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RESIDUAL RF SURFACE RESISTANCE DUE TO TRAPPED MAGNETIC FLUX

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Residual RF surface resistance due to trapped magnetic flux

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Abstract

Surface resistance due to trapped flux is theoretically established for type II superconductors with a Ginzburg-Landau parameter both above and near the limit $1/\sqrt{2}$ which separates the two types. The expression for Niobium is compared to a compilation of the different measurements of sensitivities to magnetic flux. The consequences of trapped flux on the behaviour of superconducting RF cavities are discussed.

Keywords [7460] [7460G]

Introduction

The understanding of the causes of residual surface resistance of superconductors is an important topic for fundamental and practical applications (e.g superconducting cavities accelerators).

Magnetic flux lines pervading a superconductor is now a well documented (ref. 1) cause of RF dissipation in superconductors. All the existing theories describing the trapped flux or the mixed state regime are based on the flux line *viscous motion.* Many different approaches can be found in the literature (ref.1), but no synthesis has been attempted so far to cast in a general frame all the possible cases, e.g large or small κ superconductors in large or small static magnetic fields. The only restriction of the present model is that the fluxons will be assumed to be perpendicular to the superconductor surface.

In a previous paper (ref.2), the flux trapping behavior of Niobium and other superconductors was investigated. The main outcome of this study is that 100% of the flux is trapped in Niobium samples cooled in magnetic fields smaller than 3 Gauss. This situation, hereafter called "trapped magnetic flux regime" corresponds to a low fluxon density, and is of special interest because it is encountered in experiments or applications using superconducting RF cavities cooled down in a nonzero magnetic field. From the knowledge of the proportion of trapped flux, the above mentioned theoretical model can be used to evaluate the corresponding RF dissipation. We demonstrate here that dissipation due to trapped flux accounts for a significant proportion of the residual RF surface resistance of superconducting Niobium cavities, even when these cavities are cooled down in carefully shielded cryostats.

Theory

Abrikosov characterized the mixed state of a type II superconductor containing a magnetic field H as a lattice of vortices (density n) of superconducting electrons. Each vortex (or flux line) contains one flux quantum ($\phi_o = \frac{h}{2e}$), a cylinder (or core) of radius ξ approximately in the normal state, surrounded by circulating superconducting electrons at a distance λ.

Most of the previous theoretical studies (ref.1) on surface resistance due to a static magnetic field H concerned this mixed state, though rarely the trapped flux regime. However, we showed experimentally in a previous paper (ref.2) that 100 % of the external magnetic field H present during cool down is trapped in Niobium; pinning centers inside the specimen prevent the Meissner state (expulsion of flux lines) to occur for magnetic field below the lower critical field H_{c_1}.

Vortex dynamics:

Trapped flux is a well known cause of residual surface resistance in superconductors (ref.7). According to L.P. Gor'kov and N.B. Kopnin or Bardeen and Stephen (ref.3), the origin of the dissipation is due to the viscous motion of the vortices under the influence of the Lorentz force $f_L = \mu_o j \times \phi_o$. The viscosity $\eta = \frac{\mu_o \phi_o H_{c_2}}{\rho_n}$, (ref.2) where ρ_n is the resistivity in the normal state, is related to the induction of current through the (normal) core of the vortices during their motion.

Then, forces per unit length acting on a vortex line of velocity v and lineic mass m under the influence of an alternating field are the following:

$$f_L = \mu_o j \times \phi_o \quad \text{Lorentz force}$$
$$\text{(applied only on the penetration depth } \lambda)$$

$$f_\eta = \eta v \qquad \text{Viscous force}$$
$$f_m = m\dot{v} \qquad \text{Inertial force} \tag{1}$$
$$f_r = T\frac{\partial^2 y}{\partial z^2} \qquad \text{Restoring force}$$

where T = dW/dl (W: energy) is the tension (or vortex energy per unit length).

To evaluate the surface resistance, we use an analogy between a magnetic flux line oscillating under the influence of an alternating Lorentz force and a vibrating string of mass m (fig. 1). Above the depinning frequency (ref.5), the pinning force acting on the vortices can be neglected. Moreover, Suhl (ref.16) shows that $m/\eta \sim \tau$ (τ: electronic collision time); we can then neglect the inertial term ($m\omega < \eta$) as it is equivalent to $\tau << 1/\omega$ which is verified for Niobium for frequencies larger than 100 MHz. The equation of motion for the vibrating string (or the depinned vortex) in an alternating field ($H_{RF} = H_{RFo} \exp(i\omega t)$) is then:

$$T\frac{\partial^2 y(z,t)}{\partial z^2} = \eta\frac{\partial y}{\partial t} \tag{2}$$

where z is the depth in material and $y(z,t) = y(0)\ exp\{i(kz - \omega t)\}$ the transverse displacement. The corresponding dispersion relation is:

$$k^2 = -\frac{i\omega\eta}{T} \tag{3}$$

and the oscillation amplitude y(0) is determined by the boundary condition at the surface of the specimen:

$$T\frac{\partial y}{\partial z}|_{z=0} = H_{RFo}\phi_o \tag{4}$$

where H_{RFo} is the RF magnetic field.

