THE DEVELOPMENT OF LOW TEMPERATURE TECHNOLOGY AT STANFORD AND ITS RELEVANCE TO HIGH ENERGY PHYSICS*

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I. INTRODUCTION

In the history of nuclear and high energy physics there have been a few pioneering laboratories which have developed the new technology that has made possible the complex accelerators of today. The High Energy Physics Laboratory (HEPL) at Stanford played this role in the development of the electron linear accelerator and the related microwave technology a little over one decade ago, and this same laboratory is now pioneering the development of the superconducting accelerator (SCA) and the related low temperature technology. The objective of our laboratory is simultaneously to provide modernized facilities to continue basic research at the frontiers of high energy physics and to develop all aspects of this new technology that are required to demonstrate its relevance to the future of low temperature physics and high energy physics.

To make a substantial contribution to this emerging low temperature technology requires the combined efforts of physicists who are both knowledgeable about the fundamental properties of matter at low temperature and willing to explore their applications, and engineers who are prepared to transform these ideas into a viable technology. At HEPL an energetic group of approximately 50 technical personnel are engaged in this effort. As a result, there is now a sizable literature (see for example the HEPL reports referred to in the text) describing the progress in solving the many detailed problems encountered in this development. This paper attempts to outline briefly a few of the major technological innovations that are being developed at HEPL and to indicate their relevance to several applications in high energy physics.

II. TECHNOLOGICAL INNOVATIONS

1. Development of Niobium Cavities

The preparation of a suitable superconducting surface is one of the principal technological problems in the development of th superconducting accelerator. The superconductor must provide extremely high conductivity at microwave frequencies and it must be capable of sustaining high electric and magnetic fields.

Nature has provided a variety of possible candidates among the elemental superconductors and the many "alloys" to satisfy the requirements of this new technology. In the Physics Department at Stanford where there is active research in the problems of low temperature physics we have a strong motivation for understanding the fundamental microwave properties of superconductors over the entire range of physical character-

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istics. We are investigating in detail[1-4] materials with small κ values* which are good type I superconductors, the elemental superconductors with the highest transition temperature where κ values are near unity, and the very high κ value alloys where type II behavior is marked. But among this broad selection of materials that of greatest practical importance is pure niobium.

With pure niobium it should be possible to maintain very high accelerating fields continuously in a SCA. At 1.85°K the lower critical field H_{c1} for niobium is 1650 G. In a standing wave biperiodic $\pi/2$-mode structure this corresponds to an energy gradient of 11 MeV/ft, while for a traveling wave $\pi/2$-mode structure the corresponding energy gradient is 19 MeV/ft. It is likely that loading due to field emission of electrons will become important at gradients smaller than the values quoted above since these correspond to a peak electric field of 1.2×10^6 V/cm. However, the superior electric breakdown characteristics of niobium are well known and thus it is plausible that this material will provide the very highest attainable energy gradient. We are optimistic that energy gradients as high as 6 MeV/ft in a standing wave structure or 10 MeV/ft in a traveling wave structure can be achieved. In addition, the theoretical conductivity of niobium is sufficient to make continuous operation of a SCA at these high gradients feasible. At 1.3 GHz and 1.85°K the power dissipation in a traveling wave structure at 10 MeV/ft is 2.8 W/ft.

We have made rapid progress in the development of high Q, high field niobium cavities. As shown in Fig. 1, Q's exceeding 10^{10} and energy gradients exceeding 3 MeV/ft in a standing wave structure or 5 MeV/ft in a traveling wave structure have been achieved in cavities fabricated from commercially available niobium[5,6] and it is expected that niobium of greater purity will produce even better results.† There is, however, another practical consideration: can niobium cavities be fabricated at reasonable cost? This problem is most acute in considering the application of these techniques to construction of very large, say 1000-2000 GeV, accelerators. When we first achieved high Q in solid niobium cavities through a joint development effort with the Central Research Laboratory of Varian Associates, it was commented that making a linear accelerator of niobium is like making it of platinum. This attitude ignores a wide range of techniques that can be used in fabricating niobium cavities. At Stanford we have investigated a number of these possibilities: electrodeposition, vapor deposition, sputtering, forming of solid niobium and others. Each of these techniques holds real promise as a practical fabrication technique.

The electrodeposition technique as a method for fabricating niobium cavities is particularly attractive, and in cooperation with the Linde Division of Union Carbide

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[*] κ represents the ratio of penetration depth to coherence length.

[†] Preliminary measurements on very pure electrodeposited niobium cavities using the techniques described below have already yielded similar Q's and still higher gradients.

