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FLUXON INDUCED RESISTANCE AND FIELD EMISSION

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Abstract

The surface resistance of superconducting niobium films induced by the presence of trapped magnetic flux, presumably in the form of a pinned fluxon lattice, is shown to be modified by the presence of a field emitting impurity or defect. The modification takes the form of an additional surface resistance proportional to the density of the fluxon lattice and increasing linearly with the amplitude of the microwave above a threshold significantly lower than the field emission threshold. Such an effect, precursor of electron emission, is observed here for the first time in a study using radiofrequency cavities operated at their fundamental 1.5 GHz frequency. The measured properties of the additional surface resistance severely constrain possible explanations of the observed effect.

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1. INTRODUCTION

In a recent publication we reported on a study of superconducting niobium films and of their response to 1.5 GHz microwaves [1]. The study uses radiofrequency cavities operated in the fundamental TM_{010} mode. The cavities are made of copper coated with a thin (1.5 μm) niobium film grown by sputtering on the inside wall. The surface resistance (as a function of temperature and microwave amplitude), the critical temperature and the penetration depth are measured for each film, and the influence of the presence of magnetic flux trapped in the film is systematically investigated. The study covers a wide spectrum of sputtering conditions and results in a variety of films having accordingly a wide spectrum of properties.

In the present note we report on a correlation observed between two phenomena, the occasional presence of field emitted electrons inside the cavity and the dependence on microwave amplitude of the surface resistance induced by the presence of trapped magnetic flux.

The presence of field emitted electrons inside a cavity is one of the main limitations in reaching very large microwave amplitudes and has been the subject of extensive investigations [2-6]. It is generally described as resulting from a Fowler-Nordheim type tunnelling [7] of electrons across the surface barrier at a spot where the amplitude of the electric field is strongly enhanced by the presence of a conducting impurity or defect on the surface. Some doubts still exist on the possible role of an insulating layer between the superconducting surface and the impurity [8,9] but this should not have much impact on the content of the present note. The field emitted electrons are accelerated by the electric field inside the cavity whenever they appear at the right phase with respect to the microwave. Their trajectories usually end elsewhere on the cavity wall where they produce X-rays which can be detected outside the cavity. When the field emission current is large enough, their impacts generate sufficient heat to cause a measurable temperature increase on the outer cavity wall. As all electrons emitted from a point source are expected to impact on a same meridian, a trivial consequence of the cavity geometry, the experimental observation [10] of such a meridian temperature enhancement has been a spectacular demonstration of the validity of the accepted picture. Some electron trajectories, typically in the per mil range, reach through the cavity cut-off to the antenna used to collect the outgoing radiofrequency power. This antenna is capacitively coupled to the radiofrequency circuit in order to measure the resulting electron current. Typical antenna currents are measured in the nanoampere range, corresponding to field emission currents in the microampere range. In principle the presence of field emitted electrons may affect the cavity surface resistance in three different ways: a temperature increase at the emission site, a temperature increase at the impact sites and what is referred to as “electron loading” [11,12]. The first two sources, a direct deterioration of the surface resistance resulting from temperature increases, are relatively unimportant in the low field emission current domain considered in the present work. The third source, electron loading, is indirect. It corresponds to the power absorbed by the electrons in the acceleration process, typically in the watt range (a few MV/m over a few centimetres for a microampere electron current and a duty cycle of the order of 0.3). This power is lost in the cavity wall and is expected to be proportional to the field emitted current and to the excess of the microwave amplitude H_{rf} over the field emission threshold H_{fe}, at least as long as this excess is not too large. It appears as a net power loss in the radiofrequency measurement, being therefore interpreted as an increase ΔR_s of the surface resistance such that the power loss P_{loss} is equal to $\frac{1}{2} \Delta R_s H_{rf}^2$.

The second phenomenon of relevance to the present work is the trapping of magnetic flux in the superconducting film. It was shown in Reference [1] that when a niobium film cavity is cooled down from above the film critical temperature in the presence of a uniform magnetic field H_{ext} of a few gauss parallel to the cavity axis, the magnetic flux is always fully trapped below transition. Moreover, evidence was presented in favour of an important rôle being played in the fluxon pinning mechanism by the noble gas of the sputtering discharge and by the nature of the substrate. The presence of pinned fluxons in the film results in an additional surface resistance R_{fl} which, at a temperature of 1.7 K, takes the form $R_{fl} = (R_{fl}^{0} + R_{fl}^{1} H_{rf})\, H_{ext}$. Here R_{fl}^{0} and R_{fl}^{1} are two parameters which can take vastly different values for different types of films, as illustrated in Figure 1. The temperature dependence of R_{fl} is relatively weak and is measured by $k_{fl} = R_{fl}(4.2K) / R_{fl}(1.7K)$ which typically takes values ranging between 1 and 3. Films grown with a heavy discharge gas, argon, krypton or xenon, on an oxidised copper substrate display particularly low values of R_{fl}^{0} and R_{fl}^{1}, the minimum being reached for krypton, for which $R_{fl}^{0} \cong 3$ nΩ/G and $R_{fl}^{1} \cong 0.5$ nΩ/G/mT.

