.7×10^{-7}
Bridge Ratio (β)	2.19×10^4	0.546×10^4
Normalized Circulating Power P_0 at η_{max}	219 MW	54.6 MW

*The values of parameters in this table are based upon operation at 100 GeV. The ranges of these parameters for other beam energies are shown in Fig. 1 assuming constant rf dissipation in the accelerator.

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gradient of 33 MeV/m. As will be discussed below, such a gradient will not be easy to achieve. For this reason, it is planned to adopt a design for the accelerator structure with the lowest obtainable peak-to-effective field ratio. A tentative decision has been made to use a traveling-wave design with rf feedback. Computer calculations indicate that the equivalent ideal standing-wave structure would have a peak-to-effective field ratio at least 1.3 times higher. A practical standing-wave structure would probably include axial idler cavities which would increase the peak-to-effective field ratio even more.

The possibility of achieving a high duty cycle is one of the attractive features of a superconducting accelerator. However, adopting a 100% duty cycle for a projected 100 GeV two-mile machine would lead to excessive refrigeration costs on the basis of present-day estimates. For this reason, the duty cycle in this preliminary study has been limited to 1/16 (~6%) when the machine is operating at the full 100 GeV energy level. Even so, this duty cycle is 100 times better than that of the existing SLAC accelerator and would result in greatly improved experimental statistics. If at a later date, the cost of providing refrigeration decreases, the duty cycle could be increased by adding more refrigeration units to the system.

When the energy is less than 100 GeV, the duty cycle can be increased because of the reduced rf power loss in the structure. For constant rf dissipation at a given beam energy V, the permissible duty cycle varies as V^{-2}. Thus, at a beam energy of 25 GeV, the duty cycle can be 100% if desired, without exceeding refrigeration specifications. A curve of maximum duty cycle, peak and average beam current, and peak and average beam power versus beam energy is given in Fig. 1.

From Fig. 1 it is clear that, while the maximum design average beam power is limited to 300 kW at the maximum energy level of 100 GeV, the beam power can be higher at lower energies. A maximum design average beam power of 2.1 MW can be obtained at a beam energy of 25 GeV and a current of 84 μA with unity duty cycle. This is the highest average beam power which can be achieved with this machine without increasing either the level of rf power or the capacity of the refrigeration system. At energies above 100 GeV, the curves of Fig. 1 are shown dotted since 100 GeV is assumed to be the maximum energy achievable in this machine.

The preliminary design and cost analysis of this study are being carried out for two different frequencies: 1428 and 2856 MHz. The lower frequency has the advantage of higher Q's, lower rf losses and thus, lower refrigeration costs. The higher frequency, 2856 MHz, has the compensating advantage that it is the same as that of the existing accelerator. Thus, its use can result in considerable cost savings through the utilization of the existing waveguide system. A final comparison and choice of frequency have not yet been made.

To take maximum advantage of equipment already available in the SLAC klystron gallery, the same number of klystrons (≈240) as used with the present SLAC accelerator will be employed. Practically speaking, an rf source capable of producing full power for a period on the order of a second must, for cathode emission and heat dissipation purposes, be designed to operate in a cw manner. Moreover, the existing ac distribution system in the SLAC klystron gallery has sufficient capacity to supply the required ac power for 50% efficient klystrons operating at 20 kW cw output. Thus, the rf peak power and average power from each klystron will be 20 kW and 1.25 kW, respectively.

When the peak beam current in the accelerator is less than the design value of 48 μA, it will be necessary to reduce the level of the rf peak power input in order to prevent the energy gradient from exceeding the critical value (assumed) of 33 MeV/m. Power reduction can be accomplished either by decreasing the beam voltage applied to the klystron or by decreasing the rf drive power to the tube. However, both these methods result in phase shift of the output power from the tube which greatly complicates the phasing problem.

