APPLICATION OF HIGH TEMPERATURE SUPERCONDUCTIVITY TO ULTRASTABLE FREQUENCY SOURCES*

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ABSTRACT

The advent of superconductivity at temperatures above 77 Kelvin[1] will make possible new capabilities in frequency sources for both ground based and space borne applications. In this paper we assess the impact of these new materials on atomic frequency standards. As an example, an active hydrogen maser could use Josephson junctions and infinite conductivity to sense and shield magnetic fields to high precision while enabling a significant reduction in size and mass. Similar benefits are found in the use of a small, heavily loaded superconducting cavity for the maser. High temperature superconductors will also have ramifications for other frequency standards, and for technologies related to frequency sources such as distribution networks.

High temperature superconductivity is discussed from a technologists point of view, with particular emphasis on the temperature dependence of various properties of superconducting shields, sensors, cavities, etc. While some aspects of superconductivity, such as shielding effectiveness, are essentially completely developed at temperatures only slightly below the critical temperature T_c, others, such as microwave surface losses, require much lower temperatures. The most important aspects which relate to ultra–high stability appear to relate to the sensing and shielding of magnetic fields. Light weight and small size can result from effective shields and also from application of small persistent mode electromagnets in (e.g.) ion pumps. The temperature dependence of trapped fields is discussed, since, while external fields may be completely shielded, any field which may be necessary inside the shield is affected by variations in the penetration depth.

INTRODUCTION

Temperature and magnetic fields are the two parameters[2,3] having perhaps the most influence on the stability of frequency standards. Measures to reduce the thermal and magnetic influences of the environment on frequency standards are thus constantly practiced by the designers and developers. Such measures, which produce various degrees of success, nevertheless inevitably add to the mass, and ultimately the cost, of frequency standards. The development of techniques which would improve on the state of the art then is of considerable interest to the practitioners in the field of frequency standards.

The technology of superconductivity is naturally suited for providing effective solutions for the problem of magnetic shielding and temperature sensing. Because superconductors shield magnetic fields with surface current rather than bulk susceptibility, relatively thin films of superconductors can provide effective shielding. Superconducting Josephson junctions can be used in extremely accurate and stable thermometers, and so can greatly benefit the sensing and controlling of the temperature of the thermally sensitive components of frequency standards. Other benefits of superconductors include the provision of

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stable magnetic fields and very high Q resonators for suitable applications with frequency standards. For example, all of these aspects could be applied to a hydrogen maser to reduce size and weight and to improve performance.

Despite the obvious benefits that could result from the use of superconducting material and the superconductor technology in frequency standard applications, the unwieldiness of the associated cryogenics has prevented their widespread use. Recently, however, the advent of the high temperature superconducting material has provided an important opportunity for the designers in the field of frequency stability to consider such benefits. Currently, the state of the technology of high T_c superconductors is such that serious consideration may be given to their applications at 77 K, the temperature easily attainable with liquid nitrogen. It is now generally believed that the arrival of superconducting material useful at temperatures higher than 77 K is imminent.

The progress towards practical applications of high T_c superconductors has provided the impetus to consider their applications for frequency standards. In this paper we present a resume of the state of the art of high temperature superconductors, and draw attention to a number of ways in which their applications can result in direct benefits to the field of stable frequencies.

While we provide examples assuming the use of 95 K material, we shall draw attention to applications where further benefits may be obtained with material having even higher T_c's. We shall also enumerate some possible future applications of room temperature superconductors for stable frequency generation and distribution.

BACKGROUND

Many of the aspects of superconductivity relate directly to maintaining the extreme stability of some quantity. Because of this, it is imperative to evaluate possible and likely consequences of superconducting applications to the performance and the form of the frequency sources of tomorrow. Five aspects of technical capability are likely to make the greatest impact:

1) Josephson junctions and infinite conductivity make practical both the sensing and shielding of magnetic fields to a precision not otherwise possible.

2) Thermometers using Josephson junctions to measure a temperature dependent susceptibility or thermoelectric voltage may make possible nano-degree temperature resolution.

3) Heavy magnets can be replaced by persistent current coils, possibly with much larger magnetic fields.

4) The present rules balancing rf and microwave cavity Q's against physical size may be circumvented.

5) Voltages and currents can be generated by (or stabilized by) Josephson devices with a precision not otherwise available. Frequency sources can in principle "bootstrap" to higher stability by use of the output frequency to stabilize internal voltages.

