RF SUPERCONDUCTIVITY FOR ACCELERATORS -- IS IT A HOLLOW PROMISE?

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SUMMARY

This review will attempt to offer a realistic and coherent overview of the failures and partial successes in harnessing rf superconductivity of niobium to particle acceleration. Work in materials, preparation processes, heat transfer, cavity structures and vacuum electronic phenomena are discussed and put in perspective. An attempt is made to draw lessons from these observations and to outline the tasks and opportunities for the future.

INTRODUCTION

Since the early 60's and the measurements of Banford and Stafford[1] and of Wilson et al[2], we have known that it is possible to sustain rf electric fields of many millions of volts per meter in large volumes by the expenditure of a few watts of rf power. Since those early days of inflated hopes and expectations, almost twenty years ago now, we have become considerably sadder and, I hope, a little wiser.

It is my intention here to evaluate, critically, the accomplishments of this period in practical terms and to try and draw from this evaluation indications about profitable future approaches and applications and about needs for research and development. I will argue that before we can expect a realization of the full potential of rf superconductivity for accelerators a two pronged approach will be necessary. On the one hand we need to select a very few accelerator applications where the existing state of the art is competitively advantageous with respect to alternative existing technologies. Having selected these applications and accepted the limitations of the existing state of the art, the construction and putting into useful, continuous operation of the devices must be aggressively pursued. Success in this will provide the motivational and economic support necessary to continue on the second front, namely, the discovery and invention of the new ideas, techniques and materials that will be required to make devices approaching the ideal in performance. To some extent these two avenues are already being travelled.

GENERAL BACKGROUND

The theory of rf superconductivity and expermental progress up to a year ago are dealt with in a number of readily available review articles.[3,4,5,6,7]

Below the superconducting transition temperature, the condensed Cooper pairs of electrons can carry current without dissipation. They do, however, have inertia so that fields must be present inside the conductor to make the pairs carry an alternating current. These fields will drive the other charges present and thereby engender dissipation, even in the ideal case. The phenomena are described by the approximate rule

$$R_S \sim \frac{\text{const. } f^2}{T} \exp\left(-\text{const. } T_{c/T}\right) + R_{residual},\ T < T_c/2 \qquad (1)$$

The first term, the BCS part of the resistance, takes into account the processes in an ideal material. The R_{res} term represents all of the non-idealities of the surface and is, in general, a composite of terms depending on f, the operating frequency, T the operating temperature of the surface, and many other physical and chemical parameters of the surface.[7,9,10] It cannot be calculated from first principles. Once the material parameters are known, the first term can be computed from basic principles.[8] The residual effects, coming from a wide variety of sources, are less well understood although some progress has been made. As we shall see, these residual resistances do not limit the performance of devices now being constructed.

In addition to the surface losses, the maximum supportable field is also important. If only the ideal superconductor properties were involved, one would expect to be able to reach a surface magnetic field of about the thermodynamic critical field at least. In macroscopic samples of several type I superconductors, rf fields in excess of B_c are possible[11]. In accelerating type cavities of Nb[12,13] and Nb_3Sn[14,15], the first flux penetration critical field, B_{c1}, has been exceeded. The achievement of these fields in extended accelerating devices would correspond to 10's of MV/m. Thus, as is the case with the surface losses, very good performance is within the fundamental capability of rf superconductivity.

PRESENT LEVEL OF ACHIEVEMENT

By now a bewildering array of superconducting accelerating devices have been made from various materials, utilizing a wide range of forming, polishing, cleaning and final preparation procedures. The mainstream of activity has focussed on structure made from niobium and to some extent lead plated copper. Since it is my purpose to emphasize the practical and the search for near term payoffs, I will emphasize Nb based devices. They have received the most attention, have given the best performance, and have the most well elaborated lore for successful preparation.

A. Technology Base

Before discussing levels of performance presently achieved in devices, a brief review of the scientific and technological base upon which these devices rest is in order. In this I include, besides the basic superconductivity phenomenon itself, provenance of material, construction and processing procedures, rf structures, trouble shooting procedures and instrumentation, knowledge of the basic surface physics and chemistry of Nb and knowledge about vacuum electronic phenomena which affect device performance.

a) Provenance of Material

Virtually all of the work done so far is with so called reactor grade Nb. Several companies* provide the material in ingot, bar, plate, sheet, and tube form. As far as is known, the materials from the various suppliers perform equally well. Impurities of the common elements range from a few ppm to a few hundred ppm. Since significantly purer material