Finally, we find the surface resistance R_s due to trapped flux B = n ϕ_o (where n is the vortex density) writing the dissipated power per unit area:

$$P = \frac{1}{2}R_s H_{RFo}^2 = \frac{1}{2}n\omega^2\eta\ y^*(0)\ y(0) \int_0^\infty exp(i(k^* - k)z)\ dz$$
$$= \frac{1}{2}R_n\ H_{RFo}^2 \sqrt{\frac{\phi_o}{2}}\ \frac{1}{|T|}\ \frac{H}{\sqrt{H_{c_2}}}\ \frac{i}{\sqrt{\frac{i}{T^*}} - \sqrt{\frac{-i}{T}}} \tag{5}$$

(we suppose here that 100% of the magnetic field is trapped, so B = μ_o H where H is the external magnetic field) where T is the tension or energy per unit length of vortex; the normal state resistance R_n is equal to ρ_n / δ where ρ_n is the normal state resistivity and δ the skin depth in the normal state. The physics of the problem is now contained in the evaluation of the vortex tension T = dW/dl. So, in the following, we will evaluate T distinguishing different cases depending on the vortex density (or the external field) and the value of the Ginzburg-Landau parameter $\kappa = \lambda/\xi$. Usually, the vortex energy can be separated in three parts: $W = W_{core} + (W_{magnetic} + W_{kinetic})_{supercurrents}$. The first part is related to the contribution of the normal core, the second to the magnetic energy and the third to the kinetic energy of the supercurrents circulating around the core on a radius λ.

extreme type II superconductors: as $\lambda >> \xi$, contribution of the pointlike core to vortex energy is negligible. The contributions from the field energy and the kinetic energy of the currents are the only remaining ones. We distinguished the following cases:

1) *trapped flux regime* ($H \leq H_{c_1}$) : vortices are virtually independent; then using the London equation ($\lambda^2 \, rot \, rot \, h(r) + h(r) = \phi_o \, \delta(r)$) to describe the magnetic field h inside the flux line, the vortex energy per unit length becomes: $T = \frac{dW_{magnetic}}{dl} + \frac{dW_{kinetic}}{dl} = \frac{\mu_o}{2} \int \left(h^2 + \lambda^2 \, |rot \, h|^2\right) dS = H_{c_1} \phi_o$ (ref.6). Injecting this expression in equation (3), we find for the flux sensitivity in the case of 100 % trapped external magnetic field:

$$R_s = R_n \frac{H}{\sqrt{H_{c_1} H_{c_2}}}; \tag{6}$$

the characteristic depth on which fluxon motion occurs is:

$$d = (Im(k))^{-1} = \delta \sqrt{\frac{H_{c_1}}{H_{c_2}}} \tag{7}$$

where $\delta = \sqrt{2\rho_n/(\omega\mu_o)}$ and $R_n = \rho_n$ / δ.

2) *mixed state* ($H_{c_1} < H < H_{c_2}$) : we have to take into account vortice interactions in the expression of energy. It is easier to establish a relation between T and the resistivity ρ proposed by Marcon and al. (ref.1) valid in the mixed state and in the high-frequency range where inertial and pinning terms can be neglected in the motion's equation ($\eta v = j\phi_o \quad with \quad j = j_o \, exp(i\omega t)$). Adding the current due to the electric field produced by the moving fluxon ($E_{motion} = -vB$ where v is the vortex velocity and B the magnetic field inside the specimen):

$$j_{diss} = -\frac{\eta}{\phi_o B} E_{motion} \tag{8}$$

and the superconducting current calculated with the London equation:

$$j_{super} = -\frac{A}{\mu_o \lambda^2} \qquad with \qquad \frac{\partial A}{\partial t} = -E \tag{9}$$

we find the following expression for the resistivity:

$$\rho = \rho_n \frac{H}{H_{c_2}} - i\omega\mu_o\lambda^2 \tag{10}$$

Finally using Maxwell's equations and Ohm's law:

$$rot\, E = -\mu_o \frac{\partial H}{\partial t} \qquad rot\, H = j = \frac{E}{\rho}$$

then

$$k = \sqrt{\frac{i\omega\mu_o}{\rho}} \tag{11}$$

we find for the vortex tension:

$$T = \frac{\eta\rho}{\mu_o} = H\phi_o - i\frac{2\lambda^2}{\delta^2} H_{c_2}\phi_o$$

