STANFORD'S SUPERCONDUCTING ACCELERATOR PROGRAM*

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Introduction

The advantages of superconducting linear accelerators over conventional linacs have been discussed at length in many articles.[1,2] Consequently, we shall treat these advantages rather briefly here, and concentrate on the progress of Stanford University's program to develop a useful superconducting electron linear accelerator.

Basically, the limitations of conventional linear accelerators arise from the large amount of RF power necessary to produce reasonable energy gradients (2-3 MeV/ft) in a structure made of an ordinary conductor, such as copper. By making the structure superconducting, these same energy gradients can be obtained with about five orders of magnitude less RF power. Thus, while the beam in a conventional linac must be pulsed, with a duty cycle of less than 10^{-3}, a superconducting linac can operate with a unity duty cycle beam. Aside from offering the lowest signal to noise ratio for most experiments, a continuous beam offers another advantage in that the absence of transient effects due to pulsing the RF will allow much greater energy resolution and operating stability than otherwise possible. Finally, since a superconducting linac will be extremely efficient, in that almost all of the RF power will be delivered directly to the beam, very large beam currents will be practical with relatively modest power sources.

Description of Stanford University's Superconducting Linac Program

For the past several years Stanford University[3-6] has been investigating the properties of superconducting microwave cavities. Last year (September, 1965) a three cavity superconducting accelerator 4 inches long was succesfully operated in the $2\pi/3$ mode at 2856 Mcs. The accelerator produced 500 kV electrons with a beam current of about 1 μa. (The beam current was limited by the injecting electron gun.)

With the success of this accelerator it was decided that the performance of Stanford's Mark II linear accelerator (75 MeV) should be improved by making it superconducting. As a preliminary step in this process we are building a 10 foot long test accelerator, which we expect to have operating in less than **two** months **(Dec.** 1, 1966). The energy gain of this accelerator should be in the vicinity of 30 MeV, and beam currents of about 100 μa are expected. Details of this test accelerator will be discussed in the following section.

The ten foot test section is to be used to study various accelerator structures and other parameters affecting the construction of the Mark II-S accelerator, which should be in operation by December, 1967. It is expected that this accelerator will consist of a 60 foot linear accelerator, with the beam passing two or three times through the accelerator section. The accelerator will probably be made of three separate twenty foot sections, with room temperature regions for beam handling between sections. Two methods of returning the beam through the accelerator are currently being considered. In one, the beam is bent by 180° magnets at each end of the accelerator and always passes through the accelerator in the same direction. In the other, the beam takes advantage of the standing wave nature of the accelerator and passes through the accelerator in both directions. It is expected that energy gains of 2-3 MeV/ft will be obtained with a power loss of about 2 watts/foot ($R \approx 10^{12}$ ohms/meter). A refrigerator capable of removing 300 watts at 1.85°K, the operating temperature of the accelerator, has been ordered, and will be available by the end of 1967.

Details of the Ten Foot Test Section

Since the ten foot section is to be a test vehicle for a larger machine, many portions of its design have been made flexible, to allow for modifications. Figure 1 is a schematic drawing of the accelerator and its dewar. The essential features of nearly any superconducting accelerator are included. (In future dewars it may be desirable to eliminate the liquid nitrogen bath. This can be accomplished by careful design.) Accelerator structures can be interchanged by removing the end plates of the dewar. To provide flexibility there is a rather large amount of free space in the helium region above the accelerator structure. The operating temperature of 1.85°K will be attained in this dewar simply by pumping on the liquid helium bath.

In contrast to normal accelerator structures, in which the shunt impedance increases with increasing frequency ($R_s \propto \omega^{1/2}$), the shunt impedance in a superconducting machine should increase with decreasing frequency ($R_s \propto 1/\omega$). In addition to increasing the shunt impedance, lower frequencies also require fewer cavities per unit length in the accelerator structure. Since the machining tolerances[7] required for a $\pi/2$ mode structure increase as $1/N$, and those for a π mode structure increase as $1/N^2$, where N is the number of cavities/unit length, low frequencies are desirable. Compromising between the advantages gained by low frequency operation, and the bulkiness of the increasing dimensions required, the operating frequency has been chosen to be 952 Mcs.

