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RF Surface Resistance Measurements of High T_c Superconducting Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O samples

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Abstract

In order to extend our knowledge of rf performance of High T_c Superconductors, (HTSC), we have measured rf surface resistance and break-down magnetic fields of YBCO and BSCCO pellets. These pellets were exposed, inside a superconducting Niobium cavity ($T_c = 9.2\ K$), to an increasing electromagnetic field.

At $f = 4.8\ GHz$ and $T = 4.2\ K$ the rf minimum surface resistance for the YBCO samples were $1.7 \cdot 10^{-2}\ \Omega$ and $10^{-1}\ \Omega$, while for the BSCCO system we obtained $2 \cdot 10^{-2}\ \Omega$.

By increasing the power into the cavity that is the applied magnetic field, the BSCCO sample showed only a slow rise, while in the case of the two YBCO samples investigated a drastic increase of the rf surface resistance was recorded.

The rf surface resistance at the break-down magnetic fields of the YBCO pellets were $2 \cdot 10^{-2}\ \Omega$ and $2 \cdot 10^{-1}\ \Omega$ while for the BSCCO sample we obtained $3 \cdot 10^{-2}\ \Omega$.

The break-down fields of the three cases correspond to surface current density, estimated according a simple skin effect theory, of about $5 \cdot 10^5 A/cm^2$, $7 \cdot 10^5\ A/cm^2$ and

$2 \cdot 10^6\ A/cm^2$.

The ratio

$$\frac{R_s(4.2\ K)}{R_s(T_c+)}$$

indicates that respectively 1.3%, 2.2% and 0.5% of the three samples is non superconducting at liquid helium temperature.

Introduction

High T_c Superconductors have arosen a great interest since their discovery, because they seemed to enlarge the potentialities of superconductivity.

As a step in our search for new materials for applications in future accelerator cavities, we have investigated by radiofrequency the systems Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O. The former ($T_c \approx 90\ K$) seems to have great potentialities because its extrapolated thermodinamic critical field is 1 T [1]. Such value would correspond to an accelerating electric field of about 200 MV/m! The latter is a recent compound with a still higher T_c ($T_c \approx 110\ K$).

Theoretical concepts

When a cavity is fed by rf energy, part of it is stored in the cavity and part is lost in ohmic heating of the cavity walls. The Q_{walls} factor measures the losses of the cavity walls; in fact

$$Q_{walls} = \frac{\omega_0 W}{P_{walls}} \tag{1}$$

where ω_0 is the resonant frequency, W is the stored electromagnetic energy and P_{walls} the power lost in the cavity walls.

When a sample is put inside the cavity, the factor Q_{walls} will no longer be the figure of merit of the cavity alone because we must consider also the Joule losses of the sample. The figure of merit "Q unloaded" will now be

$$\frac{1}{Q_0} = \frac{P}{\omega_0 W} = \frac{1}{Q_{walls}} + \frac{1}{Q_{sample}} = \frac{P_{walls}}{\omega_0 W} + \frac{P_{sample}}{\omega_0 W} \tag{2}$$

where Q_0 can be related to the "Q loaded" (which considers the effect on resonance of the coupling system) by the relation:

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{external}} = \frac{P}{\omega_0 W} + \frac{P_{rad}}{\omega_0 W} \tag{3}$$

where P, P_{walls}, P_{sample}, P_{rad} are respectively power losses due to cavity and sample, losses of the walls only, of the sample only, power loss radiated by the cavity.

As Joule losses of the Niobium cavity ($T_c = 9.2\ K$) at 4.2 K are orders of magnitude less than HTSC ones, a Niobium cavity is a useful microwave laboratory; below T_c, in fact, the whole measured loss is to be attributed to the sample. From this loss we get information about rf physical properties of the HTSC.

The electric field induced in the sample by the time-varying magnetic field scales as the pulsation ω and therefore Joule losses will be expected to be proportional to ω^2. But they must be proportional to the number n_e of unpaired electrons: below $\frac{T_c}{2}$, n_e will be proportional to $\exp(-\frac{\Delta}{kT})$, Δ being interpretable as the binding energy per electron in a Cooper pair.