So, two regimes can be distinguished here:

$$\begin{aligned} H_{c_1} < H << H_{c_2} : \qquad & R_s \simeq R_n \left(\frac{\delta}{2\lambda}\right)\frac{H}{H_{c_2}}, \qquad d \simeq \lambda; \\ H_{c_1} << H < H_{c_2} : \qquad & R_s \simeq R_n \frac{H}{H_{c_2}}, \qquad d \simeq \delta\sqrt{\frac{H}{H_{c_2}}} \ . \end{aligned} \tag{12}$$

The surface resistance due to static magnetic flux in type II superconductors has a linear behavior in the trapped flux regime and near the lower critical field in the mixed state. For higher field, H appears in R_s with a square root.

superconductors between type I and II *($\kappa \simeq 1/\sqrt{2}$):* superconductors like Niobium are characterized by a mixed–intermediate state. Before studying this kind, we will rapidly evaluate the surface resistance for Type I superconductors. Type I does not show a mixed state over a wide range of magnetic field H like type II, but an intermediate state with a coexistence of superconducting and normal macroscopic regions over a relatively small range of H ((1–n) H_c < H < H_c, where n is the demagnetizing coefficient). Normal regions have normal resistance R_n and critical field H_c; then, surface resistance is directly proportional to the specimen surface in the normal state:

$$R_s \simeq R_n \frac{H}{H_c} \tag{13}$$

This expression is valid for any value of H between 0 and H_c and shows a linear behavior.

The intermediate–mixed state of Niobium consists of a coexistence of Meissner (no flux inside) and Shubnikov macroscopic phases. Each Shubnikov region contains a lattice of vortices virtually independent (ref.13) where surface energy ($\propto (\xi - \lambda)$ ref. 14) is equal to zero. It means that the loss of condensation energy on a scale ξ and the gain in energy due to magnetic field penetration on a scale λ balance each other. Thus, contribution of normal core and currents to energy per vortex unit length are of the same order: $T = \frac{dW_{core}}{dl} + \left(\frac{dW_{magnetic}}{dl} + \frac{dW_{kinetic}}{dl}\right) \simeq 2\frac{dW_{core}}{dl}$. The fluxon can be viewed as a normal conducting core of radius $\sqrt{2}\xi$, therefore: $T = 2(\frac{dW_{core}}{dl}) = 2\mu_o H_c^2 \pi \xi^2$. Injecting this expression in (3) gives:

$$R_s \simeq R_n \frac{H}{H_c} \tag{14}$$

Since $H_c \simeq H_{c_2}$ for the particular class of type II superconductors considered here, we regain the well known formula:

$$R_s \simeq R_n \frac{H}{H_{c2}} \qquad d \simeq \delta \tag{15}$$

valid for H between 0 and H_{c_2} if 100 % of magnetic flux is trapped and if we neglect interactions between vortices. So, type II superconductors with $\kappa \simeq 1/\sqrt{2}$ have a linear relation between surface resistance and the trapped magnetic field.

Experiment

Experimentally, the RF dissipation due to trapped flux is usually studied by cooling a superconducting resonator in a known static magnetic field, and by measuring its Q value.

Many experiments are reported in the literature. We repeated one in order to determine the flux trapping behavior of this irregularly shaped object, and to investigate with a thermometer mapping system the repartition of the RF losses due to trapped flux.

We used a single cell accelerating cavity on the TM010 mode at 1.5 GHz, made out of a 2 mm thick high purity Niobium sheet. The cavity was immersed in a cryostat equipped with a solenoid able to produce a uniform static magnetic field B < 3 Gauss at the cavity location. The cavity was equipped with a thermometer arm and with a gaussmeter (Förster probe fixed to another arm) (ref.15) able to rotate along parallels around the cavity axis.

The cavity was measured both in field-cooled and zero field-cooled conditions. As for the disc samples studied in an earlier work (ref.2), the gaussmeter yielded a ratio: $B_{(T<T_c)}/B_{(T>T_c)}$ = 1 (figure 1) compatible with 100% trapped flux in the cavity. The peak present at around 120 degrees on figure 1 comes from the magnetic springs of the thermometers. The springs' magnetic field is trapped during cool down at T_c (9.2 K) and thus, is only detected in the superconductor state. In the normal state, it moves with the thermometer arm and therefore is never measured by the Förster probe.

