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MEASUREMENT TECHNIQUES AND APPLICATION OF COMBINED PARALLEL/ORTHOGONAL MAGNETIC BIAS ON A FERRITE TUNED RESONATOR IN LOW FREQUENCY RANGE (3-10 MHz)

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Abstract

We present several measurement methods for evaluation of magnetic properties of magnetically biased and non-biased ferrite samples in a coaxial test fixture. One important aspect is the crosscheck of results obtained by using different and independent measurement and evaluation methods. Since a rather high DC bias current has to be applied, a dedicated network was designed that allows the passage of up to 50 A DC without degradation of the RF performance. With a combination of calibration methods and a compensating topology with two identical sample holders, a good performance was achieved. In this context, magnetic material parameters for about 10 different types of ferrite were obtained. The orthogonal magnetic bias was added by placing the entire test fixture into a large toroidal coil. Thus, the bias field can be supplied independently from, and in addition to the classical parallel bias. An optimal combination between the two biasing fields was found, resulting in a reduction of magnetic losses up to 50 % on certain ferrites. We show that the mixed magnetization, normally used for garnets only, is beneficial also for other types of ferrites.

INTRODUCTION

Ferrite materials are used in the accelerator field as the core of the resonators for cavity frequency tuning purposes. The application of the ferrite however results in an increase of the losses and the inductance, since ferrite materials are characterized by their complex permeability μ_r that is expressed by: $\mu_r = \mu' - j\mu''$, where μ' contains information about the inductance and μ'' represents the magnetic losses. When exposed to a magnetic orthogonal or parallel bias field, one can observe a reduction of the ferrite permeability. Since the resonant frequency varies with the relative permeability as $1/\sqrt{\mu_r}$, it is therefore possible to tune a resonator by applying an external field. An accurate characterisation of the ferrites properties is essential since the choice of the ferrite has to take into account the range of the required frequency as well as the tolerated losses.

There exist many standard methods for μ-evaluation on ferrites, but we have to adapt one of them for the sample and core size in our applications. Indeed, we need to measure ferrite complex permeability and its dependence on external bias field for several reasons: datasheet information insufficient for our requirements, identification of unknown ferrite samples, study of the different behaviour of the samples caused by the magnetic remanence and characterization of special production ferrites.

OVERVIEW OF THE MEASUREMENT TECHNIQUES

The measurement test set consists of a coaxial line with one shorted end partially or completely filled with one or more toroidal shaped samples, placed at the shorted end. Ferrite samples of different shapes and materials have been characterized; that resulted in most of the cases in re-designing the sample holders to allow the implementation of the needed connections and a better fitting of the ferrite under test within the structure. Moreover, as will be described in the following, the measurements of the ferrite parameters were carried out with and without a magnetic bias field.

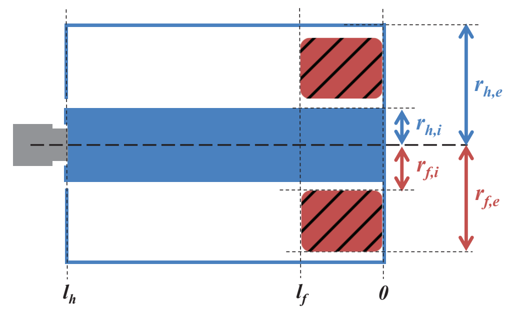

Figure 1: Schematic drawing of the experimental setup. The metallic holder (blue) houses a toroidal shaped ferrite (red) and features a connector (grey) used for S_{11} measurements.

Unbiased Measurements Technique

The permeability of the ferrite samples is evaluated from reflection coefficient measurements, performed with a Vector Network Analyzer (VNA). All measurements were performed using OSM (Open-Short-Matched) one-port calibration at the end of the test cable.

The S_{11} parameter calculated at the short end is obtained by normalizing the measured reflection coefficient of the sample holder filled by the ferrite sample $S_{11_{filled}}$ to the one of the empty sample holder $S_{11_{empty}}$:

$$S_{11} = \frac{S_{11_{filled}}}{S_{11_{empty}}}. \tag{1}$$

The input impedance of the ferrite under test, Z_f, is a complex number and is determined by:

$$Z_f = Z_0 \frac{1 + S_{11}}{1 - S_{11}} \tag{2}$$

with $Z_0 = 50\ \Omega$ being the characteristic impedance of the VNA. A first approach to evaluate the ferrite permeability

