

Q MEASUREMENTS ON SUPERCONDUCTING CAVITIES AT S-BAND*

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I. INTRODUCTION

The investigation of the behavior of superconducting materials was started at this laboratory because of the potential usefulness of these materials for long-pulse rf beam separators which are suitable for counter experiments.¹ The realization of such a device will require the solution of many problems; questions related to the beam optics will be discussed during this Summer Study by Brown, and those related to the microwave system by Halama. Relevant measurements on superconducting lead cavities are the subject of this talk.

The materials of interest to us are pure lead and niobium. The technology of niobium appears to be more difficult, and our investigations have been limited so far to lead, electroplated on OFHC copper. However, cavities have been ordered from Varian which will be machined from electron-beam-melted niobium.²

In order to make our results more meaningful for the construction of superconducting deflectors, the investigations were carried out on cavities resonant at 2.87 GHz, which is close to the anticipated operating frequency of the rf beam separator. We also started with a TE₀₁₁ cavity which permits the elimination of losses caused by electric fields on the walls. The effects of a normal electric field will be investigated shortly in a TM₀₁₁ cavity.

II. SURFACE IMPEDANCE

The microwave behavior of a superconducting material is conveniently described by the complex surface impedance $Z = R + jX$, which is in general a function of material, frequency, temperature and power level. In this paper, the experimental results for the temperature dependence of the surface impedance of superconducting lead at constant frequency and low power levels will be presented.

The measurement of the surface impedance is possible because it is related to the unloaded quality factor Q_0 and the normalized shift of resonant frequency $\delta\omega/\omega$ of a cavity according to³:

$$R + jX \approx \left(\frac{1}{Q_0} - j \frac{2\Delta\omega}{\omega} \right) G Z_0 \quad (1)$$

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1. H. Hahn and H.J. Halama, IEEE Trans. Nucl. Sci. NS-14, No. 3, 356 (1967).
2. J.P. Turneaure and I. Weissman, J. Appl. Phys. 39, 4417 (1968).
3. J.C. Slater, Rev. Mod. Phys. 18, 441 (1946).

with $Z = c\mu_0$ being the impedance of free space and the geometrical constant G being defined by

$$G = \frac{\omega \int \vec{H}^* \cdot \vec{H} dV}{c \int \vec{H}^* \cdot \vec{H} dF} \quad (2)$$

For geometrically simple structures, this constant is calculable; it can always be obtained from a Q measurement on a copper cavity at room temperature, where the surface resistance is known from the classical skin effect. Accurate results, however, require a smooth surface which can be obtained by electropolishing of the surface.⁴

The geometrical constant G is usually considered to be temperature-independent, which, however, is only true if the surface roughness is small compared to the skin depth. The penetration depth of superconducting lead is about $0.039 \mu\text{m}$;⁵ it is therefore possible that a microroughness changes the value of G . The influence of a surface roughness at unchanged material properties was discussed by Lending,⁶ Morgan,⁷ and in the case of superconducting lead, by Halbritter.⁸ As a result of the microroughness, the observed Q values will be lower than expected from theory, or, alternatively, the constant G of a superconducting cavity is not directly measurable. The measurement of the surface impedance of superconductors is, therefore, subject to systematic errors which are not easily corrected. For practical usage it seems preferable to quote the improvement factor, which is defined as the ratio $I = Q_0/Q_{\text{Cu},300^\circ\text{K}}$, and the variation of the resonant frequency with temperature.

The change of resonant frequency of the test cavity can be caused by a variation of the surface reactance or by dimensional changes with temperature. The selective measurement of the contribution due to the reactance involving the application of a magnetic field to destroy the superconducting state was described by Pippard.⁹ The improvement factor is obtained from Q measurements on the test cavity. The measurement of the quality factor is a classical problem which is, however, somewhat complicated by the extremely high Q values of superconducting cavities; $Q > 10^6$ requires some form of decrement method.¹⁰ We found it advantageous to shock-excite a transmission-type cavity by a frequency-swept signal and to observe the decaying eigenoscillations at the cavity output.¹¹ This method is ideal for low level measurements involving the smallest possible rf heating but it would be less suitable for high power measurements.

