214-0116-01-01_00

RF Note 115
F. Pigeaud

June 1993

Ferrite Measurement at NSCL

1. Introduction

An interest in ferrite materials at NSCL began in 1990 in an effort to assemble design rules and ferrite material characteristics to use in future accelerator designs. The primary application of these materials would be for rapid tuning in a synchrocyclotron. Currently, synchrocyclotrons employ rotating capacitors to achieve frequency modulation, though this method of tuning, while proven, has serious limitations on maximum achievable repetition rate and demands significant mechanical maintenance.

The common application of low loss ferrites in accelerators has been limited to booster cavities in ring accelerators. In these RF structures, the frequency is usually swept over 40 to 60 MHz with a repetition rate on the order of 60 Hz. Other RF cavities used as bunchers operate over a smaller frequency range but with a higher repetition rate The tuning variation is achieved by constructing the cavity with a ferrite loaded section or by using a separate ferrite loaded tuner coupled to the main cavity. Biasing the ferrite with a DC field alters the relative RF permeability over a small range, typically from a value of $\mu = 1.5$ (at saturation) to about 4. The higher the permeability, the lower the magnetic Q which introduces a tradeoff into the design.

Currently there is no complete data on common ferrite materials and their characteristics under bias. The required information is the real and imaginary parts of the permeability versus frequency with B_i (internal B-field of the media) as a parameter. In these curves, B is the actual internal field experienced by the ferrite *not* a value corresponding to the applied external field. Much of the available data gives permeability variation vs. external H-field for a particular geometry which makes it difficult to estimate the response of a different system or geometry. Data is available on specific loaded cavity Q's under various conditions but this obscures information about the ferrite alone.

The available data is not useful for systematically engineering new structures. For new designs the initial task would be to define the permeability required in some volume. This is determined by modelling the structure and computing the resonant frequency. The next task would be to determine how to apply an external field to arrive at that effective permeability. A consistent set of design curves would also provide an engineer with the corresponding losses (u") so the tradeoff between power loss and permeability could be adequately addressed. Also, in an actual structure the bulk ferrite will not be uniformly magnetized, which will result in a volume with non-homogeneous permeability and losses. The ability to accurately model the variation in permeability (stored energy) and losses throughout the ferrite volume is especially important in high power structures. The most useful design tool would be a set of material parameters, separate from any structure to allow for precise computer modeling. Ferrite manufacturers seem particularly loath in providing this data, and experimenters have been characteristically concerned with a few very similar designs and have not needed to assemble generic data. Our initial measurements were an attempt to address this problem and determine what type of equipment and fixtures would be required to produce material data for future design purposes.

This note includes a brief description of ferrite loaded cavities, current devices, and measurement techniques. More extensive work was not completed at the NSCL since sufficient interest and funding for a synchrocyclotron did not arise. This note does outline what data is needed and describes possible measurement methods for improved accuracy.

2. Biased Ferrites.

Many discussions of ferrite applications cover electron resonance phenomena though this is not particularly necessary since ferrite tuners for accelerators do not take advantage of these effects. The bias fields (near saturation) used in accelerator applications create spin resonance effects at relatively high frequencies which are well beyond the operating range of accelerator ferrite tuners. For completeness, a brief mention is included here.

The electron can be viewed as a spinning top with an associated magnetic moment. If a DC magnetic field is applied to the spinning electron at some angle to its magnetic moment, the electron will precess around the DC magnetic field. The rate of this precession is determined by the gyromagnetic ratio (a constant) and the strength of the field. If an incident RF field couples into the electron's precession, absorption will occur. This absorption will occur with the RF polarization either parallel, or perpendicular to the DC field, although the latter couples more strongly. Even an unbiased ferrite will possess a gyromagnetic resonance because of effective internal fields present in certain polycrystalline structures. The typical number encountered in textbooks for this resonant frequency is approximately 2.8 MHz/Gauss.

It is important to note that the internal field which defines the precession frequency is a sum of several fields: the applied field, the polarization field, and the anisotropy field. The polarization field, as defined in classical electro-magnetics, is the result of dipoles induced at the ferrite/air interface of a sample immersed in a constant H field. The induced field acts to reduce the internal field below that of the applied H, and is dependent on the sample geometry. The anisotropy field is not considered a true field in most texts, but is an artifice used to describe the effect of a preferred or 'easy' crystal axis in the sample. By 'preferred direction', we mean the spins will align more readily in one crystallographic orientation than in another. In reading background material, it was not obvious how large a perturbation this field has on the effective internal field. For our purposes (well below resonance) this is not a vital issue.