The subject of the present report is the observation, when H_{rf} increases, of a sudden jump of R_{fl}^{1} to a higher value (by typically a few nΩ/G/mT) correlated with the presence of field emission and occurring at a value H_{kink} of H_{rf} significantly lower than the field emission threshold H_{fe}. Such a jump appears as a kink in the graphical representation of the dependence of R_{fl} on H_{rf} and its existence had been already mentioned in Reference [1] where, however, the study of R_{fl} had been restricted to H_{rf} values smaller than H_{kink}.

2. EVIDENCE FOR A CORRELATION BETWEEN FIELD EMISSION AND THE R_{FL} KINK

Most cavities which have been studied display a field emission threshold preventing operation above some H_{rf} threshold, H_{fe}, typically between 20 mT and 50 mT. The threshold is characterised by a sudden increase of the residual resistance, accompanied by the detection of X-rays on top of the cryostat near the cavity axis and by the presence of an electron current on the output antenna. In practice these three phenomena do not occur at precisely the same value of H_{rf}, a trivial consequence of the dependence of the electron trajectories on the position of the emitting site. A precise measurement of H_{fe} is accordingly impossible when the position of the emitting site is unknown, as is generally the case. Emitting sites near the equator will give apparent H_{fe} values higher than those for emitting sites near one of the irises, where the accelerating electric field is comparatively much larger. Throughout the present work H_{rf} values are in fact values averaged over the cavity wall, obtained by simply multiplying the accelerating field by 4.55 mT/MV/m [1], and may differ significantly from the actual H_{rf} values at the points of interest.

The observation of a R_{fl} kink is not as general a feature. It is restricted to cavities having a low value of R_{fl} , *i.e.* to films coated on an oxidised copper substrate (or equivalent, see Reference [1]) in an argon, krypton or xenon atmosphere. This may be because indeed only such films display a kink or, more plausibly, because the jump in R_{fl}^{1} is too small to be observed when R_{fl} is large. Figure 2 illustrates the correlation between the values of H_{kink} and H_{fe} for 34 cavities displaying both a field emission threshold and a R_{fl} kink. It gives evidence for a positive correlation between the two quantities, typically $H_{kink} = H_{fe}$ -10mT or $H_{kink} = 2/3\, H_{fe}$, the latter form giving a better fit to the data. A direct confirmation is provided by a cavity which has been studied before and after the appearance of a field emission site. This cavity was coated with a 1.5 μm thick niobium film grown on oxidised copper using a krypton sputtering discharge. The variables characterising the superconducting properties of the film were measured a first time, a selection of the main variables are listed in Table 1. As there was evidence for field emission near an accelerating field of 10 MV/m, it was decided to rinse the cavity a second time, using again the standard high-pressure water rinsing procedure [1]. However, during this second rinsing operation, a small scratch was accidentally made on the film near the cavity iris. A second measurement of the variables characterising the film properties revealed that they had been essentially unaffected, with however two exceptions (see Table 1): the lowering of the field emission threshold from 43 mT down to 19 mT and the simultaneous lowering of the R_{fl} kink from 26 mT down to 11 mT, thus providing a spectacular and direct demonstration of the correlation between the two phenomena.

3. PROPERTIES OF THE R_{FL} KINK

Figure 3 displays the dependence on H_{rf} of the surface resistance R_s of the scratched cavity measured at 1.7 K for $H_{ext} = 0$ and $H_{ext} = 7.92$ G before and after the scratch was made. At such a low temperature the BCS resistance [1] is so small that it can simply be neglected. Consequently the $H_{ext} = 0$ data are a direct measure of the residual resistance R_{res} and the difference between the $H_{ext} = 7.92$ G data and the $H_{ext} = 0$ data is a direct measure of $R_{fl}(7.92\ \mathrm{G})$. As R_{res} is essentially H_{rf} independent below H_{fe}, the H_{rf} dependence of R_{fl} is directly visible from the $H_{ext} = 7.92$ G data. Several features are illustrated in the figure and deserve some comments.

i) The residual resistance after the scratch was made differs from what it was initially by the simple addition of an approximately exponential term starting at $H_{fe} = 19.3$ mT. Its shape is consistent with a Fowler-Nordheim law for the electron current, modified as it should be by the relation relating ΔR_s to P_{loss} as given above.

