PROGRESS IN THE DEVELOPMENT OF SUPERCONDUCTING RESONATORS FOR HEAVY ION ACCELERATION

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I. Introduction

A group at Argonne has been working on a heavy-ion accelerator concept involving a tandem electrostatic accelerator with two stripping stages followed by a superconducting-helix linear accelerator(Fig.1). This paper is concerned with efforts to understand and solve the technical problems associated with the linac part of the system.

The concept of a superconducting linac for heavy-ion acceleration is attractive because of its low rf losses and the compactness of the associated rf equipment. The accelerator can readily be designed in modular form; this and the small size of the system tend to limit the cost both of the accelerator and its housing. However, considerable work needs to be done before such a system can be constructed and operated in a practical manner.

In addition to the problems associated with any linear accelerator, there are several arising from the use of superconducting resonators:

Deterioration of rf properties.

Because heat removal from a superconducting helix is expensive and only a limited quantity can be removed, rf losses must be small. These losses are determined by the quality of the surface, since the rf currents flow in a thin surface layer. For a practical accelerator, the surface treatment that is used to reduce the losses to suitable levels should also protect the surface from changes resulting from conditions such as a) long-time operation in high rf fields, b) thermal cycling from room to liquid-He temperatures, c) exposure to air, and d) radiation damage.

In addition, the surface treatment must minimize the enhancement of surface magnetic and electric fields. If large enough, these fields can make the system inoperable through quenching of superconductivity or generation of intolerable parasitic electron current losses.

Frequency variation due to vibration.

Changes in dimensions due to mechanical vibrations cause a variable change of magnitude Δf in the characteristic frequency of a resonator. Unlike room temperature resonators, Δf greatly exceeds the resonance bandwidth (typical Δf is 500 Hz and the resonance width is 1 Hz). A single resonator can be operated by phase-locking the oscillator to the resonator's varying resonator frequency, but in an accelerator, all of the resonators must be kept in resonance and properly phased with a single oscillator. This requires that the independent vibration-induced Δf's in the various resonators be compensated.

Our activities have been directed at establishing the feasibility of the superconducting-linac concept by finding solutions for these two main problems — surface stability and vibration control. Also, some effort has been devoted to practical-design problems such as methods of helix construction, cryostat design, and liquid-helium cooling. We discuss now our solutions for some of the problems and programs aimed at developing solutions for the others.

II. Stability and Reproducibility

Much of our testing has been carried out (1) with resonators of the kind shown in Figs. 2 and 3. The most successful device (unit A_1) was heat treated in the Stanford HEPL furnace,(2) electropolished, (3) and anodized (4) with a 400 A layer of Nb_2O_5. Prior to our use of anodization, we found that the Q values of the resonator deteriorated seriously with time. In marked contrast, after the Nb_2O_5 layer was applied, the characteristics of the unit were entirely stable despite repeated exposure to air and to thermal cycling. Moreover, the resonator was operated at high power for 323 hours during an 8-week period, during which there was no shift in the Q at low power and some improvement (with time) in performance at high power was observed. (Fig. 4).

At the largest rf energy sustainable, the axial accelerating field E_{ax} exceeded 2.7 MV/m. In this experiment, the power was limited by the maximum field E_{max} sustainable by the helix surface. In the resonator for an accelerator (which would have a longer helix) the value of E_{ax} corresponding to the same limiting E_{max} would be about 3.2 MV/m.

Recent tests on the resonator described above (unit A_1) have shown that it has suffered no apparent deterioration in performance in the 7-month period since the previous tests. During this period, it was exposed to the atmosphere and to repeated handling.

The main result of the tests outlined above is the demonstration that it is feasible to make superconducting-helix resonators that can provide rf fields and Q values that are more than adequate for a practical accelerator. Moreover, the structure is rugged, since it does not deteriorate with extended use nor with exposure to air and to thermal cycling. Even after considerable handling, washing with a solvent prior to pump down is the only treatment required to restore the resonator to its original performance.