Other aspects may also make a major impact. Some of these include;

6) Transmission of a frequency by means of conversion to d.c. voltage by means of the Josephson effect and conduction by superconducting wire. The voltage would then be converted again into a frequency by a similar device.

7) The elimination of thermoelectric effects by the use of superconducting wire.

8) Greatly increased electrical conductivity without the associated thermal conduction characteristic of all normal conductors.

Application of all of these aspects would be greatly eased by operation at room temperature or above. The present availability of superconductors with transition temperatures of about 90K and the modest cost and complexity associated with operation at liquid nitrogen temperature make this special case technically very interesting. Emphasis is placed here on the properties which may be expected at 77 Kelvin using the YBaCuO–type superconductors.

It is important to note that not all of the properties listed above, or those which we discuss below have been verified for YBaCuO. Many of its properties are very different from those of "ordinary" superconductors. However, because the properties and consequences of BCS and other previously developed superconducting models have been very well explored, and because of their very general applicability to other superconductors, suitable application of these models is a very good way to obtain a general idea of what is in store.

The demonstration of interference effects[4] identical in quantization to other superconductors is perhaps the strongest evidence that previous models will prove generally applicable. This evidence also implies that the performance of Josephson junction devices may be very little degraded by the higher temperature and other aspects relating to the details of superconductivity in YBaCuO.

We have chosen to examine in more detail three of the technological aspects indicated above with particular emphasis on their temperature dependence. These three are magnetic shields, high Q cavities, and Josephson applications.

MAGNETIC SHIELDING PROPERTIES NEAR T_c

While the resistivity of a superconducting wire becomes absolutely zero for temperatures only slightly below the critical temperature, most technologically significant superconducting properties develop continuously, even slowly as the temperature is lowered. At low current density a very few superconducting electrons suffice to give a measurement of zero resistance. However, many superconducting properties are greatly modified near the critical temperature. Even more importantly from the point of view of ultra–high stability, the sensitivity of these properties to temperature changes is increased.

While superceded by the BCS theory, the London theory provides a good description of macroscopic superconducting behavior for temperatures near T_c.[5] In this theory, superconducting behavior is described in terms of a two-fluid model, where some of the electrons are superconducting and some are normal. The superconducting fraction is given by $N_s/N = n_s = 1 - t^4$ where t is the reduced temperature $t = T/T_c$. n_s is plotted in Figure 1 for $T_c = 95K$, together with the corresponding dependence of the thermodynamic critical field H_c given by $H_c = H_o(1 - t^2)$, where H_o is the limiting value at low temperature. It is apparent from the curves that these properties develop linearly as temperature is lowered below T_c, and that 50% of the electrons are superconducting by the time a temperature of $0.85T_c$ is reached, approximately the condition of YBaCuO at liquid nitrogen temperature.

The field exclusion and stabilization properties of a superconducting magnetic shield depend on its penetration depth λ. The temperature dependence of λ is given in the London theory by

$$\frac{\lambda(T)}{\lambda_0} = \frac{1}{(1 - (T/T_c)^4)^{1/2}}. \tag{1}$$

where λ_0 is the penetration depth at zero temperature. The small value of this penetration depth (typically $0.05\mu m$ to $0.1\mu m$) and the exponential character of field decay give extremely effective shielding even for thin superconducting films. Actual electromagnetic measurements of the penetration depth for high temperature superconductors are scarce. Indirect measurements have yielded values as small as $0.1\mu m$,[6] but electromagnetic probes have shown values as large as $5\mu m$. Figure 2 shows such the results of such a measurement by Sridhar, et al[7] together with predictions of the London theory for $\lambda_0 = 2.5\mu m$. The substantial deviation from the London theory near T_c could be due either to fundamental differences in the high–temperature superconductors or to effects such as inhomogeneity in the material. However, the data represent a considerable demonstration of superconducting capability.

In Figures 3 and 4, parameters are shown relating to effectiveness of a superconducting shield with a thickness d given by $d = 0.5\ mm$. The parameters were derived from the penetration depth data and theory shown in Figure 2 on the assumption that the characteristic penetration depth measured represents a true exponential decay. For temperatures below about 85K both the exclusion factor $\exp(-d/\lambda(T))$ and its derivative are small enough ($< 10^{-10}$) to make such shields extremely attractive. Clearly, this is one of the great strengths of superconductivity.