ii) When subtracting this additional nearly exponential term from the $H_{ext} = 7.92$ G data measured after the scratch was made, one obtains a line, shown as a dotted line in Figure 3, which continues smoothly the data measured at H_{rf} values lower than H_{fe}.

iii) The R_{fl} kink generated by the presence of the scratch is clearly visible. It occurs at $H_{rf} = H_{kink} = 11.1 \pm 0.5$ mT and, between H_{kink} and H_{fe}, the dependence of R_{fl} on H_{rf} is again linear, but this time with a larger value of the slope, $R_{fl}^{1} \cong 1.44$ rather than 0.65 nΩ/G/mT.

iv) The above comments suggest defining the additional R_{fl} term induced by the presence of the field emitter as $\Delta R_{fl} = \Delta R_{fl}^{1}\ (\ H_{rf} - H_{kink}\ )\ H_{ext}$ for $H_{rf} > H_{kink}$ and 0 otherwise. The proportionality to H_{ext} is not visible from Figure 3, where data are shown for a single non-zero value of H_{ext}, but it can be verified from the mutual consistency of the ΔR_{fl}^{1} values obtained for different values of H_{ext}. For $H_{ext} = 2.64$, 5.28 and 7.92 G we find $\Delta R_{fl}^{1} = 0.79 \pm 0.10$, 0.76 ± 0.06, and 0.79 ± 0.03 nΩ/G/mT respectively. Moreover the data taken at different values of H_{ext} give mutually consistent values of H_{kink}, 10.9 ± 1.0, 10.9 ± 0.7 and 11.1 ± 0.5 mT respectively, which justifies the form of the expression written above for ΔR_{fl}.

Table 1

Variable	First measurement	Second measurement
T_c [K]	9.458 ± 0.013	9.466 ± 0.014
Δ [K]	18.26 ± 0.85	18.23 ± 0.40
R_{BCS}(4.2K) [nΩ]	444 ± 14	444 ± 9
R_{fl}^{0}(1.7K) [nΩ/G]	3.87 ± 0.18	3.81 ± 0.14
R_{fl}^{1}(1.7K) [nΩ/G/mT]	0.65 ± 0.03	0.65 ± 0.03
k_{fl}	3.02 ± 0.20	3.16 ± 0.23
$R_{res}(H_{rf}=0)$ [nΩ]	12.1 ± 0.8	14.0 ± 0.8
H_{kink} [mT]	26 ± 2	11.0 ± 0.5
H_{fe} [mT]	43.2 ± 2.3	19.3 ± 1.1

v) Each set of data corresponding to a given value of H_{ext} was measured twice in order to check their reproducibility. Excellent agreement was obtained between the R_s measurements made at a same H_{ext} value but a small drift was observed in the measurement of the antenna current, however corresponding to a negligible shift in H_{fe}. As the antenna current probes only a very small fraction of the total field emitted current, it can be expected to be very sensitive to small changes in the geometry of the scratch, an explanation which seems reasonable in the present case. Correcting for the small shift of the measured antenna current with time, one can look for a possible H_{ext} dependence. While the current threshold is found to be independent of H_{ext}, smaller currents are measured for larger H_{ext} values, by approximately a factor of two when H_{ext} increases from 0 to 10 G. Again this can be easily understood in terms of the defocusing effect of the magnetic field trapped within the cavity volume, the electron trajectories being no longer confined to a meridian plane.

4. REVIEW OF THE KINK CHARACTERISTICS OVER A LARGE NUMBER OF DIFFERENT FILMS

The features described in the previous section on the basis of the data illustrated in Figure 3 are quite general. All cavities with a low enough value of R_{fl} and containing a field emitting site, display a kink in the R_{fl} *vs* H_{rf} curve at a value H_{kink} of the RF amplitude significantly lower than the field emission threshold H_{fe}. In all cases R_{fl} is well described by a form $R_{fl} = (R_{fl}^0 + R_{fl}^1 H_{rf} + \Delta R_{fl}^1\ [\ H_{rf} - H_{kink}]\ )\ H_{ext}$ where the term in the square brackets is to be ignored for $H_{rf} < H_{kink}$ and where H_{ext} must be corrected for a small threshold effect. As noted earlier [1] a better fit to the data is obtained by replacing H_{ext} by $H_{ext} - H_{thr}$, where H_{thr} is a small threshold of typically 0.34 G for films grown on oxidised copper in an argon discharge. More recent studies have confirmed this result and have shown that H_{thr} takes smaller values (typically 0.13 G) for films grown on oxide-free copper and larger values (typically 0.65 G) for films grown on oxidised copper in a krypton discharge. As suggested in Reference [1] such a threshold effect might result from the presence of a large density of normal conducting defects, having dimensions exceeding the coherence length. The threshold would then correspond to the saturation of the defects with magnetic flux. A detailed account of this study will be published elsewhere [13].