1. J.P. Turneaure, Thesis, Stanford University (1967).
2. J.M. Pierce, Thesis, Stanford University (1967).
3. J.P. Turneaure and H.A. Schwettman, High Energy Physics Laboratory Report HEPL 553 (1968).
4. J.M. Pierce, High Energy Physics Laboratory Report HEPL 576 (1968).
5. J.P. Turneaure and I. Weissman, High Energy Physics Laboratory Report HEPL 522 (1968).
6. J.P. Turneaure and I. Weissman, High Energy Physics Laboratory Report HEPL 571 (1968).

we are vigorously pursuing its development. The niobium is electrodeposited on a copper mandrel in the geometry of the final accelerator structure. The mandrel is subsequently removed by chemical means leaving a free standing niobium structure. The advantage of the method is that two important steps are taken simultaneously: 1) the niobium is formed in the complicated geometry required, and 2) the niobium is refined in the electrodeposition process. In fact the purity of the electrodeposited niobium exceeds that of triply zone-refined niobium. This, of course, dispels the oft repeated concern about material cost in fabricating niobium cavities. One can start with low grade niobium which in large quantities sells at $10 per pound and thus for the estimated weight of the accelerator structure at 1.3 GHz (20 lb/ft) the material costs are $200 per foot.

The development of a practical niobium accelerator structure is progressing rapidly and it is expected that the operation of experimental 20 ft sections will be accomplished within a year.

2. Development of Superfluid Refrigeration

Once it was recognized that superfluid helium plays an essential role in the operation of a practical SCA we began serious discussions with interested manufacturers concerning the development of superfluid refrigeration. In describing our plans to accelerator physicists we were frequently told that to develop the first superfluid refrigerator in cooperation with industry would require ten years. Under many circumstances this is probably true. But one unique advantage of a small laboratory engaged in the construction of modernized facilities is that it is possible to talk to industry about the development of important new technology not in terms of the needs of an indefinite future but rather in terms of an immediate requirement. Motivated by the immediate requirement for a 300 W superfluid helium refrigerator Dr. Sam Collins at Arthur D. Little, Inc. modified an existing refrigerator for superfluid operation. Experiments with this 30 W system were performed at company expense and provided design information for the 300 W unit shown in Fig. 2 and now being installed at Stanford just 2½ years after beginning the original discussion.

Operation of the 300 W superfluid refrigerator over an extended period of time will demonstrate the reliability and the economics of large-scale refrigeration. In addition, this unit is an essential part of our plans to demonstrate the feasibility of operating a large and complex laboratory from a central refrigerator. Before discussing the problem of a laboratory using central refrigeration, however, it is advisable to comment on the future of large-scale refrigerators.

Large low temperature refrigerators have most often been used in systems, for instance space simulation chambers, which are required to operate over periods of days. Under these conditions efficiency and reliability have usually been sacrificed in the interest of low initial cost. If cryogenics is to become a viable technology applicable to a broad spectrum of really large-scale problems of practical importance, the questions of efficiency and reliability are in fact the central problems. Also, in the case of superfluid refrigerators where the vapor pressure of helium is low, substantial expense is involved in the room temperature pumping equipment and the space it requires. Thus it is very desirable to recompress the returning helium vapor at low temperature where it is more dense. We are now beginning a cooperative program to investigate the problems of efficiency and low temperature recompression with the expectation of constructing a 1000-2000 W superfluid refrigerator that operates at 25-35% of Carnot efficiency. Such a system would represent a further advance in the state of the art.

3. Laboratory with Central Refrigeration

The SCA provides an excellent opportunity to demonstrate the feasibility of operating a large and complex laboratory with central refrigeration. In total our laboratory is 800 ft long, 60 ft wide and 60 ft high and we expect to make refrigeration available throughout this space to serve a large number of separate experimental units. A cryogenic system of this magnitude and this complexity is quite different than any considered previously. It is out of the question to shut down and warm up an entire laboratory in order to replace a single defective component and it is essential that a new experimental unit can be connected into the central refrigeration system at any time.

The SCA itself is illustrative of the problems encountered in a central refrigeration system.[7,8] The accelerator Dewar and the accelerator structure are constructed in 20 ft sections. A single cryogenic unit consists of four of these sections and there are in total six units plus the injector unit. First, it should be recognized that even a single cryogenic unit is quite complex. There are perhaps 100 seals in each unit and even a one percent chance that a seal will fail is intolerable. There is no alternative to reliability and thus we have expended a sizable effort in designing satisfactory seals. Second, in the event of some component failure the relevant cryogenic unit must be isolated from the rest of the system and the defective section must be replaced with a spare section. In order to accomplish this in minimum time without disruption of the central refrigeration system we have made provisions for the necessary manifolding and cryogenic valving and we have demanded interchangeability of components. Third, refrigeration must be provided from the central plant to each of the cryogenic units. In the SCA, superfluid helium is distributed to each of the units via a one inch liquid line that extends the length of the accelerator; the liquid vaporizes and the cold vapor is then transported back to the refrigerator in a 5 in. diameter insulated line. This method of heat transport is consistent with the desire to split the entire low temperature system into smaller units for ease of maintenance and with this method it appears entirely possible to transport 1000 W a distance of 1000 ft and still maintain the temperature constant to within 10-20 m^{o}K.

