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PRACTICAL CONSIDERATIONS IN THE DESIGN AND OPERATION OF SUPERCONDUCTING STRUCTURES*

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Summary

During the past few years considerable experience has been gained in the operation of prototype superconducting accelerators under beam line conditions. As a result of this experience, important aspects of structure design and important questions related to the long term operation of superconducting structures have been brought into sharper focus. For applications where low power loss and high duty factor, or exceptional beam quality and stable operation, are essential properties, and where modest energy gradients can be tolerated, superconducting structures are distinctly superior to conventional room temperature structures.

Introduction

The early hope that rf superconductivity would provide the means of constructing a high gradient linear accelerator has been dashed upon the rocks of physical reality. Investigations at numerous laboratories have clearly indicated that the technical problems of achieving very high gradients in full-scale superconducting structures are extremely difficult and that success in this venture will be slow, if indeed it can be achieved at all. Despite this setback, rf superconductivity has an important future in particle accelerators. Energy gradients of 2-4 MeV/m, although they are less than originally hoped for in superconducting structures, are still competitive in many applications, and the other specific properties of superconducting accelerators offer important advantages including high duty factor, excellent beam quality and beam stability, and high intensity.

Indeed much of the current activity in rf superconductivity is motivated by the need for particle beams of very high duty factor. Recently in a review of U. S. Medium Energy Science a joint AEC-NSF committee noted the importance of high duty factor electron beams in the nation's long range medium energy program.[1] At Stanford, the superconducting accelerator program is directed toward laying the foundation for meeting that need.[2] High duty factor beams of electrons and heavy ions are also important in nuclear physics, and at the University of Illinois the development of a superconducting racetrack microtron is in progress,[3] while at Argonne[4] Karlsruhe,[5] Cal Tech,[6] and Stanford[7] low beta superconducting structures are being developed for heavy-ion particle accelerators. Even in high energy physics there are important applications for low power loss, high duty factor superconducting structures. At Cornell superconducting structures are being used successfully in their electron synchrotron,[8] and in Germany a joint Karlsruhe/CERN group is constructing a superconducting rf particle separator.[9] In all of these applications low power loss and high duty factor are essential properties and modest energy gradients can be tolerated. In this area superconducting structures are distinctly superior to conventional room temperature structures.

The other attractive properties of a superconducting accelerator, the excellent beam quality and beam stability, and the high intensity, are also important in nuclear and particle physics. And these properties can be important in other areas of research as well. For example, at Stanford we have been interested in the development of a free electron laser.[10] In the free electron laser an electron beam transverses a spatially periodic magnetic field which is transverse to the beam direction. As shown in the upper trace of Fig. 1, the spontaneous radiation which would ordinarily

