ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRI053

FERRITE MATERIAL CHARACTERIZATION IN A STATIC BIAS FIELD FOR THE DESIGN OF A TUNEABLE CAVITY

J. Eberhardt, CERN, Geneva, Switzerland; TU Darmstadt, Darmstadt, Germany
F. Caspers, C. Vollinger, CERN, Geneva, Switzerland

Abstract

During the development of ferrite-loaded accelerating cavities, the electromagnetic properties of the dispersive ferrite material need to be known. We describe a coaxial short-circuit measurement technique to measure the complex permeability of toroidal-shaped samples (127 mm outer and 70 mm inner diameter) that are exposed to an external magnetic bias field. The external magnetic bias field is applied perpendicular to the RF magnetic field. With this method it is possible to characterize the frequency dependence of the permeability for a frequency range of 1-100 MHz. The dependence of the permeability on the external magnetic bias is presented for the ferrite G-510 from Trans-Tech Inc. and the material characterization is shown in the same frequency range. The measurement results are verified by simulations of the measurement set-up.

INTRODUCTION

Accelerating cavities are filled with ferrite material for frequency tuning purpose. The resonance frequency depends on the relative permeability μ_r with $f_\mathrm{res} \sim 1/\sqrt{\mu_\mathrm{r}}$ and can be tuned by applying an external magnetic bias field H_bias to the ferrite material. This dependence of the relative permeability on a magnetic bias field needs to be known for the development of a ferrite-loaded accelerating cavity. The relative permeability is complex and can be expressed as: $\mu_\mathrm{r} = \mu' - i\mu''$, where μ'' accounts for magnetic losses. μ' of the ferrite material of interest G-510 exposed to an external magnetic bias field was presented by [1] for ferrite tiles for 1 to 100 MHz. The real part of the relative permeability and the magnetic losses of G-510 rings exposed to an external magnetic bias field were shown by [2] for 51 to 52 MHz. The desired accelerating cavity should cover a frequency range of 18 to 40 MHz. For this purpose the real part of the relative permeability and the magnetic losses of G-510 rings over a larger frequency range of 1 MHz to 100 MHz are investigated.

MEASUREMENT TECHNIQUE

To determine the relative permeability $\mu_\mathrm{r}(f)$ of G-510 ferrite rings, a material sample holder is chosen for which the relation of $S_{11}(\mu_\mathrm{r})$ can be analytically calculated, see Fig. 1. The ferrite sample of d_ferr = 70 mm inner and D_ferr = 127 mm outer diameter is placed at the shorted end. The sample holder consists of five intersections i to realize the transition of the sample size to a 50 Ω Type N connector, which can be connected to a Vector Network Analyzer. At each intersection the line impedance $Z_{\mathrm{i,\,i-1}}$ is changing based on different coaxial line diameters or the filling material.

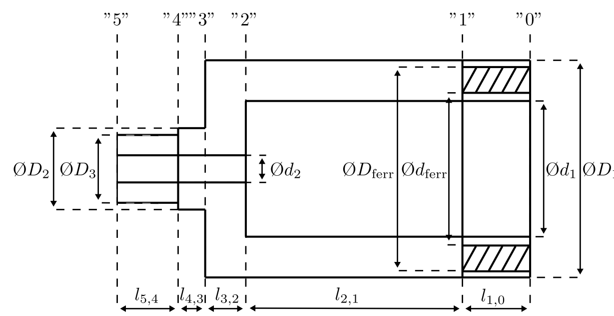

Figure 1: Schematic drawing of sample holder.

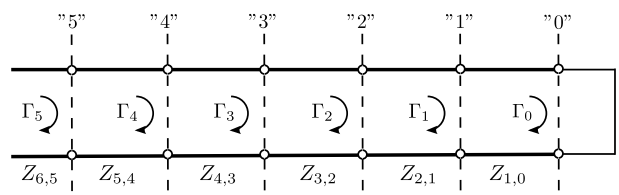

Figure 2: Equivalent circuit of sample holder.

