

EXPERIENCE IN RECIRCULATING ELECTRONS THROUGH A SUPERCONDUCTING LINAC

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Summary

An electron beam of several microamperes has been accelerated by a 6 foot 1.3 GHz superconducting niobium linac to 3.5 MeV on its first pass. It has been returned to the linac for two additional passes with energy gains around 3 MeV per pass to a final energy of 9.5 MeV. The recirculation is accomplished by means of two uniform field magnets placed at each end of the accelerating section in a racetrack microtron geometry which will accommodate the return beams for six passes through the linac.

Introduction

The general design of a proposed racetrack microtron employing a superconducting linac has been presented previously.¹ The general arrangement of the components making up the small superconducting linac and the initial performance of the 3 $\lambda/2$ injector section was described at the 1971 Accelerator Conference.² Since that time a coaxial tuner was mounted in the exit end of the 3 $\lambda/2$ section. The second 13 $\lambda/2$ section has been installed without high temperature processing with the microwave power probe at the exit end of the cryostat as shown in Fig. 1. The two sections were cooled to 4.2°K and it was found that the 3 $\lambda/2$ section accepted 15 watts of microwave power at a Q of 10^6 and the 13 $\lambda/2$, 40 watts at a Q of 1.5×10^6 at a duty factor of about 30 percent. The energy gain in each section was about 0.6 MeV/foot. A beam of 4 microamperes was accelerated to 3.5 MeV in March 1972. Although the energy gain per foot was below that obtained in the initial test of the 3 $\lambda/2$ section, the beam was stable and we decided to postpone any work on cavity improvement and to examine the problems involved in recirculating the beam through the linac.

The first problem was the expected strong vertical defocusing of the beam in passing through the fringing fields of the 180° magnets. A test was carried out in June when a 180° magnet was installed to return the beam from the linac. This uniform field magnet has an active field clamp which reduces the extent of the fringe field and produces a short region of reverse field as shown in Fig. 2. This reverse field was designed to compensate for the vertical defocusing and it was found that this clamp was effective in retaining the quality of the beam without further optical elements.

The next test system required moving the injector system off the linac axis to allow the installation of the second 180° magnet on the other side of the linac as shown in Fig. 3. This arrangement was completed and the 3.5 MeV beam was returned to the linac and boosted to 6.5 MeV in September. This beam

was sent into the experimental area where it was used for several weeks to investigate an arrangement for a resonance fluorescence experiment.

At high energy no special adjustments due to the velocity of the electron being less than that of light need be made. However, at our low energy these phase lags require special attention. In order to make the recirculating scheme work at our low energies a 'bypass' on the first return was constructed to provide the necessary phase correction on the first return and to alleviate the need for the first return to go through the linac cryostat. The 'bypass' hardware was installed and the beam was recirculated through the linac with the new hardware in January, 1973. A second return path was installed and the beam was sent through the linac 3 times to a final energy of 10 MeV a short time later.

The only large components that are needed for the six pass system are new vacuum chambers for the 180° magnets. The other components that will be needed are duplicates of proven components that are in use elsewhere in the system. The following section gives details about some parts of the system and about some of the experiences involved in their operation.

General Description

The two pass system that was tested beginning in September 1972 is shown in Fig. 3. A 270 keV electron beam from the gun was deflected onto the accelerator axis and was accelerated in passing through the linac. In this test the return beam was sent around the outside of the cryostat and directed back to the linac axis by 180° magnets. No focusing elements were used on the return line. The active clamps provided all the focusing that was required. The return phase was controlled by the position of the last magnet. A number of steering coils (not shown) were used to correct for stray magnetic fields and misalignments. Although the quality of this beam was not as good as expected it was sufficiently useful to be sent in the experimental area.

The six pass system is shown in Fig. 4. At the present time the bypass has been completed and a temporary second return line around the other side of the cryostat has been installed for operating the system with three passes. Arrangements are being made to send this beam and the beams after subsequent passes into the experimental area as indicated in the figure. Descriptions of some of the major components are given in the following subsections.