In addition, we are developing another interesting application of superfluid helium.[9] If two reservoirs are connected by a plug which is porous only to the superfluid, then associated with any temperature difference between the reservoirs there is a large pressure difference known as the fountain pressure. For $\Delta T \sim 0.2^{o}K$ this pressure difference can be used to raise the helium level in the "hot" reservoir on the order of 100 ft. Thus, refrigeration can be provided to equipment, for instance a superconducting spectrometer, at elevations far above the normal helium level in the SCA itself and this can be accomplished without the necessity of a cryogenic mechanical pump.

The idea of central refrigeration and the demonstration of its practicality is extremely important to the development of low temperature technology for a broad spectrum of large-scale applications. In high energy physics central refrigeration could be important in a superconducting proton synchrotron, in a superconductong storage ring,

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[7] H.A. Schwettman, J.P. Turneaure, W.M. Fairbank, T.I. Smith, M.S. McAshan, P.B. Wilson, and E.E. Chambers, High Energy Physics Laboratory Report HEPL 503 (1967).

[8] M.S. McAshan, High Energy Physics Laboratory Report HEPL 526 (1967).

[9] C.M. Lyneis and H.A. Schwettman, High Energy Physics Laboratory Report HEPL 577 (1968).

or in a superconducting beam switchyard,* in addition to the specific application we are considering. Cryogenic technology as it exists today in commercially available equipment is not prepared to cope with the problems of central refrigeration. It is an important objective of our laboratory to take the steps required in its development.

4. Stabilization Using Feedback Control

In a SCA essentially all of the incident microwave power is absorbed by the beam. This situation has prompted questions from accelerator physicists relating to stability in a beam-loaded SCA. But concern about the possibility of achieving stable operation in a SCA is a holdover from conventional linacs. In the conventional linac 80-90% of the microwave power is lost in the structure or in the termination. Thus, fluctuations in the beam loading result at most in modest variations of the load seen by the klystron. As a physical principle, this is a poor way to achieve stability; it has proved adequate in conventional linacs but it is not an appropriate method for the SCA. The SCA, on the other hand, is an ideal system in which to use the more general principle of dynamic stability.

Dynamic stability using feedback control has been used in many systems. An excellent example is provided by electrostatic gyroscopes. It is well known that an electrostatic field does not provide a stable support for a conducting sphere. Yet by sensing the position of the sphere and using feedback to control the voltage on the supporting electrodes, it is possible to hold the position of a gyroscope to one millionth of an inch. The stabilization of the SCA, as illustrated in Fig. 3, is analogous. The fields in the accelerator structure are sampled with a probe and the output from this probe is compared to a reference signal with respect to both amplitude and phase. The error signals are then fed to an electronic phase shifter and a variable attenuator at the input of the klystron to close the feedback loop. The long time constant ($> 10^{-3}$ sec) for changing the fields in the SCA (due to the high Q) simplifies the feedback problem and stabilization to one part in 10^4 in amplitude and to 0.1° in phase has been achieved in preliminary tests.[10]

5. Minimum Radiation Facility

The new technology presently being developed using either low temperature techniques or plasma techniques (in an electron ring accelerator) offer a real opportunity for substantial reduction in the cost of high energy accelerators. Despite this encouraging outlook, the prospects for substantial reduction in the cost of the entire facility is less certain. Smith and Lewin[11] of the Rutherford Laboratory, for example, suggest that a superconducting proton synchrotron could be built for half the cost of its conventional counterpart, but note that this represents only a 20% reduction in total costs. It is clear that one cannot make any real progress without changing the economics of the over-all facility.

One important contributor to the cost of a high energy facility is radiation. The total cost attributable to radiation, including permanent shielding throughout

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*The recent report "Refrigeration for Superconducting Magnets in the 200 BeV Accelerator at Weston, Illinois" correctly concludes that with presently available components, superconducting magnets in a beam switchyard would be served best by individual refrigerators. The work in progress at Stanford, however, will change significantly the possibility of using central refrigeration.

[10] L.R. Suelzle, High Energy Physics Laboratory Report HEPL 564 (1968).

[11] P.F. Smith and J.D. Lewin, Nucl. Instr. Methods 52, 298 (1967).