The dependence of $H_\Delta = \Delta R_{fl} / \{(H_{ext} - H_{thr})\ \Delta R_{fl}^1\}$ on $H_{rf} - H_{kink}$ is illustrated in Figure 4 for the 34 cavities displayed in Figure 2 (selected for having a low R_{fl} value and for showing a clear field emission threshold). The error bars account properly for the small spread of the data. There is no doubt that a two-straight-lines fit, $H_\Delta = 0$ below the kink and $H_\Delta = H_{rf} - H_{kink}$ above the kink, is the simplest and most sensible way to describe the data. In particular a power law is clearly excluded.

As was shown earlier (Figure 2) H_{kink} and H_{fe} are related by an approximate relation of proportionality, $H_{kink} \simeq 2/3\ H_{fe}$. Other positive but weaker correlations exist between ΔR_{fl}^1 and R_{fl}^1 (Figure 5) and between ΔR_{fl}^1 and H_{kink} (Figure 6), but the spread of the data is larger. One might then expect another positive correlation to relate H_{fe} to R_{fl}^1 as these quantities are indirectly related to each other through the three preceding correlations. However such a correlation would contradict the fact that the two quantities are supposed to have completely different origins: H_{fe} should depend on the accidental presence of a field emitter in the cavity and on its location, while R_{fl}^1 should depend on film properties essentially governed by the nature of the substrate and of the noble gas used for sputtering. Indeed, as shown in Figure 7, no significant correlation is visible between H_{fe} and R_{fl}^1.

5. DISCUSSION OF THE RESULTS

The observed properties of the R_{fl} kink, in particular the facts that H_{kink} is significantly lower than H_{fe} and independent of H_{ext} , and that ΔR_{fl} is linear in both H_{ext} and H_{rf} , severely constrain possible explanations of the effect.

An important conclusion is that the effect is a precursor of electron emission. One may remark that electron emission is in principle already present at H_{rf} values smaller than H_{fe} but is only revealed above H_{fe} by at least one of the three standard signals, X-rays, antenna current and sudden increase of the residual resistance. One may then argue that the presence of trapped flux could be expected to modify the state of the system and possibly lower the value of the apparent field emission threshold. When H_{ext} is increased from zero, one would expect such a modification to make the system evolve smoothly to a new state. Specifically, at least for small enough values of H_{ext} , the additional surface resistance induced by the presence of trapped flux should be proportional both to the current of field emitted electrons and to H_{ext} , and therefore should take the form $\Delta R_{fl}(H_{ext}) \propto H_{ext} \Delta R_{fl}(0)$. But this is in sharp contradiction with the observation that ΔR_{fl} has a linear dependence on H_{rf} (as opposed to the nearly exponential dependence of the electron current) and that the lowering of the apparent field emission threshold is independent of H_{ext} and is already significant for small H_{ext} values. One must therefore conclude that the observed effect is not a mere modification of the standard field emission process but is instead a precursor of it in the sense that it already occurs at lower H_{rf} values where essentially no electron is emitted. This conclusion is independent of the nature of the mechanism held responsible for the increase of the surface resistance. Such a mechanism may be acting on the emission process proper, on the phenomena occurring at electron impact or on the electron trajectories inside the cavity volume (the cyclotron frequency for H_{ext} = 10 G is 0.18 GHz, corresponding typically to no more than a 10° bend), the same conclusion will remain valid.

A consequence is that the effect must be localised near the field emitting site. When there is no electron emission there should be no way for the film to know about the existence of a field emitter except for a very small field enhanced region in its immediate neighbourhood. The effect should therefore be confined to a very small fraction of the cavity area, say at most $(100\ \mu\text{m}/10\ \text{cm})^2$, namely $\cong 10^{-6}$. As $\Delta R_{fl}^{\,1}$, $R_{fl}^{\,1}$ and $R_{fl}^{\,0} \langle H_{rf} \rangle$ are of the same order of magnitude, this implies that one is looking for a mechanism enhancing the RF losses normally caused by the presence of fluxons by at least six orders of magnitude over what they are in the absence of field emitter. Note that with the relatively small H_{ext} values used in the study the density of the fluxon lattice is accordingly low, of the order of 0.5 fluxon per square micron for H_{ext} = 10 G, and only a few fluxons can sense the enhanced electric field induced by the field emitter.

