# INVESTIGATION OF ADDITIONAL LOSSES OF SUPERCONDUCTING CAVITIES DUE TO FIELD DEPENDENT EFFECTS AT HIGH LEVELS

W. Kühn

Institut für Experimentelle Kernphysik
der Universität und des Kernforschungszentrum Karlsruhe

## Introduction

So far the surface resistance of superconducting rf cavities has usually been measured at low field levels. For the design and the operation of a superconducting linear accelerator, however, the realization of the sources and consequences of possible field dependent effects seem important, since these may lead to additional losses and field limitations. As a first step such phenomena should be studied in principle. Consequences, concerning the operation of linear accelertors or the design of structures taking into account these effects will be subject of further investigations.

## The model-cavity

A simple $\lambda/2$-coaxial cavity (fig. 1) without gap has been chosen where the field is readily computed at any point. Electrons accelerated from the inner to the outer conductor in the region of maximum electric field are not perturbed by the magnetic field, which crosses zero, there. There are electrons accelerated in other field regions, which because of the stronger magnetic field may or may not arrive at the outer conductor and only partly contribute to the losses. These electrons outside the maximum field region, however, are disregarded since it is obvious from the very strong field dependence of the field emission current

$$I_{FE} = C_1 A \frac{\beta^2 \cdot E_c^2}{\varphi} e^{-\frac{C_2 \varphi^{3/2}}{\beta E_c} F(E_c,\varphi)} \qquad (1)$$

(R.H. Fowler, L. Nordheim [1]. $E_c$ = electric surface field; $\beta$ = field enhancement factor; $\varphi$ = workfunction; A = effective emitting surface area; $C_1 = 1.54 \cdot 10^{-6}$; $C_2 = 6.83 \cdot 10^7$; $F(E_c,\varphi) \simeq$ const. = .9)

that the number of field emission electrons from the maximum field neighbourhood will be far dominant.

The rf power coupler consists of a loop whose damping influence has been reduced by a slotted superconducting disk. The dimensions of the slot were such as just to allow a critical coupling at low field levels. With this coupling device and with the usual lead plating technique of our institute a low field Q-value of $Q_o = 1.3 \cdot 10^8$ has been obtained.

## Principle of measurements

The field amplitudes inside the resonator have been computed from

$$E_c = K \sqrt{P_g Q_o} \qquad (2)$$

($E_c$ = field amplitude in a macroscopic distance from the surface; $P_g$ = total resonator power dissipation; $Q_o$ = resonator Q-value; K = constant, depending on the resonator geometry and the ordinates of the point in question).

$P_g$ has been determined from the transmitted power and the coupling coefficient k. The $Q_o$-value $Q_o = Q_L(1+k)$ was obtained from the decay constant $\tau = Q_L/\omega$ observed at pulsed operation and the coupling coefficient k from the standing wave ratio on the rf supply line.

The additional losses $P_{FE+S}(E)$ besides the ohmic losses $P_W(E)$

$$P_g(E) - P_W(E) = P_{FE+S}(E) = P_g(E)\left(1 - \frac{Q_o(E)}{Q_o(E \to 0)}\right) \qquad (3)$$

are computed from the measured total power dissipation $P_g(E)$, the actual $Q_o(E)$ and the $Q_o$-value which has been obtained at a sufficiently low field level.

## The experimental results

Fig. 2 indicates the heavy decease of $Q_o$ with increasing field amplitudes. The total of the power dissipation and the two fractions have been plotted in fig. 3. The determination of the parabola describing the ohmic losses was based on the low field $Q_o$-value. It seems worthwhile emphasizing that the additional losses are already exceeding the ohmic ones at a field level of 5 MV/m.

If the dependence of the field emission current $I_{FE}$ on the field strength is plotted according to Fowler-Nordheim ($I_{FE} \approx P_{FE+S}/E_c^3$ within the range of validity of the field emission law (1), plotted vs $1/E_c$) a curve (cf. fig. 4, where similar results of Wilson [2] are added for comparison) is obtained, which shows up to 5 MV/m that straigth characteristic, which one would expect for field emission effects according to equ. (1). Other effects leading to a similar behaviour may, however, contribute. The deviation from a straight line towards smaller $P_{FE+S}$-values and for higher $E_c$-levels proves that effects other than described by equ. (1) do play a role, here.

