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DESIGN OF A 600-MeV MICROTRON USING A SUPERCONDUCTING LINAC†

J. S. ALLEN, P. AXEL, A. O. HANSON, J. R. HARLAN, R. A. HOFFSWELL, D. JAMNIK‡,
C. S. ROBINSON, J. W. STAPLES, AND D. C. SUTTON
Physics Department, University of Illinois, Urbana, Illinois, USA

A proposed 600 MeV racetrack microtron is described which uses a superconducting linac as the accelerating section. This linac, which is being constructed, will use niobium cavities cooled to 1.8 °K and will provide a continuous electron beam, except for the 1.3 GHz microstructure. The electron beam will be recirculated through the linac 20 times by two 180° bending magnets having uniform fields of about 14 kG. Focusing of the recirculating electrons is provided on each return path by a quadrupole pair close to each magnet. Calculations show that the requirements for space and phase stability are easily satisfied and that the microtron arrangement offers an electron beam with exceptional energy resolution.

1. INTRODUCTION

In examining a number of possibilities for replacing the betatrons at the University of Illinois for studying nuclear reactions at intermediate energies, the superconducting microtron seemed to be the most promising since it can supply an effectively continuous electron beam of a few microamperes with an exceptionally low energy spread. It is particularly suitable for nuclear research at a University since it is modest in size and is economical to operate and to maintain. The motivation and the development of some specific ideas have been presented at a number of conferences and in some specific reports.$^{(1-6)}$ This article presents some of the results from these reports on electron trajectories and describes the components which are being assembled for the operation of a superconducting accelerating section 7.5 ft long.

The racetrack microtron, as an arrangement for producing electron beams of intermediate energies, was discussed in some detail by Wiik and Wilson.$^{(7)}$ A more recent review by the same authors includes references to earlier work as well as a systematic treatment of some of the problems involved in the design.$^{(8)}$ The superconducting accelerator section is based on the developments at Stanford University which have been extensively described.$^{(9-13)}$

2. GENERAL ARRANGEMENT

The proposed 600 MeV microtron consists of a 30 MeV superconducting linac, operating C.W. at 1.3 GHz, placed between two 13.63 kG bending magnets 640 cm apart as shown schematically in Fig. 1. There are 19 parallel return tubes, separated by 14.7 cm, each with two quadrupole pairs to guide the electrons back through the accelerating section until they finally emerge with the desired final energy.

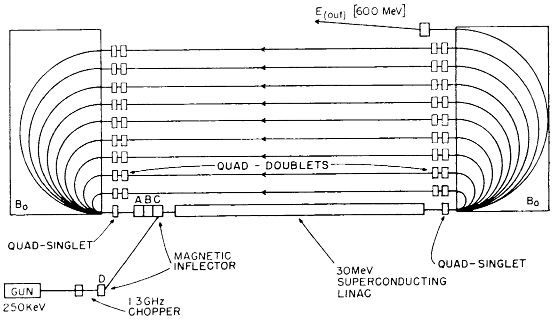

FIG. 1. Schematic microtron arrangement. A, B, C, and D are small magnets with fields around 100 G. The electrons are inflected by an achromatic pair C and D. A and B are introduced to restore the beam to its initial path after being deflected by C.

Electrons start from the dc electron gun and gain a kinetic energy of 250 keV. These enter a TM_{210} mode microwave chopper which selects only those electrons within a 6° phase interval to be inflected by small magnets into the superconducting linac and subsequent microtron transport system.

3. CHOICE OF MICROTRON PARAMETERS

In contrast to the design of Wiik and Wilson$^{(7)}$ which uses a separate 20 MeV linac for an injector, our arrangement uses a low energy injector and

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‡ Permanent address: Institute 'J. Stefan', Ljubljana, Yugoslavia.

places the entire length of the superconducting linac between the magnets. This arrangement uses the expensive linac structure more efficiently since the electrons traverse the whole linac on every orbit. The low initial injection energy, however, limits the lower energy range to which the microtron can be varied by simply changing the linac energy gain and the related magnetic fields because incompletely relativistic electrons slip in phase while traversing the long straight sections. To obtain a usable injection condition for 20-orbit operation at 15 MeV per turn, it is necessary to make small changes in the magnet separation or other equivalent changes.