Although the resonator (unit A_1) described above has excellent properties, it would be desirable to be able to forego the very high-temperature baking procedure used in its preparation. Tests to determine the minimum requirements are in progress. An electropolished-anodized resonator (unit B_1) that has had no heat treatment has been thoroughly tested. Both the Q and the maximum electric field are about half of the values obtained with the resonator (unit A_1) baked at 1850°C. The surface of unit B_1 was removed and retreated numerous times, but no improvement in performance was obtained. Thus, we tentatively attribute the poorer performance of B_1 to its lack of heat treatment.

The coil of unit B_1 was removed and replaced by a new coil that was prepared in the same way as the original coil of B_1. The characteristics of the modified system (unit B_2) were effectively the same as for the initial system. This result is important since it demonstrates the reproducibility of the techniques used for surface treatment.

The characteristics of the resonators studied to date are summarized in the upper part of Table I, and investigations now in progress or in preparation are described in the lower part of the table. Some of these tests are concerned with the influence of surface treatment. From electron-microscope studies of electropolished samples, it appears that smoother surfaces result if the helix is heated to temperatures of about 1200°C prior to electropolishing. Unit B_2 has recently been baked at this temperature and put into operation, but the results of rf tests are not available at this writing.

III. Vibration Studies

The problem of mechanical vibration is being examined from two directions. First, an attempt has been made to understand the natural vibration spectrum of the resonator and the spectrum of ambient vibrations in its environment. Second, because the frequency variations due to vibrations of the helix are larger than can be tolerated, it is necessary to develop a feedback control system which compensates for the frequency change Δf. Such compensation is simplified if the magnitude of Δf is kept low by minimizing external sources of vibration and the coupling of these sources to the helix.

In order to learn how to minimize Δf, studies have been initiated to understand the vibration characteristics of the helix coil itself and to determine if there is a correlation between the ambient external vibration and the frequency stability of a superconducting-helix resonator. This work is being carried out by the vibration group of Argonne's Engineering and Technology Division (5). The following three sets of results have been obtained.

1. Vibration surveys of typical experimental areas have shown that acceleration levels are <0.002g rms on the floor and walls. The predominant frequency components are in the range 120 to 160 Hz. The helix resonator has been subjected to characterized external vibrations (from a force generator), and the results have been monitored by accelerometers mounted on the support structure within the cryostat and correlated with the frequency variation as measured by the rf error signal (from the oscillator phase-lock loop).

2. Theoretical and experimental studies of the dynamics of the helix coil have been carried out, and the results are in good agreement. The vibrations of niobium and of copper helices have been measured by means of optical motion-transducers. Figure 5 shows the frequency distribution of the axial motion of a point on a copper coil driven by random vibration. The output of the

transducer has been computer-analyzed into component frequencies. Contributions of the compression, bending, and torsional vibration modes of the coil are indicated by the letters C, B, and T in Fig. 5.

A similar plot in Fig. 6 was obtained by Fourier analysis of the rf error signal of the niobium helix B_1 while it operated as a superconducting resonator. The resulting complex vibration pattern is similar to that of the copper model. These studies have enabled us to understand coil vibrations to the extent that most of the dominant modes can be identified.

3. Theoretical studies of the interaction between the vibrational motion of a single helix and the rf field have been reviewed. The present theory, approximate as it is, seems to be adequate for predicting, at least semi-quantitatively, stable operating conditions. These analyses of electro-mechanical coupling and coil stability relate to a single helix. Extending these analyses to multi-coil resonators is difficult because of the uncertainty as to the effect of small mechanical differences between the various coils. Further work in this area will probably be experimental.

It is evident from Figs. 5 and 6 that the vibration spectrum is too complex to allow dealing with individual components. Since most of the energy lies between 30 and 200 Hz, mounting design and frequency compensation must be addressed to this frequency band.

IV. RF Control

The rf system for any accelerating system must provide an electric field that is stable in amplitude, frequency, and phase. As already mentioned, this requirement is complicated here by the high Q ($> 10^8$) and the vibration-induced frequency variation, and hence sophisticated control techniques are needed. The system that has been developed to provide the needed controls is a composite of three feedback loops, of which two (loops 1 and 3) have been successfully operated with a superconductor-helix model (Fig. 7). The main control loop supplies the above-mentioned frequency compensation and is scheduled for tests in a few weeks. Control functions, loops, and transfer functions have been formulated.