Whether this decrease of the slope of the Fowler Nordheim-plot is due to changes in the microstructure of the surfaces which, according to (1) are bound to have a strong influence on the field emission, or whether phenomena of superconductivity are the reason of these changes has not yet been clarified. It cannot be excluded either that the surface resistance shows a field dependence similar to function (1) which does not contradict the linear section of the plot after fig. 4 so that the field emission, which does take place and is proved by bremsstrahlung measurements, does not have to be the sole cause of the linear characteristics. A striking feature is the relatively slight slope of the straight lines, which would result in a field enhancement of ß > 6000 relative to values around 200 which were measured by other authors in assemblies at normal temperatures [3].

The field enhancement factors ß calculated from the linear part of the plot for $TM_{010}$ resonators of Wilson and the λ/2 coaxial resonator differ by a factor of about 1.5. Thus, they are in satisfactory agreement, if it is considered that ß represents a statement on the microstructure of galvanic surface lead coating performed in various baths. The different effective emission areas, is not surprising in view of the given structures with completely different modes of oscillation. Unfortunately, it is not possible to derive from this a potential agreement in deviation from the straight line, since Wilson carried his measurements only up to about 5 million V/m, i.e. up to the threshold of the deviation discovered in this work.

## Conclusions

According to the state of the experiment the following consequences can be drawn already now:

I. The losses due to field intensity-dependent effects may by far exceed the basic losses according to Ohm's law occurring in superconducting resonators of high Q-values in the range above some 5 million V/m.

II. The load imposed by the additional losses and, of course, also by the regular beam current in accelerating resonators requires a flexible coupling-in mechanism with a high coupling reserve to safeguard sufficient coupling factor for power transmission. Hence, it will become necessary to make also the coupling-in mechanism superconducting.

III. In the design of superconducting structures it will be necessary to consider the field dependent effects. Already the emission of electrons on exposed surfaces, which has been recognized with certainty in this experiment by radiation measurement, makes it imperative to make these critical regions as small as possible. Because of the strong field dependence of the field emission current (cf. (1)) high electrical fields, which become effective on structural surfaces and do not contribute towards the acceleration of the regular beam current, should be avoided.

There are numerous phenomena which have been observed through their effects but are still largely unexplained. The experiments will be continued with other structures and with methods of measurement specially devised for specific problems.

## Acknowledgement

The author expresses his thanks to Mr. Schittenhelm and Mr. Jochimsen for their collaboration in the measurements and for building up the equipment of the experiment.

## References

[1] R. H. Fowler and L. Nordheim
Proc. Roy. Soc. Lond. Ser. A 119, 173
(1928)

[2] P.B. Wilson
Sixth International Conference on
High Energy Accelerators, Sept. 1967
HEPL 529

[3] D. Alpert, D.A. Lee, E.M. Lyman,
H.E. Tomaschke
J. Vacuum Sci. and Tech. 1, No. 2,
35 (1964)

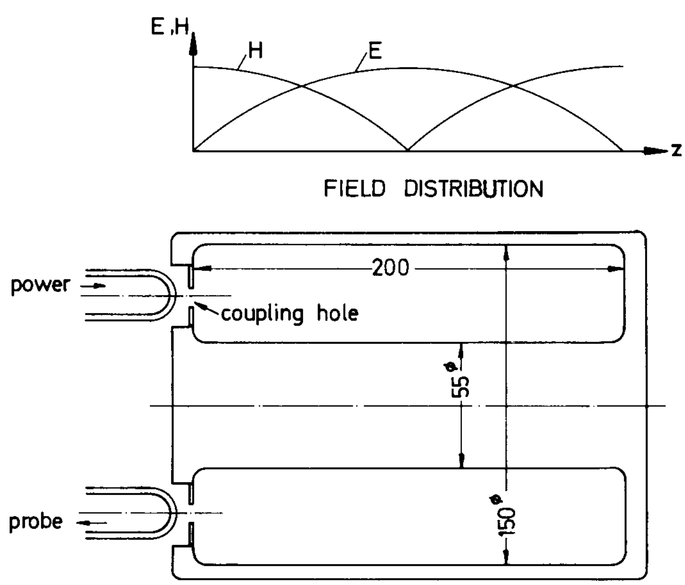


Figure 1). Coaxial cavity $\lambda/2$, f=751.65 MHz.