the facility, movable concrete shielding blocks, radiation resistant materials in various components, large collimators, energy defining slits and so forth, is enormous. In the cost estimate for a conventional proton synchrotron of 200 GeV presented in 1965 to the Joint Committee on Atomic Energy, it was estimated that thirty million dollars would be required for movable shielding alone. In principle there is no reason for generating large amounts of radiation except in the target and in the beam dump. If radiation levels elsewhere were minimal, and there are good reasons to believe that in a SCA this could be achieved, then a high energy facility could be quite different than at present. In a linac, for example, there would be no need for a separate klystron gallery and long rf feed lines. Indeed, for a SCA where the rf power level required is modest it is likely that solid state rf sources will in time be used. Even the accelerator hall itself could be modestly shielded by present standards. Also, with the excellent energy resolution and stability possible in a SCA (one part in 10^4) the radiation level in the beam switchyard could be held to a minimum. Instead of energy defining slits which are designed to handle 10% of the beam power, beam position monitors could be used supplemented perhaps with slits that are set for several times the inherent width of the beam. Low radiation levels along the accelerator and throughout the beam switchyard could make a significant impact on the cost of a high energy facility. Of course, monitoring devices would be required to shut down the accelerator immediately and automatically in the event that radiation levels increase. But it is expected that this can be accomplished in a simple fashion at relatively small expense. With strict interlocks against increased radiation levels it might appear that initial tune-up of the machine would be difficult. In a fully regulated SCA, however, the initial steering and focusing can be performed at very low intensity. Subsequently, as the current is increased, the feedback stabilization compensates automatically for the increased beam loading.

The suggestion that an accelerator could be operated as a minimum radiation facility is likely to be viewed as fantasy, but if still larger accelerators are to be built, it is probable that all of the traditional ideas of accelerator physics must be reexamined. It is our intention at Stanford to examine carefully this idea and to develop completely the control and interlock systems required.

III. A FEW APPLICATIONS TO HIGH ENERGY PHYSICS

1. High Resolution CW Linac

One of the frontiers we intended to explore fully at Stanford is the high energy resolution that is possible in a cw SCA. As indicated earlier, the SCA is an ideal system for use of feedback to achieve dynamic stability and it is this fact that has encouraged us to strive for energy resolution of 0.01% in the SCA (100 keV at 1 GeV), as compared to the 1% resolution typical of conventional linacs. This effort is essential to our objective of doing high resolution physics at high energy and to our intention of exploring the feasibility of a minimum radiation facility.

To produce a beam monoenergetic within one part in 10^4 requires, in addition to stability of the accelerating fields, that the electrons be confined to a 1° phase bunch. This bunching is accomplished in the injector section and the capture section of the accelerator. As illustrated in Fig. 4, the electrons are emitted from a regulated triode gun and accelerated to 80 kV. The continuous stream of electrons then passes through a chopper cavity and the aperture on the far side stops all electrons except those in a 20° phase bunch. These electrons are injected into a specially designed capture section where they are accelerated to about 2 MeV and where the electron bunch is compressed in phase to 1°. The capture section is a $\beta = 0.95$ structure of $2\frac{1}{2}$ wavelengths and the design energy gradient is 1 MeV/ft. The injector section and the capture section complete with electronic stabilization are under construction and will be tested carefully this fall. Particle motion in the accelerator sections beyond the capture section has been calculated,[12] using the fields in a computer optimized biperiodic $\pi/2$-mode structure,[13] including the effects of radial motion and misalignment of individual accelerator sections.

How far resolution can be pushed in a SCA is not entirely clear. But we are considering even more sophisticated techniques in conjunction with a feasibility study for an electron microscope where energy resolution of one part in 10^6 is required at 5-10 MeV.

2. High Intensity Linac

From a superficial point of view it would appear that the SCA has little to offer in the design of high intensity linacs such as the meson factory at Los Alamos or the intense neutron generator (ING) proposed at Chalk River. It is easily argued that at high intensity the conventional linac is quite efficient (about 80% of the microwave power is converted to beam power according to the Chalk River design for the ING) and thus superconductivity is simply not required. But this argument misses the essential point; efficiency in the conventional linac is achieved only at great sacrifice. The energy gradient for the meson factory at Los Alamos is about 0.30 MeV/ft (800 MeV in 2600 ft) and for the proposed ING at Chalk River is about 0.2 MeV/ft (1 GeV in 5000 ft). In fact, since the power dissipated in the structure walls is proportional to $(V/L)^2$ and the power extracted by the beam is proportional to (V/L), it is not surprising that for low energy gradient a conventional linac is efficient.

What superconductivity offers in the high intensity linac is a great deal of flexibility in the design of the accelerator. Let us consider just two examples of what this flexibility can provide. First, it is obvious that efficient operation can be achieved at much higher energy gradients. The meson factory at Los Alamos or the ING at Chalk River could be a few hundred feet in length rather than a few thousand feet. Alternatively, the final energy could be increased substantially and it would then be possible to produce K mesons in abundance. Second, the problem of beam loading is simple in the SCA as compared to the conventional linac. In the limit of heavy beam loading the time constant, defined as the ratio of microwave energy stored in the accelerator structure divided by the rate that energy is extracted, is:

$$\tau = \frac{1}{\omega(r/Q)} \cdot \frac{(V/L)}{I} ,$$

where ω is the angular frequency, r/Q is the shunt impedance per unit length divided by the Q of the structure, V/L is the energy gradient, and I is the beam current. For the conventional intense linac this time constant is a few microseconds, but, principally due to the high energy gradient, the time constant for the SCA is a fraction of a millisecond. Thus feedback stabilization in the SCA even for the heavy beam loading of a meson factory or an ING, is quite simple. It should be added that stability in a proton linac where the velocity of the particle is changing is far more important than in an electron linac where the velocity is constant.