Injector

A 300 keV Texas Nuclear Corporation electron gun with the capability of giving a DC current of 5 mA is normally operated at 270 keV and at a current of no more than 0.6 mA. The operation of the gun at these values proved more reliable than at the maximum capabilities of the gun. The voltage control of this gun was improved this last year because proper operation of the recirculation required better than 0.1% voltage stability. The original voltage control, which could not be used conveniently for changes of less than 1 keV, was supplemented by a variable 3 kV power supply placed in series with the main 300 kV supply. The total voltage, which is monitored by a digital voltmeter, is now adjusted manually to be within 100 volts of the desired value.

Microwave Electronics

The microwave control system for the superconducting linac has been described previously.³ The microwave system uses feedback stabilization methods to control the phase and amplitude of the rf fields in the linac and in the room temperature chopping and bunching cavities. The system has achieved an rf amplitude stability of about two parts in 10^4 and a phase stability of about 0.5 degree.

The longterm stability of the system is sufficiently good that the beam is accelerated through three passes without any adjustments after a short warm up of the electronics, even if the system had not been operated for several days.

Choppers

The two chopper cavities operate at room temperature in a TM210 mode. One cavity deflects the beam vertically while the other causes a larger horizontal deflection. An 8 watt transistor is adequate to supply the 1.3 GHz signal to the vertical chopper and a 100 watt tube-type amplifier (Siemens YD 1380) is used for the horizontal chopper. After the beam passes through these cavities it makes an elliptical scan across a 1/8" chopping aperture in a 1/4" thick water cooled copper plate and a phase bunch of 6 degrees is transmitted.

Inflector

The inflection of the beam is accomplished by the deflecting magnet which bends the beam 30° north to bring it to the linac axis, and an inflecting magnet on the linac axis which bends the electrons 30° south so that they travel along the linac axis. Two other components of the inflector system on the linac axis are used to keep the recirculating electrons on the linac axis despite the 30° bend that the low energy injected beam receives.

Linac

The superconducting linac consists of two separately powered accelerating sections;

the phase of the 3 $\lambda/2$ capture section and the phase of the 13 $\lambda/2$ main section are set independently for efficient capture and acceleration. There is a mechanically adjustable coaxial E field tuner mounted at the exit of the capture section; the resonant frequency of the capture section can be tuned to 1 Hz over a range of 0.3 MHz. As the linac is operating at present, the capture section increases the injected electron beam energy from 270 keV to 750 keV; the main section then increases this energy to about 3.5 MeV with an energy resolution of 0.1%. The phase of the capture section makes it incapable of adding much energy to the recirculated beam; as seen by the recirculating beam, the phase difference between the capture section and the main section is about 90°. The 3.5 MeV recirculated beam gains about 3.0 MeV in the main section during the second traversal and emerges with an energy of about 6.5 MeV. The energy after the third pass through the linac was more than 9.5 MeV. An Elmec Varian one kilowatt C.W. klystron is used to power the 13 $\lambda/2$ linac section. The smaller section is powered by one of the 100 watt tube type amplifiers.

180° Magnets

There are two matched 180° uniform field bending magnets, one to the west (i.e., the left on Fig. 1) and the other to the east of the linac. The electron beam traverses the linac moving westward. It then enters the west magnet, moves in a semicircle, and emerges traveling eastward. It travels eastward 25 feet on a path parallel to the linac axis, and it enters the east magnet which returns the beam to the linac axis traveling westward, and ready for another traversal. These 180° magnets have a 1" gap; the pole pieces are 22" deep and 45" wide. The width will accommodate a recirculation system in which the beam passes through the linac 6 times. The magnetic saturation properties of the magnets could allow the handling of a maximum beam energy of 60 MeV if the energy gain per traversal could be increased to about 10 MeV in an improved linac. Each 180° magnet has an active reverse-field clamp magnet which compensates for the vertical defocusing that otherwise would be introduced by the 180° deflection in the horizontal plane. The east 180° magnet is mounted on rollers and can be moved by a reversible motor so that the distance between the west and east magnets can be adjusted to bring the recirculated beam back to the linac in the proper phase for maximum acceleration.