An important effect of electron resonance phenomena is that the RF permeability has a tensor form. This means oppositely polarized waves will experience different permeabilities, which in turn leads to Faraday rotation; where linearly polarized waves rotate as they propagate through the material. This phenomena is exploited in non-linear microwave devices such as isolators and circulators. These devices usually operate near or at the spin resonance frequency because the difference between the propagation constants of oppositely polarized waves increases near resonance. Also, over a small range at resonance, one polarization will not propagate at all (an evanescent mode) which leads to a useful class of microwave devices.

As mentioned above, with the bias fields (at or above saturation) employed in accelerator tuners, the spin resonance frequency is well into the microwave regime and is therefore not an issue. The effect in ferrites we are primarily concerned with is the change in permeability and losses far below the spin resonance. This change in permeability can be achieved by placing a DC magnetic bias field parallel or perpendicular to the RF magnetic field. The difference between these two biasing methods is important. and can be explained graphically using the B-H curve of the ferrite following a discussion from Smythe's paper (see Appendix A). If we assume that B is parallel to H, the B-H curve can be written as

$$\overline{B} = \overline{H}[1 + \frac{4\pi M_s}{|H|} f(H)]$$

where f(H) is a function approaching unity at saturation. If we also assume that the RF field is small compared to the bias then the RF permeability can be expressed as

$$\mu_{ij} = \frac{\partial B_i}{\partial H_j}$$

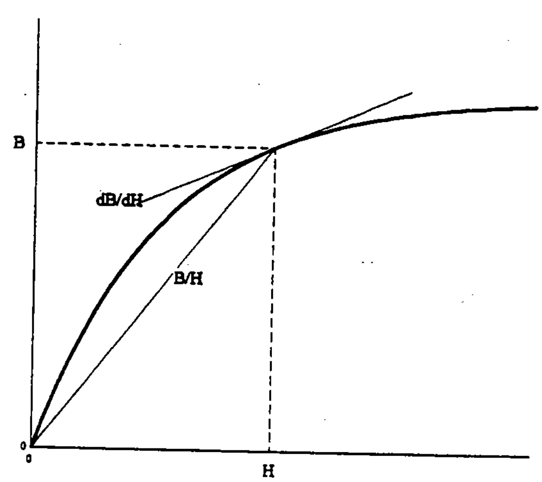
Working out the math for a general case (see Appendix A), we arrive at the following results:

Parallel bias $\mu = \frac{\partial B}{\partial H}$

Perpendicular bias $\mu = \frac{B}{H}$

Graphically, we can see that the parallel RF permeability is the slope of the B-H curve at a given applied field, whereas the perpendicular bias RF permeability is the slope of the line from the origin to the bias point. From these relations it is obvious that the perpendicular case will

Figure 1 - Graphical representation of RF permeabilities.



require a much greater variation in H than the parallel case to achieve the same change in μ. It is also evident, however, that the perpendicular case will be biased closer to saturation over a given tuning range, and will consequently have lower losses.

Early accelerators employed Ni-Zn type ferrites, which possess a relatively high saturation magnetization. This characteristic of the material required the use of parallel bias to ease demands on the bias coil system. Operating at the knee of the B-H curve, however, results in higher power losses. Present systems usually employ a perpendicular biasing scheme using YIG (Yttrium-Iron-Garnet) ferrites. The choice of perpendicular biasing results primarily from the requirement of lower RF power loss in the ferrites, which have poor thermal conductivity. Since operation is always above saturation in this method the losses are significantly reduced. YIG ferrites generally have a lower saturation magnetization (500-1000G) which eases requirements on the bias coil, while they also have a significantly higher magnetic and electric material Q than Ni-Zn ferrites.

3. Systems.

Development work in this field has occurred at several labs. Early work was done at NAL (FERMILAB) where they utilized parallel biased Ni-Zn ferrites. I believe both the booster and main-ring cavities still use parallel biased Ni-Zn type structures. The Los Alamos PSR buncher was designed with perpendicularly biased YIG ferrites to operate at 500 MHz and cycle at a very high repetition rate. A LAMPF developed booster cavity operates with perpendicularly biased YIG ferrites from 40 to 60 MHz at low rep. rates (~60Hz). Most recent is the development of the TRIUMF Kaon Factory booster cells which have advanced the LAMPF design. Work is also underway on developing similar booster cavities for the SSC.