Joule losses P_L depend on the rf surface resistance of a cavity by the relation

$$P_L = \frac{1}{2} R_s \int_A H_s^2 dA \tag{4}$$

and so an analytic approximation for R_s is

$$R_s = A \frac{\omega^2}{T} \exp\left(-\frac{\Delta}{kT}\right) + R_{res} \tag{5}$$

where R_{res} seems to be connected to normal conducting impurities on the surface of the cavity.

These losses are inversely proportional to Q_{walls} and between R_s of the walls of the cavity and Q_{walls} holds the relation:

$$R_{s,walls} = \frac{G}{Q_{walls}} \tag{6}$$

where G, indipendent of frequency, is the geometry factor of the cavity. When a sample is present a similar relation holds between R_s of the sample and Q_{sample}

$$R_{s,sample} = \frac{\Gamma}{Q_{sample}} \tag{7}$$

A magnetical characterization of R_s needs a definition of the applied magnetic field. Applied surface magnetic field H_s, power into the cavity P_i and Q factor Q_0 are related by the following expression:

$$H_s = K_M \sqrt{P}_i Q_0 \tag{8}$$

where K_M is a costant.

Samples

Our samples were:

1) sample VDV - YBCO parallelepiped (7.1 mm, 2.1 mm, 1.6 mm) fabricated at the Istituto di Chimica Fisica of the University of Genoa starting with stoichiometric amounts of yttrium oxide, copper oxide and barium carbonate. Powders have been reacted at 950 C for 18 h in fluent O_2 and then slowly cooled till 50 C in 3 h. Powders have then been macinated till grains dimensions became $< 50\ \mu m$. Sinterization temperature have been 980 C for 18 h in fluent O_2.

Density was about $3.7\ g/cm^3$, $\frac{\rho(300\ K)}{\rho(100\ K)} = 1.73$, $T_c = 90.1\ K$, $\Delta T_c = 3.4\ K$.

2) sample LMI - YBCO cylinder (diameter 8 mm, 3 mm high) fabricated at Europa Metalli - LMI Research Center starting with stoichiometric amounts of yttrium oxide, copper oxide and barium carbonate. Powders have been reacted at 930 C for 15 h in fluent oxigen and macinated. Three other heat treatments took place (940 C for 15 h in fluent O_2; 450 C for 15 h in fluent O_2; 300 C for 1 h in air) before sinterization at 940 C for 15 h. Then two other heat treatments (650 C for 3 h; 450 C for 10 h) [2].

The density was $\approx 75\%$ of the theoretical value and stoichiometry was:

$Y_{1.02\pm0.05}Ba_{1.97\pm0.09}Cu_xO_{6.8}$.

From resistivity measurements $\frac{\rho(300\ K)}{\rho(100\ K)} \approx 1.5$, $T_c = 91\ K$, $\Delta T_c = 1\ K$.

3) sample ITM - BSCCO cylinder (diameter 13.2 mm, 1.6 mm) fabricated at CNR-ITM laboratories at Cinisello Balsamo by the citrate polimeric precursors (CPP) method [3].

Experimental

In Fig.(1) the experimental set-up of the cavity is shown. A moving antenna feeds rf power from the amplifier into the cavity, while a fixed antenna takes the transmitted power to a spectrum analyzer. A moving antenna was necessary to maximize the power entering the cavity.

We put the pellets inside the cavity in a region of uniform and high magnetic field (Fig.(2)).

At 4.2 K the host cavity is superconducting so that Joule losses from the sample can be measured.