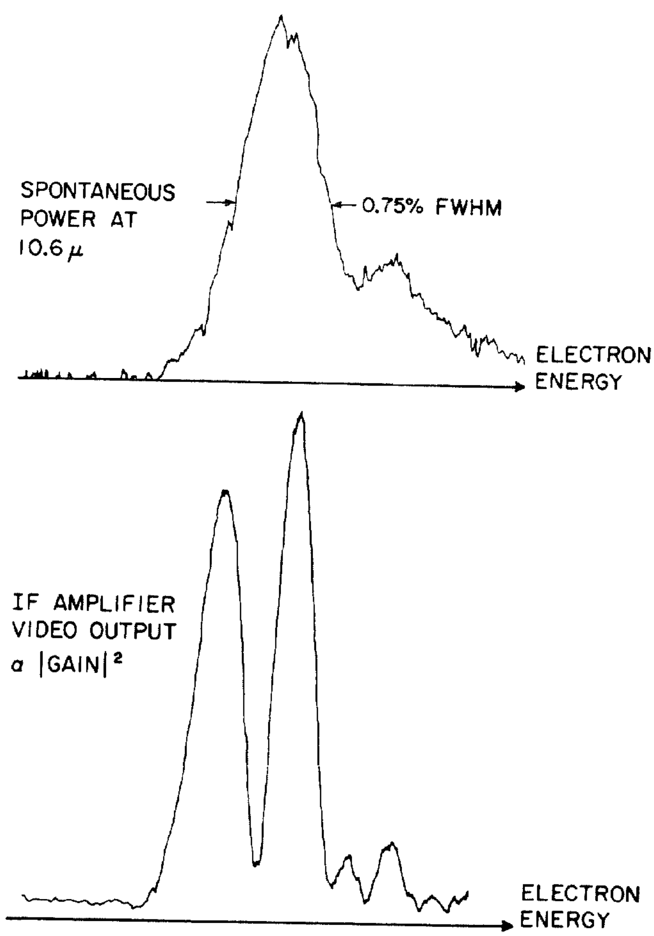

Figure 1. Upper trace: Spontaneous radiated power at 10.6 μ as a function of the electron beam energy. A similar curve is observed if the radiated power is measured as a function of wavelength for a given electron beam energy. Lower trace: Amplification or attenuation of a CO_2 laser beam as a function of the electron beam energy. The peak on the low energy side of the spontaneous line corresponds to attenuation of the CO_2 laser beam while the peak on the high energy side corresponds to amplification.

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be distributed over a broad range of frequencies, is compressed into a narrow band due to the periodicity of the perturbing magnetic field. Recently, using the intense, high quality beam from the superconducting accelerator we have observed stimulated emission in this system.[11] Due to a small kinematic shift between the emission process and the absorption process, one expects a net absorption on the left hand side of the spontaneous line and a net gain on the right. The observation of gain in this system, illustrated in the lower trace of Fig. 1, is extremely interesting, and was only possible because of the exceptional beam quality and the extraordinary beam stability that is achieved at high intensity in the superconducting accelerator. The free electron laser experiment required an energy resolution of 0.1% and a transverse phase space of 0.1π mm mrad at an energy of 25 MeV and a current of 200 μA. It was imperative in this experiment that the beam quality and position, and the beam energy and intensity remain extremely stable for periods of several hours; and it was essential that, following an interruption of beam for the purpose of changing detectors, the initial beam properties could be restored with precision and with confidence in a few minutes time. The superconducting accelerator performed consistently in this experiment, 24 hours per day for several weeks. Again, in applications where beam quality and beam stability at high intensity are <u>essential</u>, superconducting structures are distinctly <u>superior</u> to conventional room temperature structures.

The most important task now before us in the development of rf superconducting devices is that of achieving and demonstrating reliability in long term operation. This task is being performed, both in structure design and in tests, at a number of different laboratories for a broad range of different structures. The current studies of superconducting structures, and appropriate references to the literature are listed in Table I. As can be seen in the table, considerable effort is being expended on the development of low beta superconducting structures for accelerating protons and heavy ions. Major programs have been initiated at the Argonne National Laboratory and at Karlsruhe (IEKP) to demonstrate reliable performance of the helical structure, and important work on the split ring structure, the re-entrant cavity, the Alvarez structure, and the slotted-iris structure is in progress at the California Institute of Technology, at Stanford University (HEPL) and at Karlsruhe (IEKP).

For velocity of light beams there are currently three major structure development programs in progress: the iris-loaded structure study at Stanford University (HEPL), the muffin tin structure study at Cornell University, and the rf separator structure study at Karlsruhe (IEKP)/CERN. In the following sections of this paper we will discuss several aspects of structure design and a number of questions related to long term operation of superconducting structures which, as a result of operating experience, have been brought into sharper focus.

Design Problems of Superconducting Structures

There are many important design factors which influence the performance of a superconducting structure. For example, the shunt impedance determines the refrigeration power requirement, and the peak surface fields influence the maximum attainable energy gradient. These important design considerations have been discussed at some length in the literature cited in Table I. Rather than summarizing all the work reported there, I would like to restrict the discussion in this paper to three aspects of structure design which relate directly to the simplicity and the reliability of operating superconducting structures. These are thermal instability, electron multipacting, and electromechanical instability. These aspects of structure design are qualitatively different in superconducting structures than in conventional structures, and they have proved to be of considerable importance in the operation of full-scale structures.