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consists in using the rectangular cross section toroid approximation. The inductance of a ferrite toroid with such a geometry can be approximated by:

$$L = \mu_e \mu_0 \frac{A_e}{l_m}, \tag{3}$$

where μ_0 is the vacuum magnetic permeability, $A_e = l_f(r_{f,e} - r_{f,i})$ is the equivalent area crossed by the RF magnetic field lines and $l_m = \pi(r_{f,e} + r_{f,i})$ is the equivalent magnetic length. In our approximations $\mu_e = \mu_r + 1$ due to the effect of the normalization.
Knowing that $Z_f = 2\pi f L$, being a complex quantity, one can compute μ' and μ'' from its real and imaginary part since $\mu' \propto Im(Z_f)$ and $\mu" \propto Re(Z_f)$. Similarly, a second approach based on the coaxial lines theory is considered, where the input impedance of the sample placed at the shorted end of the coaxial cable is expressed by:

$$Z_f = jZ_s \tan(\beta l_f), \tag{4}$$

with $Z_s = Z_c\sqrt{\mu_e}$ being the impedance of a coaxial line with a core of ferrite, Z_c the characteristic impedance of an empty coaxial line (that depends on its geometrical dimension), $\beta = \frac{2\pi}{\lambda_0}\sqrt{\mu_e}$ the propagation constant and l_f the ferrite length.
If the ferrite length is much smaller than the measurement wavelength: $l < \lambda_0/10$, (Eq. 4) can be approximated by:

$$Z_f \simeq jZ_s\beta l = jZ_c \frac{2\pi l}{\lambda_0}\mu_e. \tag{5}$$

Equation (5) shows again how μ'_e and μ''_e can be computed from the measured real and imaginary part of Z_f. If the ferrite completely fills the sample holder $\mu_e = \mu_r$. However, there could be a radial air gap between the ferrite ring and the inner and outer conductor; in that case it is possible to compute μ_r from μ_e by following [1]. For the sake

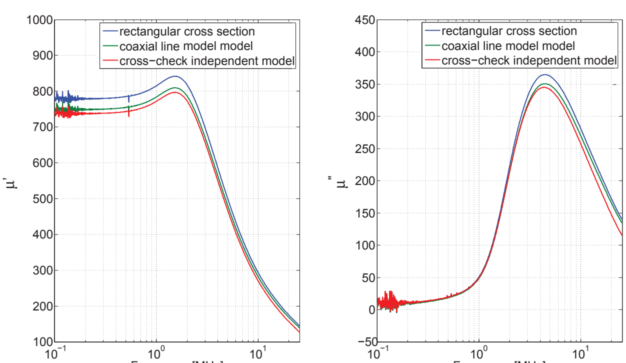

Figure 2: 4s2 ferrite parameters evaluated through three different methods.

of completeness, Fig. 2 shows a comparison between the magnetic properties of a chosen ferrite evaluated using the two aforementioned approaches and an independent data analysis method [2], that takes into account more parameters of the test set geometry. It is worth noting that the three approaches provide coherent estimations of μ' and $\mu"$ and are in good agreement with each other; however the coaxial line theory was adopted throughout the rest of the analysis presented in this study.

Table 1: Permeability values of several ferrites material under test. The table contains the μ' evaluated on samples with some magnetic remanence and after a demagnetization process.

Ferrite material	μ' **demagnetized**	μ' **remanence**	μ' **datasheet**
4s2	780	640	850
5x13	520	410	NN
43	600	500	800
46	450	300	500
61	135	110	125
4W620	540	430	620
c2010	310	280	350
4L2	200	190	200

Biased Measurement Technique

Since the characterization of the ferrites at different working frequencies is of our interest for the cavity resonator studies, this measurement technique allows tuning the ferrite with an external field. The orientation of the external DC field applied can be either orthogonal or parallel with respect to the magnetic RF field.
On one hand, the parallel bias has been introduced using a special setup where a power supply is used to provide the current to the sample holder along with the RF through a T-connector.
Since the RF impedance of the DC power supply is below 5 Ω in the frequency range of interest, an RF choke coil is necessary to filter out the RF propagating towards the output of the power supply. Such a setup can withstand a DC current up to 50 A. Fig. 3 shows the results of a measurement performed following the described technique and the resulting permeability reduction due to the application of a bias current up to 40 A on a test ferrite sample. It is important

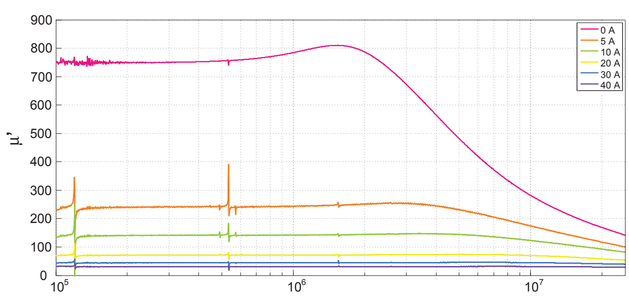

Figure 3: Permeability variation due to the application of a parallel bias field of 4s2 ferrite samples.

to note that an accurate VNA calibration is crucial for the measurement accuracy which is not easy to perform since

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it is sensitive to any bad contacts or any instrument drifts. On the other hand, the perpendicular bias for our studies was provided either by means of a cylindrical solenoid or by windings put around the resonator.