Q factor measurements were made by means of the decrement method. In pulsed operation, when the rf generator is switched off, the transmitted power from the cavity is:

$$P_T\ \alpha\ \exp\Big(-\frac{\omega t}{Q_L}\Big) \tag{9}$$

Two sets of measurements as a function of the increasing surface magnetic field were undertaken with and without the sample for each sample. In the first case, by measuring Q_L we obtain Q_0, while in the second we get Q_{walls}. As a difference we have Q_{sample} (2) which is related to the rf surface resistence of the sample by (7). In our case $\Gamma = 8.3 \cdot 10^3$.

Results

RF surface resistance vs. applied rf magnetic field (duty cycle 50%) of our samples are shown [4].

1) Fig.(3) shows the R_s vs. H_s pattern for sample VDV. A plateau is visible till a break-down field of about $H_s = 740\ A/m$ when a marked increase of the R_s is visible. The current density, corresponding to this field, estimated by a simple skin effect theory, assuming a penetration depth of about 1400 A, is about $5 \cdot 10^5\ A/cm^2$; it is a typical value for critical density current and therefore this abrupt rise in surface resistance could be hint of transition for sample VDV.

The residual restance was $R_{res} = 1.7{\cdot}10^{-2}\ \Omega$ whereas the theoretical BCS contribution in (5) is at least three orders of magnitude less.

2) Sample LMI shows a rise of R_s within a very weak field (a few G) Fig.(4); this behaviour reminds us of "weak links" effect noted on similar samples by magnetization measurements. Then R_s mantains a costant value till 1000 A/m when the increase in power is not sufficient to compensate Q_0 decrease (8) so that R_s increases with a drop in the applied magnetic field. 1000 A/m means an estimated value for current density $j \approx 7 \cdot 10^5\ A/cm^2$. We could have measured a transition but much more power into the cavity would be needed to investigate R_s behaviour at constant field. Our values are comparable with measurements done at the Wuppertal University [5]. The Wuppertal group notes a remarkable increase in R_s at an applied magnetic field of about 700 A/m.

The residual restance was $R_{res} = 10^{-1}\ \Omega$.

3) In Fig.(5) the R_s vs. H_s plot for the BSCCO ITM sample is visible. A slow increase of R_s that is a slow degradation of the Q_0 of the cavity seems to be due to the granular nature of the HTSC. The thermal contact between grain and the bulk is, in fact, poor so that rf losses in single grains heat them up above T_c. Increasing the field means then raising the percentage of non superconducting grains.

The residual restance was $R_{res} = 2 \cdot 10^{-2}\ \Omega$.

The maximum field ($H_{max} = 2300\ A/m$) corresponds to a power of 18.6 W into the cavity.

For a penetration depth at 4.2 K of about 1400 A we get that the surface current density is $1.7 \cdot 10^6\ A/cm^2$. This value has not comparable measurements in the literature yet.

Conclusions

RF superconductivity measurements on Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O samples have provided useful information on their charge transport properties.

Their rf surface resistance at T = 4.2 K and f = 4.8 GHz and low field level are greater than $10^{-2}\ \Omega$. These values are too high to evaluate their Δ from (5). These high values are attribuable to still imperfect contacts between grains.

The ratio

$$\eta = \frac{R_s(4.2\ K)}{R_s(T_c+)}$$

indicates the percentage of the sample which, at 4.2 K, is still non superconducting. This is therefore an evaluation of the quality of the sample.

$\eta = 1.3\%$ for sample VDV

$\eta = 2.2\%$ for sample LMI

$\eta = 0.5\%$ for sample ITM.

With such η values is not surprising having so high rf residual resistances. Such values are still very high for immediate application as building material in accelerator cavities but progress is being made. In fact, our two YBCO samples have residual resistances whose ratio is 5. Refined production techniques may still drop R_{res} of these High T_c Superconductors and make their application for acceleration cavities more attractive than conventional materials.