Thermal Instability

In retrospect it appears to this author that in the development of superconducting structures too much effort has been devoted to producing defect-free superconducting surfaces and too little effort has been devoted to minimizing the consequences of such defects. If one demands, as the principal objective in the development of superconducting structures, that exceedingly high energy gradients be achieved, then one is forced to produce defect-free surfaces. On the other hand, if one is prepared to accept modest, but competitive, energy gradients, then one can design a thermally stable superconducting structure and be assured of reliable operation.

TABLE I

Current Studies of Superconducting Structures

Structure	Resonant Frequency f(MHz)	Particle Velocity β	Laboratory
Helical Structure	90	0.04	Argonne Nat'l. Lab.,[4] Karlsruhe (IEKP)[5]
Split Ring Structure	150	0.05, 0.10	California Institute of Technology[6]
Re-entrant Cavity	433	0.10	Stanford University (HEPL)[7]
Alvarez Structure	720	0.10	Karlsruhe (IEKP)[12]
Slotted Iris Structure	720	0.20	Karlsruhe (IEKP)[12]
Iris-Loaded Structure	1300, 2600	1.00	Stanford University (HEPL)[13]
Muffin Tin Structure	3000	1.00	Cornell University[8]
RF Separator Structure	2855	1.00	Karlsruhe (IEKP)/CERN[9]

In order to understand what is meant by thermal instability, let us consider first the thermal response of a defect-free superconducting structure. For an operating frequency, ω , and a surface temperature, T_s , the power per unit area dissipated at the surface is

$$P/A = 1/2 \; R_{SC}(\omega, T_s) H^2 \quad ,$$

where R_{SC} is the BCS surface resistance of the superconductor and H is the surface magnetic field. This power must be transported to the outer wall of the structure and transferred to the liquid helium. To simplify the discussion let us ignore the problem of heat transfer to the liquid helium and assume that the outer wall of the structure is maintained at the bath temperature, T_b . The power per unit area which can be transported from the inner surface of the structure to the outer surface in this case is

$$P/A = (1/t) \int_{T_b}^{T_s} K(T)\, dT \quad ,$$

where $K(T)$ is the thermal conductivity of the structure wall and t is the wall thickness. In steady state the power dissipated must be equal to the power transported and this leads to the relation:

$$H_{TS}^2 = \frac{(2/t) \int_{T_b}^{T_s} K(T)\, dT}{R_{SC}(\omega, T_s)}$$

which defines the thermally stable magnetic field. The thermally stable magnetic field, H_{TS} , depends on ω, T_b, and , $\Delta T \equiv T_s - T_b$. Now the surface resistance increases exponentially with ΔT , while in the temperature range of interest the thermal conductivity integral is roughly proportional to ΔT . Thus as a function of ΔT , the stable field, H_{TS} , initially increases, but it subsequently reaches a maximum and decreases as the exponential increase in the surface resistance becomes dominant. Thus for a given configuration there is a maximum magnetic field for which thermally stable operation is possible, even for a defect-free superconducting structure. Since the BCS surface resistance increases as ω^2 , $H_{TS}(\max)$ is proportional to $1/\omega$ for a defect-free structure.

This kind of argument, modified to include the problem of heat transfer to the helium bath has been advanced by Hillenbrand et. al. at Siemens[14] and by Turneaure at Stanford[15] to explain the observed limitation on field level (in the 1000 Oe to 2000 Oe region) in superconducting X-band test cavities.

If defects are present on the superconducting surface, thermal instability can be expected to occur at lower field levels. The presence of such defects must provide the explanation for the relatively low field levels (100 Oe to 300 Oe) at which thermal instability is observed to occur in large superconducting L-band and S-band structures. The most important defect geometry in a superconducting structure is likely to be the line defect since it is less stable thermally than the point defect, and since crystal grain boundaries provide a natural means for their occurence. At the present time, we are working on a detailed computer study of thermal instability for line defects. However, on the basis of an approximate analysis of a simplified model, one expects that the maximum stable field, $H_{TS}(\max)$, will vary roughly as the inverse square root of the defect width.

