The first section of the 1.3 GHz superconducting linac, being constructed for the proposed 600 MeV microtron, was installed into the cryostat and operated as an accelerator for the first time. An electron beam of 270 keV, chopped to a select phase spread of 6 degrees, was injected into the 3A/2 niobium structure and accelerated to 1 MeV with an input of 30 watts of microwave power at 4.2°K. The accelerated beam was 2 mm in diameter 3 meters beyond the accelerating section. The energy spread was less than 1%. The niobium section had not been outgassed at high temperature and had a Q of 1.4 x 10^9. The energy gain seemed to be limited to about 1 MeV per foot by field emission, as indicated by the rapid rise of the x-ray yield as the microwave power was increased.

**Introduction**

The design of the proposed Illinois microtron using a superconducting microwave linac between two magnets has been described previously. (1,2,3) Except for the fabrication and processing of a second 1A/2 accelerator structure, all components for operation of the linac are complete. This report describes the arrangement of these components and the results of a recent test in which the first 3A/2 section of the structure was cooled to 4.2°K and operated as an accelerator.

Although the performance of the niobium structure was not exceptional, this initial test was gratifying for several reasons, namely, (1) the vacuum seals in the cryogenic section caused no difficulty, (2) the microwave control electronics operated satisfactorily, (3) the heat exchanger installed into the neck of the cryostat operated as expected at 1.85°K, and (4) the accelerated electron beam was stable, small, easily controlled, and well defined in energy.

**Accelerator Components**

**General Arrangement**

The components used along the beam line, as well as the method of operating them are similar to those described by Jones, McAshan, and Suelzle for their lead plated prototype injector section. (4) The arrangement of the components in our system are represented in Fig. 1. Electrons from the gun pass through the microwave choppers and the chopping aperture and are accelerated by 3A/2 superconducting section inside the liquid helium cryostat. The accelerated beam travels about 10 feet to get out of the cryostat and then through a magnetic analyzer to a rotatable Be 0 screen where it can be observed through a television camera. The beam profile can also be studied electrically by observing the secondary electron current as the beam is deflected across a 20 mil wire. The beam line is terminated by a Faraday cup for measuring the total current.

**Injector Section**

The injection arrangement is shown in more detail in Fig. 2 together with a diagram illustrating the beam optics. The electron gun is a variation of a 300 KV ion accelerator made by the Texas Nuclear Corporation. It has a completely enclosed high voltage electrode. The separated power supply can supply 5 milliamperes of current at any voltage up to 300 KV with a precision of 0.1 percent. In this test the gun was operated at 270 KV. The current was limited to 60 microamperes by some components in the beam line which could not tolerate higher powers. The beam was steered as it leaves the gun enclosure and at a number of other points along the beam line as indicated. There was no magnetic shielding along the beam line nor around the superconducting cavity. A set of four large coils around the outside of the cryostat were used to reduce the field in the region of the superconducting cavity and served as the final steering coils.

The first magnetic lens is adjusted to focus the beam through the microwave chopper cavities, through the adjustable slit box onto the beryllium oxide screen just ahead of the chopping aperture which is a 1/8 inch hole in a solid aluminum block 1.5 inches thick.

The second magnetic lens is about 5 feet beyond the first image and is adjusted to focus the beam through the superconducting accelerator section onto the view screen outside the cryostat which is about 15 feet beyond the second magnetic lens.

Two microwave cavities operating in the TM210 mode are oriented such as to displace the beam in the X and Y directions. By suitably controlling the phase of the input power to these cavities the beam is swept in an elliptical path across the chopping aperture so as to pass a 60 phase bunch into the superconducting section with the correct phase for the maximum energy gain.

**Microwave Electronics**

The choppers and the accelerator section had separate microwave power sources. The horizontal chopper was supplied by a transistor oscillator having a maximum output of 8 watts. The vertical chopper used power from a voltage tunable magnetron with a maximum output of 100 watts and the superconducting section received power from a 1000 watt cw klystron.

Microwave probes in each of the choppers and the accelerating cavity are used to sense the amplitudes and phases of the fields and are used in a feedback control system to stabilize the amplitudes and phases relative to the accelerator section. The description of the microwave system and the modular components developed to implement it is given in a report to this conference by R. A. Hoffswell (5).

The microwave power from the klystron is transmitted to the accelerator section by means of an adjustable coaxial electric probe.
as shown in Fig. 3. The center conductor is a tube which serves as the entrance for the injected electrons. There are two sensing probes in this section which are inserted into 1/2 inch holes which penetrate the heavy end about halfway toward the maximum diameter. These are used in the circuits controlling the amplitude and phase of the accelerating field.