A preferred method consists of adjusting the period of time during which the rf power remains turned on so that a predetermined buildup level is achieved within the accelerator structure. Obviously, the "on" period of rf power must vary with the peak beam current which is being accelerated. When the peak current is at the design level (48 μA), the rf power will remain on steadily during the entire pulse length. When the peak current is less than the design level, the rf power will be turned off and on with the proper periods to maintain the desired accelerating voltage gradient. Calculated values of "on-off" periods for a beam energy of 100 GeV are given in Table 2. In practice, the field level in the feedback loop will be compared with an adjustable reference level. When the difference of these signals exceeds a predetermined value, the rf power will be turned on or off as appropriate.

TABLE 2

RF ON-OFF PERIODS FOR FIELD STABILIZATION*

Beam Current	[Beam Current / Design Current]	Length of On and Off Periods During Steady State Portion of rf Pulse	
		ON	OFF
0	0	36 μsec	36 μsec
12 μA	0.25	48 μsec	28.8 μsec
24 μA	0.50	72 μsec	24 μsec
36 μA	0.75	144 μsec	20.6 μsec
48 μA	1.00	(On approx. full time)	18 μsec

*For beam energy of 100 GeV and klystron power of 20 kW.

In the preliminary listing of criteria shown in Table 1, it has been assumed that a 20-ft feed interval will be adopted. This choice results in reduced instrumentation and control requirements when compared to a 10-ft feed interval and one-half the value of the bridge ratio g. A reduced value of g eases phasing and matching problems in the feedback loop. The power output from each klystron is split two ways in order to feed the two 20-ft accelerator sections. If higher beam power is needed in the future, the number of klystrons can be doubled and the accelerator can be fed through waveguides already in existence.

A number of basic tolerances of the superconducting accelerator are given in Table 3.

TABLE 3

TOLERANCES IN A SUPERCONDUCTING ACCELERATOR

	1428 MHz	2856 MHz
Frequency($\Delta\omega/\omega$)	2.2×10^{-10} during filling time	4.4×10^{-10} during filling time
Phasing in Feedback Loop	2.6×10^{-4} degrees	10.4×10^{-4} degrees
Impedance Mismatch in Feedback Loop	$\Gamma \leq 1 \times 10^{-5}$	$\Gamma \leq 4 \times 10^{-5}$
Time Constant of Phase and Impedance Corrections in Feedback Loop	4 msec (5% of filling time)	1 msec (5% of filling time)
Phasing of Loop to Beam (Setting)	$\pm 1^{o}$	$\pm 1^{o}$
Phasing of Loop to Beam (Stability)	$\pm 1^{o}$	$\pm 1^{o}$
Beam Current Stability	± 0.01%	± 0.01%
Spectrum Width at Half Max	0.2%	0.2%
Phase Space at Output (max)	0.005π(MeV/c) (cm)	0.005π(MeV/c) (cm)
Maximum Beam Diameter	4 mm	2 mm
Beam Loss in Accelerator (max)	1000 watts uniformly distributed	1000 watts uniformly distributed

IV. Materials and Prototype Studies

As pointed out above, one of the crucial stepping stones towards realizing a linac structure capable of sustaining gradients of 33 MeV/m is the discovery and preparation of a suitable material. The criteria to be met by the material are: 1) Q-improvement factors of the order of 10^5 - 10^6; 2) Critical magnetic field comfortably above the operating level;* 3) A surface which is smooth and free of whiskers that might induce field emission; 4) Heat conductivity sufficiently high to prevent temperature gradients across the accelerator wall of more than $\sim 0.1^{o}K$; 5) Satisfactory mechanical and chemical properties to provide the proper rigidity, tunability and reliability under operating conditions including resistance to deterioration through contamination by air and other gases, radiation damage, etc. Of the three available superconductors presently under study, namely lead, niobium and technetium, niobium so far seems to be the most likely candidate. Plated lead suffers from field emission and deterioration under exposure to air. Work with plated technetium at SLAC is very encouraging but not advanced enough to draw any conclusions. Furthermore, technetium is radioactive and may pose insoluble manufacturing problems. Solid niobium, on the other hand, has been successfully formed into microwave cavities and recent tests at 8 GHz with an electron beam welded TM_{010} cavity[1] have yielded Q's of the order of 10^{11}, critical magnetic fields above 1000 gauss and peak electric fields above 70 MV/m. This results in an equivalent accelerating gradient of 24 MeV/m.