The reflection coefficient $S_{11}(\mu_\mathrm{r}) = \Gamma_5$ at plane "5" can be obtained by calculating step by step each reflection coefficient Γ_i at every intersection according to Fig. 2 and Eq. (1) starting for i = 1 and $\Gamma_0 = -1$ approximated at the short.

$$\Gamma_\mathrm{i} = \frac{Z_{\mathrm{i,\,i-1}} \frac{1+\Gamma_{\mathrm{i-1}} e^{-2\gamma_{\mathrm{i,\,i-1}} l_{\mathrm{i,\,i-1}}}}{1-\Gamma_{\mathrm{i-1}} e^{-2\gamma_{\mathrm{i,\,i-1}} l_{\mathrm{i,\,i-1}}}} - Z_{\mathrm{i+1,\,i}}}{Z_{\mathrm{i,\,i-1}} \frac{1+\Gamma_{\mathrm{i-1}} e^{-2\gamma_{\mathrm{i,\,i-1}} l_{\mathrm{i,\,i-1}}}}{1-\Gamma_{\mathrm{i-1}} e^{-2\gamma_{\mathrm{i,\,i-1}} l_{\mathrm{i,\,i-1}}}} + Z_{\mathrm{i+1,\,i}}}. \tag{1}$$

The reflection coefficient depends on the differing line impedance $Z_{\mathrm{i,\,i-1}}$ before the intersection and $Z_{\mathrm{i+1,\,i}}$ after the intersection. Furthermore, it consists of the reflection coefficient before the intersection $\Gamma_{\mathrm{i-1}}$, the propagation constant $\gamma_{\mathrm{i,\,i-1}}$ and the line length $l_{\mathrm{i,\,i-1}}$. The propagation constant $\gamma_{1,\,0}$ and the line impedance $Z_{1,\,0}$ between plane "0" and "1" contain the electromagnetic properties of the ferrite material. The transmission line losses are smaller than 0.01 dB and can be neglected. A radial air gap between the ferrite ring and the inner and outer conductor is unavoidable in the set-up and is considered following [3]. The propagation constant leads to:

$$\gamma_{1,\,0} = i\omega\sqrt{\mu_0\varepsilon_0}\sqrt{\frac{\ln\frac{d_\mathrm{ferr}}{d_1} + (\mu' - i\mu'')\ln\frac{D_\mathrm{ferr}}{d_\mathrm{ferr}} + \ln\frac{D_1}{D_\mathrm{ferr}}}{\ln\frac{d_\mathrm{ferr}}{d_1} + \frac{1}{(\varepsilon' - i\varepsilon'')}\ln\frac{D_\mathrm{ferr}}{d_\mathrm{ferr}} + \ln\frac{D_1}{D_\mathrm{ferr}}}}. \tag{2}$$

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRI053

The line impedance $Z_{1,0}$ between plane "0" and "1" reads:

$$Z_{1,0} = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\sqrt{(\ln\frac{d_{\mathrm{ferr}}}{d_1} + (\mu' - i\mu'')\ln\frac{D_{\mathrm{ferr}}}{d_{\mathrm{ferr}}} + \ln\frac{D_1}{D_{\mathrm{ferr}}})} \sqrt{(\ln\frac{d_{\mathrm{ferr}}}{d_1} + \frac{1}{(\varepsilon' - i\varepsilon'')}\ln\frac{D_{\mathrm{ferr}}}{d_{\mathrm{ferr}}} + \ln\frac{D_1}{D_{\mathrm{ferr}}})}. \quad (3)$$

The analytical model of the sample holder is air-filled between plane "1" and "5", hence the propagation constant according Eq. (2) reduces to $\gamma = i\omega\sqrt{\mu_0\varepsilon_0}$ with $\varepsilon' = \mu' = 1$ and $\varepsilon'' = \mu'' = 0$. By applying Eq. (1) gradually for every intersection and taking into account the ferrite filled part by Eq. (2) and (3) we obtain an expression for $S_{11}(\mu_\mathrm{r})$ which depends on the quantity of interest, the complex permeability. Thus we are able to compute μ' and μ'' from the results of a 1-port reflection measurement for known $\varepsilon' = 14.3$ and $\varepsilon'' = 2.86 \cdot 10^{-3}$, given by the manufacturer [4]. The sample holder is put into a cylindrical solenoid, in order to carry out material measurements within an external magnetic bias field, see Fig. 3.

Figure 3: Measurement set-up: Sample holder in solenoid.

A magnetic bias field H_bias, which is perpendicular to the RF magnetic field can be generated by operating the coil with a bias current I_bias. The magnetic bias field in the vertical and horizontal center of the empty solenoid is given by $H_\mathrm{bias} = I_\mathrm{bias}\frac{mn}{2(b-a)}[\mathrm{arsinh}(\frac{2b}{h}) - \mathrm{arsinh}(\frac{2a}{h})]$, where $n = 24$ windings, $m = 6$ layers, $h = 34.5$ cm height, $a = 9$ cm inner radius and $b = 18$ cm outer radius.