Active Field Clamps

The usual 180° magnet defocuses the beam in the vertical plane due to the fringe field. The defocusing can be nullified by introducing a short region of reverse field by an active field clamp as shown in Fig. 4. The short region of reverse field changes the angle of entrance into the magnet (a) to produce a positive focusing action. Quantitatively the strength for defocusing is determined by the effective extent (b) of the fringe field, and the radius of curvature (R) of the electrons inside the magnet. The

focal length is given approximately by

$$\frac{1}{f_{\text{def}}} \approx \frac{b}{6R^2}.$$

The positive focusing action due to the reverse field is given by the familiar relation

$$\frac{1}{f} = \tan(\alpha)/R.$$

If R' is the effective radius of curvature of the beam in the reverse field and d' is the width of the field $\tan(\alpha) \approx d'/R'$. The clamp was designed to make $d' \approx 2b$ thus the condition for no net focusing is

$$\frac{1}{f_{\text{net}}} = \frac{-b}{6R^2} + \frac{2b}{RR'} = 0$$

This condition is satisfied if $R'/R = 12$. Thus the ratio of magnetic fields $B/B' = 12$. This ratio of fields was experimentally verified as the ratio required for no defocusing. The ratio is independent of the energy of the beam as long as the radius of curvature R is much greater than b . This condition is satisfied for all the recirculating beams in the system.

Cylindrical Lenses

In earlier versions of the recirculating system the defocusing of the beam in the vertical plane was corrected by the use of quadrupole pairs at each end of the straight sections. This quadrupole system required precise positioning of the return beams with respect to the quadrupole axes. Such positioning seemed particularly difficult when the energy gain of the linac was low since the horizontal positions of the return beams would shift with energy. The critical dependence on the horizontal position of the beam is eliminated by cylindrical lenses which focus only in the vertical direction and have large tolerances to the horizontal positions of the return beams. The cylindrical lenses also avoid the problems associated with the quadrupole pairs in getting vertical focusing without any horizontal focusing. The arrangement of three uniform field magnets which make up the cylindrical lens are shown in Fig. 5. It is clear from the figure that there is no net displacement or angular deflection in the horizontal plane. However, in the vertical plane, a focusing strength of $\tan(\alpha)/R$ is contributed at each internal edge where the beam crosses a boundary at an angle α . R is the radius of curvature in the uniform field regions. In terms of the length (d) of the small end magnets, $\tan(\alpha) \approx d/R$, thus the focusing strength of the system can be expressed as,

$$\frac{1}{f} \approx \frac{4d}{R^2}.$$

A cylindrical lens is used on the bypass shown in Fig. 4 and others may be used on the higher order return beams if they are found to be necessary.

Bypass

In the six pass system the phase lag on the first return path corresponds to more

than a half wavelength and some way of getting these electrons back into synchronism had to be devised. A separate channel for the first return beam in which the path length could be varied by a half wavelength has been installed and operated successfully. It is referred to as a 'bypass' since it bends the first return beam outward 30 degrees to pass around the accelerator cryostat and back by means of 4 bending magnets as shown on Fig. 4. The arrangement can accommodate deflection angles of ± 1.2 degrees around 30 degrees corresponding to phase advance of 110 ± 55 degrees. Although the maximum phase advance of 165 degrees is somewhat less than the lag in the straight section it is more than adequate since other adjustments reduce the required phase correction to about 90°. Adjustments in the fields of the 180° magnets and in their spacing are used to bring the 2nd and 3rd beams to the required phase. The remaining 4th and 5th return beams need only small corrections that can be accomplished with small changes in the strips of field covering only the outer portions of these semicircular paths without affecting the first three.

Buncher

A buncher cavity has been installed in the injector beam line immediately after the chopper aperture. Although it has not been used in operations so far it can increase the available current by a factor of 10 with some deterioration of the energy uniformity of the injected beam. If the power in the chopper cavities is reduced so that a 60° bunch will pass through the chopper aperture the buncher will give the beam an energy spread of 5.25 keV and will contract the bunch to 1.2° at the entrance to the linac capture section.

Discussion

The linac has been operated reliably without disassembling the cryostat and without other major difficulties for a period of one year. During this time the field level remained stable and unchanged and it was possible to try out some of the ideas involved in recirculating the beam a number of times.

In setting up the magnets for recirculating of the beam, the two 180° magnets were adjusted to have equal fields. The small deflecting magnets were adjusted to center the electron beams in the different channels with the aid of portable radiation monitors and BeO viewscreens which could be put into the beam path at various points by pneumatic operators. Once the fields in the magnets were adjusted they were left on continuously to avoid difficulties with hysteresis.

