SUMMARY OF RECENT INVESTIGATIONS OF THE KARLSRUHE GROUP ON RF PROPERTIES OF SUPERCONDUCTORS AND ON APPLICATIONS

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The experiments described in this collective report have been carried out by several members of the group. Their names are given in the list of references to more detailed information on the contributions. The reports mentioned there do, moreover, serve as a source of further references which have been omitted in the list.

I. THE METHOD OF Q MEASUREMENTS

The electromagnetic energy stored in a resonator with walls of finite surface resistance R decays exponentially with the time constant

$$\tau_o = \frac{Q_o}{\omega} = \mu_o \frac{\int_V |H|^2 \, dv}{\int_S R|H|^2 \, ds} ; \qquad (\tau_o)_{R\ const} = \frac{G}{\omega R} ,$$

where G is the so-called geometry factor and Q_o the rf quality factor of the unloaded resonator. An observation of τ is used for the determination of the high Q values of superconducting cavities. Unfortunately one cannot observe the decay behavior of a resonator without some of its energy coupled into a suitable external instrument. Either the additional losses thus introduced which modify the measured τ with respect to τ_o have to be kept tolerably small, or they have to be measured and corrected for. The latter method has been investigated in some detail.[1] It turns out that the usual correction $Q_o = (1 + \beta)\, Q_M$ applied to the measured Q_M value with the coupling coefficient β derived from the signal which is reflected from the coupling loop of a pulsed resonator may be insufficient for several reasons. There, β is obtained from the ratio P_i/P_e of the incident power P_i and the power P_e which is emitted from the resonator immediately after P_i is switched off during the steady state. A residual frequency modulation of the generator of the order of the cavity bandwidth, as well as reflections on the connecting lines due to improper matching, do considerably perturb the β determination. Except from errors in β the above-mentioned correction formula does not cover any extra losses in the coupling region.

A method is used, therefore, which permits the measurement of the Q value of the unloaded cavity without a β determination.[2] The resonator field is coupled to that of a piece of cut-off waveguide by a small coupling hole and the feeding coaxial line ends in a loop or a pin in this guide (Fig. 1). The distance from loop to hole is adjustable to allow for a large range of coupling coefficients. The individual losses are additive with respect to the observable Q_M value of the system:

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1. J. Halbritter, P. Kneisel, and O. Stoltz, Kernforschungszentrum Karlsruhe Report 3/67-9 (1967).

2. J. Halbritter, R. Hietschold, P. Kneisel, and H. Schopper, Kernforschungszentrum Karlsruhe Report KFK 758 (1968).

$$Q_M^{-1} \propto P_o + P_{iris} + P_{guide} + P_{loop} + P_{rad} \quad .$$

According to the cut-off behavior of the guide, the losses of the loop (in the loop itself and close to it because of its field perturbation), P_{loop}, and the power P_{rad} fed into the coaxial line depend on the loop position, z:

$$P_{loop} + P_{rad} \propto \exp(-2\alpha z) \quad ,$$

where α is the attenuation factor of the cut-off fields,

$$\alpha = 2\pi (\lambda_c^{-2} - \lambda^{-2}) \quad .$$

Usually, the vacuum wavelength λ is several times larger than the critical wavelength λ_c of the guide and α is, therefore, only weakly frequency dependent.

If the losses P_{iris} around the coupling hole and P_{guide} on the walls of the cut-off guide are kept negligibly small by carefully plating these surfaces with the superconducting material, $P_{loop} + P_{rad}$ can be separated from P_o. One has to plot Q_M^{-1} vs the loop position z which yields a curve that can be fitted by the constant term, Q_o^{-1}, and an exponential function with the slope, -2α. Figure 2 shows the result of such a measurement. The experimental value, $\alpha_{exp} = 0.185$, is in good agreement with the theoretical attenuation coefficient, $\alpha = 0.177$, which corresponds to the TE_{11} cut-off mode in a 20 mm diameter guide at 2.46 GHz. In cases such as the example of Fig. 2, where a Q measurement at large z values (very small coupling coefficients) is possible and directly yields the practically unloaded Q_o value, there is no necessity to observe all the z dependence as long as one is sure to be in the region of constant Q_M values.