MAGNETIC CHARACTERIZATION OF FERRITE G-510

Before getting to the results of the material characterization a short remark on hysteresis is made. During the material investigation it has been pointed out that the magnetic bias history of a G-510 ferrite sample can have a significant impact on the magnetization and hence on the relative permeability. The spread of $\mu'(f)$ and $\mu''(f)$ over a frequency of 1 to 100 MHz of three samples with different bias history are shown in Fig. 4. The real part of the relative permeability differs mainly at frequencies below 10 MHz, whereas the maximum difference of the imaginary part of the relative permeability is at around 8 MHz. It is obvious that

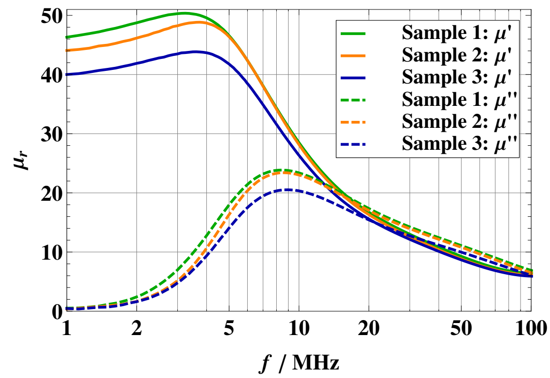

Figure 4: Complex relative permeability spectra of three samples with different bias history.

while characterizing the permeability, the present magnetization state always needs to be indicated. After degaussing the three samples, the spread of the relative permeability reduces notably as discussed below.

In a first step the relative permeability of the demagnetized material is characterized. The real and the imaginary part of the relative permeability are shown in Fig. 5. Both $\mu'(f)$ and $\mu''(f)$ of the demagnetized ferrite show typical dispersion characteristics. The real part of the relative permeability is first slightly increasing to a maximum value of 41.4 at 4 MHz and then rapidly decreasing while the imaginary part reaches a maximum of 18.8 at 9 MHz. The initial permeability provided by the manufacturer [4] of 37 at 1 kHz matches quite well with the measured permeability of 36.6 ± 1.0 at 1 MHz. The measurement uncertainty was evaluated by repetitive measurements according to the students t-distribution with 94.45 % confidence interval. The upper and lower limit of the confidence interval are indicated by the dashed traces in Fig. 5. After degaussing the three G-510 samples with different bias history, the real and imaginary part of the relative permeability were within the confidence interval.

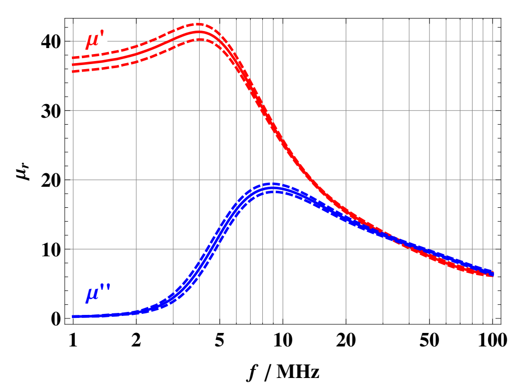

Figure 5: Complex relative permeability spectra of demagnetized material with upper and lower limit of the confidence interval (dashed traces).

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRI053

In a second step, the material is brought to the remanent state by applying one sequence of first increasing and then decreasing magnetic bias fields. The relative permeabilities in the remanent state before and after a second biasing sequence are shown in Fig. 6 by the solid and dotted red curve. They are both much higher than the relative permeability of the demagnetized sample. With increasing bias current, solid trace, both $\mu'(f, I_{\text{bias}})$ and $\mu''(f, I_{\text{bias}})$ are decreasing and the peak is shifting to higher frequencies and disappearing. While the bias current is reduced, dashed line, the downward trace of $\mu'(f, I_{\text{bias}})$ matches well with the upward magnetization values for a bias current down to 60 A considering the measurement uncertainty. Below 60 A bias current, a hysteresis effect is observed for $\mu'(f, I_{\text{bias}})$ for frequencies below 10 MHz and for $\mu''(f, I_{\text{bias}})$ below 70 A bias current over the whole frequency range. Above a bias current of 100 A, $\mu''(f, I_{\text{bias}})$ is getting smaller than 0.01 and can not be calculated accurately, because the magnitude of $S_{11}(\mu_{\text{r}})$ is becoming too close to 1. This indicates the limit of the measuring range. However, with this measurement method we are able to characterize the relative permeability in a frequency range of 1 to 100 MHz for different magnetization states of the ferrite material. It shows, that for the frequency range of interest 18 to 40 MHz, hysteresis effects can be neglected above a bias current of 70 A. Furthermore it is pointed out that the magnetic loss tangent is below $2 \cdot 10^{-3}$ above 100 A bias current in this frequency range.