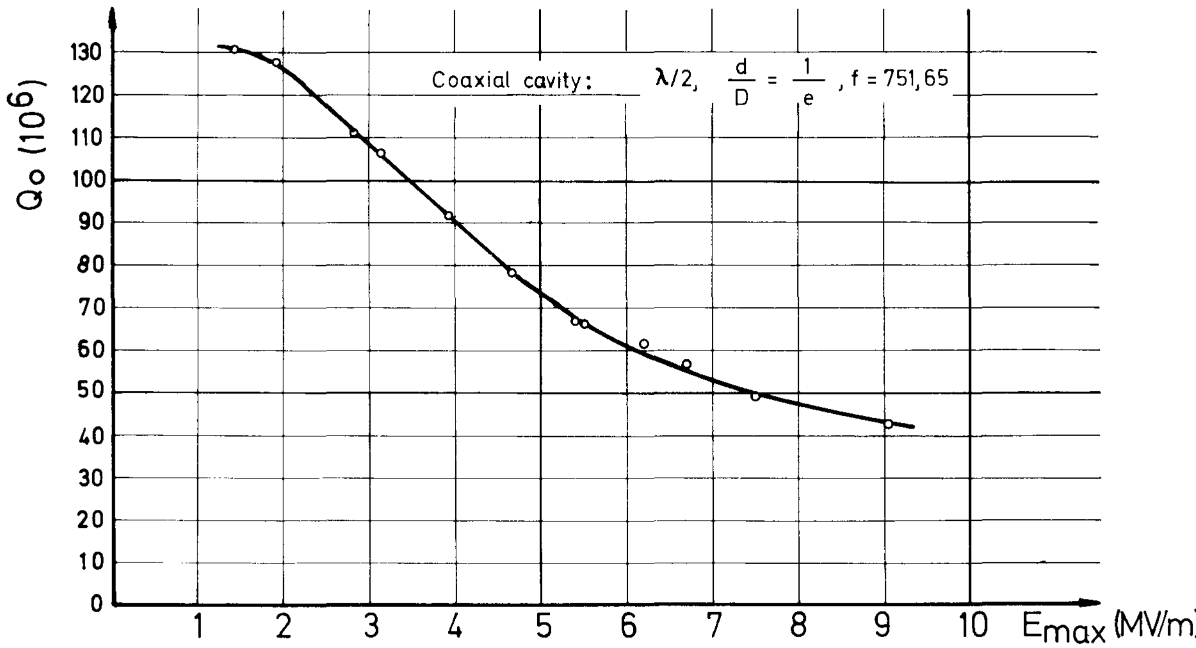


Figure 2). $Q_o$-value vs. electric field amplitude.