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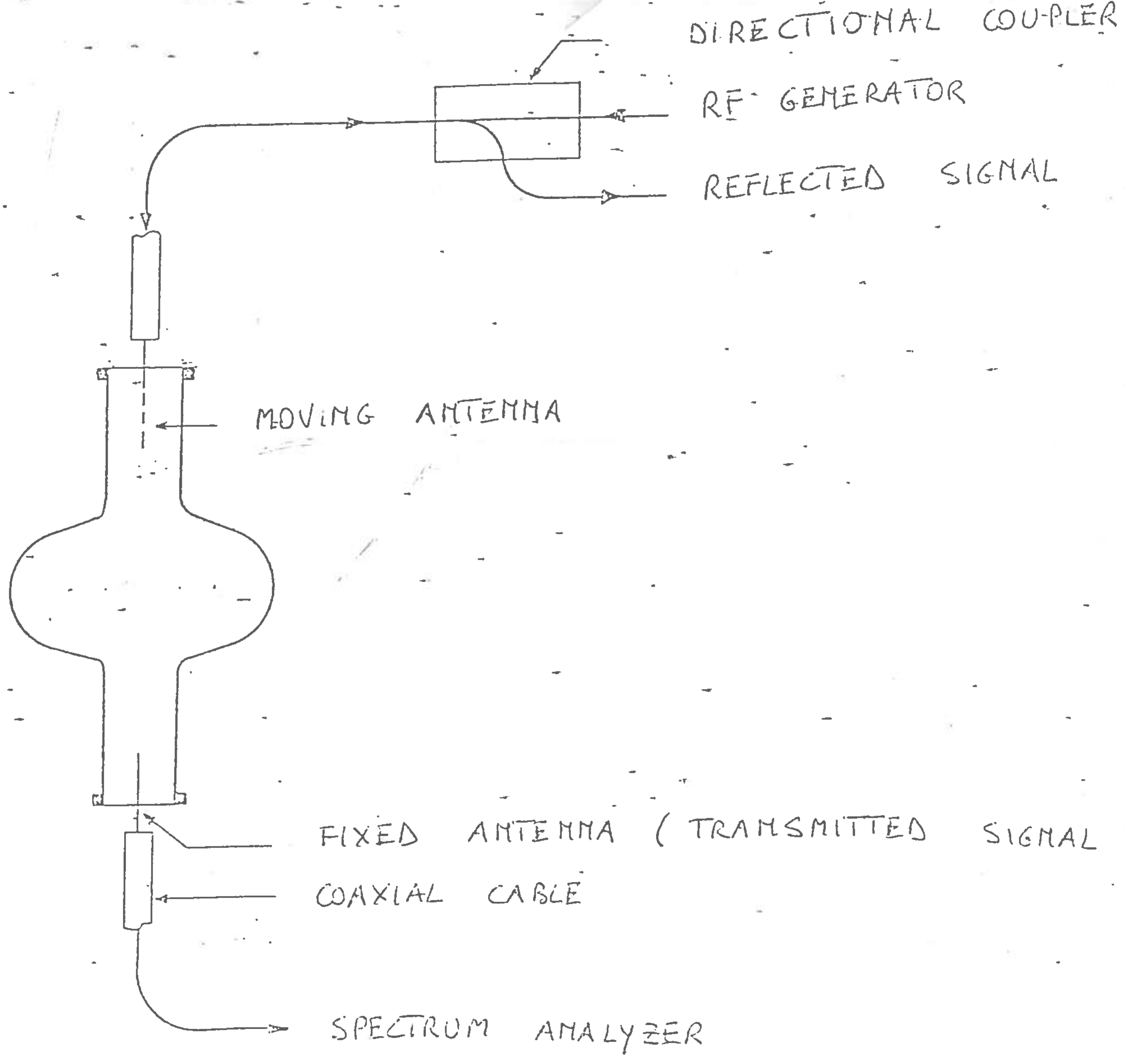

Fig.(1) Schematic set-up of the cavity.