A possible explanation of the effect could be a local increase, by several orders of magnitude, of the surface resistance over a small region around the field emitter, caused by its transition to the normal conducting state. Such a picture would imply that the fluxons act as seeds for the superconducting to normal transition and, in order to preserve the proportionality to H_{ext} , it would be necessary to assume that the normal conducting regions which grow around each fluxon do not overlap (at least as long as H_{rf} does not exceed H_{fe} and as H_{ext} does not exceed $\cong$ 10 G). For such a picture to be quantitatively tenable one needs to assume that the normal conducting area around each fluxon is approximately proportional to H_{rf} - H_{kink} . This is a non trivial but sensible assumption. In a picture where the linear H_{rf} dependence of R_{fl} [13] and R_{res} [14] are seen as consequences of the proximity effect [15], with microwaves acting on reservoirs of normal electrons (the pinned fluxon cores in the R_{fl} case and small normal conducting defects in the R_{res} case) an extension to the ΔR_{fl} case might seem reasonable. However such comments should not be taken more seriously than they deserve, they are only very qualitative and approximate indications for a possible explanation.

One may also consider more unconventional ideas but it must be remembered that a rich set of remarkable scanning tunnelling spectroscopy experiments exist [16-22] which have been performed on fluxon cores in experimental configurations presenting many similarities with that of the present work. These do not reveal any anomaly in the behaviour of the fluxon cores in the presence of electric fields and leave little room for exotic explanations.

While the above discussion is inconclusive, it illustrates the difficulty of finding a simple explanation of the observed phenomenon. One or several of the assertions made in the above discussion may be erroneous, or the physical picture we have of the relevant processes may well be unduly oversimplified, or some major point may have been overlooked. In any case, although not understood, the observed phenomenon is well established and reported here for the first time. To our knowledge, no earlier work could have revealed it.

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Figure 1 - Distribution of different films in the R_{fl}^{1} *vs* R_{fl}^{0} plane. Open symbols are for films grown on oxide-free copper and full symbols are for films grown on oxidised copper. Data points labelled with numbers are films grown using an argon-neon mixture for sputtering, the label indicating the percentage of argon in the mixture. The line passing through the data points and going from the dirty limit (top right corner) to the clean bulk limit (cross) *via* the krypton minimum (left bottom corner) is hand-drawn to guide the eye.