If with the same setup the β values are observed simultaneously,

$$\beta = P_{rad}/(P_o + P_{loop}) \quad ,$$

one gets an independent information on the losses P_{rad}, P_{loop}, which, together with the z dependence measurement, allows the determination of their ratio. It has been found that in our arrangement P_{rad} and P_{loop} were of the same order of magnitude.

II. MEASUREMENTS OF THE SURFACE RESISTANCE OF LEAD AND OF INDIUM

Mainly electroplated TE_{011} resonators with a diameter-to-length ratio equal to $\sqrt{2}$ ($G = 755\ \Omega$) have been measured (Fig. 1). The results for lead at 2.5 GHz,[1] (IF = improvement factor)

$$Q_o(4.2^oK) = 2.8 \times 10^8 \qquad Q_o(2^oK) = 3 \times 10^9$$

$$IF(4.2^oK) = 4600 \qquad IF(2^oK) = 5 \times 10^4$$

$$R(4.2^oK) = 2.7 \times 10^{-6}\ \Omega$$

do agree with those measured at Stanford and Brookhaven at 4.2°K, whereas at 2°K they are worse.

The frequency of a linear accelerator will be lower. Since the frequency dependence of the surface resistance is not known accurately, measurements at 800 MHz, too, have been performed.[3] A TE_{011} resonator (G = 755 Ω), as well as a TEM coaxial resonator (G = 84 Ω), have been lead-plated and measured. The 800 MHz results were:

$$TE_{011}: \quad Q_o(4.2^oK) = 1 \times 10^9 \qquad Q_o(2^oK) = 3 \times 10^9$$

$$IF(4.2^oK) = 1 \times 10^4 \qquad IF(2^oK) = 3 \times 10^4$$

$$R(4.2^oK) = 7.5 \times 10^{-7}\ \Omega$$

$$TEM: \quad Q_o(4.2^oK) = 2 \times 10^8$$

$$IF(4.2^oK) = 1.7 \times 10^4$$

In Fig. 3 our results for lead at 0.8 and 2.5 GHz as well as the results from other laboratories are plotted vs frequency. With both scales logarithmic, they can be fitted by a straight line which indicates the frequency dependence

$$R \propto \omega^{1.77} \quad .$$

The residual resistance, R_{res}, has not been subtracted here from the measured surface resistance. This could, in principle, have been done since R_{res} can be obtained from the measured temperature dependence of R if R_{res} is assumed to be temperature independent. Since this assumption is somewhat doubtful and since the accuracy of the measurements is not yet high enough, the correction does not appear worthwhile. It is obvious, however, that the residual resistance becomes more important at lower frequencies in that the slope would be increased.

Although indium surfaces are certainly not of interest for accelerator or separator cavities as their surface resistance is higher by more than a factor of 100 compared to lead, they have nevertheless been investigated.[4] Indium surfaces may possibly serve as protecting layers on top of lead. Indium forms a thin oxide layer and shows practically no aging effect. If the indium surface is thin enough, the superconducting properties of lead will be induced in it. This "proximity effect" will cause it to become superconducting even above its critical temperature (3.4°K) and above its critical magnetic field.

Indium and lead at room temperature form alloys which are known to have rather high critical temperatures, e.g., 5°K with only 14% Pb, an effect which acts in the same direction as the proximity effect. We hope, however, to get layers which, although thin, consist mostly of In and are chemically sufficiently resistant.

An indium layer (≈ 1000 Å) has been evaporated onto a lead layer, several microns thick, of a 2.5 GHz TE_{011} resonator. A Q value of 1.3×10^8 was found at 4.2°K.[5] With decreasing temperature no special behavior was found at the critical temperature of indium. In contrast to our experience with unprotected lead layers, no significant decrease of Q could be observed after the resonator had been exposed to air for several weeks. We have to admit that we do not yet know whether the superconducting properties are mainly those of an alloy or mainly due to the proximity effect.