The surface resistance of the cavity in the superconducting state was measured by the decrement method. The sensitivity of R_s to trapped flux is shown in Fig. 2; the slope is 0.36 nΩ/mG (this value is an average over the cavity area on the TM010 and for a static magnetic field applied parallel to the cavity axis). For a magnetic field inside the cryostat of around 15 milliGauss as in our case at Saclay, the "magnetic" surface resistance is thus about 6 nΩ for a usually obtained total residual resistance of 25 nΩ; this shows that losses due to trapped flux represent a significant proportion of the total residual resistance of Niobium.

A reanalysis of the experimental measures of the surface resistance brought about by flux trapping performed by various laboratories shows that all results (with the exception of Cornell's fired cavities (ref.4)) are compatible with the formula:

$$R_s = R_n \frac{H}{H_{c_2}} \tag{16}$$

where the normal state resistance can be expressed as:

$$R_n = \sqrt{\frac{\omega \mu_o}{2\sigma_n(300K)\ RRR}} \ . \tag{17}$$

Unfortunately, the large uncertainty on the value of H_{c_2} hinders a very precise comparison between theory and experimental results. In the table below, theoretical surface resistance is calculated for Niobium with σ_n = 0.69 10^7 $(\Omega.m)^{-1}$, H_{c2} = 4000 Gauss and the RRR used in the corresponding experiment. To obtain the "corrected sensitivity", we correct the experimental value by a geometric factor, in fact the percentage of cavity's surface perpendicular to the static applied field for the accelerating cavities.

Repartition of the dissipation:

The repartition of the dissipation due to trapped flux was determined by a temperature mapping in subcooled Helium I of a superconducting cavity field-cooled in an uniform magnetic field of 3 Gauss parallel to the cavity axis. Theoretical repartition of the temperature is evaluated from an uniform thermal calculation hypothesis. We calculate everywhere the dissipated power $\frac{1}{2}R_s(T,H)\ H^2_{RFo}$ (where R_s is locally calculated for each thermometer) and we take into account the thermal conductivity λ of the Niobium wall of thickness e with the relation $\frac{\lambda}{e}(T_{in} - T_{out})$ ($T_{in\ (resp.\ out)}$ is the wall's temperature inside (resp. outside) the cavity). Finally, we use a parametrization for the thermal transfer at the interface between Niobium and Helium I, $P = C(\Delta T)^n_{theo}$ where C and n are two coefficient determinated using experimental results (C = 149, n = 1.4). With these three expressions , we determine $(\Delta T)_{theo}{}^i$ for i = 1, 13.

As expected, the maximum heating is located at places where the fluxon density is large, i.e where the surface is roughly perpendicular to the applied field (fig.4). Conversely, the existence of a minimum heating is explained as the result of a zero fluxon density at the cavity's equator. Finally, the non-perfect symmetry of the experimental curve is attributed to convective effects in He I. Keeping this in mind, the quantitative agreement between theory and experiment is excellent. This agreement could even be exploited to calibrate in situ the efficiency of cryogenic thermometers.

Consequences of an improved magnetic shielding:

Finally, using a triplet of solenoids, we reached a residual magnetic field of about a few milliGauss on most of the cavity surface. Moreover, we reduced losses at the ends of cutoff tubes of the cavity and used Niobium of high purity (RRR = 320 instead of 200 usually used). With these ameliorations, a test on an one-cell Niobium accelerating cavity (fig.5) at 1.5 GHz at Saclay showed a Q value of 5.10^{10}, corresponding to a residual surface resistance of 4.22 nΩ (instead of 25 nΩ usually obtained). This is one of the lowest values ever obtained on an accelerating cavity in the GHz frequency range and shows that losses due to trapped flux plays an important role in dissipation.

Conclusion

We present in this paper a theory which allows us to describe the sensitivity to trapped magnetic flux for any type of superconductors and for any magnetic field inside the material. Moreover, we can safely conclude that 100% of the flux is trapped in Niobium superconducting cavities. This result is consistent with the measured surface resistance due to trapped flux in superconducting RF cavities: $R_s = R_n.\frac{H}{H_{c_2}}$. This formula, theoretically justified if one assumes 100% trapped flux, finds thus here an independent confirmation. Finally, we showed that for Niobium cavities made carefully (high RRR and long cutoff tubes) and measured in an improved magnetic shielding, residual surface resistance can be as low as a few nanoOhm. This good result bears some consequences on the technology of particle acceleration by superconducting cavities: Q values as high as a few 10^{10} can reasonably be hoped for well constructed and well used accelerating cavities.

