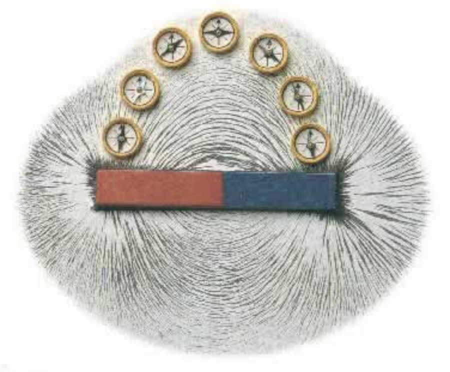
Non Magnetic Capacitors

Ultra-Low ESR, RF & Microwave Systems

In today's world of medical systems, there is a trend in MRI equipment to increase the magnetic field – mostly from 1.5T to 3.0T. The higher signal strength obtained can then be translated into higher spatial resolution, enabling doctors to see finer details on the images. Whence the importance of non magnetic properties in the electronic components used in such systems.



At present, components with a significant magnetic response create parasitic black dots on the images, which may result in inaccurate or more difficult diagnosis – for instance the electrolytic capacitors aluminium or tantalum-based (paramagnetic). Not only this, but magnetic losses will overheat the system and reduce the reliability of the electronic components. Problems such as these - system temperature and component reliability - due to a significant magnetic response can moreover occur in any electronic equipment, though usually with a lower level of criticality.

To further improve reliability in such systems:

- the electronic components used in MR systems, like the multilayer ceramic capacitors from Temex Ceramics, must have a very low magnetic response (diamagnetic);
- a classification is needed for R&D engineers designing such systems, to quantify the magnetic response. This way, any component used in new developments – irrespective of its configuration, with wires or ribbons, etc. - would be guaranteed for MR applications;
- non magnetic components should also be proposed for non medical applications involving high RF power, so as to minimize losses and thereby improve the overall system performance.

The comprehensive magnetic study described below was conducted by the I.C.M.C.B. (the Bordeaux Institute of Chemistry of condensed materials), a laboratory under the aegis of the C.N.R.S. (French National Center for Scientific Research).

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I. MAGNETIC FIELD NOTIONS

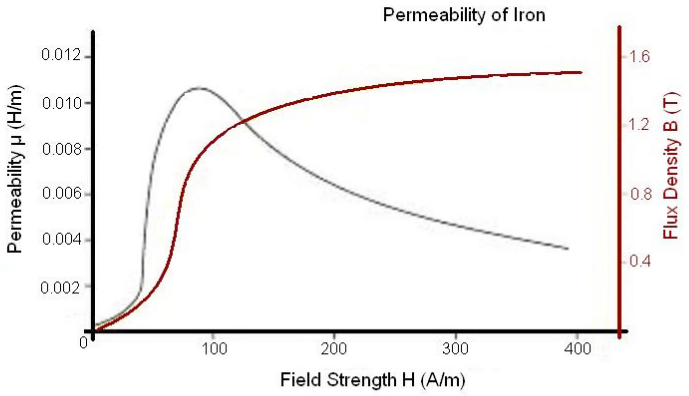
I.1. Magnetic Permeability

This is the degree of magnetization of a material that responds linearly to an applied magnetic field. The magnetic permeability (μ) of a given material is related to the permeability of vacuum (μ_0, in Henries per meter) times its relative permeability (μ_R, no unit):

$$\mu = \mu_0 \times \mu_R$$

- μ_0 is a universal constant, the magnetic constant, and has the value $4\Pi \times 10^{-7} H/m$.

- μ_r is related to the material under test.



In vacuum, air, gases, ... μ_R is equal to 1. These materials do not modify magnetic field lines. There are three types of materials:

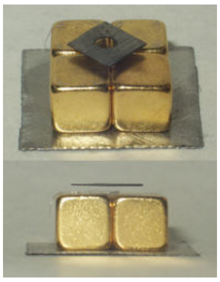
- diamagnetic (silver, copper, gold, lead, ...) in which $\mu_R \leq 1$ and close to 1;
- paramagnetic (platinum, aluminum, magnesium, ...) where $\mu_R \geq 1$ and close to 1;
- ferromagnetic (nickel, cobalt, iron, ...) with $\mu_R >> 1$.

I.2. Paramagnetism

Paramagnetism is a form of magnetism which occurs only in the presence of an externally applied magnetic field. Paramagnetic materials are attracted to magnetic fields, and hence have a relative magnetic permeability μ_R greater than one - or, equivalently, positive magnetic susceptibility. However, unlike ferromagnets, which are also attracted to magnetic fields, paramagnets do not retain any magnetization in the absence of an externally applied magnetic field.

I.3. Diamagnetism

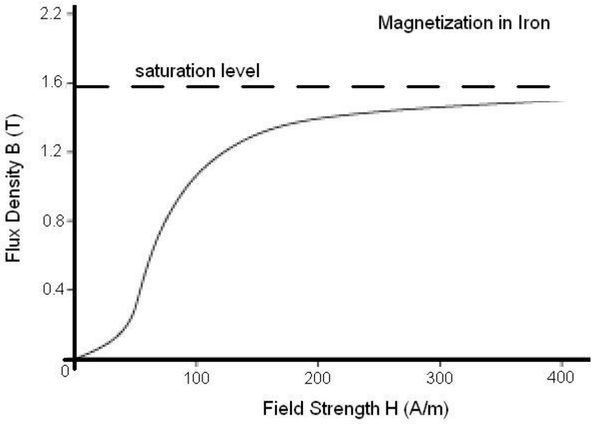
Diamagnetism is a weak repulsion from a magnetic field. It is form of magnetism that is exhibited by a substance only in the presence of an externally applied magnetic field. All materials show a diamagnetic response in an applied magnetic field but for materials which show some other form of magnetism (such as ferromagnetism or paramagnetism), the diamagnetism is completely overpowered.



Substances which display only, or mostly, diamagnetic behavior are termed diamagnetic materials, or diamagnets. Materials referred to as diamagnetic are those which are usually considered by non-physicists as "non magnetic", and include water, DNA, most organic compounds such as petroleum and certain plastics, and many metals such as mercury, gold and bismuth.