3-10 MHz PS GRID RESONATOR

In the framework of the Large Hadron Collider injectors upgrade at CERN, several modifications of the amplifiers driving the Proton Synchrotron (PS) 10 MHz cavities are required. Indeed, an internal resonator adapted for a frequency range from 3 to 10 MHz has to be designed and implemented.

A prototype of such a resonator was made of two brass coaxial lines shorted on one end, both lines completely filled with ferrite rings. A bias field was applied in opposite directions on each line to reduce to zero the total RF voltage induced in the DC biasing path. We chose to use two lines to keep the dissipated power per volume unit below the ferrite limits. At an early stage, in the resonator's first design, the two coaxial lines were biased by means of an orthogonal field generated by windings around each resonator. To achieve the required tuning specifications, the needed current range was too high and lead to an excessive heating of the structure. Therefore, this design was abandoned in favor of a parallel bias, where the induced change of μ_r for a given value of the current is greater compared to that of a perpendicular bias field.

The process of choosing the suitable ferrite to be installed in the resonator consisted in characterizing several ferrite samples with the aforementioned techniques searching the ones featuring the lowest losses in the required frequency range (Table 1).

However, the ferrite samples selected for our resonator configuration still presented excessive losses at 10 MHz. To further reduce the losses of our resonator, a superposition of either parallel and orthogonal bias was tried. At an early stage, the sample holder was put into a cylindrical solenoid providing the orthogonal external field (Fig. 4). This method,

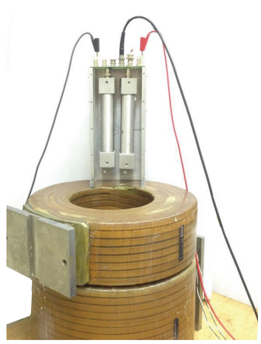

Figure 4: Combined bias measurement setup: an aluminum box holding the resonator put in a big solenoid.

according to [3] and [4], allows to enlarge the available tuning range and reduce ferrite losses in the given frequency range.

The results of the tests show that there is an optimum combination of the two bias fields amplitude and relative orientation that reduces the losses by a factor of two for the ferrites under test. Figure 5 shows that varying the orthogonal bias field at a fixed operating point given by the parallel bias, implies a resonant frequency variation and ferrite losses reduction: while the bias current is increased the resonant frequency is first increasing and then decreasing. Similarly the ferrite losses gradually decrease, reaching a minimum, and then increase again.

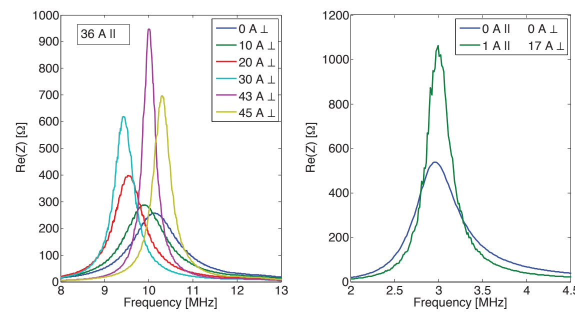

Figure 5: Results of the application of combined bias at 10 and 3 MHz. Since the resonator resonates in parallel with a capacitor the maximum of the real part of the impedance corresponds to the minimum of ferrite losses.

CONCLUSIONS

The two methods that have been adopted for the characterisation of the ferrite samples and the evaluation of their magnetic parameters were presented. Additionally a comparison was also drawn between these two methods and a third independent technique accounting for more accurate description of the test set geometry. The results showed that the adopted simplified methods were sufficiently precise for our application. However, eventual discrepancies from the parameters reported in the datasheets is thought to come from variations between batches or residual magnetization of the samples. Moreover, the effect of the superposition of perpendicular and parallel magnetic fields on the ferrite losses was studied. In fact, for some bias configurations the losses were significantly reduced. Usually used for garnets this promising technique was found promising also for our uses and will be further investigated in future studies.

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