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[12] E.E. Chambers, High Energy Physics Laboratory Report HEPL 570 (1968).

[13] T.I. Smith, High Energy Physics Laboratory Report HEPL 527 (1967).

3. High Energy Recirculating Linac

From the experience of the past decade it is generally recognized that the cost per GeV for a circular accelerator is substantially less than for a linac. However, if energy gradients of 10 MeV/ft can be achieved in the SCA, and we are confident they can, the economics of the linear accelerator are substantially improved and the question of linacs versus circular accelerators as a means of reaching very high energy must be re-examined.

One interesting possibility in the construction of a high energy accelerator, which is a compromise between the linear and the circular machines, is the recirculating linac. The possibility of recirculating a beam through a linear accelerator has been suggested a number of times in the past. An interesting example is the race track microtron for electrons of a few hundred MeV[14] which is illustrated in Fig. 5. A practical recirculating linac for very high energy particles is different in several respects from the race track microtron mentioned above. First, at very high energy, electrons radiate too much energy to make the scheme useful. But protons even for a final energy of 2000 GeV are not subject to this criticism. Second, for a very high energy accelerator the magnetic deflection system used in the race track microtron is totally impractical. Instead of solid 180° magnets it would be more reasonable to provide separate beam transport systems and arrange that the average radius of curvature for each beam is nearly the same so they could all be placed in a single tunnel. For the special case of three passes through the linac the beam transport system might be particularly simple, since, as illustrated in Fig. 6, recirculation could in principle be accomplished with a single magnet system for two thirds of the final energy.

One can give a crude "existence proof" that on economic grounds the recirculating linac is an interesting alternative for reaching high energy. For this purpose let us compare the superconducting recirculating linac and the superconducting proton synchrotron. It is clear that the rf system represents a minor contribution to the cost of a proton synchrotron while it represents a major cost in a recirculating linac. On the other hand the magnet system is less expensive for a recirculating linac since the magnets used are dc magnets (which eliminates refrigeration for ac losses and large power supplies for pulsing magnets) and since the magnet ring is for (2/3)E. The question is whether or not these factors balance. The cost estimates below were generated by P.F. Smith of the Rutherford Laboratory and the author based on the assumptions: 1) that development of filamentary superconductor low loss ac magnets will proceed without important complications, and 2) that development of practical niobium rf cavities producing 10 MeV/ft in a traveling wave structure will be accomplished.

Costs in 1000 $/GeV

	Proton Synchrotron	Recirculating Linac
Magnet system	185	75
Rf system	30	150
	215	225

These figures, of course, do not represent total costs of a high energy facility. They are intended only as comparative costs based on projected developments.

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[14] B.H. Wiik, H.A. Schwettman, and P.B. Wilson, High Energy Physics Laboratory Report HEPL 396 (1966).

Recently crude cost estimates have been generated for a number of "new technology" accelerators: the superconducting proton synchrotron, the cryogenic proton synchrotron, the superconducting recirculating linac, the superconducting FFAG, and the electron ring accelerator. Relatively little significance should be attached to any of these estimates, since all are based on important assumptions about how the relevant technology will develop over the next few years. What is far more significant and encouraging is that several possibilities exist for the construction of future high energy accelerators and these provide alternatives in the technology that must be successfully developed. This flexibility itself is our greatest asset.

IV. CONCLUSIONS

The low temperature technology being developed at Stanford can be important in a large number of applications. We have already mentioned the high resolution cw linac, the high intensity linac and the high energy recirculating linac. In addition, this technology is essential to the construction of a superconducting rf separator for use with the large proton synchrotrons, a π-meson accelerator which could be used in conjunction with the meson factory at Los Alamos, and a superconducting race track microtron for electrons of a few hundred MeV. All of these applications are now being given serious consideration by various groups throughout the world. Nor are the applications for this technology restricted to high energy physics. Superconducting cavities may in fact find application in problems as far removed from low temperature physics and high energy accelerators as the generation of electric power by thermonuclear fusion.

At Stanford we are strongly motivated to develop this technology as rapidly and as far as possible so that all of these applications can be pursued in the near future.

ACKNOWLEDGEMENTS

As noted in the introduction, to make a substantial contribution to this emerging low temperature technology requires the combined efforts of physicists who are both knowledgeable about the fundamental properties of matter at low temperature and willing to explore their applications, and engineers who are prepared to transform these ideas into a viable technology. The rapid progress in this development at Stanford is due to the enthusiastic efforts of Drs. E.E. Chambers, W.M. Fairbank, E. Jones, M.S. McAshan, T.I. Smith, L. Suelzle, J.P. Turneaure and the entire technical staff of the High Energy Physics Laboratory.