Atomic frequency sources often require the presence of a small, but non–zero magnetic field. Changes in the penetration depth of a superconducting shield change its effective size in a way similar to that of thermal expansion and contraction. Figure 5 shows this effect of field compression for a shield with radius 10cm. At 77K, the values derived are similar to thermal expansion coefficients for the same temperature. Here, some improvement over the measured values is clearly desirable in order to match the lowest thermal expansion coefficients of $10^{-6}/K$.

The change in penetration depth also effectively changes the size of a microwave cavity formed by the superconductor. If the mode has only magnetic fields at the walls (such as a TE_{011} cavity mode), the fractional frequency shift is identical in value to the magnetic compression effect just discussed. Again, a comparison to thermal expansion effects makes similar demands on the superconductor.

SUPERCONDUCTING SURFACE RESISTANCE

While magnetic shielding effects depend entirely on the superconducting fraction of the electrons as shown in Figure 1, the reduction of losses in superconducting cavities also depends on the freezing out of the normal electron fraction $(N - N_s)/N$ at lower temperatures. Figure 6 shows this effect for various superconductors. As the temperature is lowered, a rapid drop of rf loss occurs due to the shielding effect of the superconducting electrons, and then a slower but larger reduction follows which is due to the condensation of normal electrons into the superconducting ground state. Not all superconductors show this reduction. In particular, the addition of magnetic impurities can "smear" the energy gap, and thus can eliminate complete condensation. The great reduction in rf losses is directly related to the existence of an energy gap in the superconductor, which gives rise to an exponentially small number of excitations at low temperatures.[8] A more complex energy gap structure might show a different character. For these reasons, it is not certain that a new type of superconductor will allow such great reduction microwave losses as the temperature is lowered.

Based on the theory of Mattis and Bardeen[9,5] for Fig. 6 we calculate the surface resistance R_s at frequency $\omega/2\pi$ for temperatures not too close to T_c as

$$R_s = 2.6 R_n \left(\frac{\lambda_{eff}}{\lambda_L}\right)^3 \cdot \left(\frac{\hbar\omega}{\pi\Delta(T)}\right)^{3/2} \cdot e^{-\Delta(T)/kT} \cdot \ln\left(8\frac{\Delta(T)}{\hbar\omega}\right), \tag{2}$$

where R_n is the normal state DC resistance, λ_L is the London penetration depth, and λ_{eff}

is an effective penetration depth. In this approximation the energy gap $\Delta(T)$ is given by

$$\frac{\Delta(T)}{\Delta_0} = \frac{T_c}{T} \cdot \sqrt{\cos\left(\frac{\pi}{2} \cdot \left(\frac{T}{T_c}\right)^2\right)}, \tag{3}$$

and, except for the curve identified as having an enhanced gap, we assume

$$\frac{\Delta_0}{kT_c} = 1.74 \tag{4}$$

as required by the weakly coupled limit of the BCS theory. Data indicated by circles are from Ref. 7 and those indicated by crosses are from Ref. 8. Following Sridhar et al[7] we have treated $(\lambda_{eff}/\lambda_L)^2$ as a free parameter for the case of YBaCuO, finding a value of 65 to give a good match to their data. This value contrasts to the value of 2.5 characterizing ordinary superconductors, and an even larger value of 150 required to force agreement to the "enhanced gap" case, where we assume a larger gap for YBaCuO

$$\frac{\Delta_0}{kT_c} = 3 \tag{5}$$

as suggested by several experiments. The significance of the large value for $(\lambda_{eff}/\lambda_L)^2$ is that the value of the surface resistance is very much larger than it would otherwise be. If instead, the low temperature results are simply scaled to the higher critical temperature, an increase in the initial jump downward in R_s just below T_c would result compared to Nb and Nb_3Sn; instead the jump is found to be smaller. A comparison with Figure 7 showing data taken at a lower frequency (3GHz), but with identical parameters, gives credence to the procedure, since the initial downward jump in R_s at T_c for YBaCUO in that case is larger by an amount which is approximately as predicted by the theory.

The Q of an electromagnetic resonator is related to conduction losses in the walls by the geometric factor $\Gamma = Q \cdot R_s$. Typical values for Γ range from 200Ω to 600Ω for microwave cavities. If our conclusions are correct, ultra high Q's of 10^9 or more corresponding to a surface resistance of 10^{-7} or less cannot be expected at temperatures above 25 Kelvin or so. Performance at 77K, however, may very well allow Q's in the 10^6 to 10^7 range or, alternatively, allow heavily loaded small resonators to achieve Q's of 10^5 or so.