I.4. Ferromagnetism

Ferromagnetism is defined as the phenomenon by which materials, such as iron, in an external magnetic field, become magnetized and remain so for a period after the material is no longer in the field.



I.5. Magnetic Susceptibility

Magnetic susceptibility (χ_v) is the degree of magnetization of a material in response to an applied magnetic field. If χ_v is positive, then $(1+\chi_v) > 1$ and the material is said to be paramagnetic. In this case, the magnetic field is strengthened by the presence of the material. Conversely, if χ_v is negative, then $(1+\chi_v) < 1$, and the material is termed diamagnetic. As a result, the magnetic field is weakened in the presence of the material.

Class	***χ_v dependant on B?***	***Dependent on temperature?***	***Hysterisis?***	***Example***	***χ_v***
Diamagnetic	No	No	No	Water	-9×10^{-6}
Paramagnetic	No	Yes	No	Aluminum	2.2×10^{-5}
Ferromagnetic	Yes	Yes	Yes	Iron	3000

I.6. Units

The International System of Units (abbreviated “SI” from the French “*Système International d'unités*”) is the modern form of the metric system. It is the world's most widely used system of units, both in everyday commerce and in science. The older metric system included several base units. The SI was developed in 1960 from the old meter-kilogram-second (MKS) system, rather than the centimeter-gram-second (CGS) system, which, likewise, had a number of variants.

The SI introduced several newly named units. The SI is not static, but a living set of standards in which units are created and definitions are modified through international agreement as the technology of measurement progresses.

Parameter	***CGS System***	***Correcting Factor***	***SI unit***
Magnetic Induction B	G (gauss)	10^{-4}	T (tesla)
Applied Field H	Oe (oersted)	$10^3/4\pi$	A/m
Magnetization M_g	emu/erg/G	1	$A.m^2/kg$
Mass Susceptibility χ_g	cm^3/g	$4\pi \times 10^{-3}$	m^3/kg
Permeability µ	-	$4\pi \times 10^{-7}$	H/m

NB: when a material is paramagnetic, the best way to describe it is in terms of magnetic susceptibility χ_g. When the material is ferromagnetic, magnetization M_g is preferred. The following formula could be used:

$$M_g = \chi_g \times H$$

One should also note that:

$$\chi_v = \chi_g . [density]$$

II. EXPERIMENTAL SETUP

II.1. Magnetometer

Measurements were taken using a Quantum Design magnetometer, model MPMS-5. The MPMS provides solutions for a unique class of sensitive magnetic measurements in key areas such as high-temperature superconductivity, biochemistry and magnetic recording media. This began developing significantly in 1988 with the discovery of a new class of superconducting materials. While the basic application has not changed greatly, its use has expanded to more than 530 installations worldwide.

The modular MPMS design integrates a SQUID detection system - Superconducting Quantum Interference Device, a precision temperature control unit residing in the bore of a high field superconducting magnet, and a sophisticated computer operating system:

- Maximum Sample Size: 9 mm;
- Field Uniformity: 0.01% over 4 cm;
- Temperature Range: 1.9-400 K;
- Sensitivity of 10^{-7} emu-CGS.

II.2. Superconducting Quantum Interference Device

The main components of a SQUID (see Fig. 1) magnetometer are: (a) a superconducting magnet; (b) a superconducting detection coil which is coupled inductively to the sample; (c) a SQUID connected to the detection coil; (d) a superconducting magnetic shield. A description of each one is given below:

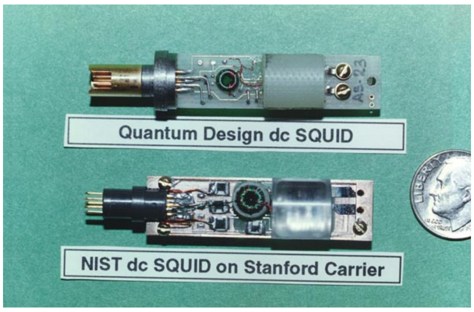


Fig. 1

II.2.1. Superconducting Magnet

A superconducting magnet is a solenoid made of superconducting wires (see Fig. 2). The solenoid must be kept at liquid helium temperature in a liquid-helium medium. The uniform magnetic field is produced along the axial cylindrical bore of the coil. Superconducting solenoids that produce magnetic fields in the range 5-18 Tesla are now commercially available. A superconducting magnet requires an appropriate programmable bipolar power supply for operation.

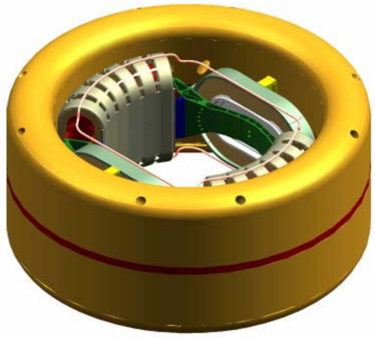


Fig. 2

II.2.2. Superconducting Detection Coil

This is a single piece of superconducting wire, configured as a second-order gradiometer (see Fig. 3). This pick-up coil system is placed in the uniform magnetic field region of the solenoidal superconducting magnet.

Fig. 3

II.2.3. SQUID

High sensitivity is possible because this device responds to a fraction of the flux quantum. The SQUID device is usually a thin film that functions as an extremely sensitive current-to-voltage-converter. A measurement is taken in this equipment by moving the sample through the second-order gradiometer. Hence, the magnetic moment of the sample induces an electric current in the pick-up coil system. A change in the magnetic flux in these coils modifies the persistent current in the detection circuit. The current change in the detection coils then produces a variation in the SQUID output voltage proportional to the magnetic moment of the sample.

II.2.4. Superconducting Magnetic Shield

This is used to shield the SQUID sensor from the fluctuations of the ambient magnetic field in the magnetometer’s location and from the large magnetic field produced by the superconducting magnet.