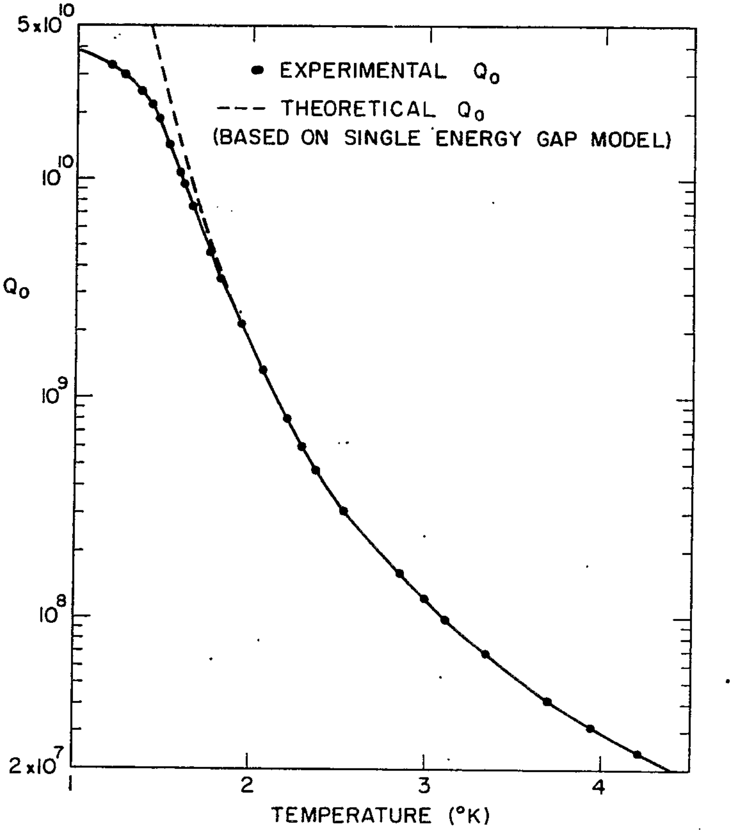

Fig. 1. The unloaded Q as a function of temperature for an X-band niobium cavity.