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3. P. Flécher, J. Halbritter, R. Hietschold, P. Kneisel, L. List, and O. Stoltz; to be published in the Proc. of the 1968 Linear Accelerator Conference at Brookhaven.

4. J. Halbritter, P. Kneisel, and L. List, Kernforschungszentrum Karlsruhe Report 3/67-10 (1967).

5. P. Flécher, private communication.

To gain experience with the electroplating of indium layers, pure indium surfaces have been prepared and measured.[4] The observed temperature dependence of the surface resistance is very close to the theoretical prediction with $\Delta(0)/kT_c = 1.75$. The absolute values turned out to be even smaller than the theoretical ones (BCS) with all reasonable sets of parameters.

III. CALCULATIONS ON SUPERCONDUCTING PROPERTIES

Based on the BCS theory the surface impedance has been computed, with frequency and temperature as free parameters, for a large number of sets of the inherent properties of the material, namely, London's penetration depth, δ_L, the coherence length, ξ_o, and the mean free path, ℓ.[6,7] Examples are given in Figs. 4 and 5.

The temperature dependence of R for $T/T_c \leq 0.5$, the range which is interesting for practical applications, is simply $R \sim \exp[-\Delta(0)/kT]$. In the figures $T/T_c = 0.2$ and $\Delta(0)/kT_c = 1.75$ are fixed values. Surface impedances for other temperatures or gap/critical temperature ratios can easily be computed with that relation.

The dependence, $R(\varkappa_F, h\nu)$, where $\varkappa_F = 2\delta_L/(\pi\xi_o)$, shows (cf. Fig. 4 for $\ell = \infty$) that the surface resistance decreases with decreasing $\varkappa_F$ at low frequencies and that the frequency dependence approaches $R \sim \omega^2$ for $\varkappa_F \to 0$ (Pippard's limiting case).

The dependence on the mean free path ℓ can be seen from Fig. 5 in the special case $\varkappa_F = 0.6$ (e.g., niobium). At low frequencies R is reduced with increasing ℓ. This reduction is significant for large $\varkappa_F$ but amounts to less than 5% at $\varkappa_F \approx 10^{-2}$ (e.g., aluminum).

IV. MEASUREMENTS AT HIGHER ELECTRIC FIELDS

The goal of these measurements has been to investigate to what extent the Q values measured at low fields might increase when the field level approaches the design figures required by various applications.

For a TEM resonator the Q_o value has been measured at various power levels.[8] If Q_{oo} denotes the Q_o value and R_o the surface resistance in the limit of very low fields, the fraction of extra losses, P_{extra}, beyond those, P_o, explained by R_o is given by

$$P_{extra}(E)/P_o = Q_{oo}/Q_o(E) - 1 \quad .$$

The first idea has been to attribute these losses to field emission. Using the Fowler-Nordheim relation for the field emission current

$$I_{FE} \propto E^2 \exp\left(\frac{-2.7 \times 10^7 \varphi^{3/2}}{K E}\right)$$

$\log(P_{extra}/E^3)$ has been plotted vs 1/E and, indeed, straight lines up to about 6 MV/m result. With the known work function φ, the slope, however, indicated a microscopic

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6. J. Halbritter, Kernforschungszentrum Karlsruhe Report 3/67-2 (1967).
7. J. Halbritter, private communication.
8. W. Kühn, to be published in the Proc. of the 1968 Linear Accelerator Conference at Brookhaven.

field enhancement factor K of nearly 7000. Since the highest K values so far observed are about 200 an explanation by mostly field emission becomes rather doubtful.

To get additional information on the field emission from superconducting lead surfaces, a less precise but more specific experiment for the determination of the field emission losses was carried out.[9,10] As it had been done before at Stanford with a warm copper cavity, we measured the X-radiation in the vicinity of the resonator, in our case, outside the cryostat. The various calibrations and corrections which have to be applied before one arrives at the field emission current as function of the electric field do introduce a rather large error, but this mainly influences the absolute values and much less the slope of the curve. The measurements were done with a lead-plated structure with a gap where the field could be raised up to 35 MV/m. The result is plotted in Fig. 6 together with the Stanford results. Regarding the experimental errors, the coincidence of the fitting straight lines can only be called fortuitous. The resulting very normal field enhancement factor, $K \approx 200$, however, proves that the extra losses of the Q-value experiment described before have to be explained by effects other than field emission.