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is not readily available, it is not known whether substantial device performance gains might be had in that direction. As some devices have achieved very high levels of performance, it is likely that present purities are sufficient.

b) Construction Procedures

Cavities have been fabricated by machining from solid material[5] without any joints, by combinations of hydroforming, machining and welding,[21] by deep drawing and welding,[16] and by rolling and welding Nb explosion bonded to copper.[19] All of these methods have been successful to a degree and show that Nb is a flexible material. Welding has been largely carried out by the electron beam method but has also been done successfully by the TIG process in a glove box that can be evacuated and filled with Argon. While successful current carrying joints have been made by welding, operating them at high fields requires UHV firing at above 1800°C. Demountable joints have been developed[22,23,19] which can carry some rf current and are suitable for specialized use.

c) Processing Procedures

Crucial to what success has been achieved are the currently used surface treatment procedures. While mechanical polishing finds some use in finishing welds[16,17] machined surfaces or commercial plate finishes are normally good enough to start with. After fabrication the structures are degreased thoroughly. Ultrasonic agitation of the bath has proved useful. The final preparation sequence varies from laboratory to laboratory but some combination of electropolishing[24], chemical polishing[21], oxypolishing[25] and UHV firing are commonly used[16,17,21,26] depending upon the type of device.

d) RF Structures

The exploitation of rf superconductivity for accelerators has inspired the development of rf structures peculiarly adapted to the task as well as the adaptation of conventional structures for cooling in helium. For low frequencies, heavily loaded structures, such as the helix, an old time favorite, and a new invention, the elegant split ring structure[31] have been used. At UHF both the alvarez[45] and reentrant, klystron, type of cavity have been built.[32] At microwave frequencies special versions in the iris loaded waveguide with both circular[33] and rectangular[16] symmetry have been designed to make use of sheetmetal techniques. A bar loaded waveguide has also been made for S-band.[46] All of these structures have been made to work at respectable levels, at least in single cell versions, and are still under active development. The helix has proven to be very difficult, although possible to control, because of its mechanical weakness and so will probably have a limited future.

e) Basic Surface Physics and Metallurgy

A large amount of work of a more or less basic nature has been carried out to date in an effort to understand the behavior of rf superconducting surfaces on a microscopic level. It has heightened the sensitivity of device builders to surface cleanliness and homogeniety and the important role of the oxides. An appreciation of that work would require a review in itself. Access to the extensive literature can be had through refs[43] and [44] concerning the role of oxygen enrichment in surface layers.

f) Trouble Shooting Methods

One of the most important developments of recent years has been the realization that most breakdowns, i.e., transitions to the normal state while the rf field is on, occur at well localized spots. Instrumentation for locating these spots easily has been indispensible in elucidating breakdown mechanisms[16,27] and in repairing defective structures.[23] The principle is simple. A network of low mass resistors is placed on or near the device body and temperature rises due to electronic heating or to breakdown are seen directly or by second sound propagation with pulse timing used to locate the fault. Also very useful have been the methods for detecting electronic activity directly by collecting electrons on probes and by measuring X-rays with counters or photographic methods.[28]

g) Vacuum Electronic Phenomena

For some time it has been known that free electrons are caught up in the fields inside the cavities and can cause wall heating[7,28] and surface damage where they strike, as well as more subtle problems such as the excitation of other modes of the structure.[27] The source of the electrons can be field emission or secondary electron multiplication, that is, multipactoring, and perhaps bremsstrahlung followed by photo emission. It is not always clear which mechanism is at work in any given instance. By means of theoretical calculations[7,27,29] and measurements[30] it has been found that one point multipactoring due to transverse electric fields, in concert with the rf magnetic field near the outside cavity walls, is an important source of wall heating in L and S-band cavities operating at or near their maximum fields. This is an important discovery, the exploitation of which has just started.

B. Device Performance

Figure 1 displays, in practical terms, our present capabilities for building large scale devices. The points plotted show the maximum accelerating fields achieved under cw conditions versus the wall power per meter required to support an accelerating field of 1 MV per meter, the surface resistance used being that appropriate to the maximum operating field. Thus, the actual rf power per meter for a given device at its maximum field operating point is found by multiplying the number given in the figure by (E_a in MV/m)^2. The operating frequency of the device is indicated by the band designation, X, S, etc. Squares indicate a multi-cell accelerating device, circles a single cell and triangles the low field losses for a selection of single cell accelerating devices. Sources of the data are indicated by superscript numerals adjacent the points. Each point represents a real accelerating device with beam holes and pertains to its operation in the fundamental accelerating mode.*

*Points plotted are representative rather than comprehensive. Separator devices are not included.