**Accelerator Structure**

The 3/2 structure installed in the cryostat for this test is based on the Stanford biperiodic 3/2 mode structure described by Weaver, Smith, and Wilson, which has a specified shunt impedance R/Q of 1260 ohms/meter.\(^{(6)}\)

This section was assembled from irises and end pieces machined from solid niobium disks which had been triple forged and annealed to achieve a fine grain structure. The fine grain material was considered desirable in order to get a surface from a careful tracer lathe machining operation which would not require subsequent abrasive polishing before chemically cleaning and high vacuum annealing at 1800°C. Although the initially machined surfaces were uniform, some smoothing with number 500 aluminum oxide abrasive around exit holes in the end pieces was necessary. Some abrasive finishing was also used in several places where there was some roughness because of spray from the electron beam welding.

Since we anticipated and subsequently experienced a number of difficulties in installing the superconducting section for this test we decided to remove only half of the usual amount of superfluid helium from the initial chemical polish. The Q of the superconducting surface was expected to be high enough to check the performance of the complete system before the final chemical polish and high vacuum bake at 1800°C. When the section was mounted and operated at about 3 torr for the test, Q value was found to be 1.4 x 10^8. We expect to bake this section in the near future and to reinstall it as the capture section.

The complete arrangement in the cryostat will include a mechanically adjusted coaxial E field tuner mounted in the exit of the 3/2 section and a second 13/2 section with no tuner. This longer section will receive microwave power through a coaxial probe penetrating the opposite end of the cryostat. The final unit of that section is shown in Fig. 4. It differs from the present end piece in that it has a larger diameter probe connection to permit the escape of the higher frequency transverse modes which cause beam breakup at high currents.

Although this subsection is somewhat special, it shows how individual irises are joined by electron beam welds and how the sections are joined to adjacent subsections by means of indium seals. The clamping arrangement is also shown in Fig. 4. The materials and the thickness of the clamp ring and the bolt are chosen to minimize any change in the clamping force with temperature. The rings will be cut into short sectors to prevent deformation of the cavity upon cooling.

**Cryogenics**

The superconducting section was mounted into the stainless steel cryostat, shown in Fig. 3, which was constructed for 7.5 feet of accelerator structure. It has a central stainless steel tank 24 inches in diameter which is wrapped with a layer of aluminum foil. It is surrounded by a nitrogen cooled copper shield which is also covered with a layer of aluminum foil. At the present time there is no superconductor in the system. The superstructure holds 50 liters of liquid nitrogen which is distributed to the ends of the shield by means of one half inch copper tubing. The loss rate of liquid nitrogen under operating conditions with liquid helium in the cryostat was around 3 liters per hour.

About 20 watts of cooling at 1.850 is obtained by means of a 1200 cubic feet per minute vacuum blower and a heat exchanger which utilizes the returning 1.850 helium vapor at 15 torr. The system includes a recovery compressor which returns some of the boil off gas through a purifier and back to the heat exchanger at 15 atmospheres. The remaining gas can be stored to be reliquefied. The liquid helium flow is at a rate of 17 liters per minute. The liquid was added to the Dewar vessel to check the performance of the cryostat and operate at 4.2 K. A 2.2 l/hr. flow rate was decreased to 2.2 l/hr. after the dewar was filled with liquid helium.

The standby loss rate of liquid helium at 4.2 K, when there were no tubes from the beam line connected into the helium vessel, was 1.9 l/hr. The additional connecting tubes installed during this test raised the loss at 4.2 K to 1.9 l/hr. which was reduced to 1.2 l/hr. if a counterflow of 2 SCFM of helium at 15 atmospheres gas was used in the heat exchanger.

At 1.850K, when the pressure was maintained at 15 torr, one required a counterflow of 4.2 SCFM of helium at 15 atmospheres and the loss rate was 1.6 liters of 1.850 liquid helium per hour. When 15 watts of power was added to the liquid by means of a resistor, the flow of gas into the heat exchanger had to be raised to 9.7 SCFM and the liquid loss was 9 liters per hour. This performance was very close to that calculated by the designers (CTI) for this mode of operation. The maximum continuous refrigeration at 1.850K which can be acquired with this superinsulation is limited to 30 watts by the capacity of the vacuum blower.
Results

A stable, well defined, beam of 60 micro-amperes at 270 kV was obtainable from the electron gun at the time of these tests. The spot diameter at the first magnetic lens was not observed during this run but was observed previously to be about 2 mm in diameter at the first viewscreen with no marked increase in diameter as it was deflected through the aperture and on into the magnetic lens just ahead of the cryostat. Pictures of this viewscreen, which is just ahead of the chopping aperture, as obtained from the television monitor, are shown in Figs. 5 and 6. Fig. 5 shows the best spot obtained by adjusting the first lens and Fig. 6 shows a part of the elliptical path traced by the beam when 2.5 and 100 watts of microwave power were fed into the X and Y choppers respectively. Under these conditions a 60° phase bunch is transmitted through the aperture and on into the accelerator.