For defects of increasing width the maximum stable field is not expected to decrease indefinitely. For extended defects, $H_{TS}(\max)$ approaches a finite limiting value. This fact is of great practical significance since it means that there is some finite field level for which thermal stability is assured independent of the extent of any defect. This limiting field level, H_∞ , is determined by the condition

$$\frac{1}{2} R_{NS}(\omega)\, H_\infty^2 \quad = \quad (1/t) \int_{T_b}^{T_{C(H_\infty)}} K(T)\, dT \quad .$$

Physically, this condition can be understood in very simple terms. Let us suppose that the entire inner surface of the structure is elevated to the critical temperature of the superconductor and that the surface resistance therefore assumes a value corresponding to the normal state. Again, ignoring the problem of heat transfer to the liquid, the power per unit area that can be transported from the inner surface of the structure to the outer surface is given by the thermal conductivity integral divided by the wall thickness. Since one integrates from the bath temperature all the way up to the critical temperature of the superconductor, $T_{C(H_\infty)}$, the power transport capability is large, and one can tolerate a large power dissipation. Although the surface resistance in the normal state is also large, one achieves thermally stable operation at a quite respectable magnetic field level. For the Stanford iris-loaded structure the wall thickness is 2.5 mm and at the operating frequency of 1.3 GHz, $H_\infty \simeq 100$ Oe which corresponds to an energy gradient of 2 MeV/m. Since the normal state surface resistance varies as $\omega^{2/3}$ the limiting magnetic field level H_∞ is proportional to $\omega^{-1/3}$.

It would be extremely desirable to build superconducting structures which are thermally stable at the design gradient. In order to appreciate more fully the advantages of this, consider the following facts:

1. The design Q-value for the Stanford 55-cell iris-loaded structure is 2×10^9 . For this Q-value a total area as large as 5 cm^2 can be permitted to operate continuously in the normal state! If the structure is thermally stable, the normal state area will not grow and one can tolerate an enormous number of extended defects.

2. It has been observed that multipacting can produce a localized normal region in a superconducting structure which, if the structure is thermally unstable, results in thermal magnetic breakdown. If, however, the structure is thermally stable at the field level in question, the localized normal region will simply not grow.

3. It is possible to build a structure which is thermally stable at an energy gradient substantially higher than 2 MeV/m. Design work in this direction is underway.

The thermal stability considerations described above apply to all superconducting structures. For the helical structure and the plit ring structure, however, there is an additional consideration. In these structures the power dissipated in the structure walls must be transported through the superfluid helium contained in a relatively small diameter tube to the main helium reservoir, and the total dissipation therefore is limited due to breakdown of superfluid heat transfer which occurs at power densities the order of one watt per cm^2.

Operation of superconducting structures is possible at gradients exceeding the thermal stability limit. At Stanford, for instance, a full length structure has operated for many months at an energy gradient of 3.0 MeV/m as compared to the thermal stability limit of 2.0 MeV/m. But, if design gradients remain in the region of 2-4 MeV/m, there is little excuse for failing to improve the thermal design to guarantee operation at the design gradient.

Electron Multipacting

Electron multipacting is a high frequency resonant conduction phenomenon which occurs both in room temperature copper structures and in helium temperature superconducting structures. Since the multipacting trajectories must satisfy a transit time condition, this phenomenon occurs only for a discrete set of field levels. In room temperature structures, electron multipacting can, under extreme conditions, prevent one from attaining high field levels since the multipacting electrons in principle can absorb all of the available rf power. In superconducting structures the situation is more serious. Multipacting electrons deliver energy to the structure walls, and since only a relatively small fraction of the available power is required to drive the surface normal, the system is more sensitive. Even when the power adsorbed is less than that required to drive the surface normal the presence of multipacting electrons can be important in the operation of a superconducting structure.