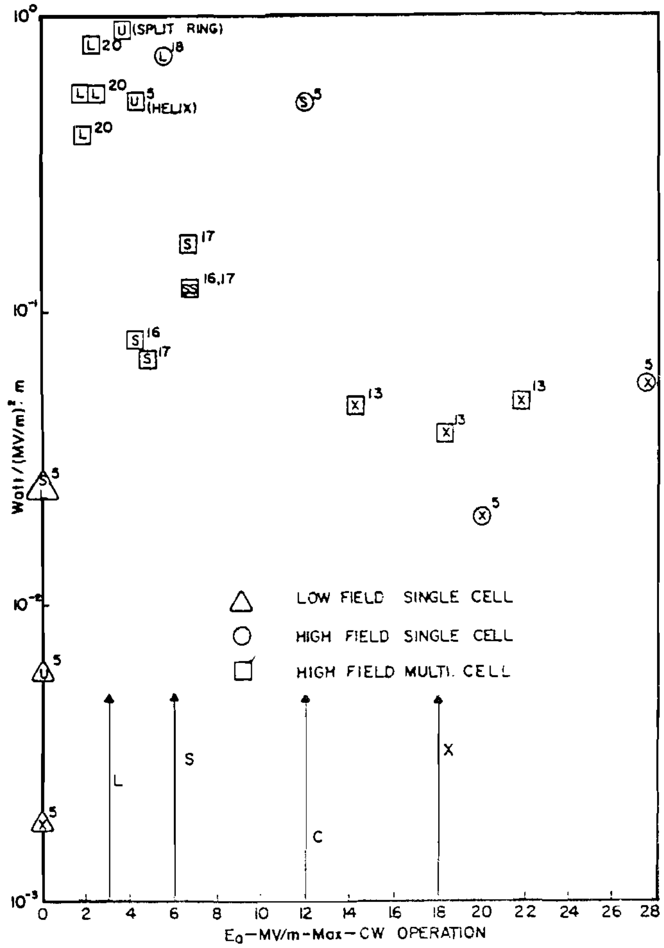

Fig. 1 Wall losses per meter per $(MV/m)^2$ v.s. max. accelerating fields at various frequencies for Nb structures of various designs.

EVALUATION OF CURRENT Nb DEVICE PERFORMANCE

The absolute values of the parameters and the trends evident in the data can be explained only partially in more fundamental terms. A more complete and quantitative understanding is still in the future.

The low field losses are very good. Despite the almost two orders of magnitude ratio of operating frequencies represented in the plot, the actual surface resistances implied are all in the nanoohm range. Thus, the achieved losses in real devices reflect the low residual resistance rather than the BCS resistance. At high fields the losses are at least an order of magnitude higher than at low fields. It is generally believed that high field effects on the residual resistance play no important role in this behavior but that, because of its exponential dependence on surface temperature, it is the BCS component that is responsible. The BCS resistance has a dependence on the surface magnetic field as well as on the temperature.[34] Perhaps this effect manifests itself at the highest frequencies where we are getting close to bulk critical fields.[26] Heating is probably still the dominant effect at present levels of performance. Putting the BCS temperature and field dependences in the rf dissipation together with the heat transfer which is governed by the thermal conductivity, wall thickness and kapitza resistance between wall and bath,, one can find, ad hoc, semi-quantitative agreement with some data at X-band.[26] For example, under certain circumstances, a decrease in wall thickness can increase the achievable field level by the predicted amount and the achieved field level is consistent with the calculation. The parameters which describe these circumstances are not clear. At S-band, assemblages of cavities having a factor of two different wall thicknesses[16,17], achieve about the same maximum fields. There are complicating factors which prevent the emergence of a clear picture at our present state of knowledge: the sources of heat vary in different frequency and geometry regimes, thermal conductivities vary over the surfaces, e.g., at welds, the kapitza resistance may play a role in some circumstances and not in others, the T_c varies over the surface,[43,44] local heating rather than general heating governs the breakdown, local breakdown of the superfluid heat transport may play a role.[35]

Likewise the general tendency to lower breakdown fields at lower frequencies can be explained only in vague terms at the moment. There are several factors which probably play a role here: the field at which a given order of multipactoring will occur is proportional to frequency, lower frequenty structures have larger surface areas and are harder to handle and process, so that the probability of having defective or poorly processed areas is larger.[47] The lower frequency structures tend to have deeper and longer welds, also increasing the probability of defects. In discussing the higher field for higher frequency trend,.one important caveat must be observed: at X-band, the multi-cell structure data plotted are for two cell structures. The only true multi-cell data are from an X- band separator model[36] where a field of 74mT was recorded, and a 32 cell accelerator unit just being put into operation,[37] no data being available at the moment. The separator field is roughly equivalent to the lowest multi-cell X-band point plotted.