Microtron designs have been discussed in terms of two parameters μ and ν, which represent the number of rf periods in the first orbit and the increase in this number between successive orbits. Our design is characterized by $\mu = 58$, and $\nu = 2$ as compared to $\mu = 39$, $\nu = 1$ for the Wiik and Wilson design. Although $\nu = 2$ constricts the maximum phase stable region by a factor of two, the region is more than ample to contain the well-defined phase bunches required in our design. The value of $\nu = 2$ was chosen because, for low energy injection, it allows the first return beam to clear the accelerator structure. Although it is possible to shift the first return orbit in a special way so as to miss the outer diameter of the linac,(14) the choice of $\nu = 2$ also increases the spacing between all successive orbits and makes the installation of quadrupoles on all the return paths more convenient.

The choice of the frequency as 1300 MHz is a compromise between a desire for low superconducting surface resistance, which favors low frequencies, and for tolerable microstructure in the accelerated electron beam.

One may note that for high energy electrons, the nominal energy gain per turn is linearly related to the magnetic field in the end magnets according to the equation,

$$\Delta E \approx \frac{\nu\lambda Bc}{2\pi} = \frac{\nu\lambda B}{20.96\ \text{kG-cm-MeV}^{-1}}$$

where the design values for our arrangement are $\Delta E = 30$ MeV, $\lambda = 23.06$ cm, $\nu = 2$, and $B = 13.63$ kG. A summary of these and other parameters is presented in Table I.

TABLE I

Microtron design parameters

General	
Output electron energy	600 MeV
Injection energy	0.250 MeV
Injection phase spread	±3°
Energy gain per traversal	30 MeV
Number of traversals	20
Spacing between return orbits	14.7 cm
Magnet field	13.63 kG
Duty factor	100%
Output current	10 μA
Output energy spread	± 60 keV
Superconducting Linac	
Nominal energy gain per traversal	30 MeV
Nominal accelerating phase	9°
Length of accelerating linac	4.6 m
Current (20 traversals)	200 μA
Beam power	6 kW
Operating frequency	1.3 GHz
Required radiofrequency power	10 kW
Input power for radiofrequency	30 kW
Refrigerator	
Cooling capacity (at 1.8° K)	100 W
Input power	200 kW
End Magnets (for each of two)	
Dimensions of the field	1.5 × 3.0 m
Height of magnet gap	2.5 cm
Weight—iron	234 tons
copper	1.33 tons
Power	5.4 kW
Orbiting Time	
First orbit	42.3 nsec
Last orbit	71.5 nsec
Total	1138 nsec

4. COMPUTER STUDIES OF ELECTRON TRAJECTORIES

The linac, as treated here, consists of two sections, the first one of 3 active cells and the second one of 36 cells. A drift tube separates the two sections so that there may be a variable rf phase difference between them. The first section which represents an injector and buncher is operated at 6.6 MV/m while the main section is operated according to the desired final electron energy. For these calculations the linac is taken to be the biperiodic structure of the Stanford design(10) which produces a standing wave field with a low space harmonic content.

For the proposed injection energy of 0.250 MeV, the required nominal energy gain of about 30 MeV at a resonant phase of 9° is obtained for an injection phase of −70°. The electrons, thus, arrive at the entrance to the first cavity 70° before the zero of the rf field. The injected beam is chopped to ± 3° to improve the energy resolution. The injected bunch is compressed by a factor of 3 to about ± 1° in phase in passing through the linac.

Space charge effects are small for the designed peak current of 0.6 mA in a 6° phase interval corresponding to an average current of 10 μA. The space charge repulsion in a 3-m drift length between the chopper and the linac is estimated to produce a divergence of only 0.15 mrad, which is negligible.

5. BEAM TRANSPORT

We require that both positions and angles of the beams returning to the entrance of the linac should independent of their momentum to first order. Such an achromatic beam behavior in the microtron can be realized by having no horizontal focusing on any of the return paths and by requiring the transport system to be symmetric about the plane midway between the magnets. With this arrangement, all of the horizontal focusing is produced on the linac axis and all large horizontal excursions from the nominal paths occur along the return paths.

