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E. Brigant, E. Haebel and E. Mahner

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THE QUADRUPOLE RESONATOR, DESIGN CONSIDERATIONS AND LAYOUT OF A NEW INSTRUMENT FOR THE RF CHARACTERIZATION OF SUPERCONDUCTING SURFACE SAMPLES.

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Abstract

A disk-shaped superconducting sample is welded onto an Nb support cylinder and exposed to the magnetic RF field of a four-wire transmission-line resonator. The fields on the cylinder wall decay in a cut-off like fashion in such a way that they perturb the measurement very little. RF dissipation of the disk is determined by substitution with a d.c. heater on the back of the sample which is made to produce the same temperature rise, controlled by thermometers.

1 INTRODUCTION

The 350 MHz superconducting (sc) LEP cavities have been produced by sputter coating a copper substrate with a 1 µm Nb film. In this way cost savings [1] could be realized (in comparison to cavities from Nb sheet material) and, at the operating temperature of 4.5 K, the RF dissipation is also diminished. In fact, the Nb/Cu cavities have higher Q_0 than their bulk Nb counterparts, at least at lower accelerating gradients E_{acc}. But Q_0 decreases with E_{acc} and at about 10 MV/m this advantage of the film technique is lost. This effect is the subject of ongoing R&D [2] especially since it becomes more pronounced when reduced beta cavities are sputter coated [3] using the standard LEP technique. To study these effects in more detail a cavity mock-up with tubular access ports has been built. Into these ports cylindrical samples are mounted so that their front-disks (the samples proper) are flush with the surrounding cavity wall (Fig. 1). Stainless steel flanges and the knife-edge sealing technique with copper gaskets assure vacuum tightness.

After sputtering the samples are removed to allow room-temperature examination of the formed Nb coating by surface analytical instruments.

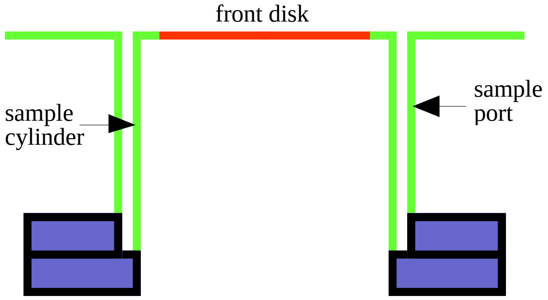

Figure 1: Outline of sample cylinder and its tubular port

We now will discuss means of also studying the superconducting properties of such samples and, in particular, their RF surface resistance R_S, by exposing selectively the front disk to an RF magnetic field.

2 CREATING A CUT-OFF EFFECT

An ideal field configuration would illuminate only the front-disk of a sample (i.e. the sc film) but not the side-wall of the cylinder. There the field should at least decay exponentially as in the cut-off tubes of an sc cavity.

The sample cylinder together with its port form a coaxial line stub and to obtain a cut-off like decay of fields its coaxial TEM-mode must not be excited. This implies that, taken over the sample surface, the integral of the electric surface field (the displacement current) is zero and remains very small even when mechanical imperfections perturb the wanted field distribution. Thus, for a given magnetic surface field average, the surface integral of the electric field's *module* should also be as small as possible.

A simple way to achieve this would be to mount the sample port on the wall of a pillbox cavity excited in its TE_{010} mode which has the particularity to have no electric field at all on the boundary. But for frequencies around 400 MHz a sc cavity with dimensions of the order of 1 m would have been needed and a more compact and less expensive solution was searched for in studying whether a compact transmission line circuit could be used.

2.1 Dipole symmetry

We may, in a thought experiment, regard the sample surface as the ground-plane of a piece of stripline formed by a flat conductor of width w at distance d from the surface (Fig. 2).

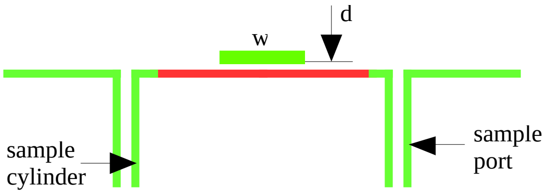

Figure 2: Stripline of width w at distance d from sample.