As now envisioned, three rf probes will be required for each helix module consisting of from 3 to 5 half-wavelength structures. Each module will be individually powered and controlled, but referenced in phase to a master oscillator (MO) system. Field amplitude will be programmed for each module and will be a part of the information applied to feedback loop No. 1, which operates in positive feedback and serves to excite the structures.

Loop No. 2, which is fast acting, compensates for the vibration-induced frequency variation and is referenced to the MO system. Slow field variations are compensated by Loop No. 3.

In operation, Loop 1 is used to excite the resonator to full operation power, at which point the static frequency shift reaches its design value, but the system is operating at the variable frequency determined by the mechanical vibrations. Frequency compensation by Loop 2 then serves to allow lock-in with the MO. Such an arrangement allows the power and phase of individual modules to be adjusted without having to correct all other modules. Loop No. 1 has been successfully operated on a superconductive helix.

The main loop (No. 2) provides the primary control of the electric field and, as such, must compensate for the mechanical vibrations of the helices. The technique of reactance tuning (6, 7, 8) is applied and this varies both the magnitude and nature of the reactance, which is closely coupled to the helix resonator. An attractive method for producing such a reactance is to use a transmission line with an effective length of $\lambda/8$ and a diode-type rf switch which shunts the far end of the line. Such a combination appears to the resonance circuit to be capacitive when the switch is open and inductive when the switch is closed.

The nature of the reactance is determined by the switch (pin-diode Unitrobe 7200 series), and the controlled duty cycle of switching establishes the magnitude of the effective reactance. Our vibration measurements show that this tuning need only provide control for a frequency variation of about ± 300 Hz, but our tuner can compensate for ± 500 Hz. The effective reactive power for each $\lambda/2$ section is estimated as a modest 1.0 kVAR for a line whose characteristic impedance is 50Ω. For these tentative parameters and a switching rate of 100 kHz, the maximum variation in the phase of the electric field is about 1.7°.

Because of power losses in the external-reactance system, the effective Q of the resonating system will be decreased to about 1×10^7; the additional power loss, however, is external to the cryogenic system.

Components for loop No. 2 have been completed and installed on a model helix. Tests of the loop are now being initiated, but no data are available yet. Upon successful completion of these tests, the control method will be applied to the prototype accelerator described later.

V. Irradiation Effects

In an accelerator, a helix resonator would be subjected to irradiation by X rays and by nuclear particles. At high power, the helix is continuously exposed to internally generated X rays. These are presumably due to field-emission electrons which are accelerated during part of the rf cycle and are stopped in the outer wall or possibly in adjacent turns of the helix.

The energy-absorption load resulting from the parasitic-electron acceleration is apparent in Fig. 4, which shows a drop in Q with increasing field. Other measurements showed that the X-ray intensity increased with this decrease in Q.

The energy spectrum and the intensity of the X-ray component which penetrated the cavity and dewar walls of a model resonator have been measured and the internal-radiation level estimated (1). Since the intensity of the softer X rays is not known, it is planned to investigate these in order to be able to evaluate more accurately the ionizing power of the internal X rays.

In the long power run on helix Unit A, there was no evidence that the accumulated dose from X-ray irradiation changed any rf properties, and both Fig.4 and X-ray intensity measurements showed that X-ray production decreased towards the end of the long run.

An experiment now in progress will increase the X-irradiation dose so as to approximate more closely the dose accumulated during the lifetime of a working accelerator. The model helix A_1 is being exposed to the beam of an X-ray radiographic machine. The calculated dose rate is about 100 R per hour. Irradiation is being carried out at liquid helium temperatures to avoid annealing out the ionization effects. The influence of the irradiation will be sensed by measuring the Q and the maximum rf field.