Multipacting electrons, driven by the accelerator mode fields, provide a non-linear coupling mechanism to the other longitudinal modes of the structure, and excitation of other modes leads to a modulation of the energy of the accelerated particle beam. For the exceptional energy resolution which can be achieved in a superconducting accelerator, the presence of other longitudinal modes, even if they are 40 db below the fundamental accelerator mode, result in an observable degradation of the beam quality.[16]

As a particular example of the character and the consequences of multipacting in a superconducting structure, let us consider the experience with the iris-loaded structure at Stanford. In the initial operation of a structure, if one monitors the excitation of the longitudinal modes, one is left with the impression that multipacting occurs at all field levels up to 2 MeV/m. If, on the other hand, one measures the power absorption as a function of field level, it is clear that enhanced absorption occurs at definite field levels. Power absorption measurements, or Q-value measurements, for one 7-cell structure are illustrated in the upper trace of Fig. 2. In the energy gradient region between 1 MeV/m and 2 MeV/m a bewildering sequence of levels is evident in the data, and one is inclined to belive that many basically different multipacting trajectories exist. In fact, the situation is surprisingly simple. The five main cells in this 7-cell structure are $\lambda/2$ in length and yield a set of levels at energy gradients $\nabla E(n) \simeq \nabla E_1/n$ where n is the multipacting order number, and ∇E_1 is the energy gradient at which first order multipacting occurs. Actually the field level in the center cell of the structure is reduced to 3/4 of the level in the other main cells to minimize the likelihood of magnetic breakdown in the rf input coupler, and thus for this cell the corresponding multipacting levels occur at energy gradients of $\nabla E(n) \simeq 4/3\ \nabla E_1/n$.

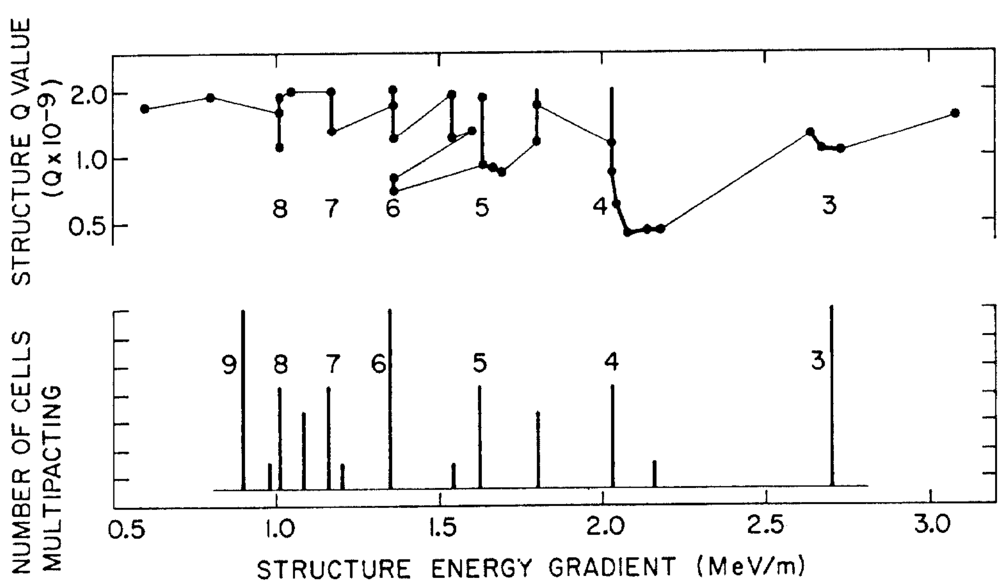

Figure 2. Upper trace: loaded Q-values as a function of energy gradient as measured during the initial processing of a Stanford iris-loaded structure. Observed Q-values less than 2×10^9 indicate power absorption by multipacting electrons. Lower trace: Expected multipacting levels in the Stanford structure. The number of cells in which multipacting can occur at a given energy gradient is plotted as a function of energy gradient. The numbers in the figure refer to the multipacting order in the main cells of the structure.