II.2.5. Applications

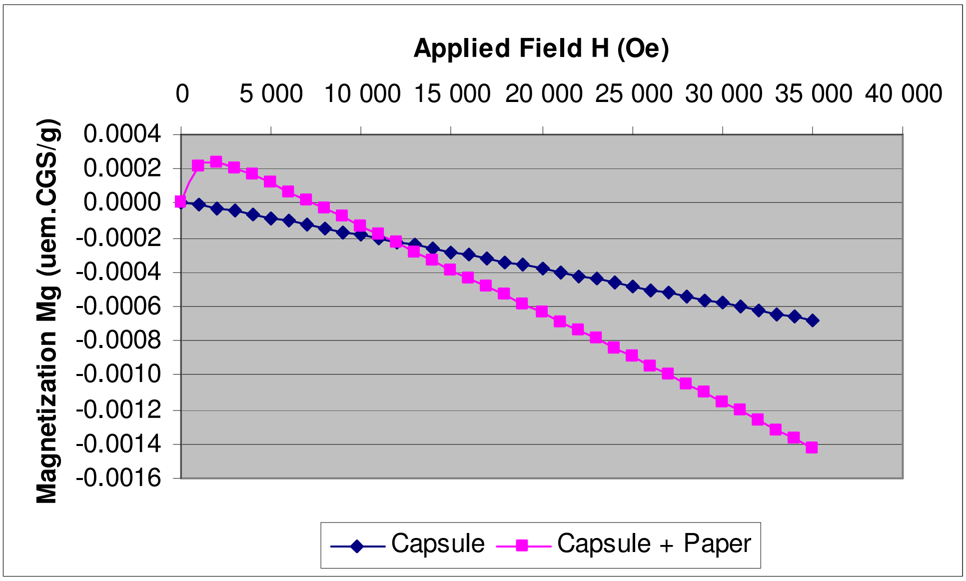
This kind of equipment can be used to measure: (a) the real and imaginary components of the AC magnetic susceptibility as a function of frequency, temperature, AC magnetic field amplitude and DC magnetic field value; (b) the DC magnetic moment as a function of temperature, DC magnetic field, and time.

II.3. Capsule Magnetization

The sample under testing has to be placed in a small capsule of 5-mm diameter and 8-mm length. Submitted to a magnetic field, the sample acquires a magnetization. The capsule is then placed in a 6-cm tube which results in a field strength variation. This is then measured in the SQUID and converted into a magnetization (uem-CGS unit in our case). Thin paper is used to secure the sample in place inside the capsule.

Measurements were made with a controlled temperature (298.0±0.1K) and in the 0 to 3.5T range (35’000 Oe) as the magnetic field declined.

The first step before measuring any sample is to define the magnetization of the sample carrier, i.e. the capsule with some thin paper. Then, as the samples are measured, all the magnetization values are corrected using the pattern below:



The signal from the capsule is diamagnetic and very weak. The signal from the capsule +the paper assembly is more complex to determine, combining a strong diamagnetic signal and a small ferromagnetic contribution (impurities in the paper material).

A constant corrective factor was then applied on all the measurements as a first approximation.

III. LABORATORY MEASUREMENTS

The aim of this study is to define a range of magnetization values within which electronic components may be considered as non-magnetic and suitable for critical medical and high RF power applications.

Several components were therefore tested to define a spectrum as wide as possible. For instance, if we consider the high-Q multilayer ceramic capacitor: we started with the chip alone, without even its terminations, adding a new variable - such as copper or silver-palladium or nickel terminations, silver ribbons and finally laser marking - at each subsequent stage. Using this protocol, it is easy to see the effect of each variable on the final magnetization.

The magnetization in the charts below is given per gram. Each sample - or set of samples - is then weighed before the test run. The following designs were tested:

Designation	***Number of Samples***	***Weight (mg)***	***Batch Number***
501 CHB 4R7	3	155.1	C706527
501 CHB 4R7 BC	1	61.5	C649212
501 CHB 4R7 BC1L	1	133.6	C649212-0
501 CHB 4R7 BAL	1	57.5	52196
501 CHB 4R7 BS	1	61.2	C645208-2
silver leads type 1	2	55.4	CK/6297
silver leads type 2	2	57.2	CK/BC/2205
AT9401	1	58.6	OT0041006P
AT9402	1	60.8	OT0111206P
AT9410	2	194.0	OT0020806P

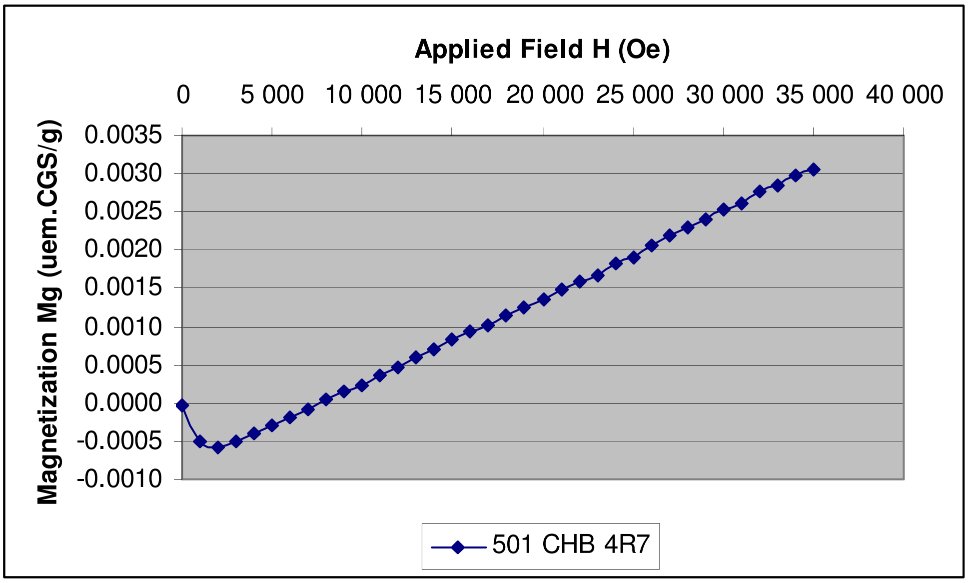
The descriptions of the samples used are as follows:

501 CHB 4R7	B size (1111) capacitor, 4.7pF, no termination
501 CHB 4R7 BC	B size (1111) capacitor, 4.7pF, copper termination
501 CHB 4R7 BC1L	B size (1111) capacitor, 4.7pF, copper termination, leads
501 CHB 4R7 BAL	B size (1111) capacitor, 4.7pF, silver-palladium termination
501 CHB 4R7 BS	B size (1111) capacitor, 4.7pF, nickel termination
silver leads type 1	silver leads used with B size capacitors
silver leads type 2	silver leads currently undergoing qualification
AT9401	ceramic trimmer capacitor, 0.6 to 2.0pF, gold termination
AT9402	ceramic trimmer capacitor, 1.0 to 5.0pF, gold termination
AT9410	ceramic trimmer capacitor, 4.0 to 18pF, gold termination

Non Magnetic Capacitors

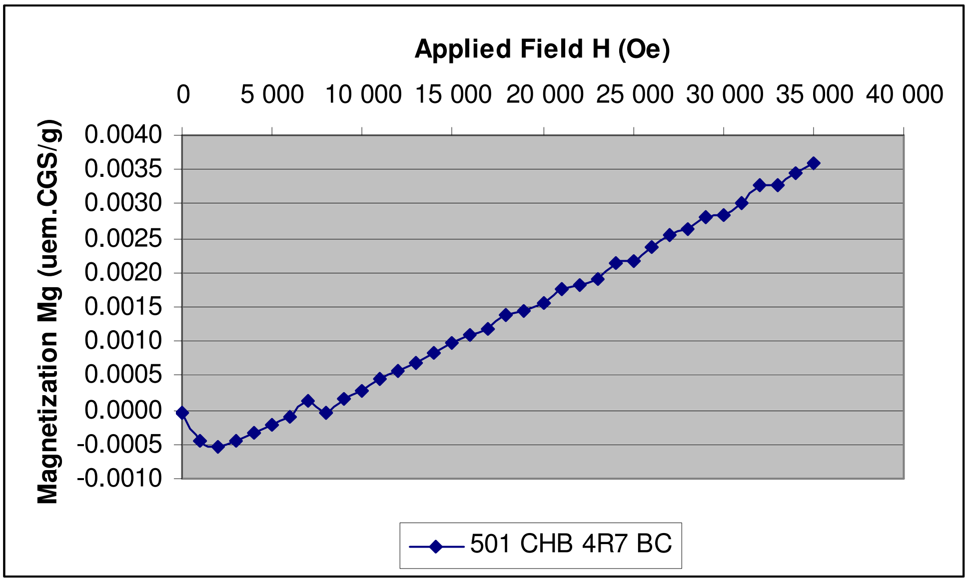
Ultra-Low ESR, RF & Microwave Systems

III.1. DUT: 501 CHB 4R7



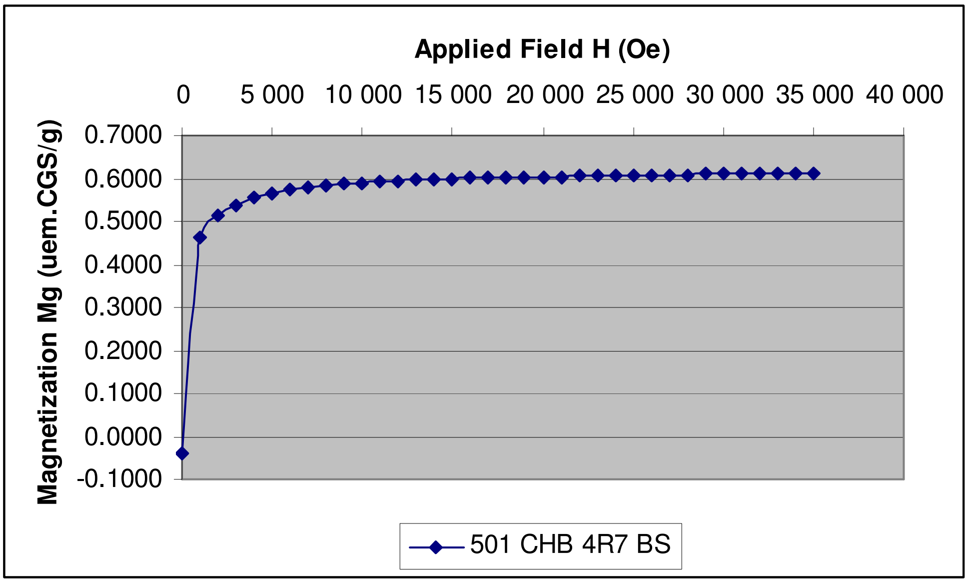
This sample shows a slightly paramagnetic behavior. Its magnetic susceptibility χ_g is around 10^{-7} uem.CGS/g which is a very low value.

III.2. DUT: 501 CHB 4R7 BC



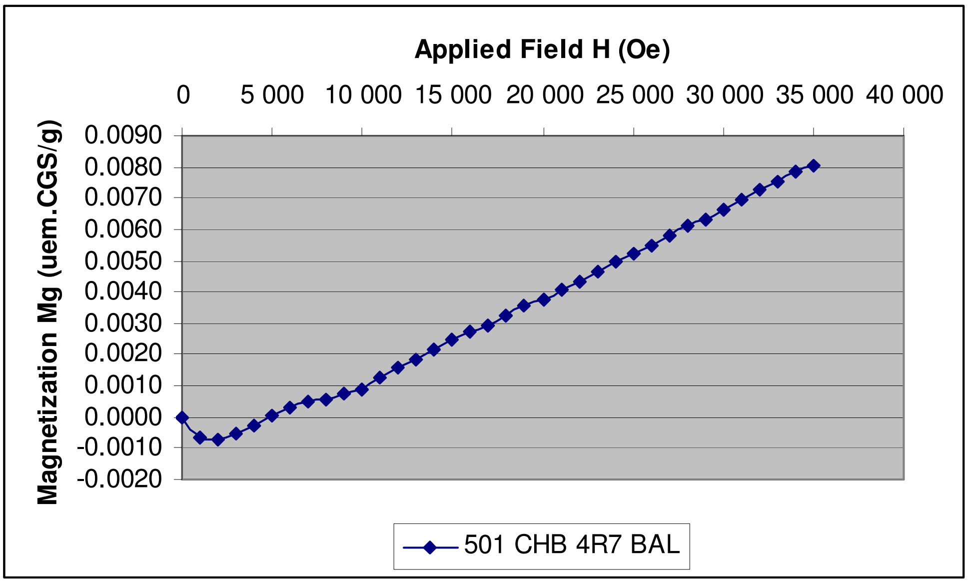
This sample has a slightly paramagnetic behavior. Its magnetic susceptibility χ_g is around 10^{-7} uem.CGS/g which is a very low value.