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Figure captions

Fig. 1 Vibration of a vortex in an high frequency magnetic field. d is the wave penetration depth inside the material.

Fig. 2 Trapped flux in the cavity cooled down with a magnetic field of 100 mG.

Fig. 3 The average surface resistance of the cavity wall, as a function of trapped flux. The full line is a calculation assuming 100% trapped flux.

Fig. 4 The measured heating of the cavity due to trapped flux. The full line with Δ symbols is a thermal model calculation assuming 100 % trapped flux, via eq. $R_s = R_n \cdot \frac{H}{H_{c_2}}$

Fig. 5 Surface resistance versus Temperature for the cavity with a residual resistance of 4 nΩ

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Table 1 trapped flux sensibility. The theoretical result of reference 11 can not directly be compared to the experimental result: the value of the RRR is just an estimation.

f (GHz)	RRR	experimental sensitivity	corrected sensitivity	theory	origin (ref.)
0.081	80	0.2 nΩ/mG	0.2 nΩ/mG	0.19 nΩ/mG	Booster (8) (Salay)
0.5	110	0.15 nΩ/mG	0.5 nΩ/mG	0.42 nΩ/mG	CERN (9)
1.5	180	0.36 nΩ/mG	0.63 nΩ/mG	0.57 nΩ/mG	GECS (Saclay)
2.17	30		1.9 nΩ/mG	1.61 nΩ/mG	Karlsruhe (10)
2.65	"		2.17 nΩ/mG	1.8 nΩ/mG	"
3.63	"		2.48 nΩ/mG	2.1 nΩ/mG	"
4.0	180	0.66 nΩ/mG	1.65 nΩ/mG	0.91 nΩ/mG	TE011 (Saclay)
4.87	30		2.82 nΩ/mG	2.41 nΩ/mG	Karlsruhe (10)
5.6	180	0.83 nΩ/mG	1.03 nΩ/mG	1.05 nΩ/mG	TE021 (Saclay)
6.5	around 30	2.65 nΩ/mG		3.4 nΩ/mG	Ibaraki (11)
8.6	100		2 nΩ/mG	1.75 nΩ/mG	Cornell (4)
8.6	100	.45 nΩ/mG		1.75 nΩ/mG	Cornell's Fired cavities (4)
21.5	40		4.25nΩ/mG	4.37 nΩ/mG	Wuppertal (12)