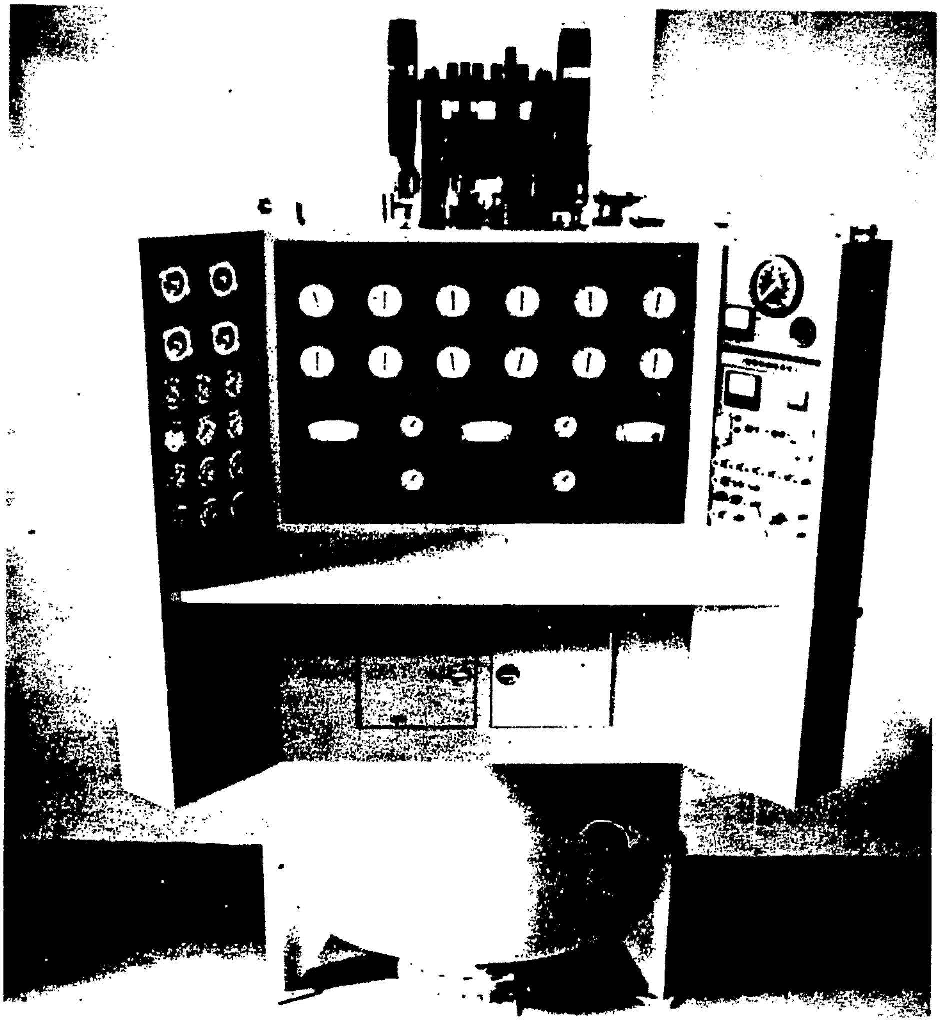

Fig. 2. Control panel and "cold box" of the 300 W superfluid helium refrigerator

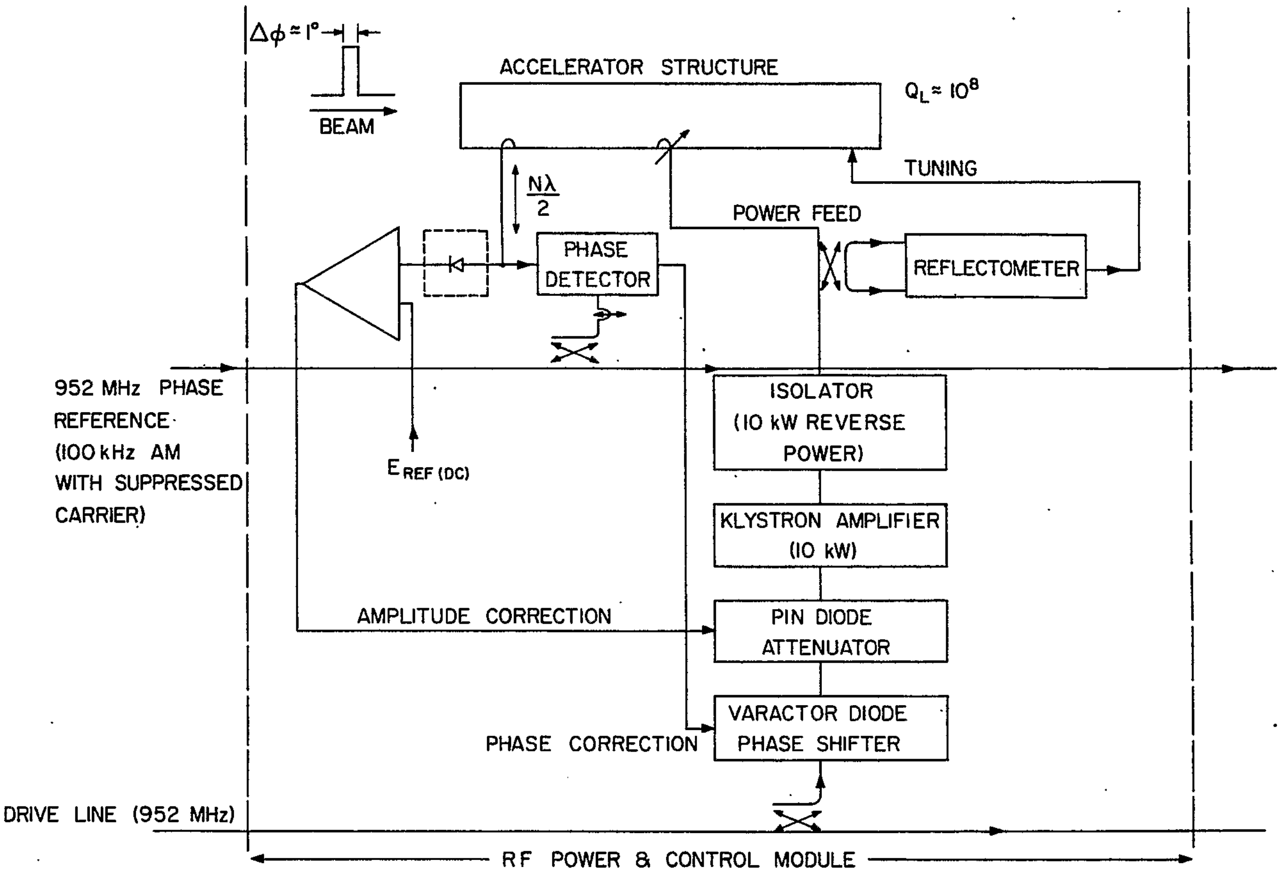

Fig. 3. Block diagram of a feedback stabilized superconducting accelerator section.