In addition, the two end cells in this structure are $\lambda/3$ in length, and thus these cells yield a set of levels at energy gradients $\nabla E(n) \simeq 2/3 \, \nabla E_1/n$. If one treats ∇E_1 as a free parameter which is chosen to fit the observed levels (typically third order multipacting is the highest level reached), one can generate the sequence of levels shown in the lower trace of Fig. 2. Here the number of cells that are multipacting at a given energy gradient is plotted as a function of energy gradient, and the order numbers for multipacting in the main cells are indicated. The correspondence between the calculated sequence of levels and the observed sequence of levels illustrated in the figure is remarkable, and it clearly indicates that the observed levels are simply the result of different order multipacting for one basic multipacting trajectory.

The multipacting levels are not all of equal importance. It can be seen in Fig. 2 that the power absorption is greatest for the levels at 1.36, 1.62, 2.02 and 2.70 MeV/m. In fact, it has been our general experience that the multipacting level at 2 MeV/m is the most severe. During the initial processing of the 7-cell structure, the power absorbed by the multipacting electrons at this level exceeded 10 watts. If this power is delivered to an area less than 10 cm^2, the power density is sufficient to generate a localized normal region. Unfortunately, as we have already pointed out, our structure becomes thermally unstable at an energy gradient of approximately 2 MeV/m, and thus a localized normal region can propagate and thereby induce magnetic breakdown.

Above an energy gradient of 2.16 MeV/m, multipacting extinguishes in our structure. The enhanced power absorption vanishes and other longitudinal modes, which are typically excited by multipacting electrons disappear. This behaviour is quite different from that observed at energy gradients between 1 MeV/m and 2 MeV/m. Between multipacting levels in the lower range of gradients one still sees the excitation of other longitudinal modes, despite the fact that the power absorption is not measurable. Finally, in the vicinity of 2.7 MeV/m one encounters the next multipacting level, and again, above this level multipacting extinguishes. The existence of regions which are completely free of multipacting can be of great practical importance.

The multipacting behaviour described above is characteristic of the <u>initial</u> operation of the 7-cell structure. After methodically processing the structure by operating it at successively higher energy gradients until multipacting ceased at each gradient, the 7-cell structure was essentially free of multipacting phenomena. Processing, however, is not always complete. In fact, in several tests with full length structures, excitation of other longitudinal modes at gradients less than 2 MeV/m persisted after extensive processing, and multipacting-induced thermal breakdown occurred near 2 MeV/m. The fourth order multipacting level appears in general to be troublesome. At Cornell the fifth and fourth order multipacting levels have been observed at energy gradients of 3.31 MeV/m and 4.19 MeV/m. The levels in the Cornell structure appear at a gradient approximately twice that in the Stanford structure due to the frequency difference. The barrier at 3.31 MeV/m processed away in a few minutes, but the barrier at 4.19 Mev/m could not be penetrated.

Electromechanical Instability

The possibility of electromechanical instability is an important consideration in the design of superconducting structures where the Q-value is relatively high. Due to radiation pressure the resonant frequency of any structure will shift to lower values as the stored energy level increases, and if this frequency shift exceeds the half width of the resonance, the resonance curve becomes double-valued. Under these conditions the structure is statically unstable on the low frequency side of resonance, while on the high frequency side, the structure is vulnerable to ponderomotive oscillations, a dynamic instability in which radiation pressure drives a mechanical resonance in the cavity walls.