JOSEPHSON JUNCTION DEVICES

The great sensitivity of Superconducting Quantum Interference Devices (SQUID's) to magnetic field is inherent in the quantum nature of the Josephson effect, the fundamental unit of measure being Φ_0, the flux quantum. That the constancy of this measure, $2 \cdot 10^{-7}$ gauss-cm^2 is related to the nature of superconductivity has been demonstrated in YBaCuO at a temperature of 68 Kelvin by Koch et al.[4] Because the minimum number of quanta observable in any given time period is limited by the signal–to–noise (S/N) ratio, the loss which is induced by thermal noise at higher temperature is a degradation of S/N ratio in proportion to the operating temperature. For example, a configuration which would allow sensitivity of $10^{-4}\Phi_0$ in 1 second at 10 Kelvins would inherently require at least 10 seconds to acquire the same sensitivity at 100 Kelvins. A sensitivity of $10^{-3}\Phi_0 Hz^{-1/2}$ was demonstrated at 40 Kelvins and 100Hz by the previously mentioned workers, with projections made to below $10^{-4}\Phi_0 Hz^{-1/2}$ at that temperature.

The noise–limited capability of a SQUID to measure a quantity of flux is more properly related to the energy in the flux. Thus, the sensitivity to flux in a small loop is greater than if the same amount of flux were placed in a large loop since the energy in the flux is greater in the smaller loop. In this framework an energy sensitivity of better than $10^5 h$ was projected at 40K, equivalent to the energy of a 100 kHz photon. Expressed in more familiar terms, this energy corresponds to a noise temperature of 4 micro-degrees.

It appears that the technical limitations to the stabilization of electrical quantities by means of these devices will be limited by the physical stability of the devices themselves due to temperature fluctuations. Some means of coupling must always be found between the circuit parameter under test and the tiny superconducting loop which constitutes the SQUID. While thermal expansion is almost completely "frozen out" at the temperatures of 10 Kelvin and below where SQUID devices are presently used, this is not the case at 77K where thermal expansion coefficients are typically greater than $10^{-6}/K$. Since the SQUID is inherently sensitive to magnetic flux, and not current or voltage, thermally generated fluctuations in the size and position of the coupling loop in which the flux is measured may very well limit its ultimate performance at this higher temperature.

Finally, SQUID devices allow the measurement of temperature with the highest resolution presently possible. Using the thermal sensitivity of the susceptibility of a paramagnetic salt, thermal sensitivities better than 10^{-9} Kelvins have been reported. At higher temperatures, the use of a material with an appropriately higher Curie temperature should allow similar sensitivity, reduced only by the S/N reduction due to thermal noise as discussed above. Thermoelectric and resistance thermometers, monitored by SQUID devices offer another means of obtaining sensitivities of $10^{-8}K$ or better.

CONCLUSIONS

The new high temperature superconductors hold the potential for significantly impacting frequency standard technology. While all the characteristics of the new materials have not been clearly determined, it is nevertheless apparent that they can lead to immediate benefits in a number of applications. Such applications include magnetic shielding of the ambient fields, stabilization of temperature by means of Josephson effect, development of high Q cavities and generation of high fields required of magnets in vacuum pumps.

It is significant that the impact of high temperature superconductors is not limited to improved stability performance. In fact, the application of these materials to frequency standards holds a great promise for reducing size, mass and cost. Where applicable, dielectric loading with superconducting coated dielectrics can lead to great reductions in size. As an example, it is now reasonable to conceive of hydrogen masers similar to passive H-masers in size, but with the performance in the range of the capability of active masers. The replacement of bulky magnetic shield with films of the new materials coated on a light substrate can result in significant reduction in mass. Finally, a corollary of improved performance is that for a given stability performance the cost is also likely to be reduced.

As an indirect consequence of the potential benefits mentioned above, it is likely that frequency standards will also find new areas of applications. Certain classes of frequency standards, such as hydrogen masers, may become more suitable for deployment on board spacecraft, as a result of the expected reduction in mass and size. Others will benefit from the technology of high T_c superconductors as improvements in cost and efficiency make improved standards available to experimenters who would otherwise be reluctant to use them because of associated costs.