For this geometry and $d/w<<1$ the RF field energy concentrates between conductor and ground-plane with, to first order, homogenous electric and magnetic fields i.e. a RF current I in the conductor generates on the sample a field strength of approximately $H = I/w$ (independent of d). A two-wire transmission line perpendicular to the sample disk (see Fig. 3) may now be used to feed current into the stripline and, placing this ensemble in a symmetry position with respect to the sample cylinder, the integrated displacement current can be made zero. Choosing further a resonant length of the two-wire feeder line which places an electric field zero on the sample's centre we will also have little sensitivity to deviations from perfect symmetry. It should be noted that here the design differs radically from the triaxial cavity approach [4] where the E-field maximum coincides with the sample's centre.

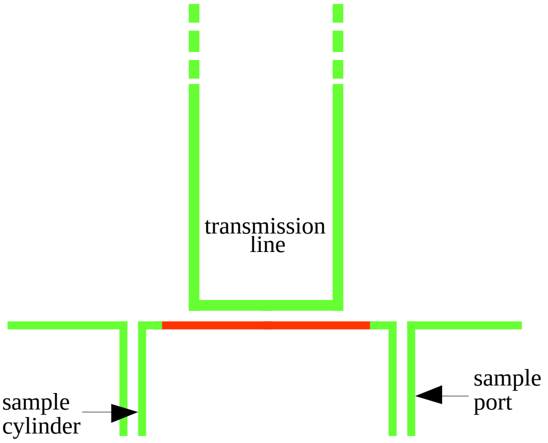

Figure 3: Stripline piece fed by two-wire transmission line. Compared to Fig. 2 the viewing angle is turned by 90°.

Fields in the annular gap around the sample cylinder can now only have the form of coaxial waveguide modes. Here the dipole mode with a cut-off wavelength of $\lambda_d \approx \pi D$ will dominate. D is the sample diameter.

2.2 Quadrupole symmetry

Arrived at this stage a further step seems evident: mounting *two* such resonant line circuits side by side on the sample will increase the illuminated surface area. But the two circuits also form a system of coupled resonators which may be excited in either their zero- or their π-mode. In the second case — with appropriate geometrical symmetry — we may suppress the dipole component and in the gap only the quadrupole mode (and higher-order modes) will subsist, with a cut-off wavelength shorter by a factor two: $\lambda_q = \lambda_d/2 \approx \pi D/2$.

The two stripline pieces are bent to form a *ring* (concentric with the sample disk) and interrupted at two opposite sides where the rods of the two feeder lines are attached. At their other side, in a resonance producing distance of about $\lambda/2$ from the ring the four rods end on the cover-plate of the cylindrical screening enclosure which surrounds the whole set-up. Regarding the rods as the conductors of a screened *four*-wire transmission line, excited in its *quadrupole* mode, we may call the device a *quadrupole resonator*.

2.3 Mechanical construction

After a copper model was built and verifying measurements were done, the instrument was constructed in bulk Nb technique using Conflat® seals for the brazed stainless-steel flanges. Details are given in a companion paper [5].

3 FIRST TESTS AND CALIBRATIONS

3.1 The test sample

For first tests of the resonator a sample cylinder manufactured from Nb sheet material with known thermal and BCS surface resistance was prepared. The front disk of this cylinder carries on its inner side (in vacuum) two calibrated diode thermometers and a 1 KΩ metal-film heater resistor which serve to vary the temperature of the front disk and to measure RF dissipation by substitution [6]. Here we make use of the heat resistance of the sample cylinder's wall and of appropriate heater powers to establish, with RF on and off, a specified constant temperature difference between the front disk and the base of the cylinder (which via its flange is in good thermal contact with the 1.8 K liquid helium bath).

We employ a pressure regulator to keep bath pressure fluctuations below 1 mBar. Heater power and temperature measurements have resolutions of the order of μW's and μK's respectively. Note that the RF dissipation P_{diss} is determined from differences of heater power measurements. Its relative error must increase when RF field-strength decreases. RF excitation is monitored by the transmitted RF power P_t from an output coupling loop.

3.2 Calibration for surface resistance measurements.

We will now show that measuring both P_{diss} and P_t at appropriate temperatures allows the RF surface resistance R_s of the sample disk to be determined at any temperature.