Because electromechanical instability is a result of radiation pressure, there is a minimum rf stored energy level which is required for the occurrence of each type of instability. This stored energy level is called the threshold energy, U_{Th} , for instability. For static instability the minimum threshold energy is

$$\text{Min}\,[U^s_{Th}] = (2K_o Q_E)^{-1} \quad ,$$

and occurs at $f = f_o - f_o/2Q_E$. Here K_o , the static electromechanical coupling constant, is the normalized static shift of the cavity resonant frequency due to radiation pressure

$$K \equiv \frac{1}{U}\frac{\Delta f_o}{f_o} \quad ,$$

and Q_E is the rf loaded Q-value of the structure. For a superconducting structure where the mechanical frequency of vibration, f_M , is much greater than the half-width of the rf resonance line, it can be shown[17] that the minimum threshold energy for dynamic instability (ponderomotive oscillations) is

$$\text{Min}\,[U^d_{Th}] = (2K_o Q_M Q_E)^{-1} \quad ,$$

and occurs at $f = f_o + f_M$. Here Q_M is the Q-value of the lowest mechanical mode of vibration for the structure.

Comparing the expressions for the minimum threshold energy for static and dynamic instability in a superconducting structure, we find that:

$$\text{Min}\,[U^d_{Th}] = \frac{1}{Q_M}\,\text{Min}\,[U^s_{Th}] \ .$$

Typically in a superconducting structure, Q_M is on the order of 100 and is determined by the loading of the mechanical resonance by the liquid helium. Thus, in general, a superconducting structure is less stable dynamically than it is statically, and ponderomotive oscillations can occur even before the resonance curve becomes double-valued.

In the design of a superconducting structure it is preferable if the structure itself is fully stabilized against both static and dynamic instability at the stored energy level corresponding to the design gradient. It should be noted, however, that in practice it is not necessary to fully stabilize against ponderomotive oscillations since the minimum threshold energy occurs at a frequency $f = f_o + f_M$ which is many bandwidths above resonance. As a rule of thumb, a superconducting structure may be considered adequately stabilized if the stored energy at the design gradient is less than $[U^S_{Th}]/10$. Of the superconducting structures which are currently being studied, the iris-loaded structures, the muffin tin structure, and the rf separator structure are adequately stabilized at the design gradient, and the re-entrant cavity probably can be stabilized adequately by the addition of support struts.

For very low beta superconducting structures, such as the helical structure and the split ring structure it does not appear to be possible to achieve electromechanical stability at the design gradient. Thus one is forced to take an alternative approach to the entire problem and provide electronic stabilization instead. Important progress in electronic stabilization of very low beta superconducting structures has been reported in the past few years.[18-20] Even if one is forced to resort to electronic stabilization, however, it is still desireable in the design of the structure to maximize the threshold energy for electromechanical instability. The split ring structure developed at Cal Tech[6] represents an important effort to reduce the magnitude of the electronic stabilization problem by increasing the electromechanical instability threshold.

Operational Problems of Superconducting Structures

During the past few years considerable experience has been gained in the operation of prototype superconducting accelerators under beam line conditions. At the University of Illinois a 3 MeV superconducting structure has been used in a six-pass 19 MeV microtron, and an electron beam for resonance fluorescence experiments and tagged photon experiments has been provided reliably on demand for two years.[3] At Cornell University[8] a 2.4 MeV superconducting structure, installed in their electron synchrotron has been used for the past two months to accelerate the synchrotron beam to 4 GeV, while at Stanford University[2] a 25 MeV superconducting linac has been operated for 15 months in an extensive series of experiments to demonstrate the feasibility of a free electron laser. Beam experiments with low beta superconducting structures are not as extensive, but they are still impressive. At the Argonne National Laboratory acceleration tests with single $\lambda/2$ helical resonators have been performed, and tests with a multiple-helix prototype accelerator are in preparation. In the prototype accelerator, three independently phased helical resonators are expected to provide an energy gain of 2 MeV/nucleon for O^{5+} ions with an incident energy of 2.8 MeV/nucleon. At Karlsruhe (IEKP)[22] extensive beam tests with single helical structures have been performed, and work is in progress on a prototype proton accelerator which consists of nine independently phased helical structures operating at 90 MHz followed by an Alvarez structure operating at 720 MHz. The prototype objectives are to achieve a proton beam energy of 10 MeV with a current exceeding 100 μA.