The present plan for the next two years at SLAC is to embark on an intensive research program to extend these performances to safer margins of operation. This research will include sample cavity studies at both X- and S-band, measurements of critical magnetic fields by rf and low frequency susceptibility techniques, measurements of field emission by both ac and dc methods, measurements of the heat conductivity of solid niobium, exploration of techniques to plate or sputter niobium, investigation of various methods of forming and joining niobium sheets or tubes into accelerator structures, optimization of the presently known thermal and chemical etching treatments required to obtain high Q's and high critical fields, studies of the effect of gas contamination, radiation damage, etc. This program would culminate in the construction and testing of a 20-ft accelerator prototype. This prototype would also serve as a vehicle to test the phasing and matching problems of the recirculating feedback system.

V. The Radiofrequency System

The rf system of the superconducting accelerator will in many ways resemble that of the existing accelerator. As mentioned above, it will consist of an array of ~240 klystron amplifiers. These amplifiers will be supplied from a two-mile, 476 MHz coaxial drive line and a common master oscillator with a proposed stability of 4×10^{-10}. Intermediate parallel stages of amplification and frequency multiplication will be provided as needed. The traveling-wave accelerator with feedback is shown schematically in Fig. 2(a) and in some greater detail in Fig. 2(b). Under steady-state design conditions, i.e., 100 GeV, 48 μA and P_s = 10 kW per 20-ft section, the bridge with fixed ratio g (as shown in Table 1) is designed to feed all the power back to the accelerator with no power going to the resistive load. Under all other conditions, including intermittent rf drive, some power will go to the load, which clearly must be outside the dewar.

The slow-wave structure will probably be of the disk-loaded type with rounded boundaries. Two computer programs are presently being developed to optimize cavity shape in terms of shunt impedance r_0, Q and peak-to-effective field ratios. For a given rf attenuation τ and a beam current i, the energy per section of length ℓ is given[2] by $V = (8\,\tau g r_0 \ell P_s)^{1/2} - 2\tau g r_0 \ell i$. This simple expression can be used to understand and optimize most of the properties of the accelerator with feedback, once the structure has been designed. In particular, it shows the relationship between P_s and i and the dependence on the product $2\,\tau g$.

Returning to Fig. 2(b), once the loop has been assembled and the bridge ratio g has been set, there are still four important rf functions to be fulfilled. The first is to adjust the rf length of the loop to an integral number of wavelengths (see "phasing transducers"). The second is to adjust the rf match of the loop (see "matching transducers"). The third is to adjust correctly the phase of the klystron with respect to the beam. Finally, the fourth is to monitor the rf level in the loop (see "coaxial probe"), and by comparison with a preset level, to adjust the rf drive "on" and "off" times in order to obtain the desired beam energy. All four operations will be performed by means of an automatic system using both analog and digital closed loop techniques. The tolerances are spelled out in Table 3.

Additional studies are also proceeding on the susceptibility of the accelerator structure with feedback to beam breakup, rf transients, coupler asymmetry and the general problems of mechanical tolerances and allowable deformations.

*A fairly accurate rule of thumb for a simple structure is that the maximum magnetic field on the surface will be 30 gauss times the maximum axial field in MV/m.

VI. Dewar System

The accelerator will be mounted in a liquid helium dewar whose cross section is shown in Fig. 3. Each dewar will be approximately 320-ft long and will contain sixteen 20-ft accelerator sections. The sections will be welded together upon installation.