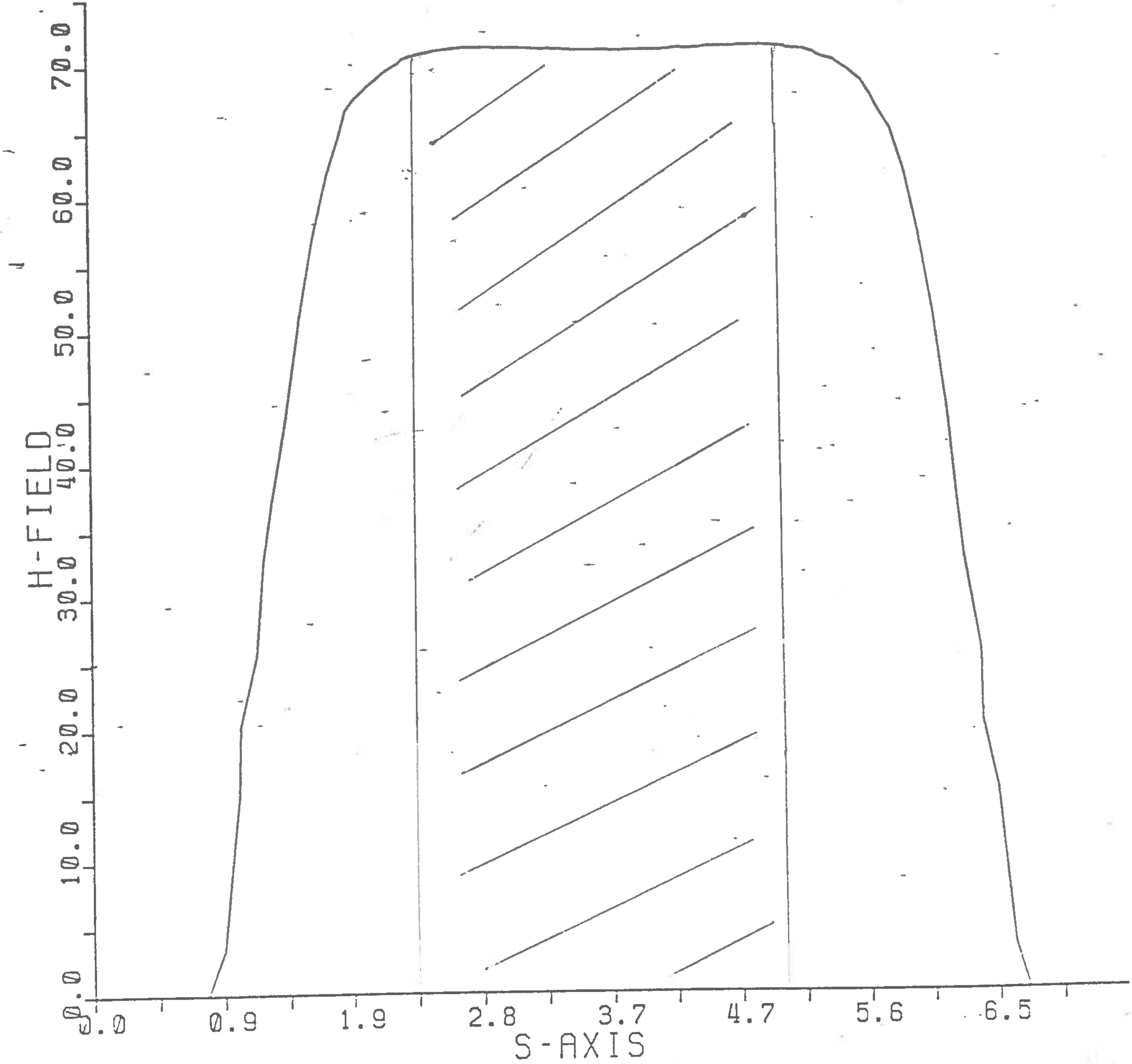

Fig.(2) Computer simulation of the magnetic field on the surface of the cavity as a function of the curvilinear abscissa. The position of the samples is hatched.