From first principles we may assume that P_{diss} is *proportional* [1] to both R_s and P_t:

$$P_{diss} = g\, R_s P_t$$

g is an apparative constant depending for a given output coupling only on the *geometry* of the apparatus and especially on the chosen distance d between stripline and sample surface g = g(d). The RF surface resistance of superconducting niobium (and other materials) can be written as the sum of two terms:

$$R_s = R_{BCS}(T) + R_{res}$$

The residual resistance R_{res} is independent of T but depends on surface preparation and is hence poorly known. R_{BCS} in contrast depends on bulk properties, is for Nb well known and decreases strongly with T in such a way that $R_{BCS} << R_{res}$ at 1.8 K. Measuring on the Nb calibration sample P_{diss} for a same $P_t = P_{t0}$ at the two temperatures 4.2 K and 1.8 K and taking the difference ΔP_{diss} of the measured dissipations it follows that

$$\Delta P_{diss} = g\, R_{BCS}(4.2)\, P_{t0} \quad .$$

g can now be calculated and for any sample or P_t :

$$R_s = (1/g)(P_{diss}/P_t) \quad .$$

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[1] As in cavity work we assume that, to first order, R_s does not depend on the applied magnetic field amplitude.

At the resonator frequency of 400 MHz and for the reactor-grade Nb quality of the test cylinder the BCS surface resistance is ≈ 60 nΩ at 4.2 K.

It is remarkable that R_S can be measured for *any* sample without a detailed knowledge of the field distribution at the sample surface once, with the help of a known sample, g(d) has been determined.

The sample distance d is difficult to measure but, since also the mode frequency f is a function of d, a convenient way out is to determine g as a function of f.

3.3 Average magnetic field amplitude

We may also make a meaningful estimate of an *average* magnetic surface field amplitude H_{av} on the sample disk.

$$P_{diss} = \frac{1}{2}\iint R_s H^2 ds \approx \frac{1}{2} R_s \iint H^2 ds = g\ R_s P_t$$

$$\Rightarrow\ SH_{av}^2 = \iint H^2 ds = 2gP_t$$

S in the second expression is the illuminated sample surface and indeed there is arbitrariness in its choice. Taking for S the stripline's projected surface on the sample disk we calculated the average magnetic surface field amplitudes used in the following plots of $R_S(T)$ against H_{av}.

As we see, above $H_{av} \approx 50$ A/cm the scatter of plotted points within the five series of measurements at 4.2, 3.8, 3.5, 3.2 and 2.5 K is comparable to the scatter familiar from cavity work. The statistical uncertainty of measurement appears to be similar for both methods. Cavity results are also well reproduced with respect to the range of R_S values obtained and to their magnetic field amplitude dependence.

4 CONCLUSIONS

An apparatus has been conceived, constructed and manufactured which allows at 400 MHz measurement and comparison of the surface resistance of sc films deposited on the front disk of a test cylinder with an Nb side wall. A validation test with a full Nb cylinder demonstrated that field strengths as high as in 350 MHz cavities can be reached and that the employed calorimetric method of dissipation measurement is sensitive enough to see surface resistances of the order of nΩ's.

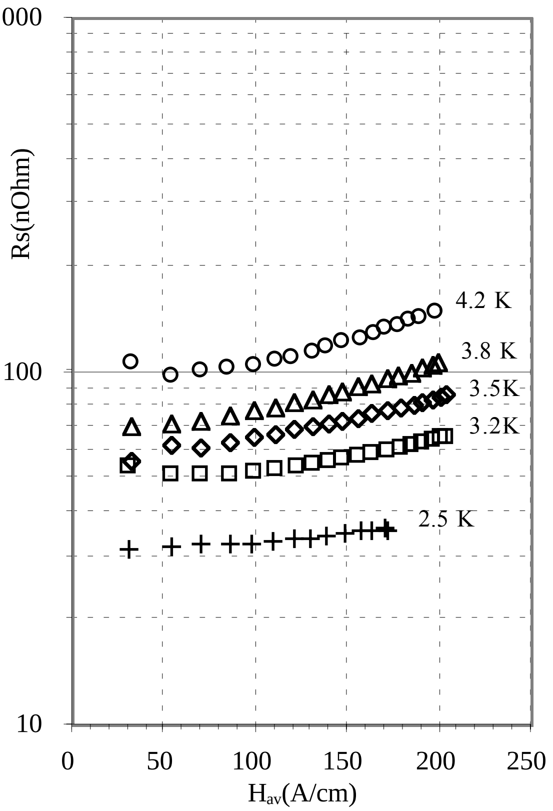

Figure 4: Results of first validation measurements on an Nb test cylinder.

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