The accelerator will be surrounded by three envelopes which will also be connected during installation. The outermost layer will be the vacuum envelope for the dewar. The next layer will be a thermal radiation shield cooled by helium gas at about 80°K. Helium gas will be used instead of frequently used liquid nitrogen because the nitrogen would require another separate refrigeration system. The heat absorbed by the shield will come from radiation from the outer jacket and from conduction through waveguides and supports. This heat will amount to about 28 kW for the 1428 MHz design and to about 20 kW for the 2856 MHz design. Even though these heat flows are higher than the total load at 1.85°K, the refrigeration required to cool the shield amounts to only 2 to 4 percent of the total refrigeration load.

The inner vacuum envelope will be the helium dewar. High performance insulation will be used between the heat shield and the outer vacuum wall and also between the dewar and the heat shield. The heat flow to the low temperature container is shown in Table 4 for the entire accelerator.

TABLE 4

Heat Flow to 1.85°K Helium Reservoir

	1428 MHz	2856 MHz
Through Insulation From Heat Shield	200W	160W
Through Waveguide Connections	700W	380W
Through Miscellaneous Supports and Connections	800W	760W
RF Loss (100 GeV at 1/16th duty cycle)	6,000W	12,000W
Beam Loss (total allowable)	1,000W	1,000W
Total Refrigeration Load at Full Power	8,700W	14,300W

The midpoint of each 20-ft section will be the axial anchor point and also the location of all instrumentation and waveguide feedthroughs. This arrangement will limit the effects of differential thermal contraction between the outer vacuum jacket and the inner dewar.

VII. Refrigeration System

The proposed refrigeration system is shown schematically in Fig. 4. It is similar conceptually to the system located at the High Energy Physics Laboratory of Stanford University. It uses commercially available pumps and compressors and could be built with presently known technology. However, progress in all areas of cryogenics is very rapid and significant improvements and savings can be expected before this conversion project is authorized and the design is frozen.

The HeII liquefier is the last stage of the refrigeration system. It is located immediately adjacent to the helium dewar and shares a common vacuum system. The pressure at the surface of the helium is 15 Torr. After flowing through several heat exchangers, the vacuum pumps compress the helium to about one atmosphere. Then, at room temperature, the helium is piped to the central compressor station where it is compressed to 15 atmospheres. The largest fraction of electrical power is used by the compressor. However, a large amount of power is also used by the vacuum pumps. Table 5 shows the electrical power requirements for the major systems on the accelerator including the ac power needs for the klystrons.

TABLE 5

Major Power Requirements (in megawatts)

	1428 MHz	2856 MHz
Central Compressor Station	7.6 MW	12 MW
Helium Vacuum Pumps	6.4 MW	10 MW
Klystron Power Supplies	12 MW	12 MW
TOTAL	26 MW	34 MW

VIII. Research Area and Beam Transport

The initial experimental program is expected to use the present beam switchyard and research area. It will be possible to use the existing end station buildings for high duty cycle experiments up to about 35 GeV. For the preliminary higher energy experiments described earlier, the central beam line will have to be used since the bending angles of the deflected beam trajectories are too great. Eventually it should be possible to expand the research area into straight-ahead unused land presently owned by SLAC.