The fringe field at the edge of each bending magnet is the predominant source of vertical defocusing along the beam path in the racetrack microtron. For the computer calculations of beam trajectories, we have used an approximation to a measured fringe field.(5) For the first few orbits the trajectories through the magnet were calculated in detail by a step-by-step procedure; for the fifth and higher orbits the trajectories can be described adequately by treating each fringe field region as a thin vertically diverging lens.

We preserve the symmetry of a two-dimensional fringe field, which leads to very simple horizontal trajectories. Vertical focusing is provided on each of the return paths by quadrupole doublets placed close to each magnet face. These quadrupoles can be treated simply and offer considerable flexibility. The horizontal focal lengths of each doublet on the return paths is required to be infinite at the nominal energy. Since the doublets at either end of each return path are completely symmetrical, only a single quadrupole gradient remains to be adjusted per return path. This gradient is adjusted to advance the vertical betatron oscillation phase by some desired amount; we chose about 90° advance per complete turn, but this is very uncritical. Quadrupole singlets at either end of the linac were adjusted to advance the horizontal betatron phase by 90° for the first orbit; this is also uncritical. The gradients of the vertical doublets in the return orbits increase monotonically; when 20 cm long quadrupole magnets are placed at a distance of 25 cm from the magnet edge and the members of each doublet are separated by 10 cm, the values of gradients for the first doublet are found to be − 149 G/cm and + 88 G/cm while those for the last are − 343 G/cm and + 318 G/cm. The gradient for each of the two singlets on the linac axis is + 6 G/cm.

Typical electron trajectories illustrating the nature of the deviations from a reference orbit are shown in Fig. 2. One may note that for three injection phases, 3° apart, the output phases after the first orbit vary about the resonant phase by only about ± 1°. Because the frequency of vertical (betatron) oscillations has been kept nearly constant by the choice of quadrupole currents, the beam becomes both smaller and more parallel vertically as the energy increases. The horizontal focusing, however, becomes relatively weaker with increasing energy so that the beams become more parallel horizontally but not much smaller.

The properties of the outgoing beam for these and other variations in the initial conditions are indicated in Table II. An increase of 1 per cent

TABLE II

Properties of the electron beam from the microtron in the 20th return path for different injection phases, accelerating voltages and magnetic fields. The nominal specifications of the beam injected into the linac for the trajectories considered here are: $V_i = 0.250$ MeV, $\phi_i = -70°$, $X_i = Y_i = +2$ mm, $(dX/dZ)_i = (dY/dZ)_i = 0$. Those from the linac after the first traversal are: $V = 29.33$ MeV, $X = Y = 0.4$ mm; $dX/dZ = dY/dZ = -0.04$ mrad. The resonant energy gain for these conditions are 29.17 MeV at a resonant final phase of 9° with a magnetic field of $B = 13\,237$ G.

Operating conditions	Outgoing beam X mm	 dX/dZ 10^{-6} rad	 Y mm	 dY/dZ 10^{-6} rad	 E_{out} MeV	 ΔE_{out} percent
Nominal phase	−0.77	−4.5	−0.28	−17.0	583.29	0.000
$\phi - \phi_i = +3°$	−0.94	+6.7	−0.36	−10.0	583.35	−0.010
$\phi - \phi_i = -3°$	−0.66	+2.4	−0.23	−21.0	583.25	+0.007
$\Delta V/V = +1.0\%$	−1.10	+0.03	−0.13	−10.0	583.42	+0.022
$\Delta B/B = -0.3\%$	−0.68	+2.0	−0.01	−10.0	585.03	+0.298