One possible explanation would be the imperfect heat conduction which at high power levels may cause a temperature rise of the lead surface. Half a degree would increase the losses by a factor of about two.

Another possible reason for the increased surface resistance may be the increased magnetic field

$$R = R_o \left[1 + k \, (H/H_c)^2 + \ldots.\right]$$

where the upper limit for the constant, k, summing up the various contributing effects, has been estimated to be about 5 where the residual resistance is not taken into account.[11] There are theoretical reasons which indicate that an equivalent constant k_{res} describing the field dependence of the residual resistance can be even much larger.[12] In order to check whether the measured extra losses are in agreement with this relation, P_{extra}/P_o has been plotted vs $(H/H_c)^2$ which is expected to yield and, in fact, does yield a straight line. Its slope, which is proportional to k, led to $k \approx 9$. We conclude that this effect, too, may be the proper explanation or part of it.

Experiments to elucidate this situation further are being prepared. So far, field emission seems not to be the limiting effect for the field amplitudes since its loading power is far smaller than that of the total of the observed additional losses. There is a chance to reduce these extra losses either by preventing temperature gradients or rf magnetic field concentrations on the surface as far as possible and it is to be expected that, for a surface with a small residual resistance, the field dependence will be less pronounced.

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9. W. Kühn and L. Szecsi, in Studie über einen supraleitenden Protonen-Linearbeschleuniger im GeV-Bereich (Kernforschungszentrum Karlsruhe, 1967) p. 202.

10. H. Schopper, H. Strube, and L. Szecsi, Kernforschungszentrum Karlsruhe Report 3/68-6 (1968).

11. J. Halbritter, Kernforschungszentrum Karlsruhe Report 3/68-1 (1968).

12. J. Halbritter, Kernforschungszentrum Karlsruhe Report 3/68-8 (1968).

V. SPECIAL INVESTIGATIONS IN VIEW OF APPLICATIONS

Two features of linac cavities have to be investigated with a finite length of full-scale accelerating structure instead of only test cavities: the maximum attainable average accelerating field with the associated power requirement, and those effects which are expected to occur under heavy beam loading. An analogue experiment in the superconducting state has therefore been prepared[13] using electrons of the same velocity as the corresponding protons. The reduction of currents and field amplitudes by the electron-proton mass ratio considerably ease the experimental requirements, while the dynamical and beam loading problems remain essentially unchanged. Although it is not necessary for these analogous measurements, the available rf power source is capable of producing rather high fields so that limitations which might influence the design of a proton linear accelerator can be investigated.

A 12-cell structure and the appropriate cryostat have been built but only the room temperature performance tests have been carried out so far. Meanwhile the structure has been lead-plated and results from experiments at 4.2°K are expected soon.

The construction of a superconducting rf particle separator is regarded as a simplified first step on the way towards the construction of a linac. It is short compared to the accelerator and a number of severe difficulties as, for example, beam loading, do not exist here. Even if an improvement factor $> 10^5$ as is imperative for the accelerator is not achieved in complicated structures, the separator project could still be continued since a few meters of a less economical structure seem tolerable.