Figure 1

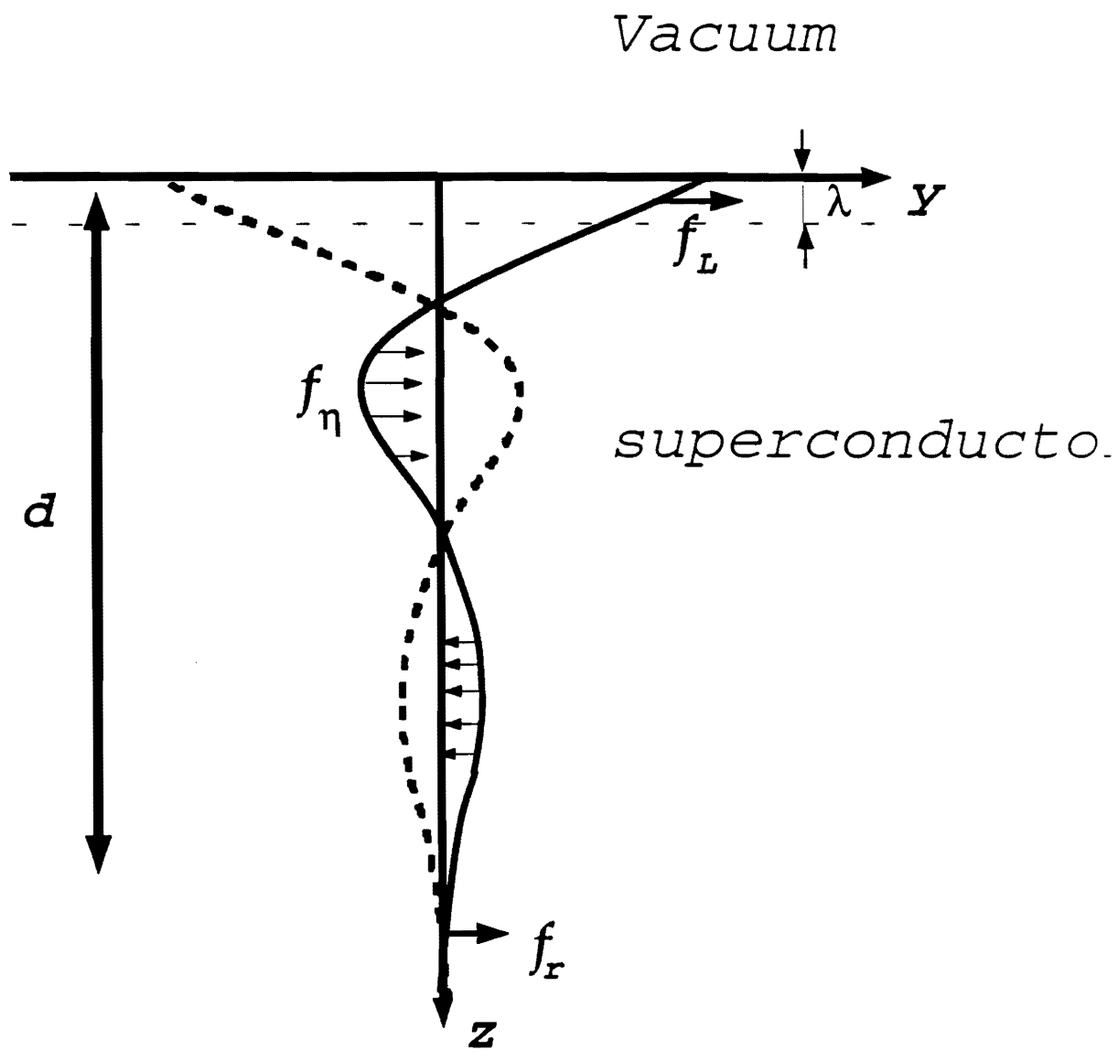


Figure 2

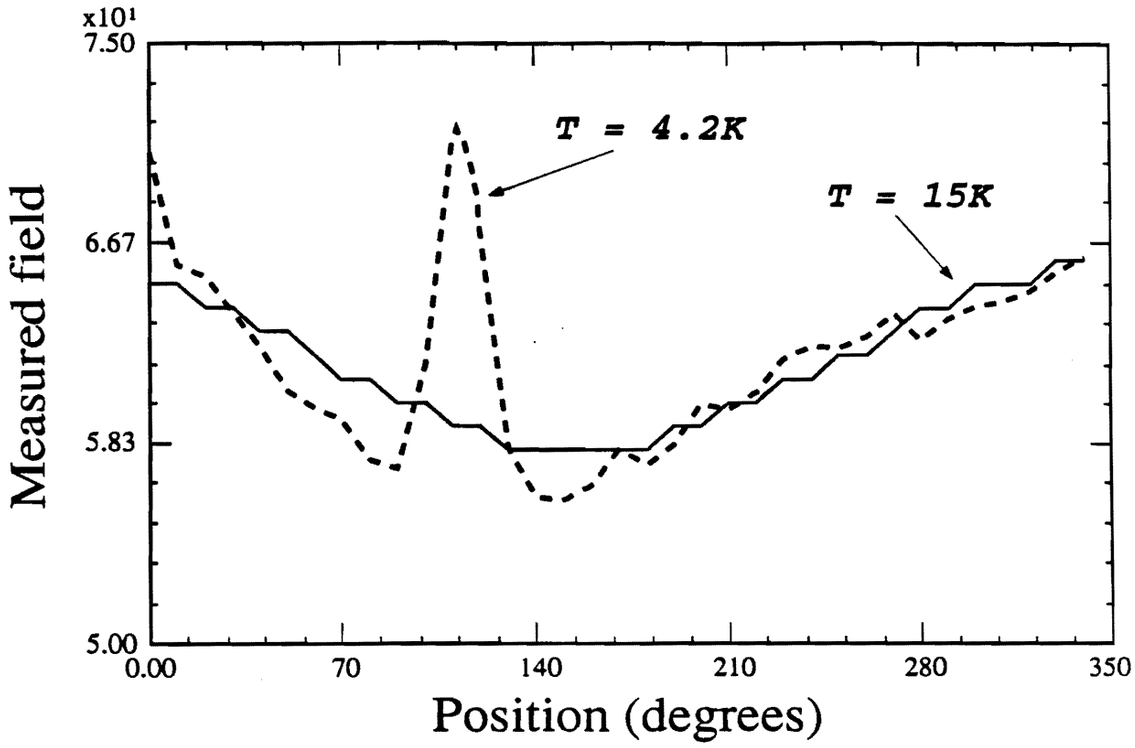

x10¹
7.50
6.67
5.83
5.00
0.00
70
140
210
280
350
Measured field
Position (degrees)
T = 4.2K
T = 15K