Although every effort would be made to keep all nuclear particles away from the helix of a working accelerator, it must be considered possible that an accident could cause the beam to momentarily strike the surface. It is desirable to evaluate the possible consequences of such an accident. After completion of the acceleration tests described below (Sec. VII), the resonator involved will be used in radiation-damage study with protons. If, as has been suggested from experiments in a 3 GHz cavity, (9) damage effects are most prominent in the Nb_2O_5 layer, the low energy protons from the Van de Graaff are most suitable. Here, too, bombardment will be at liquid-He temperatures. It is planned to apply roughly 10^{16} protons/cm^2.

VI. Magnetic Shielding and Trapped Flux

If a magnetic field B is present when the superconducting resonator is cooled through the transition temperature 9.2K, the resulting trapped magnetic flux causes power losses. Since losses due to trapping the earth's field are too large, μ-metal shielding is normally used. This reduces B to < 5 mG. Experiments were performed to evaluate the degree of shielding necessary. An exciting coil within the μ shield served to apply initial fields in the range 5 mG to 10G. Losses were evaluated by measuring low power Q_0-values, and it was found that the losses due to the trapped flux are proportional to B. Measurements for the various modes (frequencies) of the resonator also showed that these losses (at fixed B) are proportional to frequency. At 1.8°K, no losses due to added flux were observable from B=5mG to B=30mG.

VII. Helix-Accelerator Prototype Test

Preparations are well advanced for an experiment aimed at demonstrating the feasibility of the superconducting-helix accelerator concept by accelerating protons in a system consisting of two helix resonators. Initial acceleration is scheduled for the month of November, 1972.

Figure 7 illustrates the layout of the prototype test. Protons of about 0.8 MeV (β=0.04) from an existing Van de Graaff will be injected into the system. A chopper will be used to form beam pulses of 0.2 mA amplitude with a time duration as short as 2 ns; the repetition rate will be 63 MHz. This beam will provide a diagnostic probe of the two superconducting resonators. The planned energy gain is 0.4 MeV which corresponds to a maximum axial field of 2 MV/m. Beam probes and adjustable defining slits will be provided. Existing quadrupole doublets will be used for focusing. Differential pumping is used throughout the beam line to minimize possible contamination of the resonators through their acting as cyrogenic pumps. This experiment will allow us to test:

1. The practical application of the feedback control loops discussed previously. Each resonator will be compensated with separate control loops, utilizing individual fast-tuning reactances.

2. The usefulness of certain vibration-control designs. Transmission of vibration to the helix resonators will be minimized by mounting the cryostats on pneumatic vibration isolators; with these, the system will have a natural frequency < 1.5 Hz for vertical motion and 3 Hz for horizontal motion. Very soft bellows will be used in the beam lines, and spring isolators ($\sim$ 4 Hz) will be used to support the rigidly-connected helium-storage dewars.

3. Beam-dynamics studies. The accelerated beam will be energy analyzed. The time and energy distribution of the protons, as referenced to the rf, will be studied.

4. Cryostat design. The suitability of special features of the cryostat system will be tested.

Completion of the test will provide much of the information we need for designing a practical superconducting accelerator.

VIII. Future Plans

In addition to the investigations now in progress, as described above, we also have plans for studying various other problems. These include cryostat design (including cost vs number of resonator modules), field shaping and external tuning of the resonators, optimization of structure parameters as related to electric and magnetic fields, rf power and beam optics, liquid-helium pumping for possible operation at 4.2°K and the construction of another model accelerator.

This second model will consist of two helix resonators, one having a single $\lambda/2$ section and the other having 5 $\lambda/2$ sections; the accelerated beam will be focused by a quadrupole between the two resonators. This system will be installed on one of the beam lines of our tandem Van de Graaff and will accelerate heavy ions.

References and Footnotes

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9. H. J. Halama, Proc. 8th International Conf. on High Energy Accelerators (CERN, Sept. 1971), p. 242.