4. Ferrites-At-A-Glance

The following table lists some order of magnitude numbers for perpendicularly biased ferrites which were gleaned from multiple sources. Most of the numbers come from Al doped YIG type ferrites.

Saturation magnetization	500-1000 G	
Initial permeability	30-130	
Permeability range under bias	$1.2\text{-}\mu_i$	
Estimates of magnetic Q: (for YIG ferrite)	μ'	Q
	4	$<10^3$
	3	5×10^3
	2	10^4
	1.5	$>10^5$?

Permittivity	14	
Electric Q	$>10^4$	
Thermal conductivity	0.05 W/cm-deg	
RF power density (in system with appropriate cooling)	1.4 W/cm^3	
Commercial ferrites:	G-810 (Al doped YIG) G-510 (Al doped YIG) Y1 (Al doped YIG)	Trans-Tech Trans-Tech TDK Electronics

5. Initial Measurements

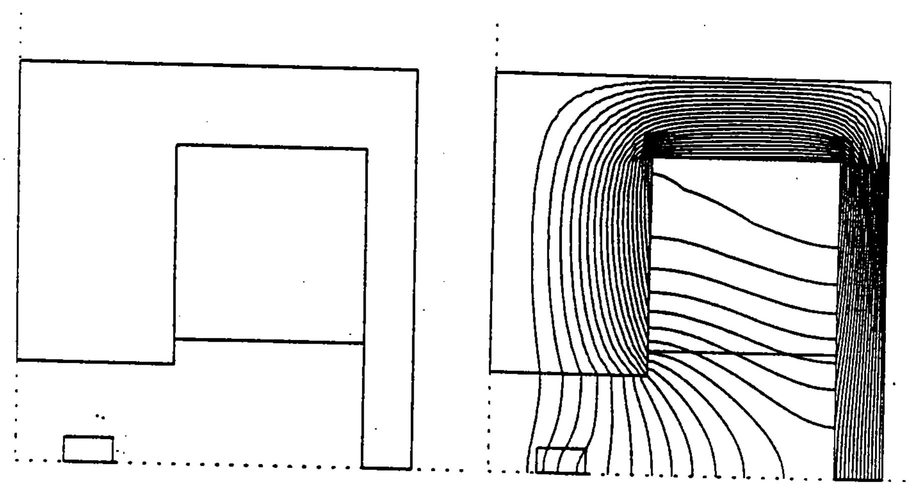
The first qualitative measurements made at the NSCL on ferrite materials were done by simply winding several turns of wire around available ferrite toroids and measuring the complex impedance without a bias field. These results gave permeability spectra similar to the manufacturer's data, showing the characteristic shape of u' and u" from 1 to 100 MHz. In these curves u' is reasonably flat up to about 1 MHz, at which point it rises slightly, then drops rapidly. The imaginary component also stays level until this point after which it rises sharply and then drops again at higher frequencies. This rise in absorption at low frequencies is associated with a broad resonance phenomena found in most ferrites. From the literature this resonance seems to be associated with domain wall motion which occurs when domains parallel to the applied field 'grow' by expanding their boundaries, and perpendicularly oriented domains contract. The frequency of this resonance is a function of the material but does not vary greatly for the materials in which we have the most interest. Note that this low frequency resonance in the permeability spectra is separate from the gyromagnetic resonance resulting from an externally applied field. These measurements confirmed results found in data books, but the accuracy was, of course, very limited. From these initial studies it became apparent that the magnetic losses were very small, especially under DC bias. The next measurements were made using a fixture which improved the accuracy and allowed for the application of a perpendicular bias field.

5. Biased Coaxial Test Fixture.

This fixture was designed to measure the complex permeability of ferrites by placing a ferrite toroid in a shorted section of coaxial line. By measuring the change in the impedance of this coax line with and without the ferrite, we arrive at values for u' and u". This coaxial section was placed between the pole tips of an H-magnet which provided a uniform perpendicular DC bias field. Complex impedance measurements were performed with an HP 4194A Impedance Analyzer since this instrument could be configured to model the measured impedance of the device under test as an equivalent circuit. Using an equivalent shunt RLC circuit, the values for R and L were recorded and then converted to values of u' and u". It is important to indicate the modeling method since some literature assumes a series circuit representation of the material. In this case the values of the complex permeability will differ from our numbers.