III.3. DUT: 501 CHB 4R7 BS



This sample exhibits a very strong magnetic behavior with a magnetization around 0.6 uem.CGS/g.

III.4. DUT: 501 CHB 4R7 BAL

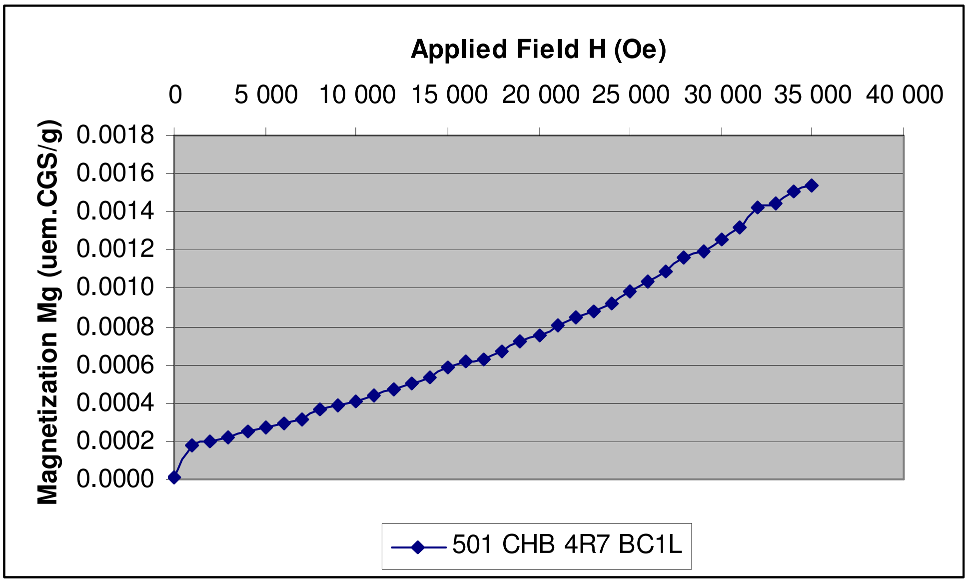


This sample has paramagnetic behavior with a magnetic susceptibility χ_g around 2.3×10^{-7} uem.CGS/g.

Non Magnetic Capacitors

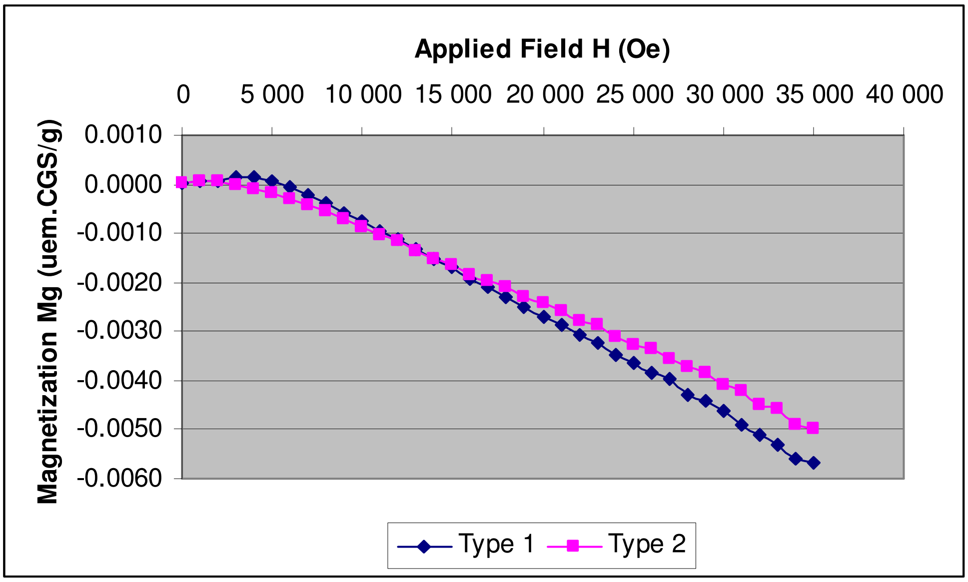
Ultra-Low ESR, RF & Microwave Systems

III.5. DUT: 501 CHB 4R7 BC1L



This sample shows a paramagnetic behavior with a magnetic susceptibility χ_g around 0.4×10^{-7} uem.CGS/g.