The difference in performance between single cell and multi-cell structures of the same design and frequency are believed to be due in large part to the less severe multipactoring encountered in single cells, owing to the slightly different field patterns, and in part to the relative ease of cleaning and treating the smaller units.

Finally, can we explain the rather large scatter in performance among different examples of the same design and frequency? Nothing more dramatically demonstrates that there are still parameters which are not under our control and are therefore not understood. Even the behavior of a single unit repeatedly subjected to an "identical" processing cycle can show factors of 2 or 3 in loss and peak field, not necessarily correlated, from cycle to cycle. These cycles remove small amounts of material. Are we revealing different bad spots in the material as we process? Do the processing solutions have inhomogeneous composition or internal temperature gradients, are physical or chemical inhomogenieties on the surface responsible for nucleating bad oxide growth in a stochastic fashion? Are residues of the processing fluids clinging to the surface more or less with each cycle? Are there physical and chemical effects we don't know about?

Despite this rather negative recital we should not lose sight of the fact that we've done rather well at X-band. I take this as a strong indication that we now understand many of the important parameters. Clearly the first order of business is to understand why structures scaled down from X-band to lower frequencies do not operate up to X-band standards. The understanding of the difference between current X-band performance and the ideal and, to some extent, of the fluctuations in individual unit performance belong to the future.

FUTURE DIRECTIONS IN Nb DEVICE DEVELOPMENT

The evidence gathered to date indicate strongly that multipactoring and limitations in heat transfer are responsible for the relatively poor performance of the lower frequency structures. This has been suspected for some time but we were unable to see how the secondary electron multiplication process could operate at the high fields achieved, even though we could see the electrons. The new element is the understanding of the one point multipactoring which depends on the interplay of the rather small transverse electric field with the large rf magnetic field at the outer wall.[27,30,7] To test these ideas the technology base needs to be expanded to include methods for suppressing multipactoring and for increasing, materially, the heat transfer ability of the structures. Methods for suppressing multipactoring by surface coatings such as TiN, Ti and Rh[38] and NbN[40] have been investigated for some time without great success. The utility of helium processing for getting through high order multipactor barriers suggests that adsorbed or frozen-on gas layers are significant contributors to the secondary emission coefficient so that such coatings may be irrelevant. Recent work shows that[29] the coatings tried so far have secondary emission coefficients greater than one if they are exposed to air. Successful application of coatings would appear to require some sort of in situ deposition and cleaning of the surfaces. The appreciation of the importance of one point multiplication gives us another handle by suggesting that cavity shaping may allow us to alleviate the problem.[27] One should not be too optimistic, given the past history of this business. The problems seem to have an onion like structure: no sooner is one layer of difficulty overcome than one sees another right behind it. If we are able to overcome the 2nd order multipactoring barrier we all now seem to be up against, we may find thermal breakdown due to defects or field emission problems right behind.

With regard to thermal transport, simultaneous increase of surface area and decrease in wall thickness need development. Some success along these lines has already been reported.[26,39] Considerable work will be necessary to learn how to build full structures with very thin walls of sufficient rigidity and enhanced surface area, should this step turn out to be crucial.

The behavior of existing devices gives other indications of areas of potential profit in structure work. The prevalence of fluctuations from unit to unit and the fact that breakdown occurs in well localized places, suggests that large accelerating units should be built up from smaller subunits which can be individually tested on a semi-automatic basis. In this way high performance units can be selected for assembly into the final unit while substandard units can be repaired by recycle or rework of the bad spot. Units that cannot be improved can be scrapped. Location and repair of bad spots has been effective at low frequencies[23] but has been less so at microwave frequencies. This clearly is an area where some emphasis should be put. Another area for potential profit is in the elimination of welds. Fabrication of multi-cell units solely by drawing or hydroforming would save on cost and reduce the probability of defects.

Finally, we should not fail to take another lesson that the accumulated experience has taught: the best structure is the simplest structure. The more complex a structure is the more costly it is to fabricate and the more difficult it is to process. It is hard to over emphasize this point.