The threading of the return beams back through the accelerating section had to be done by steering coils on the separate return sections. These beams could be observed on the linac axis near the entrance to the capture section by steering them onto a view-screen placed above the normal trajectories of the other beams. The return systems have only vertically focusing elements which are used to control the vertical size of the

beams. The horizontal aspect of the beams are affected only by the linac and some weak quadrupoles on the linac axis.

Although we expected some difficulty in operating the 30° bypass for transporting the first return beam around the cryostat, the beam was returned to the linac without significant distortion or increase in size. Since this bypass was easily managed a second temporary bypass around the other side of the cryostat was made for the second return beam to avoid the difficulty of opening up the cryostat and directing the beam through it as indicated in Fig. 4.

It may be useful to mention two problems which delayed successful attempts at recirculation. The first was due to fluctuations in the energy of the accelerated beam which made it difficult to control the return beams with sufficient accuracy. These fluctuations were traced to variations in the injection energy and the resultant variations of the injection phase into the linac. This difficulty was removed when the injector voltage was monitored by a precision digital voltmeter and an additional small power supply was installed to provide a fine adjustment to the voltage which was then manually kept to within 0.03% of the desired injector voltage. The second problem was an irregular shifting of the position of the 270 keV injected beam as observed on view screens along the beam trajectory. This movement was traced to other BeO viewscreens which were charging up and deflecting the electron beam even if they were not intercepting the beam. This effect was eliminated by covering the viewscreens with a wire mesh. The only remaining variation in beam position is a small 60 Hz modulation which seems to be due to stray fields in the region of the electron gun.

A difficulty which is still not examined very well was an observed increase of the energy spread of the twice accelerated beam. Part of the energy spread was found to be associated with variations in the phase difference between the capture section and the main accelerating section. For the recirculated beam the phase difference is about 90° so that the capture section contributes little to the energy of the return beam. Any jitter in the phase relative to the accelerating section, however, results in a large energy jitter of about 15 keV/degree. Part of the phase jitter seems to be due to frequency changes in the capture section caused by vibrations of the tuner. The energy variations associated with this jitter would be negligible if the capture section were placed on the injector axis rather than on the linac axis.

In addition to completing the six pass system future plans include the reprocessing of niobium accelerator sections. We expect to get higher Q values which will allow continuous operation at energy gains of 0.8 MeV/foot. We also plan to increase the injection energy into the linac so as to operate the accelerator sections in the present cryostat as a single section.

Conclusion

The superconducting linac has been operating reliably with an energy gain per pass of 3 MeV. The beam has been recirculated for second and third passes through the linac and no major obstacles are expected in extending the recirculation scheme to six passes.

Acknowledgements

All of the members of the Physics Research Laboratory Staff contributed to the successful operation of the accelerator. Special mention must be made of Professor A. O. Hanson who has been the technical director, and of Darko Jamnik of Ljubljana who designed most of the recirculation components. Robert A. Hoffswell designed the microwave electronics and had collaborated in all aspects of obtaining a recirculated beam.

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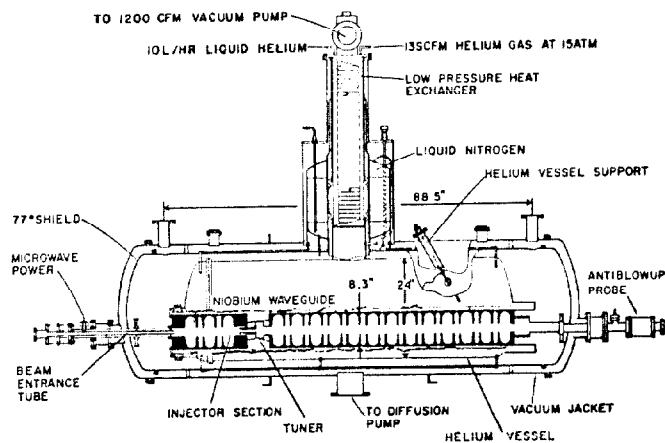


Fig. 1. Linac Cryostat with $3 \lambda/2$ Injector Section, Tuner, and $13 \lambda/2$ Accelerator Section.