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4. F. Biquard and A. Septier, Nucl. Instr. Methods 44, 18 (1966).
 5. J.M. Lock, Proc. Roy. Soc. London A208, 391 (1951).
 6. R. Lending, in The Microwave Engineer's Handbook (Horizon House, 1966), p. 84.
 7. S.P. Morgan, Jr., J. Appl. Phys. 20, 352 (1949).
 8. J. Halbritter, Report 3/68-1, Kernforschungszentrum, Karlsruhe, 1968.
 9. A.B. Pippard, Proc. Roy. Soc. London A191, 399 (1947).
 10. C.J. Grebenkemper and J.P. Hagen, Phys. Rev. 86, 673 (1952).
 11. H. Hahn, H.J. Halama, and E.H. Foster, in Proc. 6th Intern. Conf. High Energy Accelerators, Cambridge, Mass., 1967 (available from CFSTI, Springfield, Va.), p. A139.

III. TEST CAVITY

The test structure is designed as a transmission-type rather than the frequently used reaction-type cavity because of its insensitivity to stray reflections and the possibility of carrying out measurements at very loose coupling. The disadvantage of not being able to use low loss waveguide feed systems is more than compensated for by the ease with which the coupling coefficient is adjusted when coaxial cables are used. The attenuation of radiated signals in the coaxial cables is readily measured and corrected for. Details of the TE₀₁₁ test cavity are described in Ref. 12. It should be pointed out here that our biggest problems were caused by vacuum leaks and rf feed-through, that is, a direct power transmission between input and output cable.

The superconducting material is obtained by electroplating a lead film 2.5 μm thick on OFHC copper. Although a correspondence between the microstructure of the superconductor and the quality factor is not established, we feel that one should attempt to deposit the lead in as ideal a form as possible. The criteria by which we evaluate the lead surface are:

- 1) Continuity of the lead surface, i.e. absence of pinholes. This is achieved by the preparation of the copper surface and a proper choice of the plating procedure. Problems caused by trapped air bubbles are alleviated by shaping the geometry of the structure.
- 2) Large grain size as achieved by epitaxial crystal growth. This is achieved by annealing the copper prior to plating and by proper start of the crystal growth (nucleation).
- 3) High purity. This is achieved by using 99.999% pure lead anodes, by immersing the structure in the plating solution under voltage only and by plating the entire surface of the structure. Furthermore, the solution is outplated with slanted electrodes for several hours at very low current densities (0.1 mA/cm²).
- 4) Smoothness on microscopic level. This is achieved by comparatively slow electroplating or, better, by slow reverse plating.

The lead deposit is obtained by electroplating from a lead fluoborate bath. The procedure used is similar to industrial methods¹³; certain modifications, however, seem to improve the quality factor. Best results were obtained by adhering to the following procedure:

- 1) Machine the copper surface of the part to be plated to a 16-32 $\mu\text{in.}$ finish. Recrystallization by heating under hydrogen atmosphere is desirable, but has been omitted so far.
- 2) Degrease ultrasonically in vithane and then in safety solvent. Oakite 117 full strength is recommended.¹⁴
- 3) Soak clean for 3 minutes in Oakite 23 at $82 \pm 5^\circ\text{C.}$ The concentration is 60 g/l of distilled water.