The most significant applications of high temperature superconductors to the technology of ultra stable frequency sources is perhaps as yet not conceived. In fact the rapid growth of advancement in the science and technology of high T_c materials has scarcely allowed time for designers and developers to see beyond the obvious. This latter effect is likely to continue for some time, for it is apparent that the great explosion of discovery in this novel class of materials is not slackening. It is perfectly reasonable at this time to assert that we are likely to see a large number of applications of the new materials to the frequency standard technology in the future.

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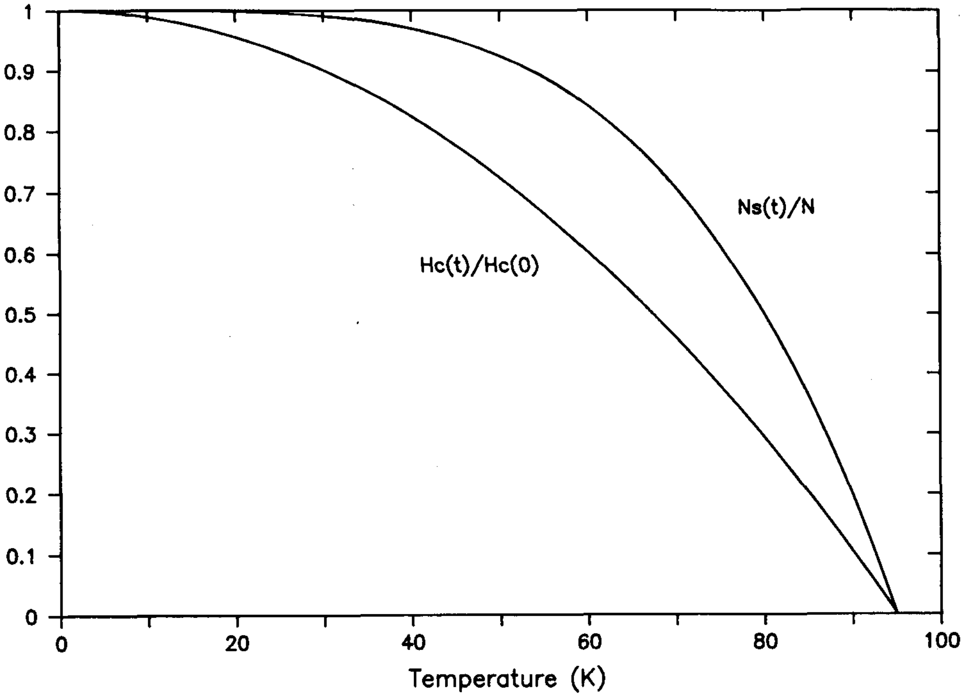

Figure 1 Fractional Superconducting electron density and critical field for YBaCuO as described by the London theory.