III.6. DUT: Silver Leads

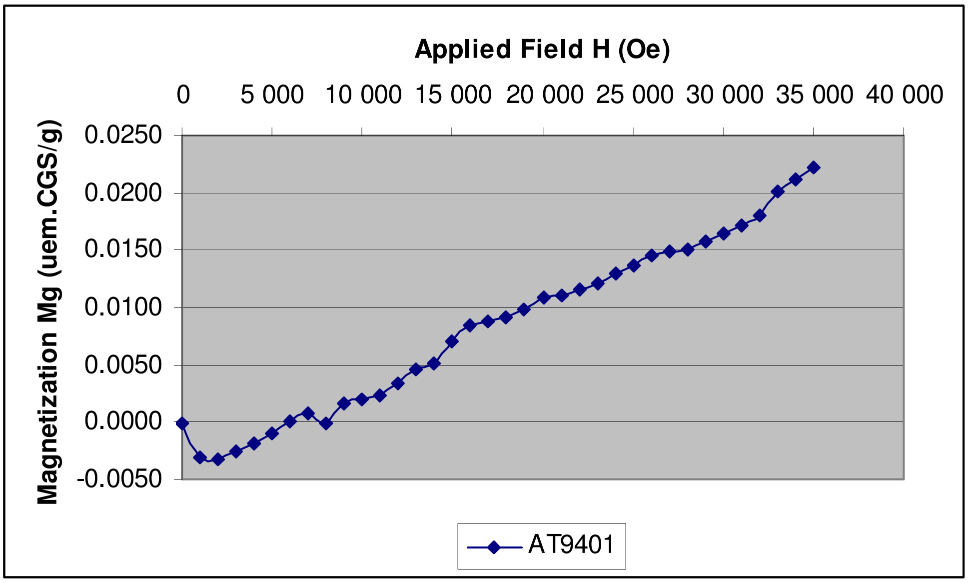


These two samples exhibit very similar diamagnetic behavior. The magnetic susceptibility χ_g is in both cases around -1.6×10^{-7} uem.CGS/g.

Non Magnetic Capacitors

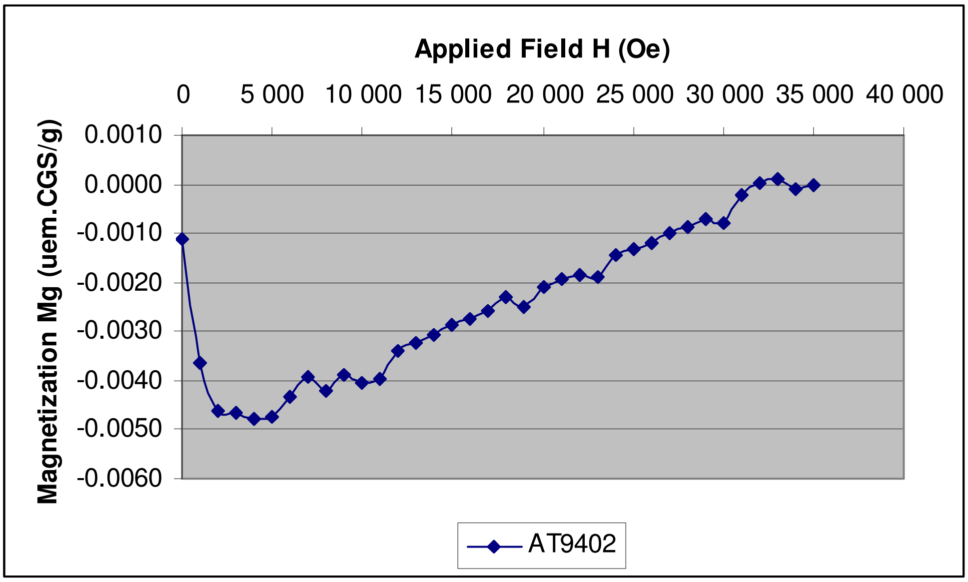
Ultra-Low ESR, RF & Microwave Systems

III.7. DUT: AT9401



This sample has a paramagnetic behavior with a relatively high magnetic susceptibility χ_g, around 7.1×10^{-7} uem.CGS/g.

III.8. DUT: AT9402

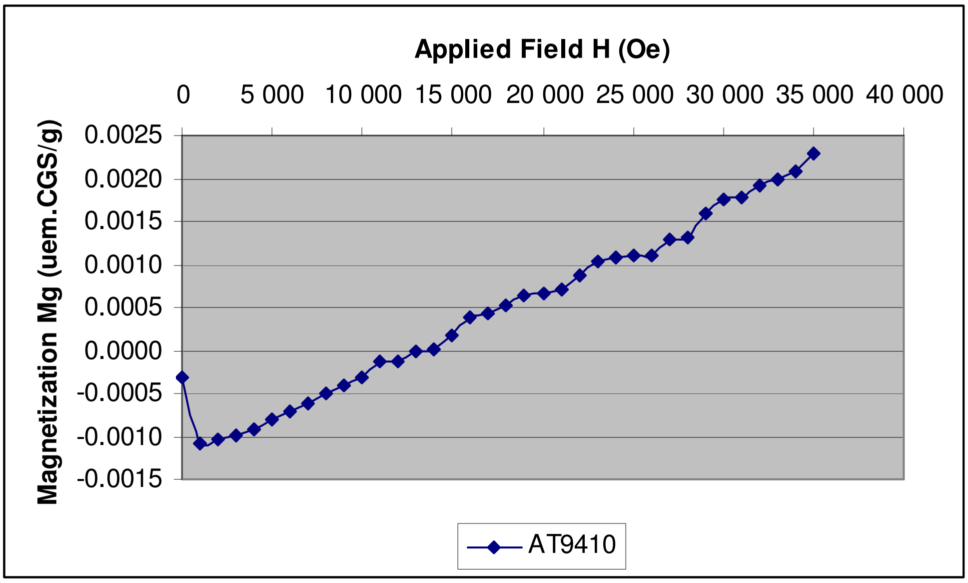


This sample has a paramagnetic behavior with a relatively low magnetic susceptibility χ_g around 10^{-7} uem.CGS/g.