The beam was about 10 mm in diameter at the viewscreen just beyond the cryostat, 5 meters from the chopping aperture, but it could be focused to a small spot by the second magnetic lens just ahead of the cryostat. This spot was not distorted by the chopper fields but was usually strongly defocused when power was fed into the accelerating section. This defocusing could be eliminated by adjusting the relative phase of the entering beam. The phase for optimum focusing was also that for which the beam gained its maximum energy. The beam appeared to be about 2 mm in diameter on this screen. The same diameter was obtained by observing the secondary emission across it.

A double exposure of the beam on the viewscreen beyond the magnetic analyzer is shown in Fig. 7 for magnet currents of 250 and 260 milliamperes. The separation of the spots is about 10 mm. The spots show no evidence of energy inhomogeneity but this is not surprising since the amplitude and phase control circuits were expected to keep the energy constant to better than 0.1 percent.

The maximum energy of the electron beam was 1.05 MeV with 30 watts of continuous microwave power going into the accelerating section. This corresponds to an energy gradient of 0.6 MeV per foot in the section or an energy gain of 0.3 MeV per active cavity.

By switching the power on intermittently more than 30 watts were fed into the cavity for short times. Fig. 8 shows an oscilloscope picture with x-ray pulses from an NaI detector on the upper trace and the signal from the sampling probe on the lower trace. The sweep speed was 20 m sec/cm. The field can be seen to grow as 60 watts of power is switched on at the start of the trace. It rises to a level 15 percent above that obtained with 30 watts. After maintaining the field level for 50 msec the cavity develops a higher resistance and the field level falls below the threshold for x-rays but rises again before the end of the trace where the power is switched off. Fig. 9 shows a similar trace with the input power raised to 74 watts. In this case the x-ray level rose faster. The field level was maintained at its maximum value for only 5 msec before it dropped, and it did not begin to recover before the power was switched off. This behavior suggests that the energy gradient is limited by field emission. In other tests with pulsed input power the energy gradients were indicated by the sampling probe to rise briefly to 1.0 and 1.1 MeV per foot for powers pulsed to 100 and 500 watts.

All the beam tests were made at 4.2K. The cryostat was pumped down to 1.85K for a day but the beam tests were not repeated since the Q did not improve appreciably over the value of 1.4 x 10^6 and there was not sufficient 1.85K liquid helium to cover the section. After the completion of the beam test the structure was removed and given a second light chemical polish and was cooled down in a small vertical dewar. The Q at 4.2K was now 2.7 x 10^6 which leveled off to 5.4 x 10^5 as the liquid helium was pumped down. At this higher Q, x-rays were observed with as little as 5 watts going into the structure.

Conclusion

The components for a section of a superconducting linac were assembled and operated successfully to produce a well defined, stable and easily controlled electron beam of 1.05 MeV. The energy gain was apparently limited by field emission and further work with the niobium accelerator sections will be required to improve this aspect of their performance.

Acknowledgements

This work is a common effort by the staff whose names appear in the references as well as other members of our staff whose support is very much appreciated. We wish to express our special thanks to the members of the superconducting accelerator staff at Stanford University who have continued to assist us in many ways.

References

Fig. 1. Linac area, G-Gate valve, P-Ion pump, L-Lens, X,Y-Chopper Cavities, S-Screen, A-Aperture, RF-uW power, M-Magnet, F-Faraday cup, SEM-Secondary emission wire.

Fig. 2. Injector arrangement.

Fig. 3. Cryostat.

Fig. 4. Antiblowup power probe at beam exit of 13X/2 section.

Fig. 5. Beam ahead of chopper aperture

Fig. 6. Beam ahead of chopper aperture with 2.5 and 100 watts of microwave power into X and Y chopper cavities

Fig. 7. Double exposure of beam spot beyond the analyzing magnet for currents of 250 and 260 mA. Spots are 10 mm apart.

Fig. 8. Oscilloscope traces of x-ray pulses and field with 60 watts of microwave power switched on at the start of the trace. The sweep speed is 20 msec/cm. The power is switched off near the end of the trace.

Fig. 9. Oscilloscope traces as above with the input power raised to 74 watts.