TABLE I

CHARACTERISTICS OF ANODIZED HELICAL RESONATORS

(Single $\lambda/2$ Sections)

Unit	Purpose	Heat Treatment (°C)	Surface Treatment	f (MHz)	$Q_o \times 10^8$	E_{max} (MV/m)
A_1	(1) Anodizing (2) Q (3) Maximum field (4) Long-term stability	1850	Chemically Etched Electropolished Anodized	97	6	25
B_1(a)	(1) Fabrication Practice	None	Electropolished Anodized	99	3	14
B_1(b-f)	(1) Electropolishing Anodizing	None	Electropolished Anodized	99	3	14
B_2(a)	(1) Reproducibility New Helix into B_1 can	None	Electropolished Anodized	98	3	14
B_2(b)	(1) Heat Treatment (2) Vibration Control	1200	Electropolished Anodized	98	To be operated	
A_1	(1) Reproducibility of "A" data (2) Radiation Damage	No change from A		97	Not completely conditioned 8	22
C	(1) Heat Treatment (2) Vibration Control	Series of Heat Treatment Cycles		98	Being Assembled	
D	(1) Removable Helix (2) Material Supplier Tests	Treatment Dependent Upon Results of C Series		98	Under Construction	
E	(1) H+ Acceleration Tests (2) Two Units Req'd.	1850	Chemically Etched Electropolished Anodized	63	Being Assembled	

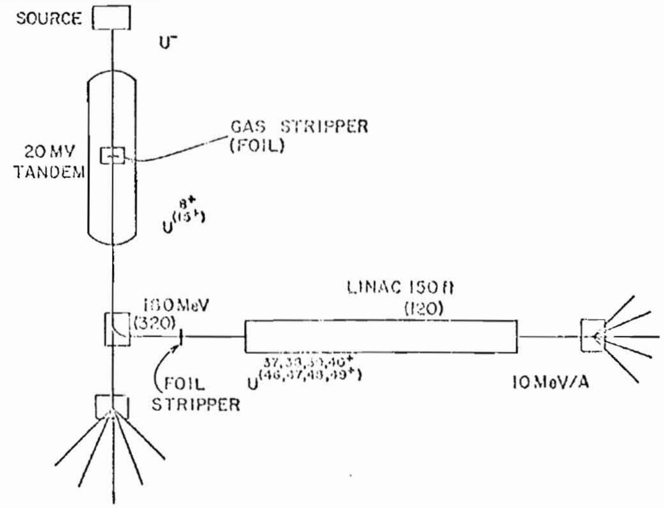

Fig. 1 Heavy ion accelerator concept.

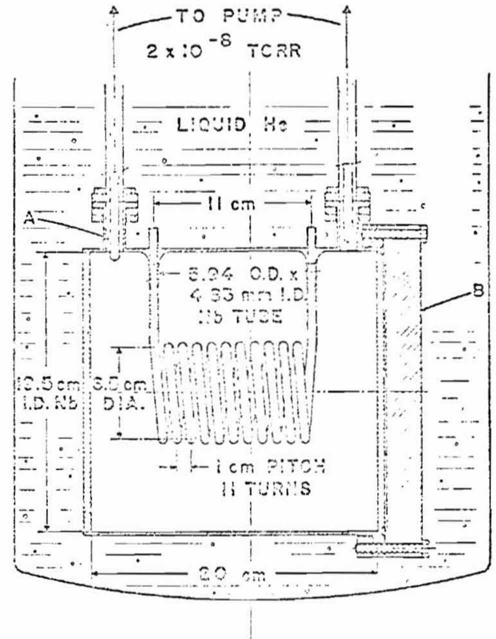

Fig. 2.

Resonator structure for Helix A and Helix B. A. Adjustable rf probes for power feed and detector. B. Titanium stiffening plate. Liquid-helium bath surrounds cylinder. Helix is cooled by superfluid heat transfer with no mass flow by helium superfluid state at 1.8°K. Later models use center probes to minimize probe losses when high coupling factor is used.