The final construction will be a two-cavity separator for around 10 GeV/c kaons at CERN. To gain experience with the operation and optimum layout of the deflectors, a prototype single-cavity separator will precede the final design.[14] The prototype is designed such that, except for the differing deflecting structure itself, practically all components, especially the cryostat, refrigerator and rf system, can later be used for the two-cavity separator. The structure (iris-loaded waveguide, HEM_{11} configuration, S-band operated in the $\pi/2$ mode) will be 3.25 m long with a beam hole diameter of about 4 cm. This rather small diameter has been chosen since it combines the advantages of high shunt impedance and the easier tolerances that are possible with the increased group velocity. The useful momentum range for kaon separation is 1.1 to 1.7 GeV/c and the angular acceptance, including the beam transport system, is ≥ 500 μsr. At an equivalent deflecting field of 3 MV/m, the highest necessary, the power dissipated in the structure will be 25 W if an improvement factor of 10^5 is assumed for lead. If the improvement factor should turn out to be much less, one could save cooling power by pulsing the system according to the slow extraction duty cycle of the accelerator. In this case pulsing seems the more feasible as the filling time of the resonator is reduced in proportion to the Q value. Iris-loaded eight-cell resonators have several times been lead-plated and measured. Satisfactory plating turned out to be much more complicated than for structures of simple geometry. Rather tricky anode shapes were necessary which at a sufficiently uniform and not too high current density could still be put in. Another difficulty was raised by the slight surface irregularities at the brazed joints of the individually machined copper parts. The best results[15] which have so far been obtained were $Q_o = 2 \times 10^7$ (IF = 2000) at 4.2°K and $Q_o = 1 \times 10^8$ (IF = 10^4) at 2°K.

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13. W. Jüngst, M. Kuntze, and J. Vetter, Kernforschungszentrum Karlsruhe Report 3/67-15 (1967).

14. W. Jüngst, Kernforschungszentrum Karlsruhe Report 3/67-16 (1967).

15. W. Bauer, H. Eschelbacher, and W. Jüngst, private communication.

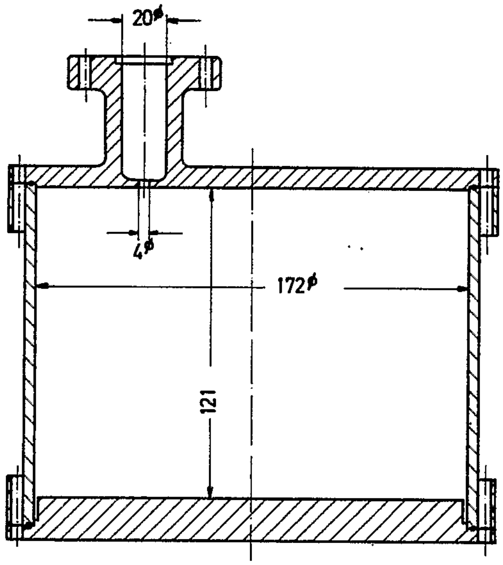

Fig. 1. TE_{011} test cavity, 2.46 GHz.

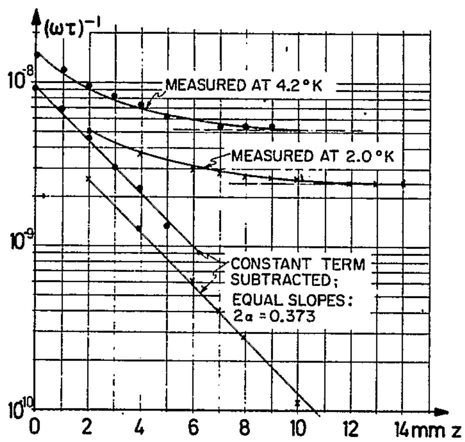

Fig. 2. Examples for the plot of $1/Q_{meas}$ as a function of loop position.

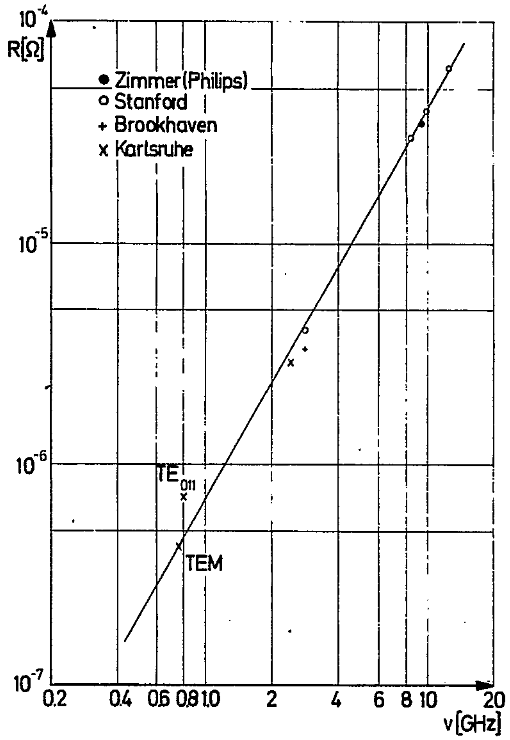

Fig. 3. Surface resistance of lead as function of frequency ($T = 4.2^{\circ}K$).