12. H. Hahn, H.J. Halama, and E.H. Foster, J. Appl. Phys. 39, 2606 (1968).

13. Technical Bulletin TA-38351, General Chemical Division, Allied Chemical Corp., Morristown, N.J.

14. Oakite Products, Inc., New York, N.Y.

- 4) Rinse in water.
 - 5) Electropolish for 6 minutes in Electro-Glo 200.¹⁵ The concentration is 75% by volume of phosphoric acid and 25% Electro-Glo 200. The voltage across the cell is about 7 V. The solution is at room temperature, but not above 27°C. If the surface is not satisfactory, repeat the electropolishing for another 4 minutes. Repeated polishing tends to etch the surface and mechanical polishing may be required.
 - 6) Rinse, first in hot and then in cold water.
 - 7) Anodically electroclean for 3 minutes in Oakite 191. The concentration is 60 g/l of distilled water. The voltage across the cell is about 6 V and the temperature of the solution is $82 \pm 5^\circ\text{C}$.
 - 8) Rinse in water. The surface must wet, otherwise repeat electrocleaning.
 - 9) Dip for 10 sec in fluoboric acid. The concentration is 25% by volume of fluoboric acid, 75% distilled water.
 - 10) Dip in distilled water. Drain excess water to avoid streaks.
 - 11) Plate in lead fluoborate bath at a current density of 2.7 mA/cm^2 , higher during the initial few seconds. The concentration is 22.9% by volume of lead fluoborate concentrate¹³ and 77.1% distilled water. Add a small amount of fluoboric acid to achieve $\text{pH} \leq 1$; add 0.4 g/l of extracted bone glue to prevent treeing.¹⁶ Normal plating requires 17 minutes to deposit $2.5 \mu\text{m}$ of lead. Surface roughness is reduced by reverse plating (20 sec plating, 10 sec polishing¹⁷) which is done for 30 minutes after 7 minutes of normal plating.
 - 12) Rinse in water.
 - 13) Dip for 3 minutes in Varsene 100. The concentration is 168 g of Varsene 100 with the addition of 5.3 cm^3 of Duponol per liter of distilled water.¹⁸
 - 14) Rinse in water.
 - 15) Dip in distilled water.
 - 16) Dip in 200-proof alcohol.
 - 17) Dry under air flow. If watermarks appear, repeat step (13) and on.
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15. Electro-Glo Company, Chicago, Illinois.
 16. Hydroquinone $\text{C}_6\text{H}_4(\text{OH})_2$ may be used instead of bone glue. D. Gorlé and D. Leroy, private communication.
 17. Better polishing is obtained by increasing the current tenfold and reducing the time correspondingly. R.W. Meyerhoff, private communication.
 18. Varsene 100 by Dow Chemical Co.; Duponol by E.I. DuPont de Nemours & Co.

- 18) Good parts are stored under vacuum until they are assembled. If the plating is inadequate, the lead is stripped,¹³ and the process is repeated starting with step (4). Repeated stripping tends to etch the surface and mechanical polishing is desirable.

IV. MEASUREMENTS

The quality factor of the superconducting cavity was measured by a frequency sweep technique. In the case of a fast adiabatic sweep through resonance ($\dot{\Omega} \ll 1/Q \ll \sqrt{\dot{\Omega}} \ll 1$), the power transmission through the cavity may be expressed by¹¹

$$\frac{P_{\text{out}}}{P_{\text{in}}} = \frac{\pi}{2 \dot{\Omega} Q^2} \left\{ \frac{4 \kappa_1 \kappa_2}{(1 + \kappa_1 + \kappa_2)^2} \right\} e^{-\omega_0 t / Q} \quad (3)$$

The loaded Q follows directly from the time constant of the decaying output signal. The unloaded $Q_0 = Q(1 + 2\kappa)$ requires the knowledge of the coupling coefficients which are made equal by a symmetric geometry. The coupling coefficient is determined from the amplitude of the output signal and the sweep rate $\dot{\Omega} = \dot{\omega}/\omega_0^2$. The transmitted signals refer directly to the cavity input and output and corrections for cable attenuation are necessary.

Errors may be caused by unequal coupling coefficients, FM noise of the source, and stray reflections. The presence of FM modulation would manifest itself by a jitter of the output power and is easily detected. The equality of the coupling coefficients can be verified by comparing the signals reflected from the input port, and from the output port when it serves as an input port. The most accurate measurements, however, are obtained by reducing the coupling coefficients to a few percent. The coupling coefficient is limited by the sensitivity of the detector at the output; the combination of a low noise TWT plus a crystal diode was found to be adequate.

The best results obtained on a TE_{011} cavity resonant at 2.87 GHz are listed in Table I. The unloaded quality factor of a congruent copper cavity at room temperature is $Q_{\text{Cu}, 300^\circ\text{K}} = 56 \times 10^3$, to which the improvement factor is normalized. The experimental results were compared with the AGK theory and adequate agreement was found.¹²

TABLE I

T ($^\circ\text{K}$)	Q_0	I
4.2	2.35×10^8	4.2×10^3
3.7	3.92×10^8	7.0×10^3
3.45	4.90×10^8	8.8×10^3
3.20	6.68×10^8	1.2×10^4
2.95	8.82×10^8	1.6×10^4
2.70	1.3×10^9	2.3×10^4
2.45	2.26×10^9	4.0×10^4
2.20	3.73×10^9	6.7×10^4
1.92	6.93×10^9	1.2×10^5
1.90	7.01×10^9	1.3×10^5
1.70	9.96×10^9	1.8×10^5
1.50	11.33×10^9	2.0×10^5

It is appropriate to mention that the above results were obtained at small power levels ($H \ll H_c$). Power measurements on TE_{011} and TM_{011} cavities are in progress and will be reported as soon as conclusive results are available.