The general experience in operating superconducting structures has been quite favorable. Superconducting systems brought into operation with satisfactory performance characteristics have been shown to maintain that performance for extended periods of time under realistic operating conditions. Without detracting from this favorable experience, I would, however, like to identify several potential problem areas in the long term operation of superconducting structures, including gas adsorption due to cryogenic pumping, exposure to the atmosphere as a result of vacuum accidents, dust collection, and radiation damage, and to report a few recent experimental observations related to these.

A superconducting structure operating at helium temperature represents an extremely effective cryopump in the beam line vacuum system, and thus, if the structure is maintained at low temperature for many months, one must expect to adsorb an appreciable quantity of gas on the structure walls. For this reason, the consequences of gas adsorption are extremely important. At Stanford[13] the Q-value of one superconducting structure at an energy gradient of 3.0 MeV/m was observed to degrade during a ten day period of continuous operation from $(7.8 \pm 1.3) \times 10^9$ to $(3.3 \pm 0.6) \times 10^9$. No degradation in the maximum field level was observed during this time. Following the accelerator run, the structure was warmed to room temperature, and a considerable amount of gas evolved from the system in this process. This structure was then kept under high vacuum at room temperature for 1-1/2 months until the next accelerator run, and it was found upon cooling to helium temperature that the Q-value was restored to its original value. Although it would be difficult to prove conclusively, there is good reason to believe that the observed degradation in Q-value is the result of adsorbed gases which are known to change their state of binding to the surface when exposed to radiation.[23] One might also expect adsorbed gases when exposed to radiation to enhance electron field emission through the mechanism of resonant tunneling[24] and to enhance multipacting through increased secondary emission. At Cornell,[8] after 20 days near or below liquid nitrogen temperature, it was observed that the energy gradient that could be achieved in their structure degraded from 4 MeV/m to 2.6 MeV/m, and the mechanism of breakdown appeared to be runaway electron loading. Again, the initial performance was restored after cycling to room temperature and evacuating the structure. Although this experience indicates the ncessity of excellent beam line vacuum and periodic temperature cycling of the structure, it would appear that the problem of gas adsorption due to cryopumping is not severe.

It has been reported by the Cornell group that exposure of a superconducting structure to dry nitrogen between accelerator runs does not result in degradation of performance.[8] However, uncontrolled exposure of a structure is more serious. At Stanford,[26] after extended operation at helium temperature spanning 3 months, a superconducting structure was exposed briefly to the atmosphere as a result of a vacuum accident. The structure which originally operated at an energy gradient of 3.0 MeV/m with a Q-value of $(7.8 \pm 1.3) \times 10^9$ degraded to a maximum energy gradient of 2.05 MeV/m with a Q-value of $(3.38 \pm .27) \times 10^9$. It should be noted that fourth order multipacting occurs at precisely this energy gradient. This experience is somewhat encouraging since uncontrolled exposure of a superconducting structure is not completely destructive, but such exposure is certainly a serious matter.

In the electron synchrotron at Cornell there is particular concern about the possible entry of dust particles into their superconducting structure. At Cornell visual observations[8] have revealed the presence of point light sources on the structure irises, and one possible explanation of this phenomenon is the incandescence of dust particles. In order to inhibit the entry of dust particles, the Cornell group has installed short electrostatic precipitators in the synchrotron beam pipes at each end of the superconducting structure. Despite the possible presence of dust particles, the Cornell structure has performed satisfactorily.

Finally, a great deal of concern has been expressed in the past about the possible effects of radiation on superconducting structures. At Stanford, structures have recorded many months of beam-line operation at full field level and at currents up to 500 μA without suffering radiation induced damage.[13] At Cornell, their superconducting structure has been exposed to 75,000 R in the electron synchrotron without observable consequences.[8] Thus, apart from the possible role played by radiation in the reversible degradation which results from cryopumped gases, it would appear that superconducting structures are quite radiation resistant.

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