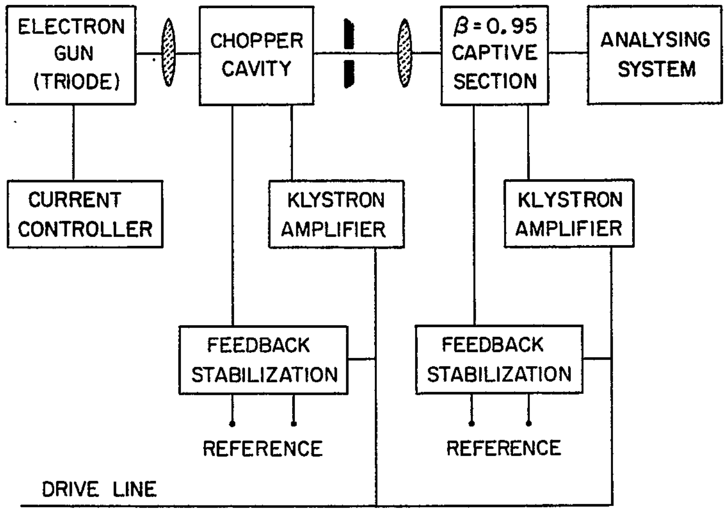

Fig. 4. Block diagram of the injector section and capture section.

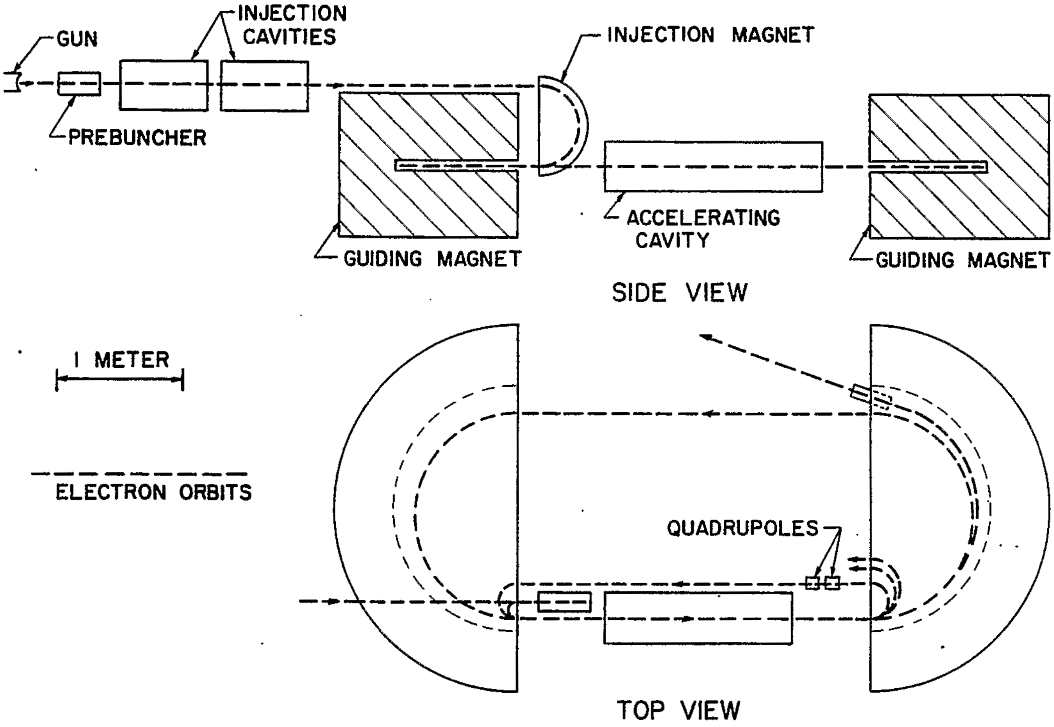

Fig. 5. Schematic drawing of the superconducting race track microtron.

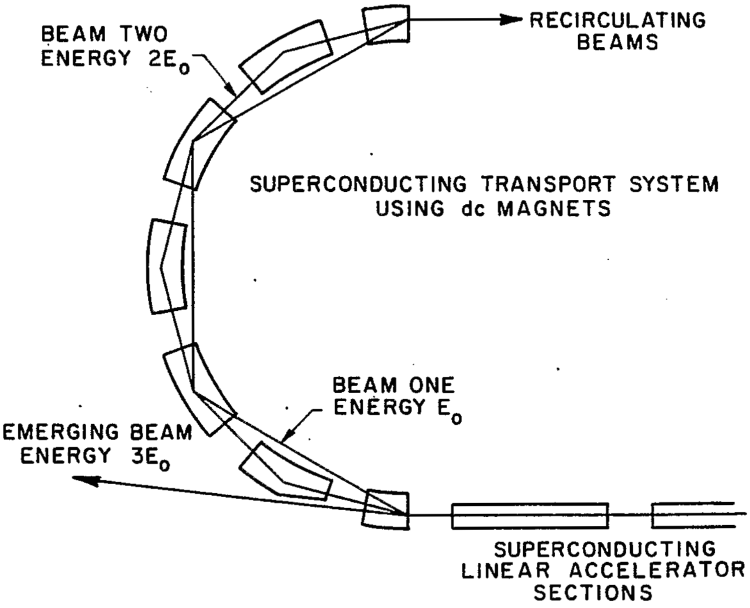

Fig. 6. Schematic drawing of a simple recirculating linac.