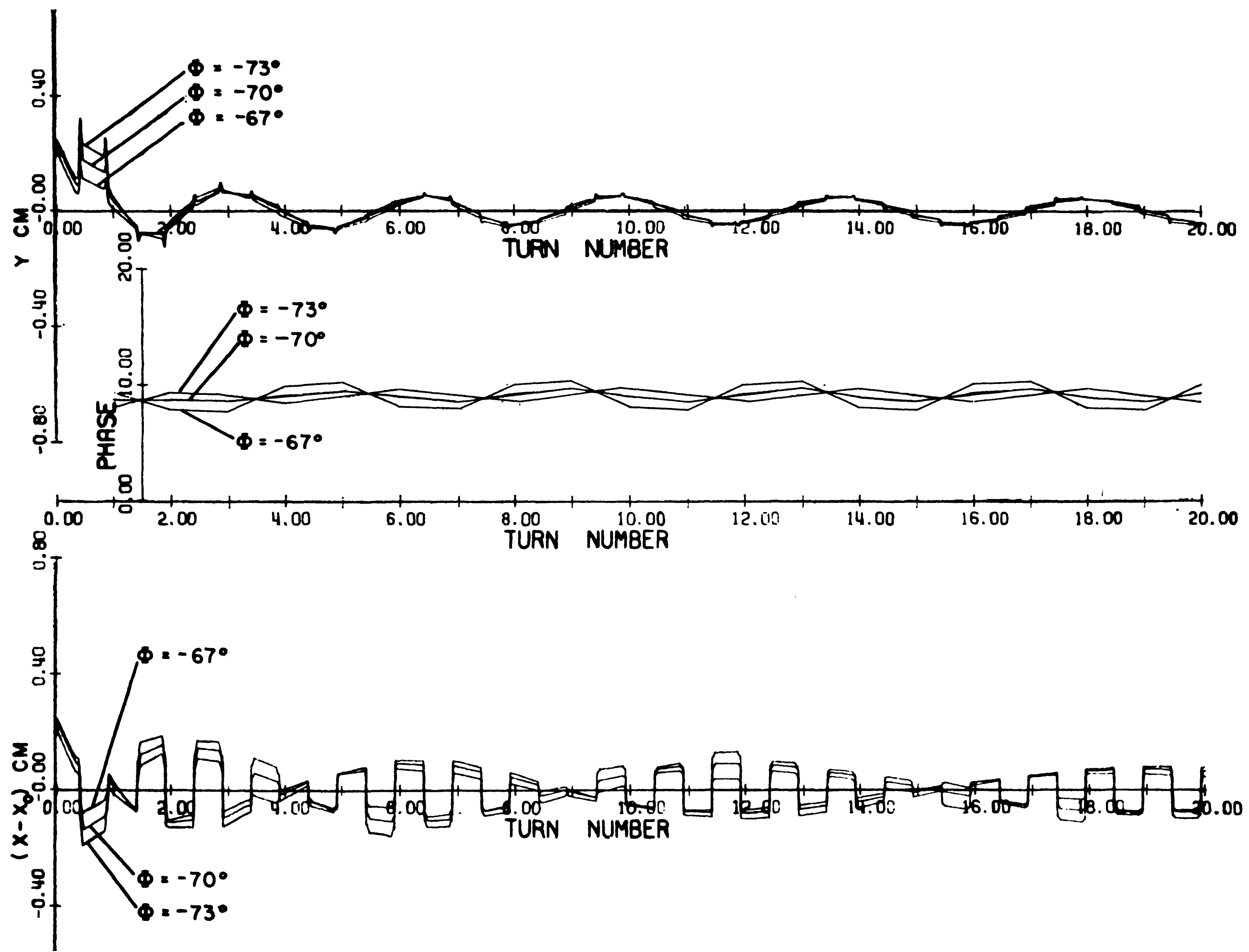

FIG. 2. Electron trajectories for three different injection phases: $\Phi = -67°$, $-70°$, or $-73°$. The phases after the first orbit differ by about ±1° and oscillate about the resonant phase with constant amplitude and period.

in the linac gradient without other changes in the nominal operating conditions leads to variations in phase and in the horizontal amplitudes in the return paths which are about three times as large as those indicated in Fig. 2. The trajectories, however, were retained through all 20 orbits and the final energy in this instance was only 0.022 per cent above the nominal energy.

A 0.3 per cent increase in the magnetic field made a negligible increase in the vertical or horizontal oscillations. The equilibrium phase changed by about 2° and the phase oscillations were larger. The output energy in this case followed the magnetic field as expected to within 0.01 per cent.

Although the trajectories seem very stable, specific calculations show that these trajectories are quite sensitive to misplacements and misalignments of the quadrupoles. The misalignment tolerances can be considerably increased by modification of the fringe field terminations of the 180° magnets such as those suggested by Babic and Sedlacek,(15) which have a narrow region of reversed field. Preliminary examination of initial orbits with different edge fields suggest that some of these may also serve to enlarge the phase stable region for low linac gradients.