The ten foot accelerator will be used to test the performance of various accelerator structures and modes. Initially it had been thought that the π mode would be used for the accelerator studies, as this mode has many advantages over other modes in an accelerator[7]. However, it has since been decided to use the $\pi/2$ mode, as this mode is much less sensitive to machining errors than the π mode. The $\pi/2$ mode has another important advantage over the π mode. The entire π mode structure would have to be plated in one rather difficult operation. However, the $\pi/2$ mode structure can be broken in the unexcited cavities and the resulting sections plated separately. After plating, the sections can be joined together with indium seals, which have proven to be able to join lead plated cavities with little, if any, degradation of the cavity Q (at temperatures well below 3.42°K, the transition temperature of indium).

Actually, the accelerating properties of the $\pi/2$ mode can be made to approach those of the π mode, while still remaining much less sensitive to machining error, by using a bi-periodic structure in which the length of the unexcited cavity is reduced. However, multipactoring has always been present in tests made on single cavities of the dimensions of the short cavity (at 2856 Mcs.) in a bi-periodic structure, and it appeared that this structure might not be suitable for this reason. Fortunately, in recent tests made on a three cavity structure in which the center cavity was one-half the length of the end cavities, multipactoring was not present in the $\pi/2$ mode, although it did appear in the 0 and π modes. Presumably the fringing fields from the neighboring cavities modify the field in the short cavity sufficiently to prevent multipactoring in the $\pi/2$ mode.

Currently, bi-periodic $\pi/2$ mode structures of 2 types are being studied. In one, the cavities are coupled by the electric field through the beam hole. In the other the beam hole is reduced in diameter, and magnetic coupling through irises is used. Because of the smaller beam hole, it is expected that the shunt impedance of the magnetically coupled structure will be higher than that of the electrically coupled structure.

It should be mentioned here that none of the cavities in these structures will have nose cones. Rather extensive use has been made of the computer program developed at Los Alamos under the direction of H.C. Hoyt [8] to study various cavity shapes. Nose cones do raise the shunt impedance of a cavity by a significant amount, but roughly speaking a 10% increase inthe shunt impedance is accompanied by a doubling of the maximum electric field on the surface of the cavity. Since our maximum cavity fields seem to be limited by electric field breakdown, it has been decided to use structures which minimize the electric field at the surface of the cavity.

In Fig. 2 a plot of the experimental[1] and theoretical [9] Q of the lead plated TE_{011} cavity at 2856 Mcs is shown. At temperatures below about 2°K the presence of a residual resistance due to trapped flux, strains, impurities, etc. begins to become important and the Q of the cavity begins to approach a temperature independence value. (For a TM_{010} mode cavity at 2856 Mcs this value typically about 3×10^8, for electroplated lead.)

The heat produced in the accelerator structure will be removed by superfluid helium (liquid helium cooled below 2.17°K), since its thermal conductivity is much greater than that of even pure copper at low temperatures.

Consideration of the temperature dependence of the cavity Q's, the thermal conductivity of liquid helium, the penetration depth of magnetic fields into superconductors, and other factors has led to the choice of 1.85°K for the operating temperature of the accelerator.

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Footnotes

* Supported in part by Office of Naval Research under Contract Nonr 225(67).

DISCUSSION

T. I. SMITH, Stanford

MONTAGUE, CERN: Have you studied the problem of tuning and phasing a multicavity super-conducting linac; let's say, keeping the separated cavities at the same frequency?

SMITH: We have thought about the problem, but we haven't done any experimental work on it. Small changes in the resonant frequency of the structure can be made by adjusting one of the cavities, and we feel that this is all that will be necessary at liquid helium temperatures. An advantage of the $\pi/2$ mode over the π mode, which was not mentioned in the talk, is that the $\pi/2$ mode can be tuned over a larger range by a single cavity without introducing too much field unflattening.

KATZ, Saskatchewan: What limits you to these low field gradients? You seem to be considerably below those in use at present.

SMITH: I don't think that 3 and 4 MeV per ft are particularly small field gradients.

KATZ: I'm sorry, I thought you said per meter.