Figure 3

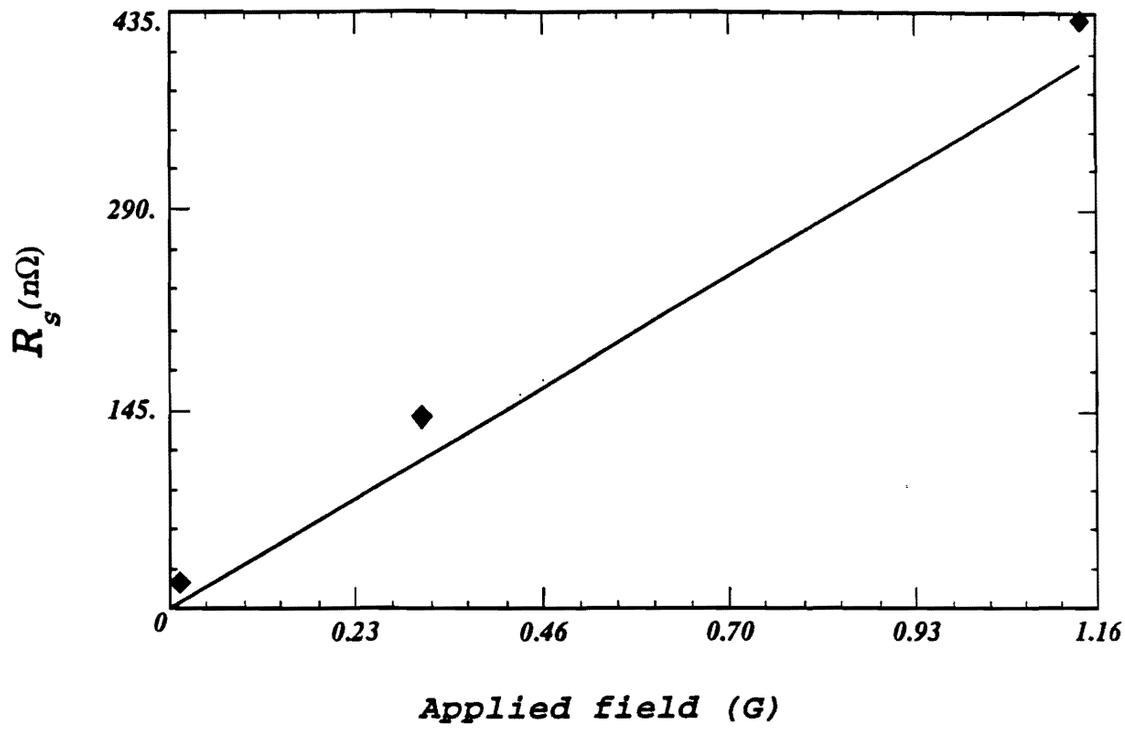


Figure 4

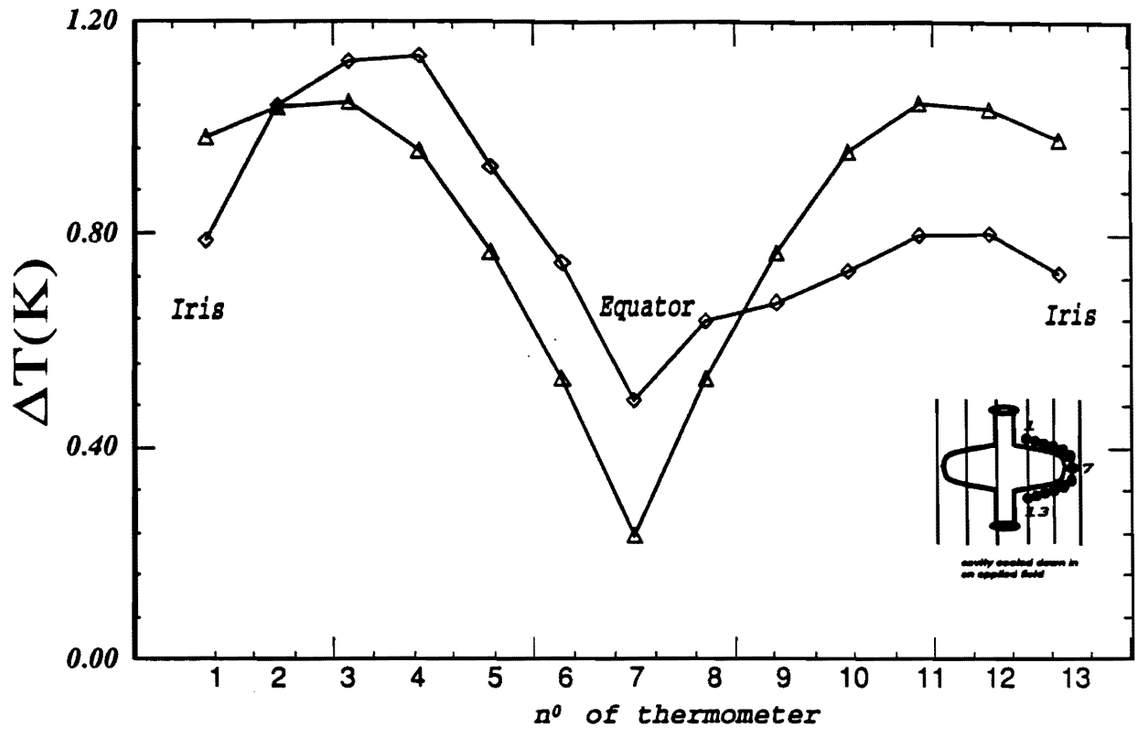
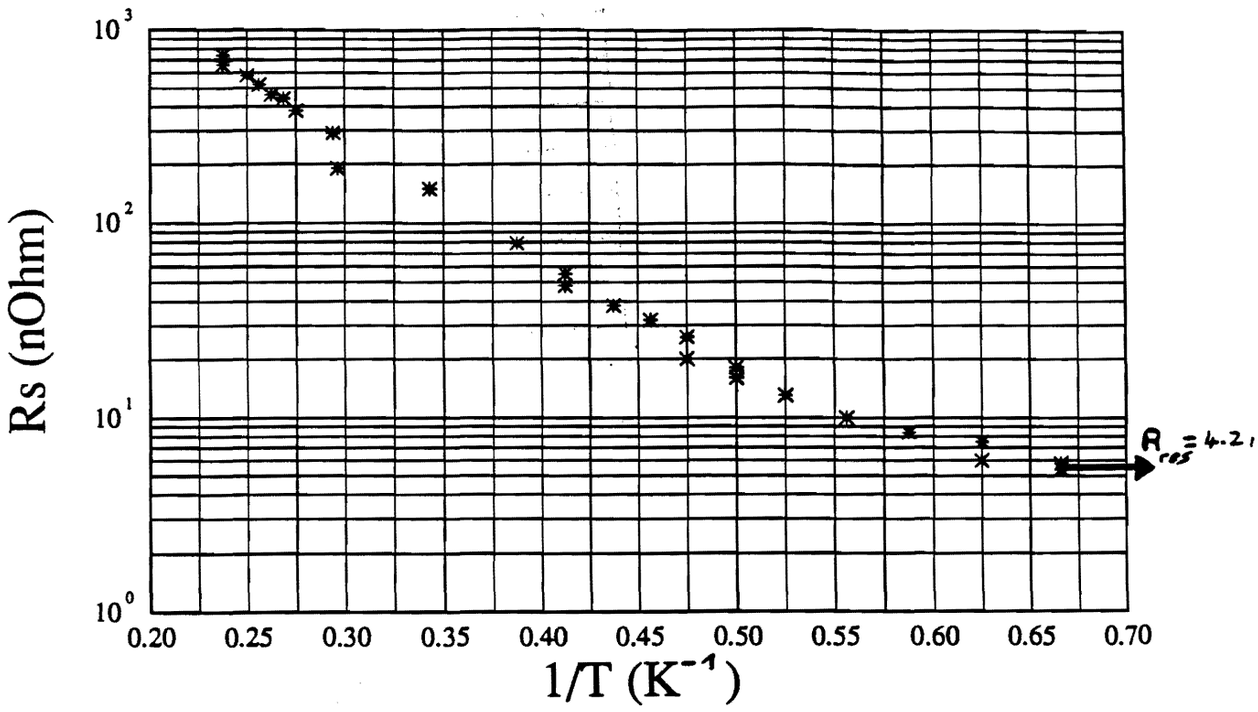

1.20
0.80
0.40
0.00
ΔT(K)
Iris
Equator
Iris
1
2
3
4
5
6
7
8
9
10
11
12
13
n⁰ of thermometer

Figure 5


Rs (nOhm)
10^3
10^2
10^1
10^0
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
1/T (K^-1)
R res = 4.2