6. DESIGN AND PROCUREMENT OF COMPONENTS

At the present time we are constructing one of two sections of the superconducting accelerator which will be placed between the two large bending magnets. This section, together with the electron gun and other associated equipment, is being installed adjacent to the 25 MeV betatron which it will replace.

The linac will be used as part of our nuclear structure research program while we are obtaining experience with the control of the beam quality. Space occupied by the 300 MeV betatron is available for the complete microtron, but funds for the large magnets and other equipment have not been appropriated.

7. MAGNETS AND QUADRUPOLES

There do not seem to be any major difficulties in designing adequate bending magnets since calculations show that the beam can be managed with magnets of a conventional type. The weights of these magnets listed in Table I were based on the use of rectangular blocks, but we are interested in possible advantages of the minimum volume concept presented by Peterson.(16)

As indicated earlier, we plan to use additional iron shields with separate windings at the entrance edges of the large magnets.

Although we plan to use a large number of quadrupoles of a conventional design, the gradients required are so low that their cost would be an order of magnitude below that of the bending magnets.

8. ELECTRON GUN AND CHOPPER

The electron gun is a modification of the 300 kV ion and electron accelerator system made by the Texas Nuclear Corporation primarily as a (D, T) neutron source. It has a completely enclosed high voltage electrode and is designed to supply 5 mA of dc current at any voltage below 300 kV with a precision of 0.1 per cent. This current and voltage are comfortably above the 0.6 mA and 250 keV planned for the microtron.

The electron beam chopper system consists of two rectangular cavities, operating in the TM_{210} mode as described by Haimson.(17) The magnetic fields in these cavities deflect the electron beam over an elliptical path so that the beam passes through a defining aperture only during a single preselected 6° phase interval in each microwave period. The power required is provided by an Eimac 1 kW 1 GHz C.W. klystron.

9. CRYOSTAT

The cryostat for the 2.4 meter niobium section is 3 m long and holds 500 liters of liquid helium at 1.85 °K. It is made of stainless steel, and the welded parts closest to the accelerating cavities were annealed before assembly to reduce undesirable magnetic effects. In addition to the ports required for the electron beam, there is an 8 in. diameter vertical channel opening to the inside of the dewar as shown in Fig. 3. This vertical channel serves as an exhaust manifold for a 1200 cfm vacuum pump which will keep the helium pressure at about 15 torr. The exiting cold gas passes through a low pressure heat exchanger. A 2 in. diameter pipe centered on the axis of the heat exchanger provides access to the accelerator structure from the inside of the helium vessel.

10. REFRIGERATION

In order to have a temporary source of continuous refrigeration at 1.85 °K, we modified an

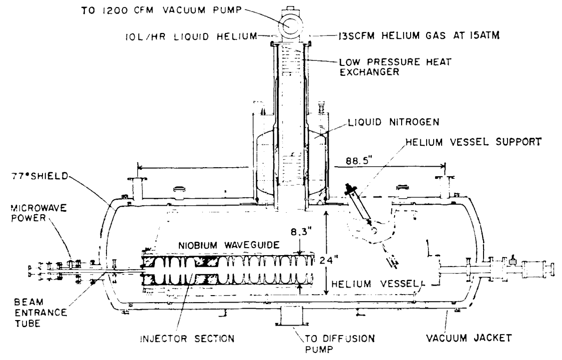

FIG. 3. Linac cryostat.

available A.D.L. helium liquefier by adding a helium gas recovery system, a 1200 cfm vacuum blower and a low pressure heat exchanger. This exchanger, which is mounted just above the dewar for maximum efficiency, should increase the refrigeration available at 1.85 °K from 5 to 20 W. This refrigeration capacity could support continuous operation of our 2.3 m section with an energy gradient of 10 MeV/m, only if a Q of 10^{10} can be attained. (The 100 W refrigeration indicated in Table I would provide the reliability and safety factor desirable for the microtron.)

11. LINAC STRUCTURE

Since our linac has a modest length we have chosen to build the $\pi/2$ mode biperiodic structure developed at Stanford University. This type of structure is tolerant of dimensional errors and of nonuniform loading in individual cavities as recently discussed by Knapp.(18) Its specific shunt impedance r/Q was reported as 920 Ω/m at 0.95 GHz which scales to 1260 at 1.3 GHz.(10) The microwave power absorbed in the linac structure is given by $V^2/(\Omega L)$ where V is the energy gain per unit charge of electrons and L is the length of the structure in meters. The power absorbed in 2.3 m of structure, operating at a 23 MeV level ($V = 23 \times 10^6$ V), with an unloaded Q of 10^{10}, is 20 W.