HAIMSON, MIT: The Q's in the dominant mode you've shown are up a factor of about five orders. It seems reasonable to assume that the Q's in the pulse shortening mode should do the same. If this is the case: (1) What sort of precautions are you taking to overcome the beam breakup effect for the reasonably heavy loading that you're intending; and, (2) Is any special consideration being given to the type of coupling to allow for the beam loading effects?

SMITH: At present no particular steps have been taken to minimize the effect of beam blowup. Discussion carried on here yesterday indicated that our 60-ft accelerator at 100 μA would not have beam blowup even with a 10^5 increase in the Q of the transverse modes. Actually, in the accelerator the rf coupling to the system will load the structure so that the Q will be only about 10^3 times higher than in present machines. And, finally, if necessary, it would seem to be quite feasible to design the structure so that the unwanted modes are more highly loaded by coupling than the accelerating mode. With reference to the beam-loading effects: On my slide of the dewar (Fig. 1), a little box indicated in the wave guide was for variable coupling so that we can adjust it to various beam currents.

BRUNET, Orsay: I assume that if you have a very high Q, you need a very stable frequency. Can you say something about your driver?

SMITH: Yes. Currently we're using as the primary frequency source a Hewlett-Packard frequency synthesizer with their standard driver, which I think has a stability of one part 10^{10}. We run this through a multiplier chain to get it up to 2856 Mc. Actually, one reason for choosing 952 Mc for this accelerator, instead of a round number like 950 Mc, is that we can get 952 Mc out of our existing multiplier chains just by removing the final frequency tripling section.

FAIRBANK, Stanford: One thing about the Q: The beam will load the Q down from 10^9 to about 10^7.

SMITH: The problem in the actual accelerator is less severe than it is in measuring the Q's in the single cavities, which is what I was attempting to describe here.

CITRON, Karlsruhe: Would you do tank flattening only at room temperature?

SMITH: Yes. If all the cavities are exactly tuned at room temperature, they should be within one part in 10^5 of each other at helium temperatures. This should not introduce a serious amount of field unflattening in the $\pi/2$ mode. The only adjustments necessary at low temperatures will be bringing the frequencies of all of the structures together.

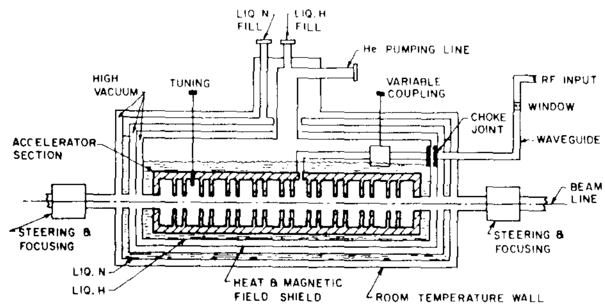

Fig. 1. Schematic of 10 foot accelerator and dewar.

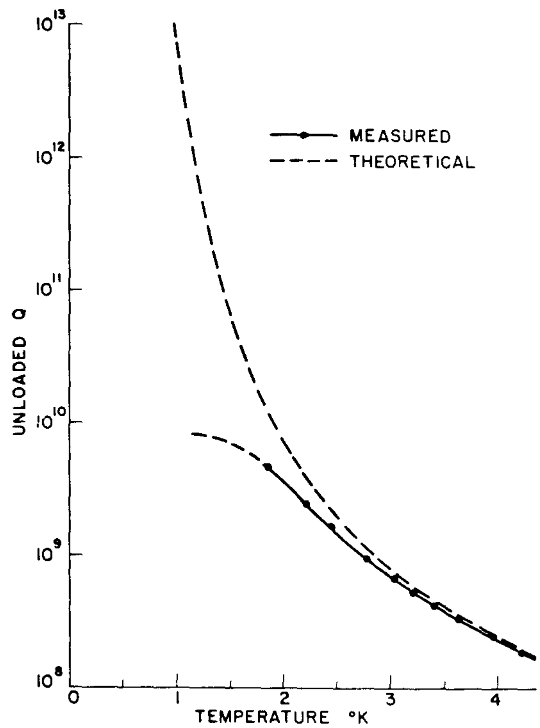

Fig. 2. Theoretical and measured Q as a function of temperature for a TE_{011}-mode cavity with an electroplated lead surface at 2856 Gc/s.