SIMULATION OF G-510 LOADED SAMPLE HOLDER

The goal of the material characterization is to get accurate data input for electromagnetic field simulations of G-510 filled cavities exposed to a static magnetic bias field. To verify the obtained results, the ferrite filled sample holder is designed with the electromagnetic field simulation programs *ANSYS HFSS* and *CST MICROWAVE STUDIO*. The G-510 material is modeled by reading in the data set of $\mu'(f)$ and $\mu''(f)$ for the different bias currents 0 A, 60 A and 100 A shown in Fig. 6. Hence, a simulation for 0 A, 60 A and 100 A bias current is performed. The corresponding complex permeabilities are calculated using the algorithm according to Eq. (1) on the basis of the simulated $S_{11}(\mu_{\text{r}})$ parameters. The results derived from the simulations show good agreement with the measurements, the absolute error of $\mu'(f)$ for all three examples is below 0.2 and the absolute error of $\mu''(f)$ is below 0.8. This shows that accurate simulation of a coaxial structures filled with G-510 rings exposed to a magnetic bias field can be obtained.

CONCLUSION

We presented a measurement method to characterize the complex permeability of toroidal-shaped samples (127 mm outer and 70 mm inner diameter) over a frequency range of 1 to 100 MHz, exposed to a magnetic bias field, which is perpendicular to the RF magnetic field. We characterized

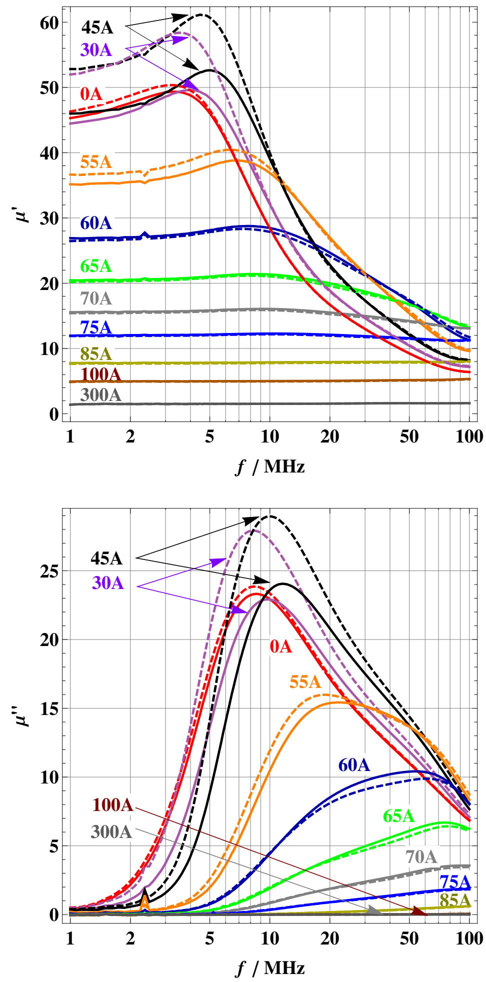

Figure 6: $\mu'(f)$ and $\mu''(f)$ for increasing (solid trace) and decreasing bias currents (dashed trace).

the relative permeability of the ferrite material for different magnetization states. The initial permeability of the demagnetized state shows good agreement with the specifications of the manufacturer. Furthermore the resulting complex permeability of a simulation of the measurement setup using electromagnetic field simulation programs shows good agreement with the measurements. Based on the results obtained, it is now possible to perform simulations of G-510 filled accelerating cavities exposed to a static external magnetic bias field.

REFERENCES

[1] C. Vollinger et. al, "Accurate Measurement of Ferrite Garnets to be used for Fast-tuned Ferrite Loaded Cavities in the Range of 20-40 MHz", IPAC, THPPC020, 2012.

[2] R.M. Hutcheon, "A Perpendicular-Biased Ferrite Tuner for the 52 MHz Petra II Cavities", PAC, 1987.

[3] I.S.K. Gardner, "Ferrite dominated cavities", CAS - CERN Accelerator School: RF Engineering for Particle Accelerators, Oxford, UK, 3 - 10 Apr 1991, pp.349-374.

[4] Trans-Tech, Inc, http://www.trans-techinc.com/