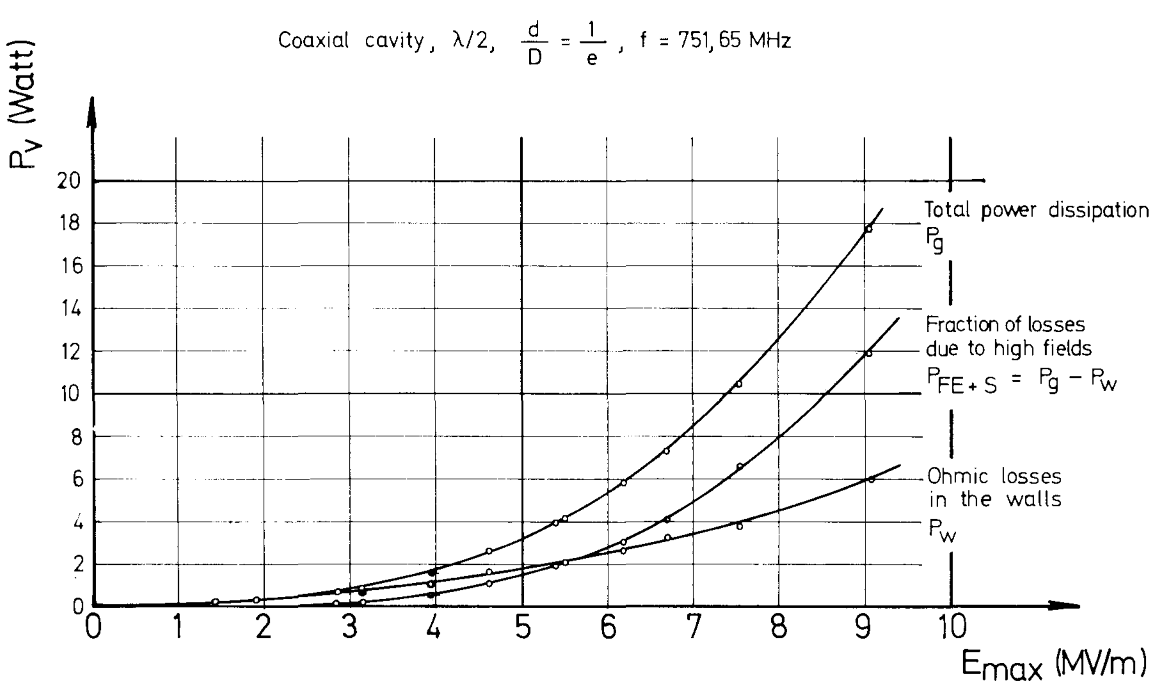


Figure 3). Power dissipation vs. field amplitude.

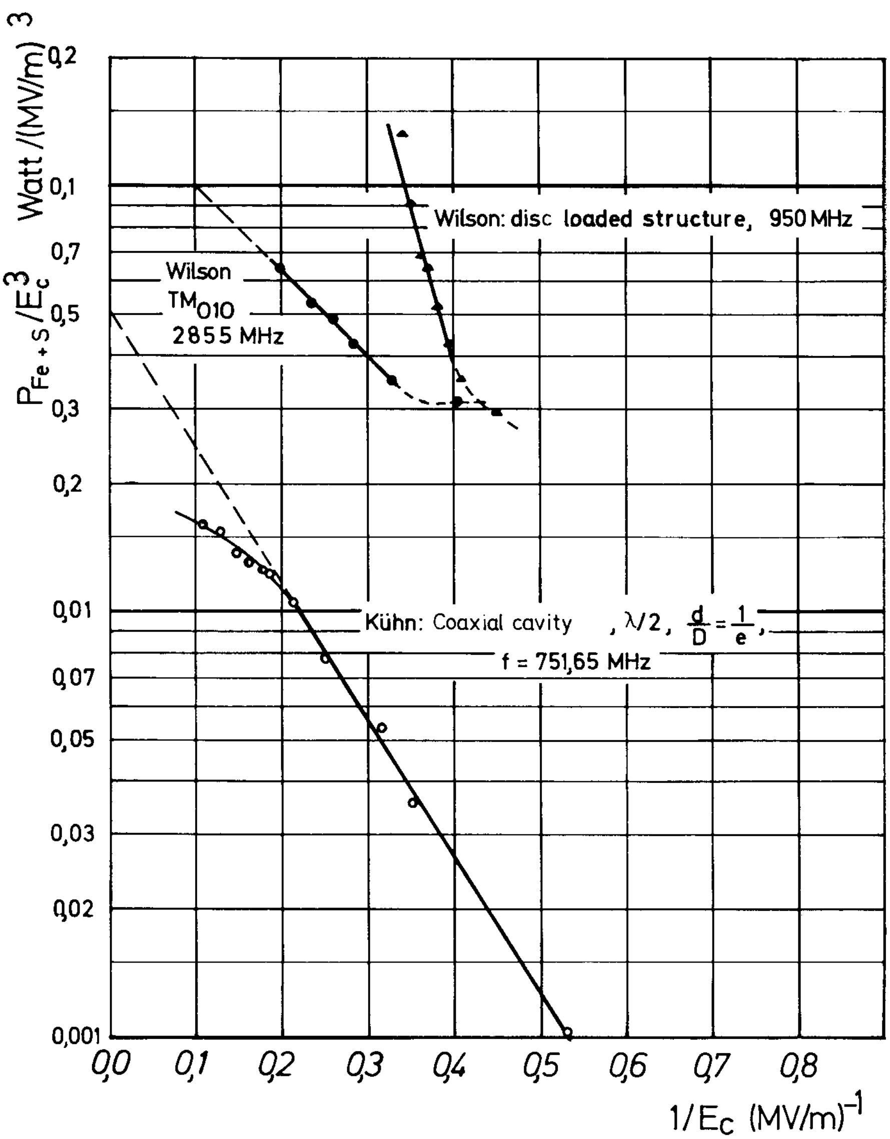


Figure 4). Fowler-Nordheim-plot.