Non Magnetic Capacitors

Ultra-Low ESR, RF & Microwave Systems

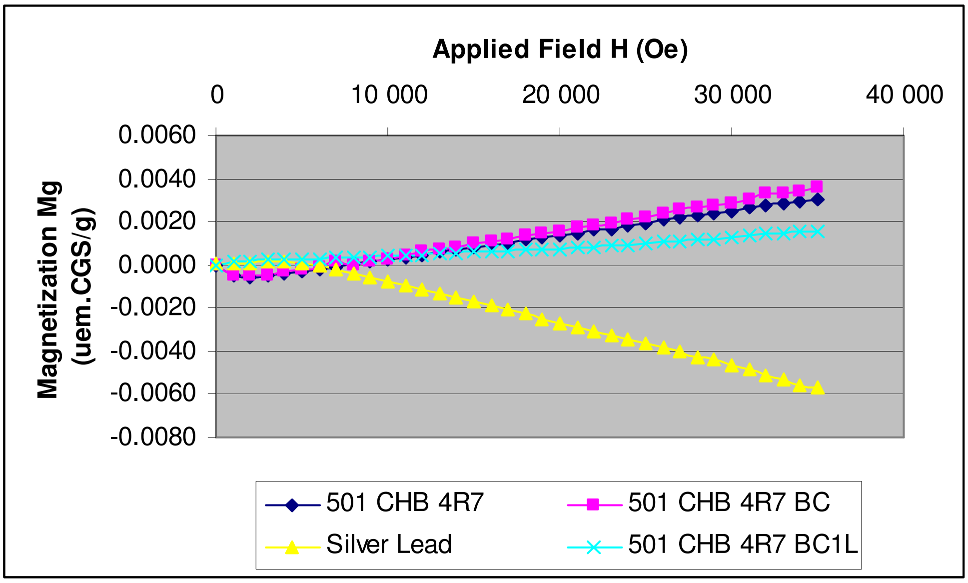
III.9. DUT: AT9410



This sample has a paramagnetic behavior with a relatively low magnetic susceptibility χ_g around 10^{-7} uem.CGS/g.

IV. ANALYSIS

IV.1. Influence Of Leads



From the above chart, the following points may be deduced:

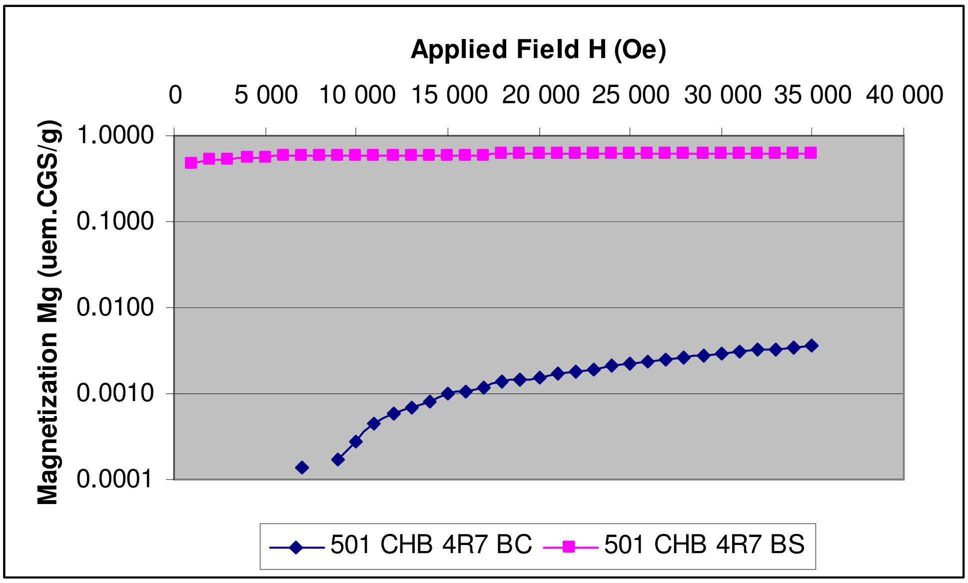
- the copper termination slightly increases the magnetic susceptibility of the chip but the total value remains very low and the paramagnetic behavior is suitable for non-magnetic applications;

- as the ribbon shows strong paramagnetic behavior, the assembly made with the capacitor and the leads has an even lower magnetic susceptibility than the chip alone. This means that for a very strong requirement for non-magnetic criteria, the assembly made of capacitor and leads is better than the capacitor itself;

- in theory, it should be possible to decrease the magnetic susceptibility of the assembly – capacitor and leads – still further to reach a nearly a nil value, by using thicker or longer silver leads. These would also improve the heat transfer and therefore allow higher working power.

IV.2. Influence Of Terminations

IV.2.1. Copper Versus Nickel Terminations



From the above chart, the following points may be deduced:

- we are comparing here a magnetic termination – nickel barrier one – and a non-magnetic termination – copper barrier one. Naturally, the nickel termination cannot be used for non-magnetic applications but it enables us to define a limit above which a termination should not be classified as non-magnetic;

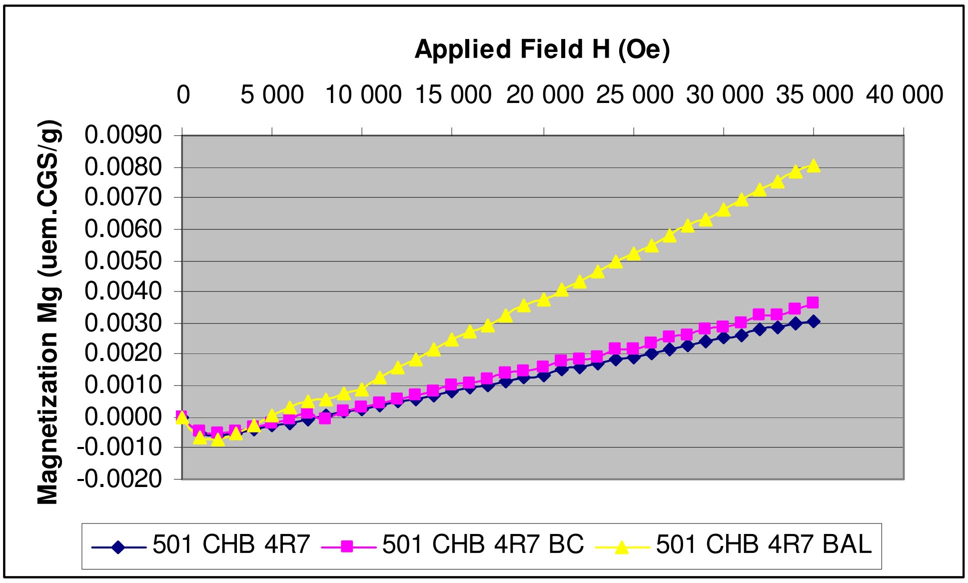
- as we are using a logarithmic axis, the best magnetization value to consider for this limit seems to be around 0.10 uem.CGS/g;

- both copper and silver-palladium terminations are below this theoretical limit of 0.10 uem.CGS/g and can therefore be considered as non-magnetic.