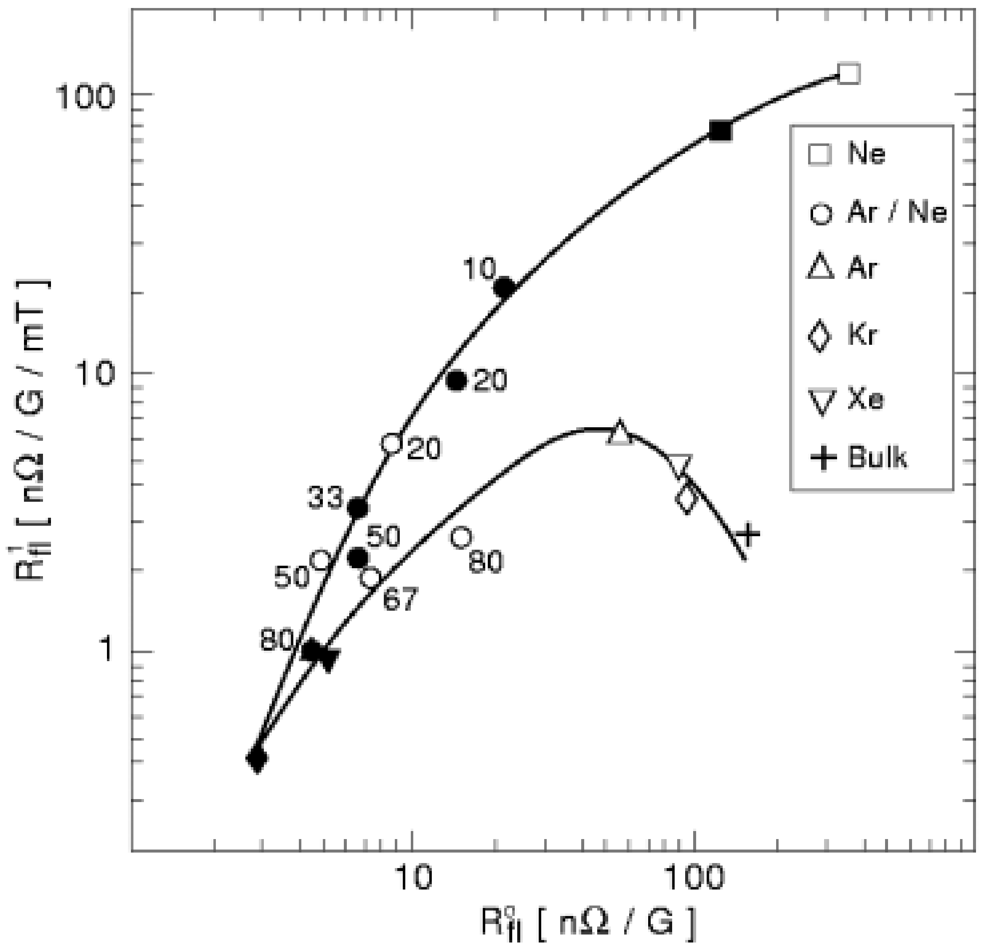

Figure 2 - Distribution in the H_{kink} *vs* H_{fe} plane of 34 films chosen for their low R_{fl} values and for the presence of a clear field emission threshold. The lines correspond to the fits $H_{kink} = 2/3\ H_{fe}$ and $H_{kink} = H_{fe} - 10\text{mT}$.

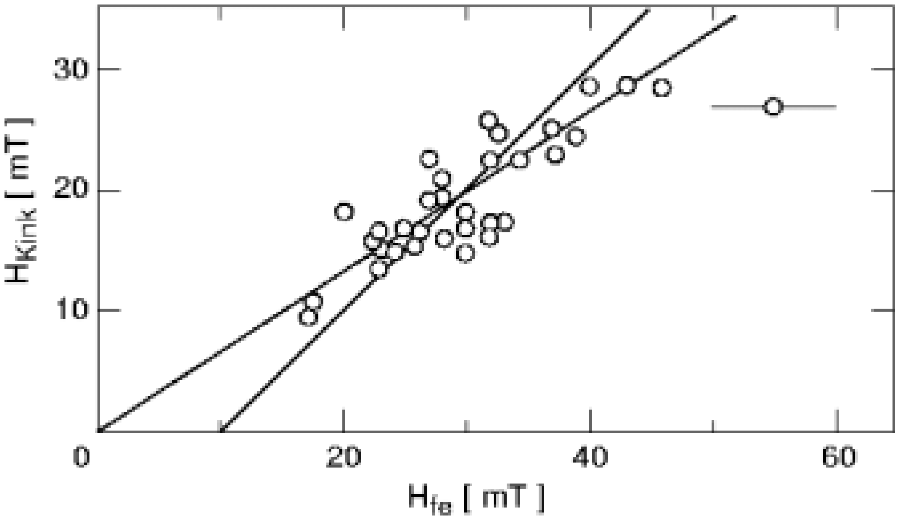

Figure 3 - The scratched cavity data before (crosses) and after (full circles) the scratch was made. The surface resistance measured at 1.7 K is shown for H_{ext} = 0 (lower curves) and for H_{ext} = 7.92 G (upper curves). The insert shows the antenna current I_e (left hand scale) and the X-ray intensity I_x (right hand scale) as a function of H_{rf} [mT].