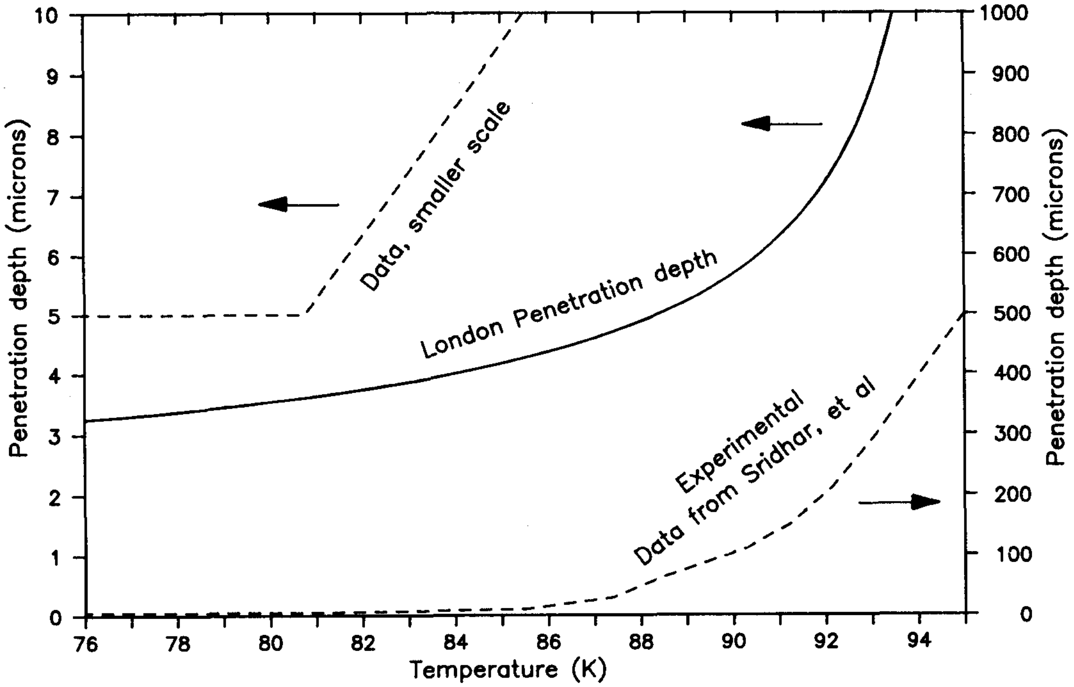

Figure 2 Superconducting penetration depth λ as measured for YBaCuO and as described by the London theory with $\lambda_o = 2.5\mu$.

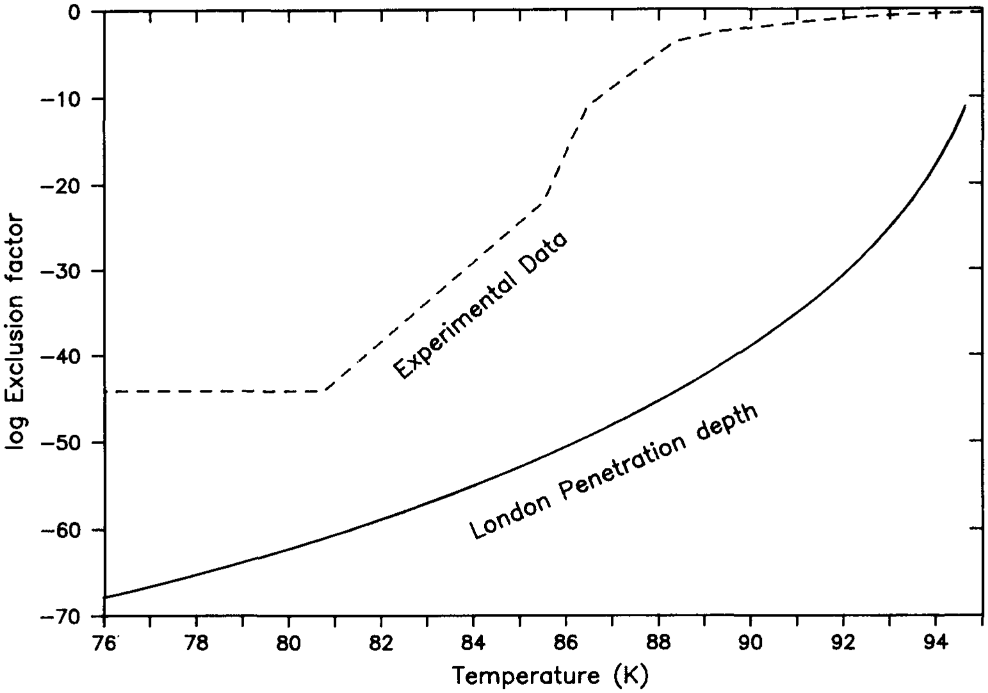

Figure 3 Temperature dependence of the magnetic field exclusion factor for a superconducting shield 0.5 mm thick.