Non Magnetic Capacitors

Ultra-Low ESR, RF & Microwave Systems

VI.2.2. Copper Versus Silver-Palladium Terminations



From the above chart, the following points may be deduced:

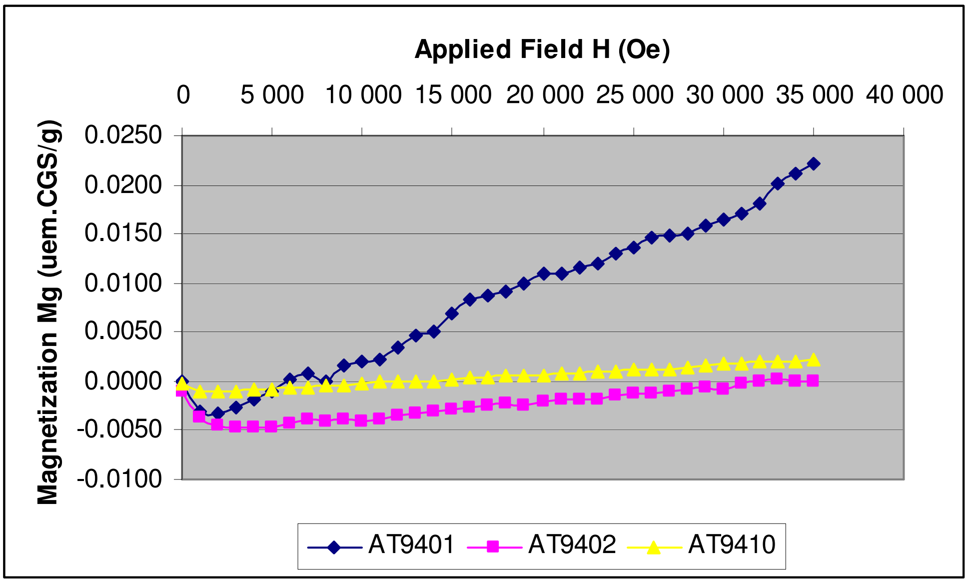
- the copper or silver-palladium terminations slightly increase the magnetic susceptibility of the chip but the total value remains very low and the paramagnetic behavior is suitable for non-magnetic applications;

- the capacitor with silver-palladium terminations exhibits a magnetic susceptibility around three times higher than that of the capacitor with copper terminations. This means that for a very strong requirement for non-magnetic criteria, the copper terminations are better than the silver-palladium ones;

- both these terminations are suitable for non-magnetic applications as their magnetization is always below 0.10 uem.CGS/g.

IV.3. Trimmer Capacitors

On the basis of the 0.10 uem.CGS/g limit previously discussed, the behavior of ceramic trimmer capacitors could also be studied.



From the above chart, the following points may be deduced:

- these three ceramic trimmer capacitors are all suitable for non-magnetic applications, as their magnetization is always below 0.10 uem.CGS/g;

- the AT9402 and AT9410 exhibit very good paramagnetic behavior and are therefore recommended for applications with a very strong non-magnetic requirement.

IV.4. Permeability

IV.4.1. Definitions

Some engineers prefer to define the magnetic behavior of a component using its permeability. Therefore, an empirical limit above which components are not suitable for non-magnetic applications seems to have been set at 1.0005 for the relative permeability μ_R.

This relative permeability could be deduced from our measurements using the following method:

- mass susceptibility χ_g is given by the slope of the $M_g = f(H)$ curve

- volume susceptibility χ_v is equal to: $\chi_g \times$ [density]

- relative permeability is finally equal to: $1 + \chi_v$

IV.4.2. Examples

Let's consider the 501 CHB 4R7 BC we measured previously. From the experimental curve, we find a mass susceptibility χ_g of 10^{-7} uem.CGS. As our components exhibit a density around 4, the volume susceptibility χ_v is then equal to 4×10^{-7} uem.CGS. Finally, permeability μ_R is then equal to 1.0000004, which is well below the theoretical limit of 1.0005

Even if there is no mass susceptibility χ_g for a magnetic component – except at very low fields but customer's applications are far above this range – we can run the exercise for the 501 CHB 4R7 BS studied previously. From the first two dots on the experimental curve, we find a mass susceptibility χ_g of 0.5×10^{-3} uem.CGS. As our components exhibit a density around 4, the volume susceptibility χ_v is then equal to 2×10^{-3} uem.CGS. Finally, permeability μ_R is then equal to 1.002, which is, as expected, well above the theoretical limit of 1.0005

V. CONCLUSIONS

C.N.R.S. and Temex Ceramics have conducted a comprehensive study of the non-magnetic behavior of electronic components. This document describes the results of that study on multilayer porcelain capacitors and ceramic trimmer capacitors.

It flags up the following points:

- the measurements made on magnetic and non-magnetic components enable us to define a first limit for magnetization of around 0.10 uem.CGS/g above which components can no longer be rated as non-magnetic;

- all our non-magnetic components – both porcelain capacitors and ceramic trimmer capacitors – are below this limit and are therefore Magnetism-free Rated. To enable R&D engineers to quickly distinguish in the Temex Ceramics portfolio which components are guaranteed for non-magnetic applications, the following specific logo will be added to specific series in our Application datasheets:

MR certified®

- the above logo certifies that a specific electronic component is Magnetism-free Rated;

- concerning non-magnetic applications - mainly medical systems -, the best solution to obtain a very low magnetization ceramic capacitor is to use one with copper terminations;

- the silver leads, made from pure silver, are completely non-magnetic;

- concerning standard applications – like telecom, industrial, military or space systems, - as any system induces a magnetic field, the use of non-magnetic components would rule out magnetic losses and therefore improve the overall performances, particularly in switch-mode operations.