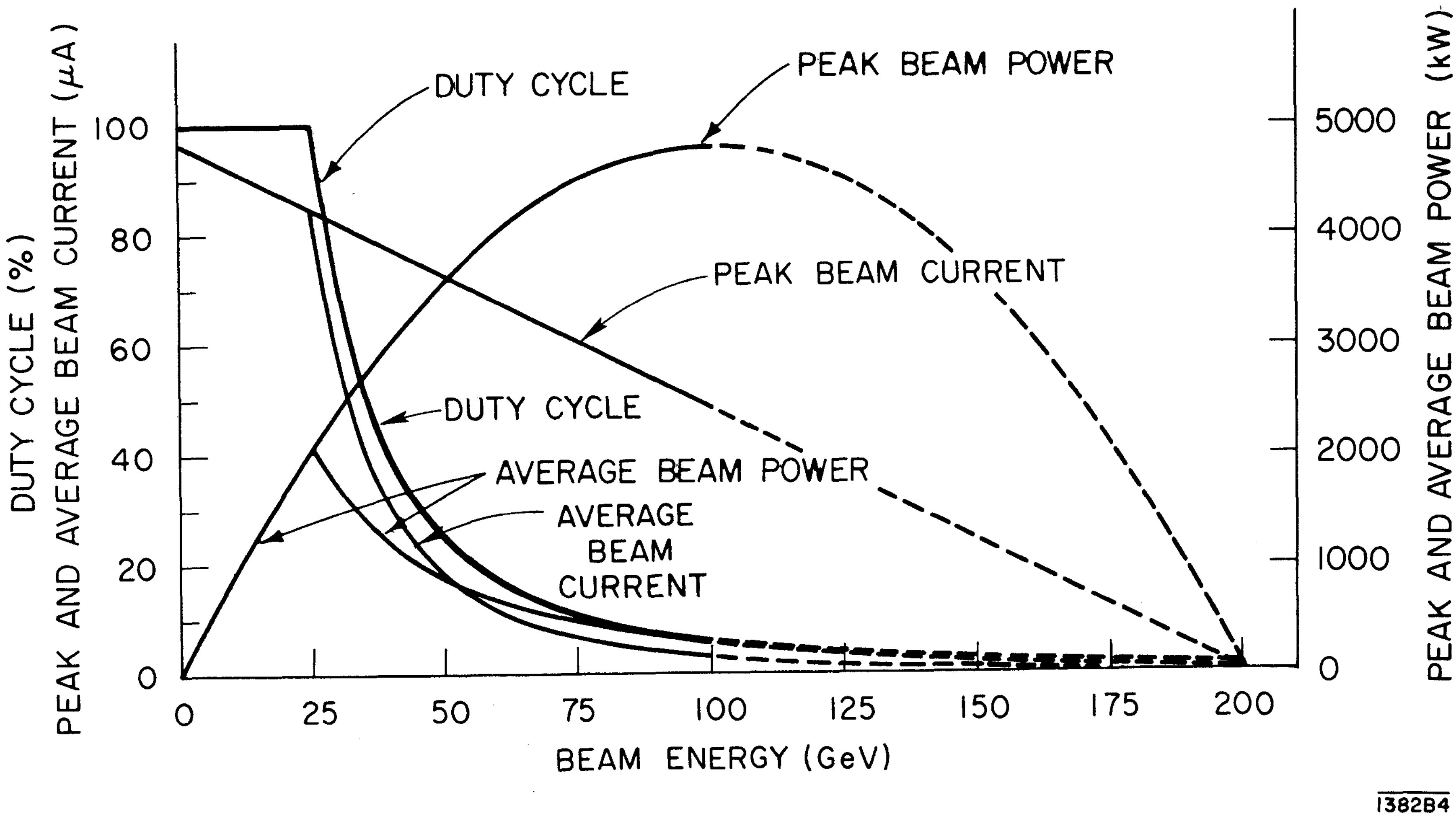
IX. Acknowledgments

The authors are indebted to Prof. S. D. Drell for the material in the section on the Physics Objectives. The feasibility study is a continuing effort for many members of the SLAC staff. The materials research program has profited greatly from the cooperation of members of the Stanford High Energy Physics Laboratory. The cooperation of staff members in both laboratories is greatly appreciated.