An important aspect of the application of rf superconductivity to accelerators often left out is that there is considerably more to an accelerator than a low loss, high field cavity. The experience with the recyclotron[41] and the microtron[42] show the central role played by modes of the structure other than the fundamental which can be beam or multipactor excited. A rather large number of ad hoc damping probes with all their attendant constructional and cryogenic complexity are absolutely necessary. Heavy damping of higher modes will also be necessary for other applications. Thus, in addition to the features listed above, the structures of the future will have to accommodate the higher mode damping ab initio.

ARE PRESENT CAPABILITIES USEFUL AND COMPETITIVE

The vertical arrows in Fig. 1 indicate performance levels we can expect today at the frequencies marked. Are there uses for the art at this present state in which the advantages offered by superconducting devices are so compelling as to justify the obvious risks? There are ongoing projects for the construction of heavy ion accelerators operating at UHF.[23,48] Some of the progress will be reported at this conference. Electron accelerators for low and intermediate energy physics have been under construction for some time.[41,49,50] For a relatively small accelerator, especially of the recirculating type, in which the facilities cost will be substantial compared to the accelerator, it is not clear that conventional technology wouldn't be very competitive. Using well shaped cavities at S-band, one might obtain 75 MΩ/m shunt impedance and so achieve an accelerating field of 2 MV/m for an expenditure of 53 KW/m. The rf power for a 50 meter linac giving 100 MeV would be 2-2/3 MW which can be supplied by two klystrons. Such a system will be very reliable and, given the relatively low Q for the higher modes, rather less liable to beam breakup problems.

If one were to opt for a superconducting solution, one would certainly use the highestpossible frequency. As will be discussed momentarily, perhaps C-band would be most appropriate.

For a separator one would certainly choose superconductivity if the device were to be used with a long pulse accelerator, just on power grounds, since the shunt impedance of the separator structure is rather low. The CERN separator[51] works. A second version would surely work better and with higher performance levels.

The most natural applications are those in which the cw field level required must be high compared to conventional standards and the total power must be kept low. Such an application is at hand. The success of electron-positron colliding beams in revealing new aspects of sub nuclear behavior has inspired many to contemplate an instrument capable of producing the neutral intermediate boson. This is desired both for studying the nature of the weak interaction itself and as a copious source of other elementary particles. Such a machine will require electron beam energies of 50-100 GeV. At present it appears that the most practical form for such a machine would be a storage ring. The copious synchrotron radiation from such an instrument will require accelerating cavity voltages in the range from 1.7 to 3.7 GV[52,53]. The nature of the beam dynamics in such a machine requires that the operating frequency be in the UHF or L bands. The high peak currents in the beams requires a large stored energy in the cavity and thus high fields. The sheer size of the acceleration requires the minimum possible power for establishing the fields if such a device is to be practical. The application of rf superconductivity to these machines have been examined by several groups.[53,54] One group concluded[53] that a factor of two overall savings in the cost of the instrument could be had by the use of superconducting rf. To produce several GV, a cavity length of the order of a km or two is needed. Clearly one would not launch such a project without a large scale test in an existing storage ring. The beginning of such tests are being planned actively in Europe.[55] It will be surprsing if studies along that line are not soon begun in the U.S. It should be noted that a central feature of cavities developed for this application must be a well engineered mechanism for the damping of the beam excited modes. The extracted power must be removed to a room temperature sink to prevent excessive refrigeration requirements and beam instabilities. For one case studied,[53] the beam excited losses to higher modes is about 2 MW total or about 2 kW per meter of structure. This represents a substantial engineering challenge.

As an exercise to expose the economic potential of the present state of the art, one might ask for the cost of a very large linac built using existing technology. Figure 2 shows the cost for a 100 GeV electron linac built using the technology developed at Cornell for S and X-bands, projected to frequencies between L and X-band. The costs of the structures and non-refrigeration items are based on current experience. The refrigeration costs are based on a compilation of recent refrigerator costs.[56] In addition, Fig. 2 contains the costs for possible advance states of superconducting technology.