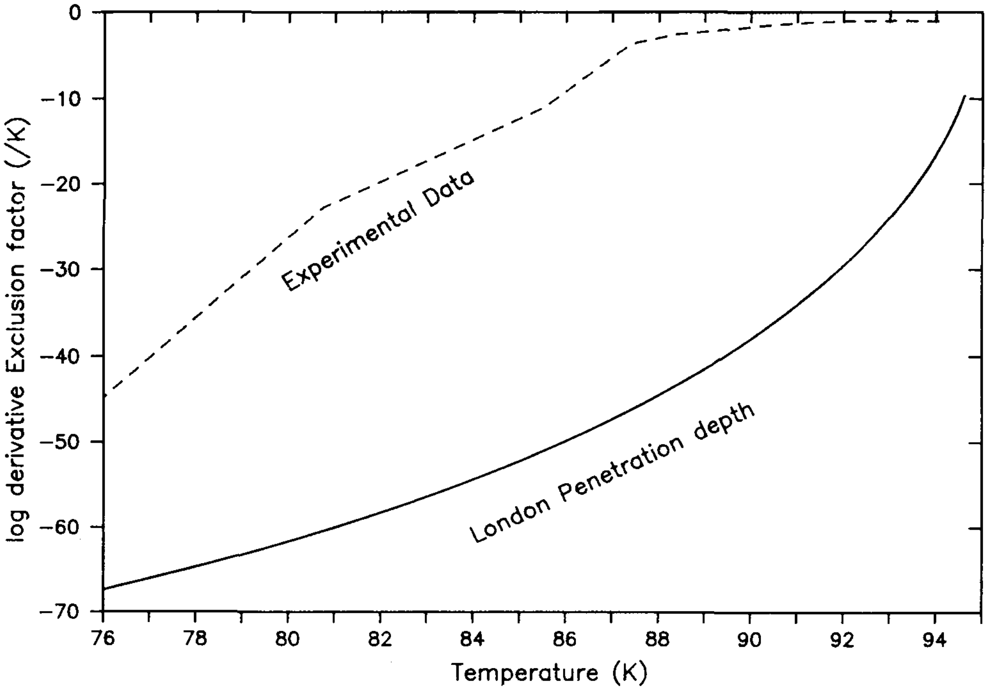

Figure 4 Temperature derivative of the magnetic field exclusion factor for the same shield.

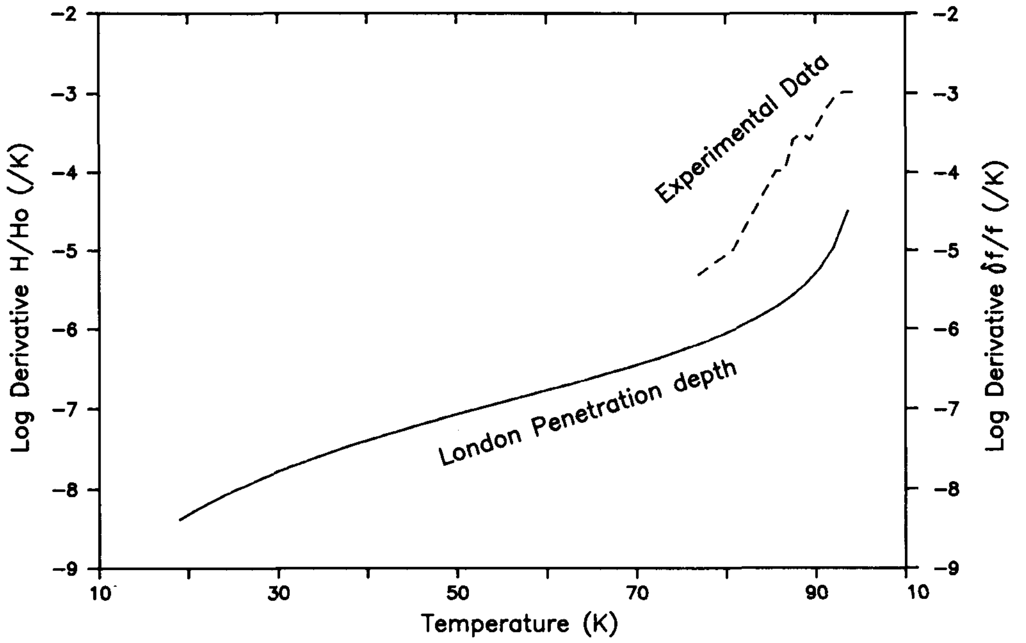

Figure 5 Temperature derivative of the fractional change in trapped magnetic field in a superconducting shield with 10cm radius (see text). This same curve describes the sensitivity to temperature of the frequency of a TE_{011} microwave cavity with 10cm radius.