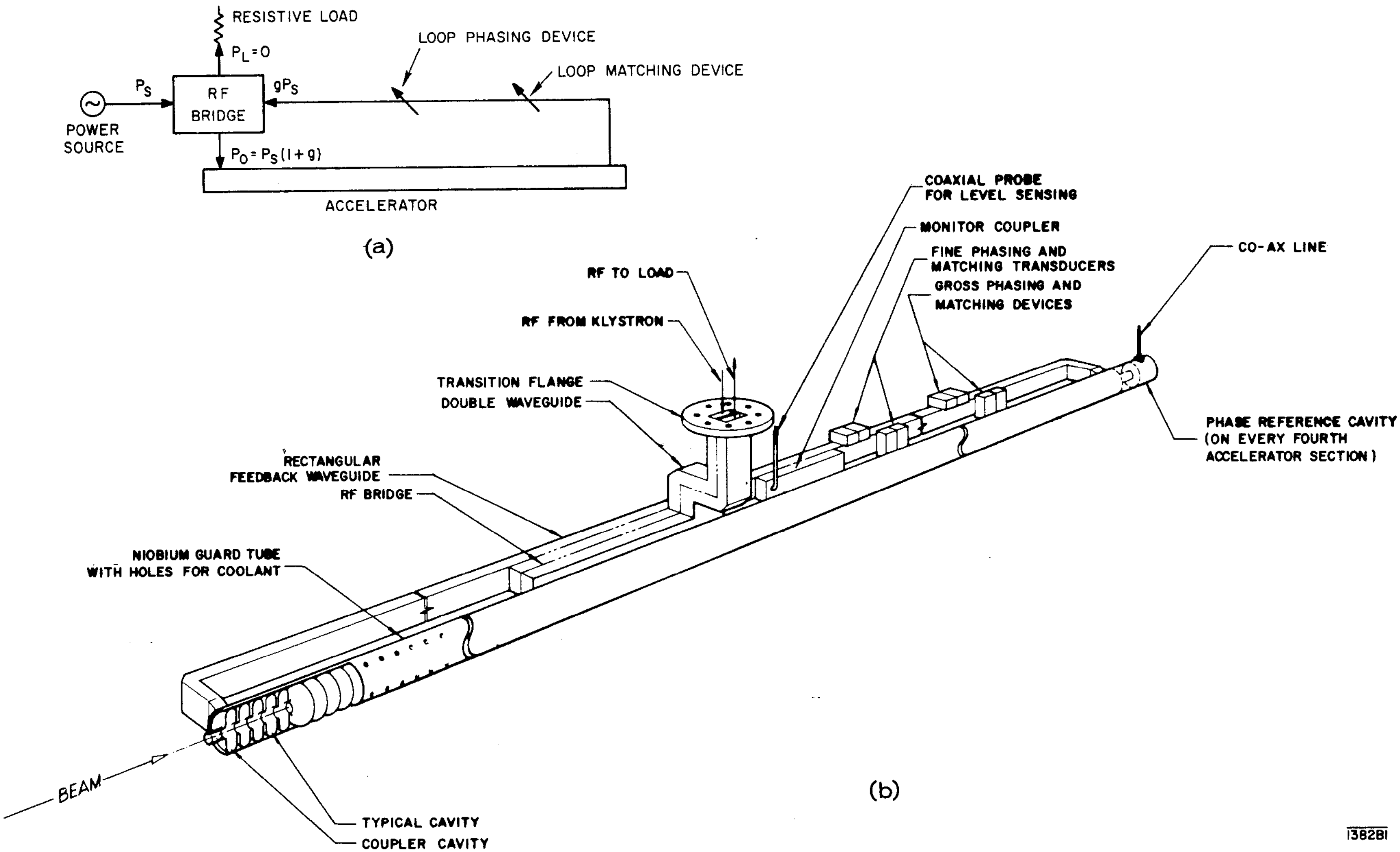
X. References

1. John Turneaure, High Energy Physics Laboratory, Stanford University, Stanford, California (private communication, June 1969).

2. W. B. Herrmannsfeldt et al., "Feasibility study of a two-mile superconducting linac," 1969 National Particle Accelerator Conference, Washington, D.C., March 5-7, 1969.