The maximum current which can be accelerated is limited by the generation of TM_{11} deflecting modes.(19) This current is given by 0.025 V $\lambda_\perp^2/(L^2 Q_\perp)$ where $\lambda_\perp$ is about $2\lambda/3$ and the $Q_\perp$ is the effective quality factor for that mode. To obtain a current of 10 μA, $Q_\perp$ must be reduced to 2×10^8. Because these undesirable modes have shorter wavelengths, their energy can be drained through a waveguide which is beyond cutoff for the accelerating mode. No special features will be introduced into our structure until we have had an opportunity to observe the phenomena associated with beam break up in this type of structure.

The cavities for the initial $3\lambda/2$ and $15\lambda/2$ sections are to be assembled from end pieces and iris pieces which are machined from solid niobium forgings. Twelve holes penetrate radially into each of the iris sections to improve the heat transport to the superfluid helium. The pieces required to form the larger cavities are assembled first and are electron beam welded from the inside by a beam passing through the iris opening. These units are then assembled into cylinders less than 32 in. in length and electron beam welded from the outside at the midpoint of the inactive cavities with complete penetration through the walls which were reduced to a thickness of 0.15 cm at this point. These will be outgassed and annealed in the large Stanford high vacuum furnace at about 1800 °C and will be joined with indium seals at the midpoints of two of the small unexcited cavities to form the structure indicated in Fig. 3.

We have not yet processed any niobium cavities through two complete baking cycles as required for energy gains above 14 MeV/m with Q's above 10^{10}.(13) We have, however, tested a single cell 1.3 GHz accelerator cavity which was chemically cleaned after being electron beam welded. Without any baking we found a residual Q of 6×10^8 at low power which was reduced to 2.5×10^8 when 20 W of microwave power was absorbed in the cavity, corresponding to an accelerating voltage of 7.2 MeV/m and a maximum magnetic field of 340 Oe. This Q deteriorated to 1×10^8 during a vacuum accident and did not improve when it was again chemically cleaned. This cavity was baked once in the Stanford high vacuum furnace at 1650 °C and the residual Q recovered to 8×10^8. We plan to complete the processing with a second bake out at somewhat higher temperatures and to make further observations on the performance of this cavity before proceeding with the processing of the accelerator sections.

12. MICROWAVE ELECTRONICS

The main microwave power sources for the initial operation are two Eimac Varian X3002A one-kilowatt klystrons which have a gain of 23 dB. For the initial tests, one of these klystrons will supply power to the chopper and the other to the main section of the linac. Although there are provisions for supplying microwave power through the top of the cryostat to the center and the ends of the accelerator structure, the initial operation will be made using coaxial probes on the axis of the cavities. These have hollow tubes as the center conductors. The electron beam will enter and leave the accelerating sections through the microwave power probes. A device, not indicated, will be necessary to tune the injector section and to lock it in phase with the resonant frequency of the longer section. The amplitudes and phases of the electromagnetic fields in the chopper cavities and in the different sections of the linac will be monitored and controlled by feedback stabilization systems similar to those developed by Suelzle.(20) The microwave components have been constructed using integrated microstrip techniques which increase the system reliability while reducing its size and cost. These are made on circuit boards to fit the standard transistor packages and power supplies developed at the University of Illinois for use in high energy physics. Drawings of these circuits and circuit boards are available.(21)

13. CONCLUSION

The superconducting microtron appears to be the answer to our search for an economical way of producing high quality continuous electron beams of intermediate energy for nuclear research. The recent work at Stanford University with the fabrication, processing, and operation of solid niobium cavities have shown that gradients of up to 10 MeV/m can be established in a superconducting structure with the expenditure of a few watts/m of microwave power at 1.8 °K.

Although the idea of recirculating an electron beam 20 times through a 30-MeV linac seemed adventurous a few years ago, experience and calculations with large transport systems for high energy physics give confidence that an electron beam can be guided accurately throughout the required 20 passes through the accelerator section.

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