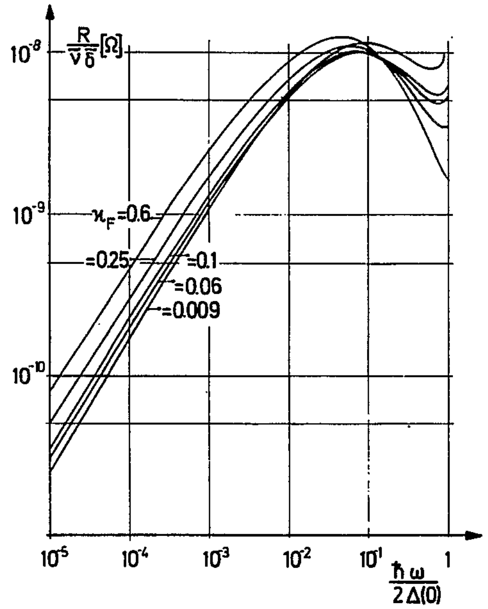

Fig. 4. Surface resistance as function of frequency for various $\varkappa_F$ (diffuse reflection, $T/T_c = 0.2$, $\Delta(0)/kT_c = 1.75$, $\tilde{\nu} = \nu/GHz$, $\tilde{\delta} = \delta_L(0)/100$ Å).

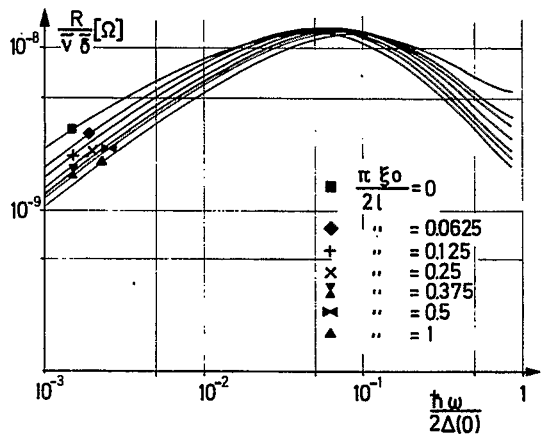

Fig. 5. Surface resistance as function of frequency for various ℓ (diffuse reflection, $T/T_{c_o} = 0.2$, $\Delta(0)/kT_c = 1.75$, $\varkappa_F = 0.6$, $\tilde{\nu} = \nu/\mathrm{GHz}$, $\tilde{\delta} = \delta_L(0)/100$ Å).

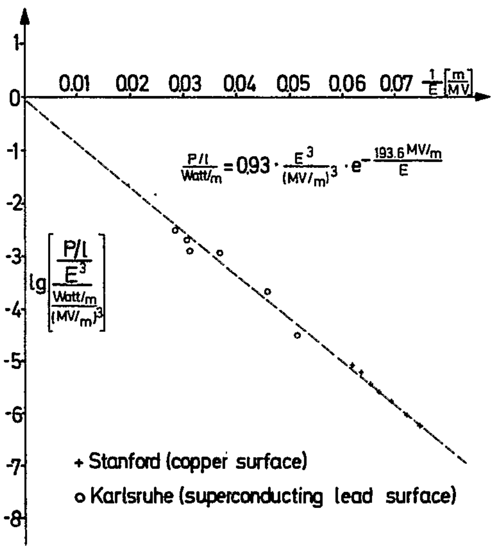

Fig. 6. Fowler-Nordheim plot of field emission losses in a superconducting lead-plated resonator.