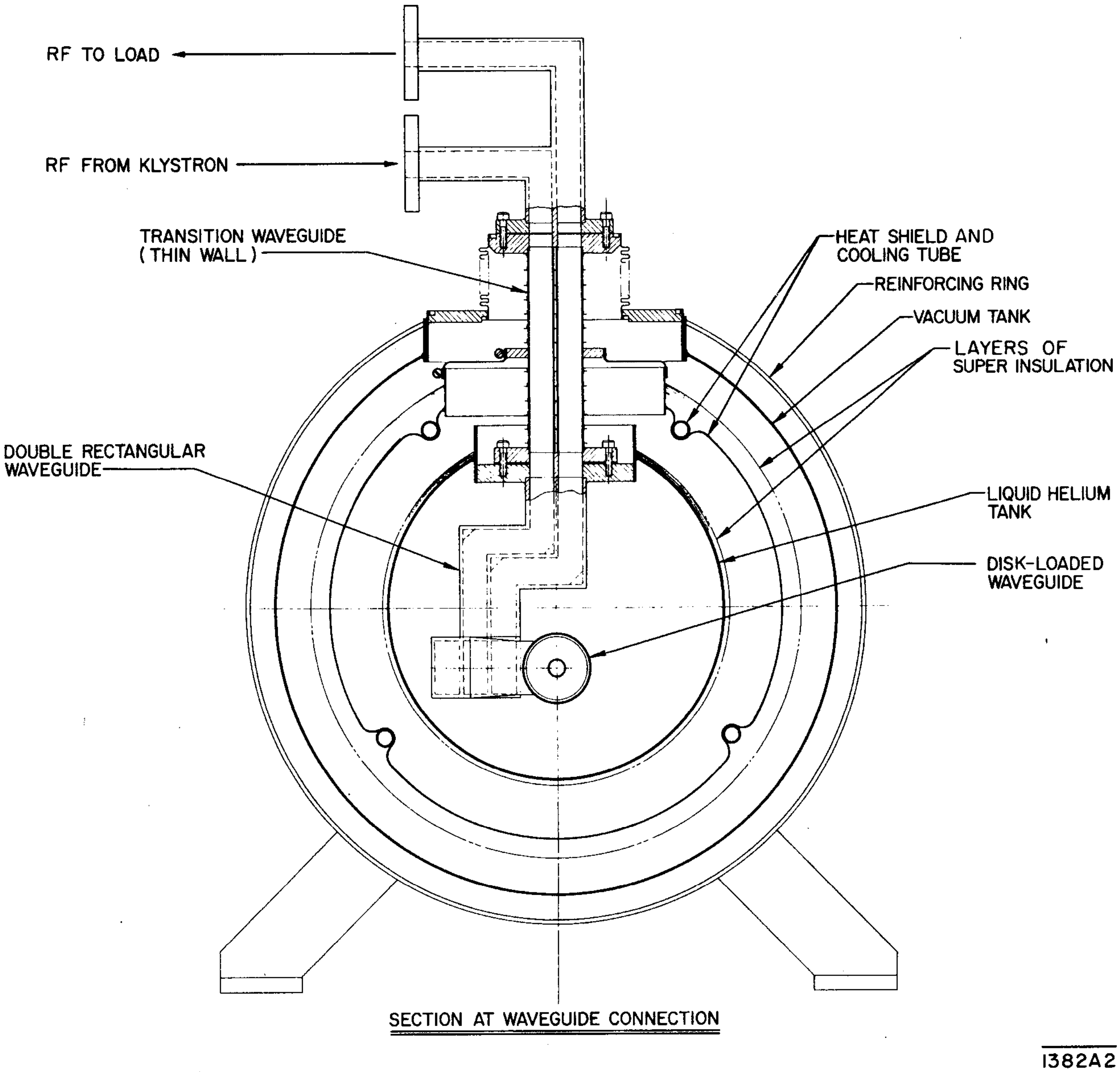


1. Duty cycle, peak and average beam power, and beam current vs. energy.

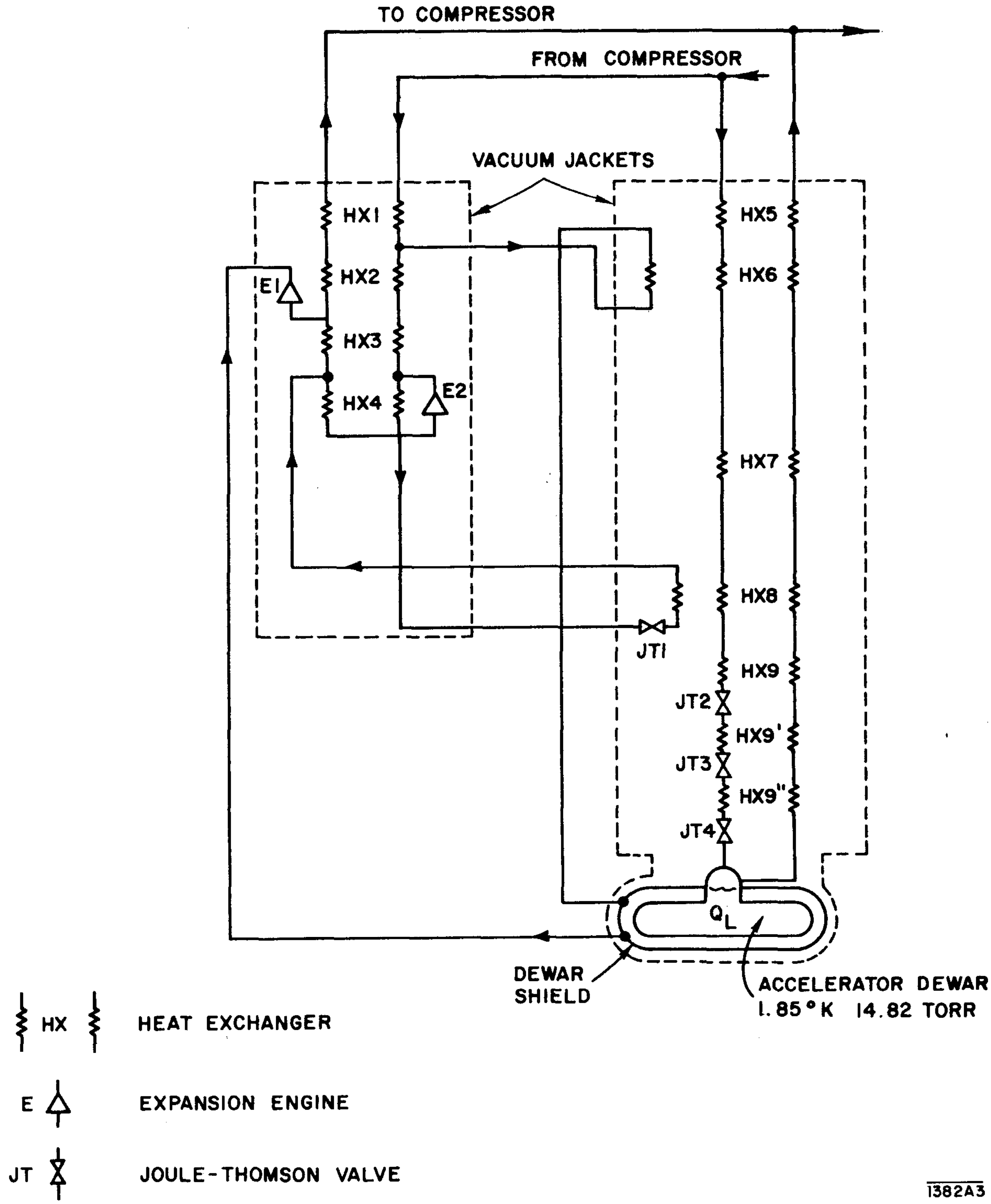


2(a). Schematic of traveling-wave accelerator with rf feedback.

2(b). Mechanical layout of accelerator section with rf feedback loop.



3. Cross section of accelerator assembly.



4. Refrigeration system schematic.