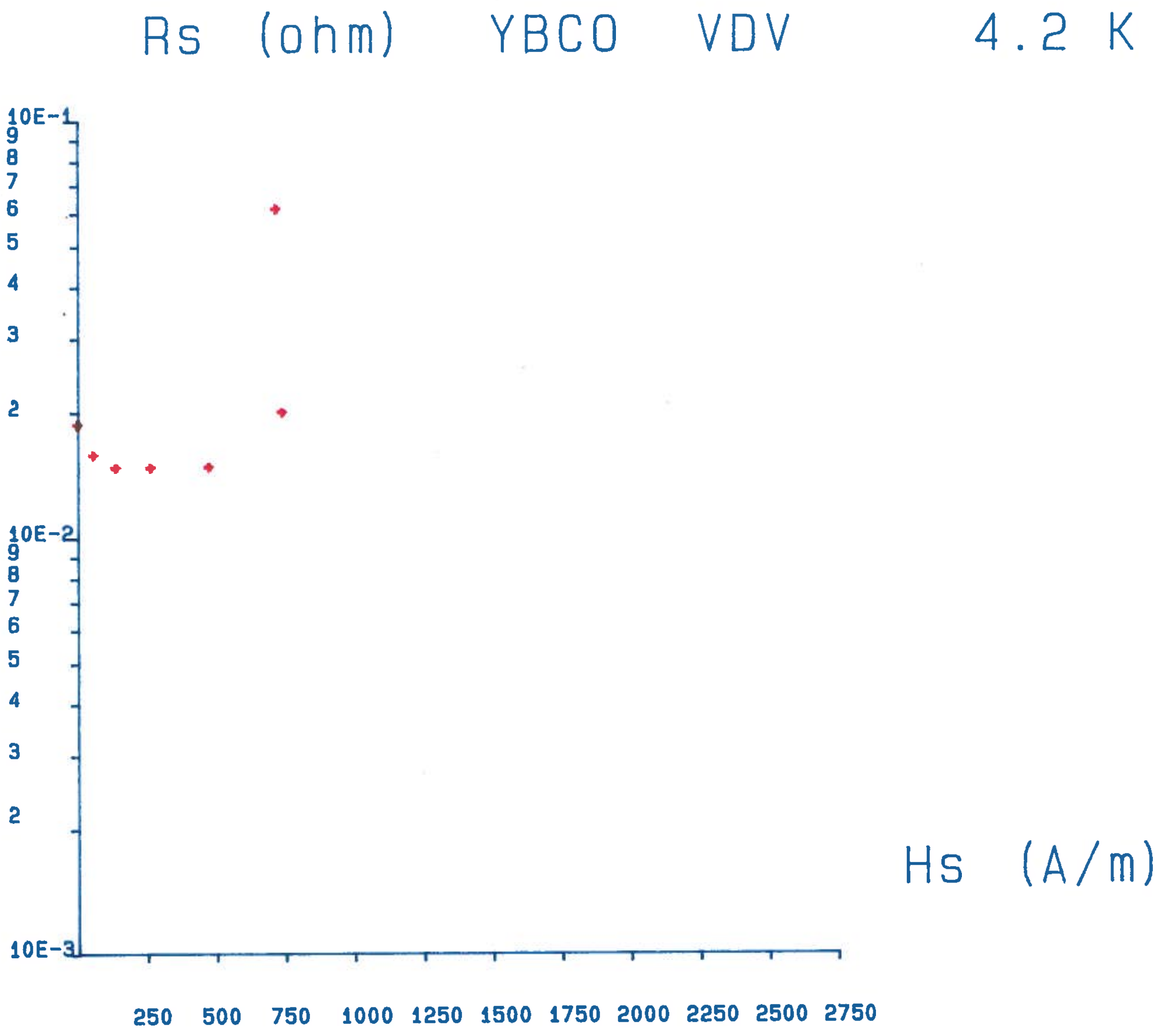

Fig.(3) R_s as a function of H_s for sample VDV.