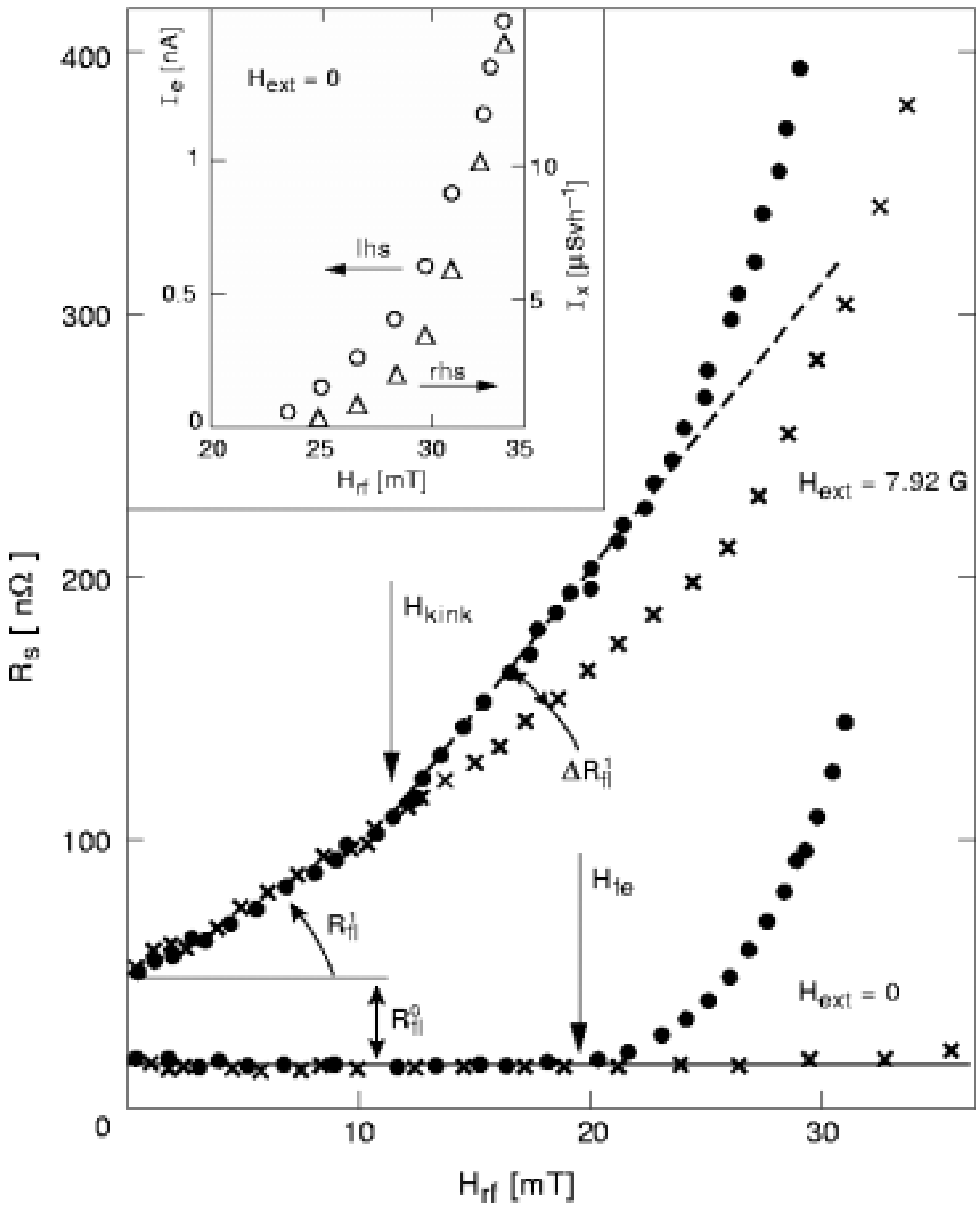

Figure 4 - Dependence of H_Δ (see text) on $H_{rf} - H_{kink}$ for the 34 films selected in Figure 2. The data of the 34 films have been averaged in each bin of $H_{rf} - H_{kink}$ and each error bar has been increased by a factor (typically of the order of 3) taking into proper account the spread of the data.

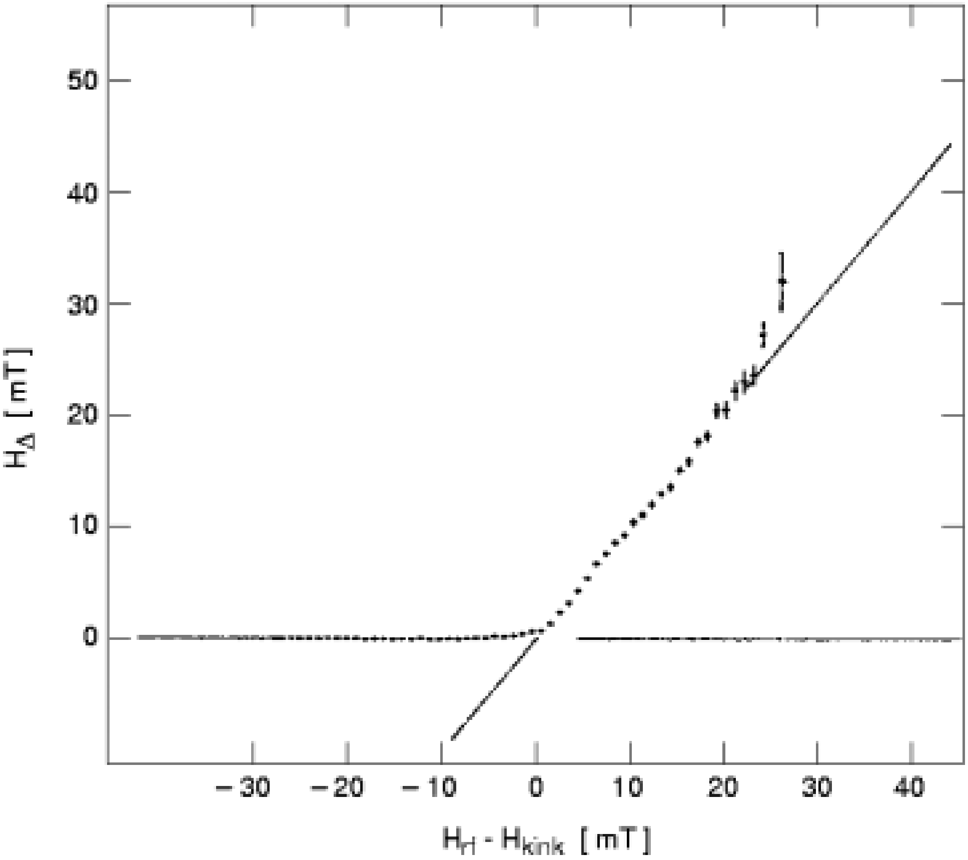

Figure 5 - Distribution of the 34 films of Figure 2 in the ΔR_{fl}^{1} *vs* R_{fl}^{1} plane.