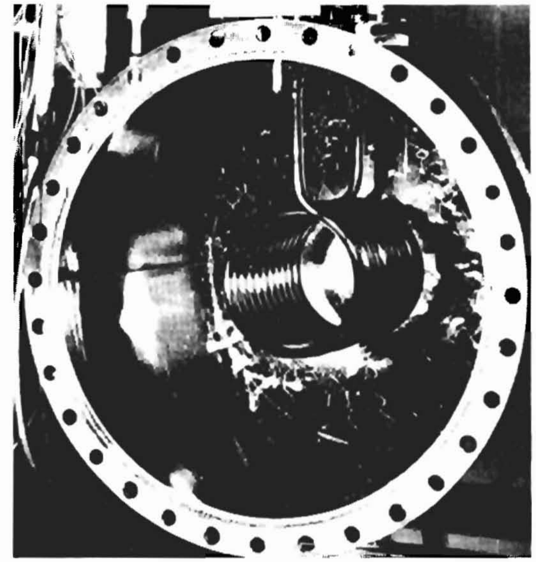

Fig. 3. A view of Helix A.

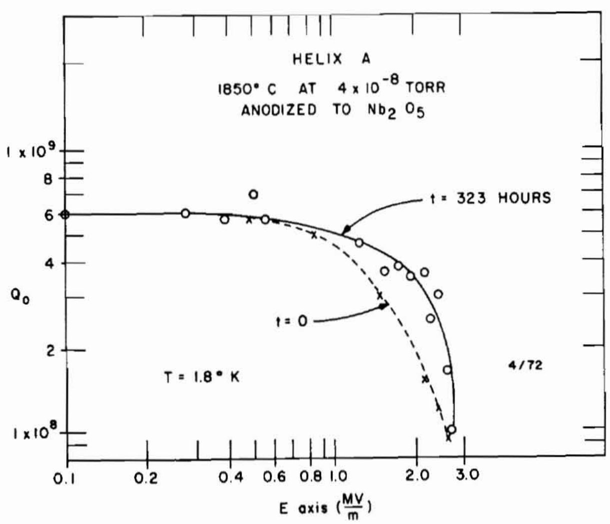

Fig. 4. Q_0 versus rf power level as measured by the axial accelerating electric field. The Q_0 drop corresponds to energy losses due to acceleration of parasitic cold-emission electrons.

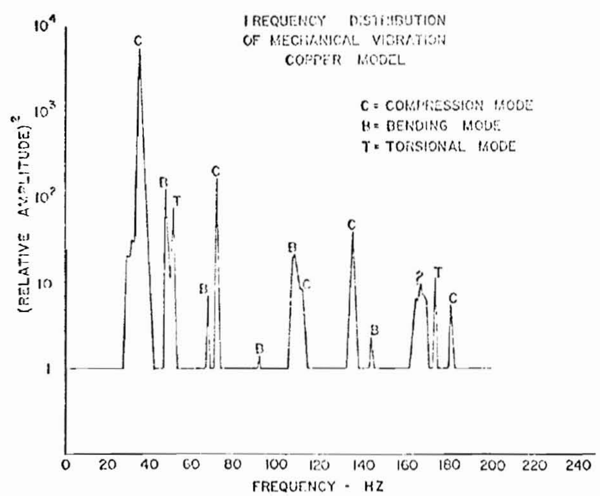

Fig. 5. Mechanical frequency distribution of copper helix model driven by force generator at room temperature. Data derived from optical measurement of axial displacements.

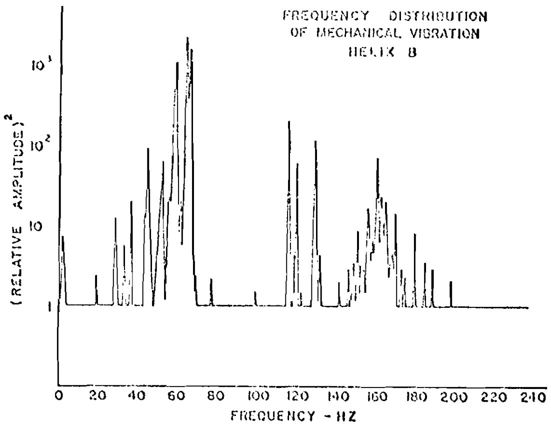

Fig. 6.
Mechanical frequency distribution of niobium helix resonator at liquid-helium temperature. Data derived from electrical error signal in phase-lock loop.