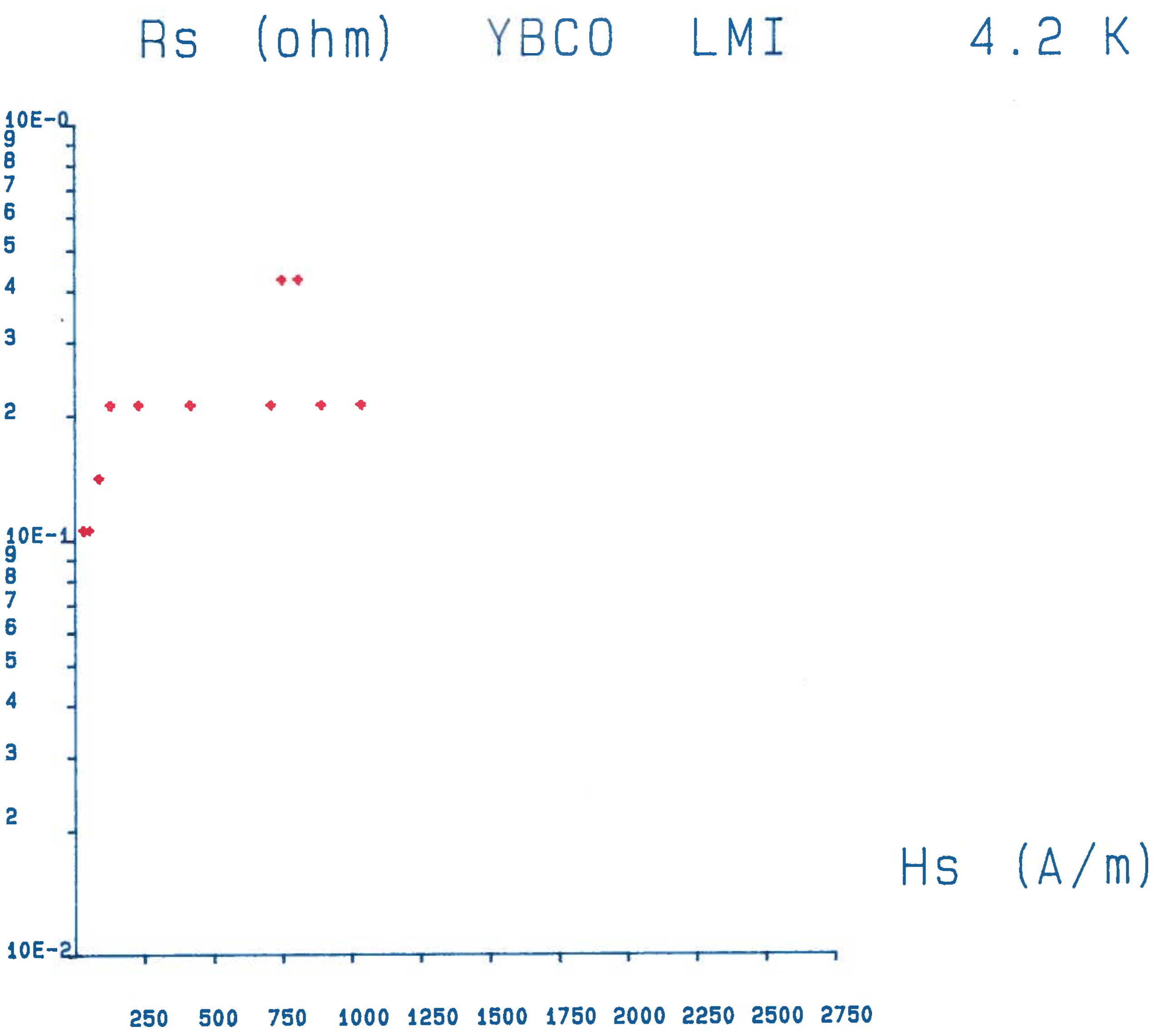

Fig.(4) R_s as a function of H_s for sample LMI.