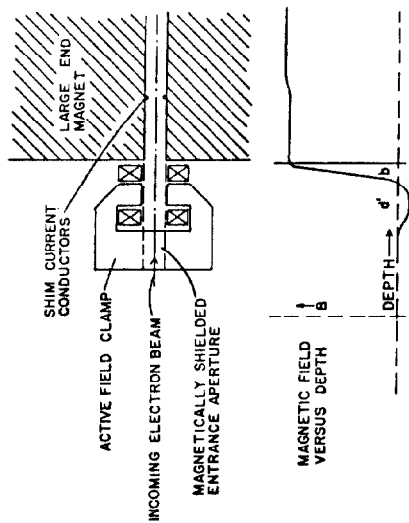


Fig. 2. The 180° Magnet with an Active Clamp.

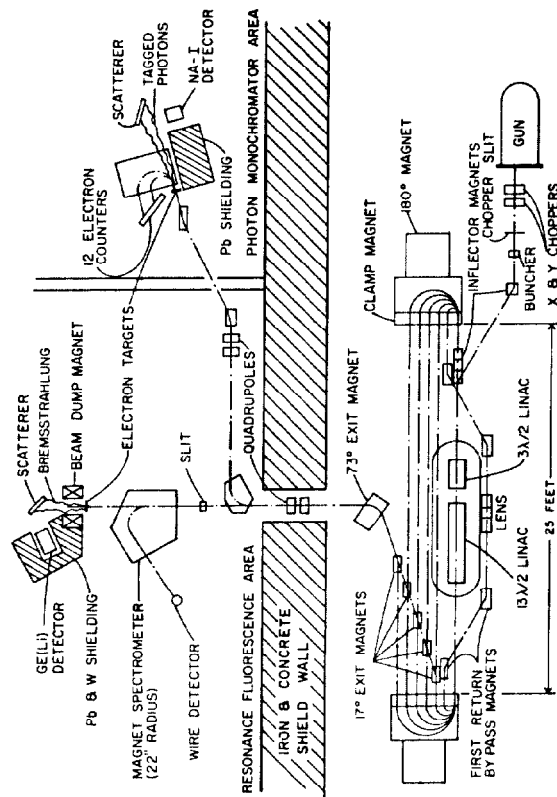


Fig. 4. Schematic of the Six Pass Microtron and the Associated Experimental Area.

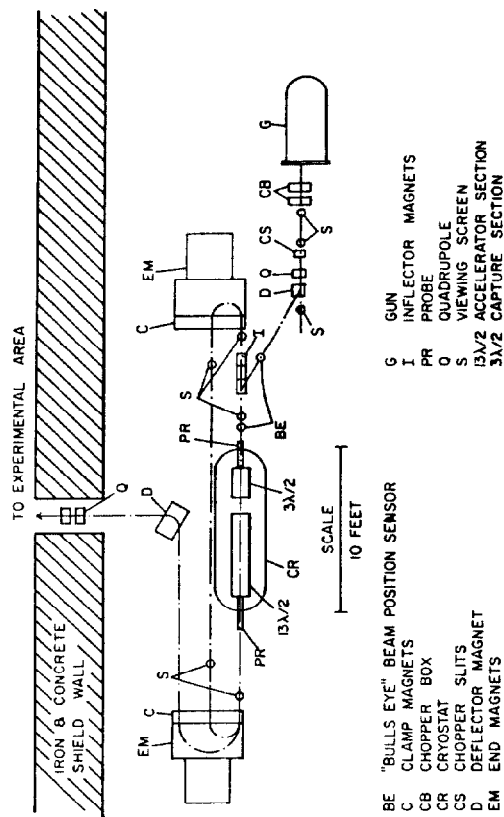


Fig. 3. Schematic of the Two Pass System Used for the First Recirculation Test.

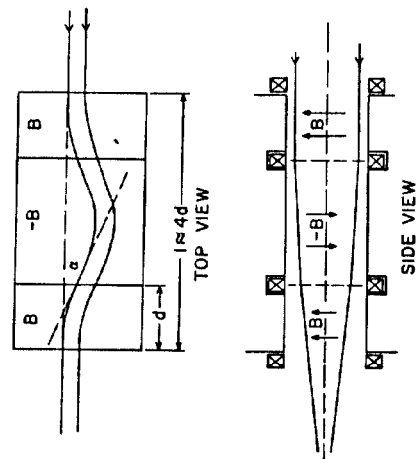


Fig. 5. Cylindrical Lens.