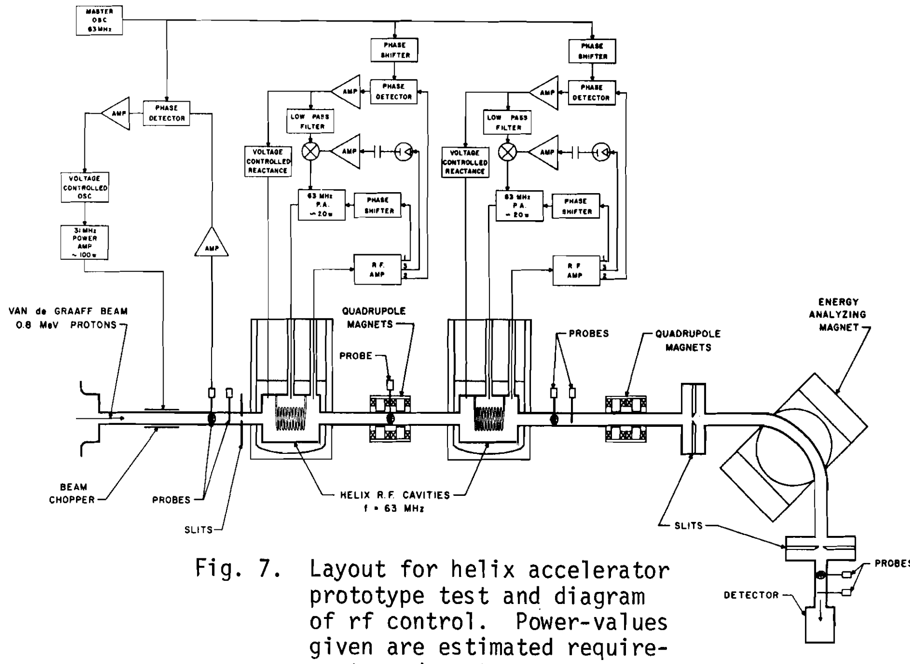

Fig. 7. Layout for helix accelerator prototype test and diagram of rf control. Power-values given are estimated requirements; adequate power reserves are provided.

DISCUSSION

P.B. Wilson, SLAC: Is your axial field the accelerating field, or is there a factor of 2 difference?

Ramler: The axial field is the accelerating field for a short structure. For a longer structure we would probably pick up about 15 or 20%.

R. Miller, SLAC: Were you limited by field emission at the 2.8 MV/m level?

Ramler: Yes, we could see thermal breakdown starting to take place with a low Q around 1×10^8. We ran 300 h sitting at the 2.5 to 2.7 MV/m level. This was really a full power situation.

Miller: Is it conceivable that the difference between your results and those from Karlsruhe is the lead plating on the outer wall even though the wall is supposed to have low loss?

Ramler: I think anything is conceivable at this point. The difference might be associated with vacuum techniques. I hope that we will get this question resolved.

J.L. Fricke, Karlsruhe: Does the trapped flux you mentioned in your introduction affect Q at high surface fields?

Ramler: For the helix B our conditions are associated with a 5 mG field. We varied the field from 5 to 30 mG and did not see a change in Q. We did go to 10 G,and that data is available.

Fricke: Are these Q values at high electric and magnetic peak fields or at low fields?

Ramler: The Q values referred to are at high fields.

J.E. Vetter, Karlsruhe: I believe that Fricke's question was the following: Was the influence of the static magnetic fields on the Q value measured at high or low fields?

Ramler: We ran load characteristic curves on the helix B, that is a no-load Q to a full-load Q. From 5 to 30 mG static field, there was no change in the curve.

Vetter: What does "removable helix" in your setup D mean?

Ramler: We are hoping to achieve a ridge type seal that gets clamped down to the structure so as to avoid welding. This seal is under development.

Vetter: Will it be an indium-type seal?

Ramler: Yes.

Vetter: What frequency excursions are expected with your fast tuning system?

Ramler: We are designing for 500 Hz, although we feel that a 300 Hz design would be adequate.

C.M. Jones, Oak Ridge: Was the Q of 6×10^8 in helix A measured at high or low field?

Ramler: Low field.

Jones: At what field level did you begin to see field emission?

Ramler: Around 1 MV/m.