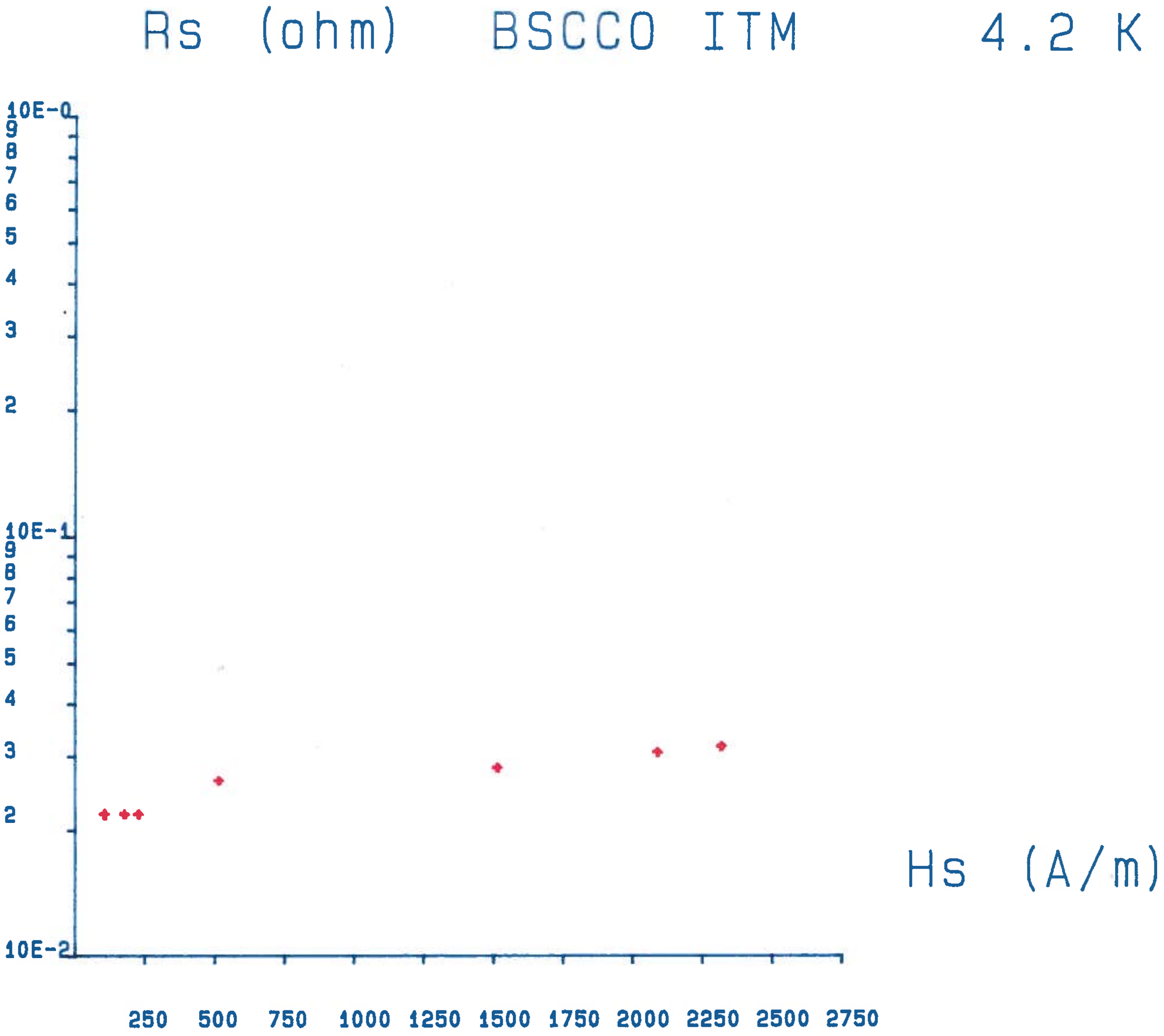

Fig.(5) R_s as a function of H_s for sample ITM.