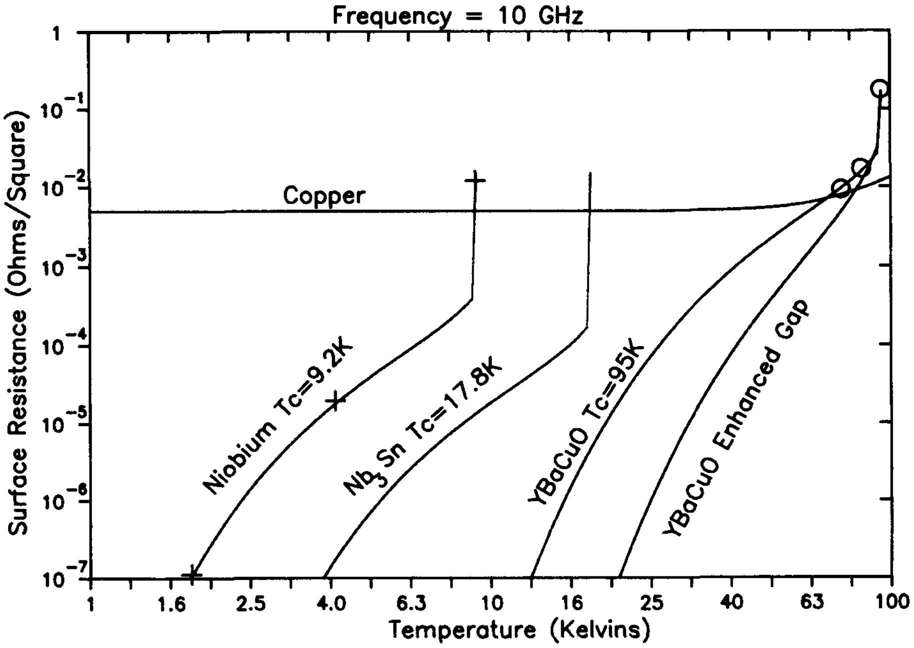

Figure 6 Microwave surface resistance at 10GHz for various superconductors as described by the theory of Mattis and Bardeen. Experimental data for YBaCuO is by Sridhar et al.

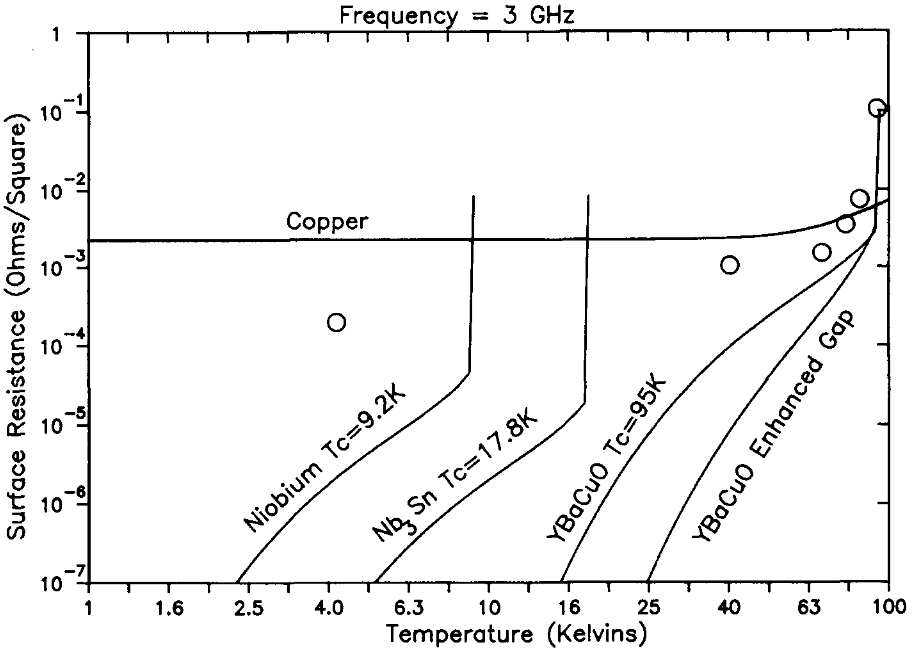

Figure 7 Microwave surface resistance at 3GHz. A single free parameter was used to fit the 10GHz data and used without adjustment here. Experimental points by Hagen, Klein, et al.

QUESTIONS AND ANSWERS

Jacques Vanier, National Research Council: Am I right in saying that by using superconductors at high temperatures we won't gain very much because of the Johnson noise?

Mr. Dick: No, the sensitivity for detecting magnetic fields looks very good. 10^{-3} of a flux quantum, by comparison to 10 degree superconductors where you can get 10^{-4}, so it is very good.

Mr. Vanier: But in Josephson junctions, for example, there you would lose a lot.

Mr. Dick: That will depend on how the technology comes along. It is not clear that you will lose. It will be difficult to develop junctions, it was difficult developing junctions using nice metals and it will be even more difficult to develop reproducible junctions using the ceramics.

Mr. Vanier: So the conclusion is that you are hopeful.

Mr. Dick: I am very hopeful.