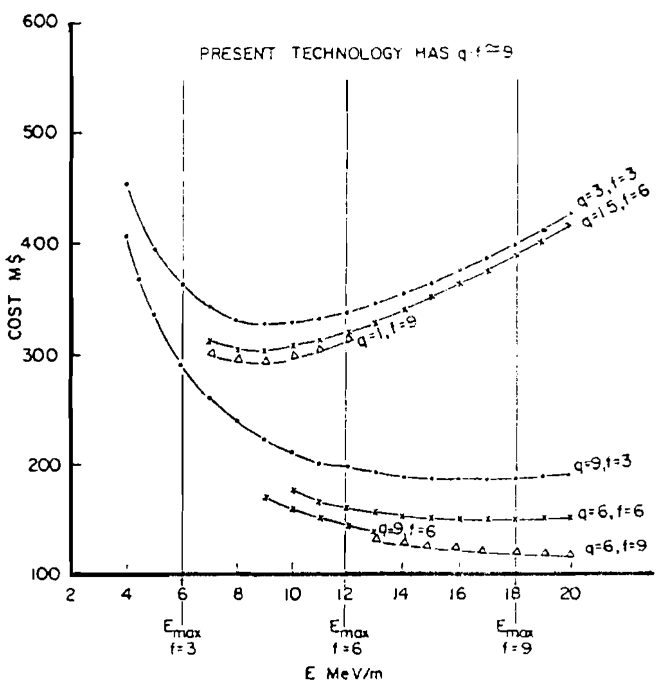

Fig. 2 Cost estimate for a 100 GeV cw linac vs. operating field with $(Q\times10^{-9})$ x frequency as a parameter.

The approximate empirical formula for the costs, is based upon costs for small structure units:

$$C_{tot} \sim \left[9000 + \left(\frac{9450}{f} + 650\right) + \left(\frac{3000}{f} + 1000\right) + \left(\frac{\mathcal{E}^2}{.8qf} + .5 \right) \times 1.26\times10^3 \right] \times \frac{E}{\mathcal{E}} \left[\$\text{-}1978 \right] \qquad (2)$$

Proceeding from l. to r. inside the large brackets on the r.h.s., we have the terms representing (1) the standard components, e.g., vacuum, instruments and controls, tunnel, piping, rf distribution, supports and alignment, quadrupoles, etc., (2) the accelerating structure, (3) the cryostat, (4) the refrigerator. f is the operating frequency in GHz, q is the Q of the structure in units of 10^9, E is the total beam energy in GeV and $\mathcal{E}$ is the operating accelerating field in MV/m. The crucial parameter turns out to be q.f., q because that governs losses at a fixed frequency and f because the r/Q for a constant geometry scales with f. For the particular type of hardware picked,[16,13] q.f. = 9. On the low field side the costs rise because the structure length becomes excessive. On the high field side the costs rise because the refrigerator cost becomes excessive. The top three curves show the present status of this particular technique. In these cases we believe the operating Q to be limited not by the superconductivity but by the structure tolerances achieved, coupled with the presence of joints, coupling ports, probes, etc.. C-band is favored because of its relatively high operating field and relative ease of meeting construction tolerances as compared with X-band. If we could increase q.f. by a factor of 4, the cost would be halved and C-band would probably still be the choice.

One might ask why we have not built small and very compact accelerators for industrial and medical uses using this technology. Perhaps a natural skepticism regarding the reliability is partially to blame. However, the biggest stumbling block is the lack of closed 2-4°K refrigeration devices with the reliability and ease of operation of home and industrial units for higher temperatures. The existence of such units would open a host of new applications.

OTHER MATERIALS

Only passing reference has been made to materials other than niobium. Great strides have been made in the use of lead plated copper structures.[57] The performance of lead is inherently worse than Nb and Nb has turned out to be quite easy to work with. Thus, lead will probably be confined to specialized applications. A large number of other materials have been discussed in the literature, especially the A-15 compounds. The technology of their use is at present so involved that evaluating their utility must await future developments.

CONCLUSIONS

Despite its rather long history, rf superconductivity still has a long way to go to prove its worth for a wide range of applications. It appears that there are applications for scientific instruments where it can make a significant impact. It will have utility for common industrial devices only in the future, if ever. To bend the phenomenon to our needs now and in the future, considerable advance in the engineering aspects of its use and in its basic development are necessary. The engineering advances will only come through the aggressive application of the art at its present level to instruments requiring its peculiar advantages. In advancing the engineering aspects through building large numbers of identical devices for an acceleration application, some more basic advances will emerge: in coping with the epidimology of a large number of supposedly identical units, some of the important parameters of the materials and preparation methods, parameters now only dimly perceived, will reveal themselves. Thus, both extensive engineering work on devices having immediate payoffs and basic development of the art and science of superconductivity will be needed for realization of the full potential of the phenomenon. Those of us, the faithful, who are striving to make rf superconductivity our servant, have a long, hard road ahead of us before we have shown that the promise is real.

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