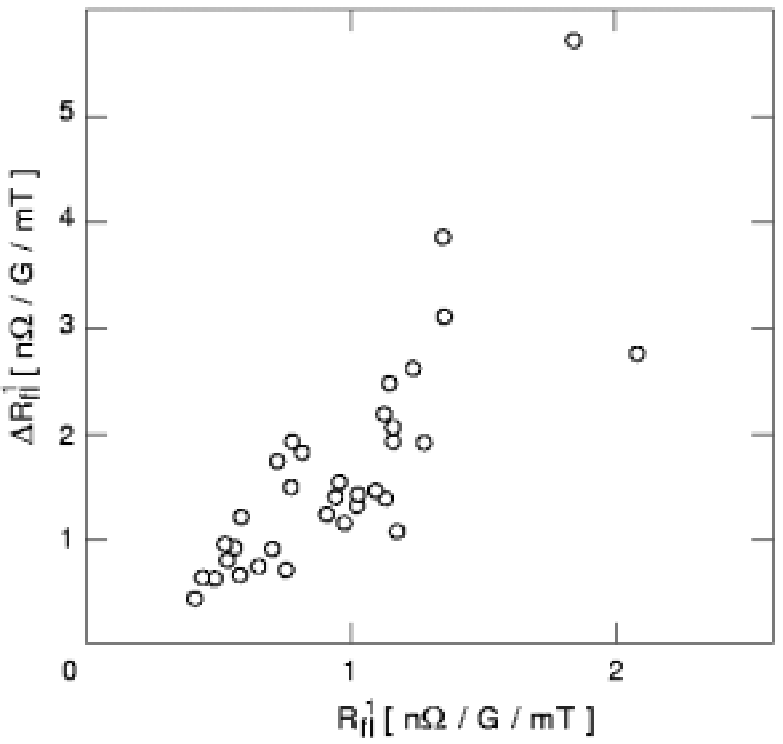

Figure 6 - Distribution of the 34 films of Figure 2 in the ΔR_{fl}^{1} *vs* H_{kink} plane.

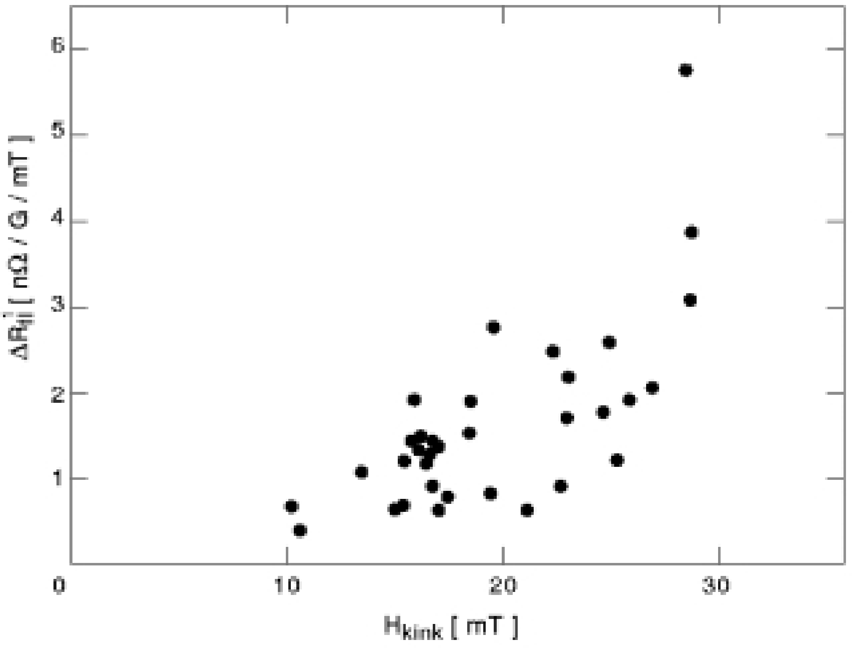

Figure 7 - Distribution of the 34 films of Figure 2 in the H_{fe} *vs* R_{fl}^{1} plane.