The first measurement task was to determine the dc bias field strength in the ferrite as a function of the magnet coil current in the test fixture. Because of the nonuniform field within the ferrite and the complex geometry of the test fixture, a closed form solution for the fields was not possible. Instead, computer modeling was used to relate the coil current in the fixture to the actual field inside the ferrite. This was done by creating an equivalent model of the fixture in POISSON with a simulated ferrite section. The actual internal field of the ferrite could then be measured throughout the toroid. Figure 2 shows a one quarter symmetry view of the simulation model with and without the B-field lines. The lower left rectangle is the ferrite region. The curves for a given bias condition are based on the *average* of these values within the ferrite. Simulation of the ferrite toroid immersed in a constant field indicates that the flux density varies significantly over radius (by as much as a factor of two), but assuming an average field over the toroid was deemed to be sufficiently accurate for our preliminary design curves.

Figure 2 - Test fixture POISSON model.



Simulation of the H-magnet structure was done with POISSON, assuming a cylindrically symmetric H-magnet structure. Since the vertical part of the real yoke was not azimuthally continuous, an approximation was used for this section of the magnetic circuit. Multiple runs were made with the model to determine the field strength at the pole tip center in air for various excitation current densities. These numbers were then compared to the same measured data for the real device. In this way a curve was created which related the actual current in the test device with the current density in the model that produced the same central field. When this analysis was complete we possessed a conversion scheme which gave the average internal bias field in the ferrite for a given magnet current in the measurement fixture.

Two YIG ferrites were analyzed using this system: Trans-Tech G810 and G510. The values of u' look reasonable and a nice family of curves were plotted showing the reduction in permeability with increased bias field (Appendix C). It is interesting to note that for the initial increase in bias field, the permeability rises slightly, and then falls with increased bias. This could be explained by a ferrite with residual magnetization, or a pole tip which was not entirely de-gaussed before the start of a run. Efforts were made, however, to ensure that this scenario did not occur by de-gaussing the ferrites, and walking the magnet back to zero field. Either these efforts were not sufficient or the results are somewhat anomalous. In any event, this unusual aspect does not disturb the overall character of the curve family since it only appears at low applied fields. At fields near saturation the permeability appears perfectly flat over the frequency range and is slowly approaching the limit of u'=1 at higher bias. It appears that the average internal field must be well above saturation to reduce u' below two.

The raw data contained in a regular series of sharp 'resonance' type peaks and glitches along each of the curves at specific frequencies, regardless of the bias field. This phenomena was not encountered until the data was analyzed, and by that time it was not possible to go back and check the measurement apparatus (which was on loan). Clearly this phenomena is not due to some yet undiscovered property of ferrites. It is due either to the modeling of the impedance data, or erroneous impedance measurements caused by the fixture or measurement device. The enclosed plots were smoothed by assuming a linear variation through the glitch, or by simply leaving the data points out of the plot. The inconsistent regions were fairly narrow, lasting 10kHz at the most and so did not cause distortion of the curve's large scale characteristics.

It is interesting to note that the anomalous points do not occur at low bias fields, but become more pronounced as the bias field increases. At higher field levels, however, the magnitude of the erroneous data decreases until, at the highest bias level, they are once again barely visible. This seems to indicate that the fringe magnetic field disturbed the impedance analyzer probe, which does contain some RF circuitry. The data taken for Trans-Tech G-810, however, showed more pronounced anomalies than the data for G-510.

The results for the complex part of the permeability were disappointing and more clearly indicated the limits of this sort of measurement apparatus. From these measurements it became apparent that small disturbances in connections to the RF fixture caused changes in the total device impedance which were at least an order of magnitude greater then the small losses we were trying to measure in the ferrite. These losses, as mentioned before, were determined from the value of R in the equivalent circuit generated for the coaxial line. Poor connection problems began with the probe tip which employed a BNC type connector which is a very un-reproducible connection. Additionally, there were problems with the coaxial line which was inserted between the pole tips. This coaxial line slid into the magnet and utilized RF fingers for contacts. Once in place the system made reasonable contact. The problem, however, was in changing the fixture from the baseline measurement with an empty coax line, to the ferrite filled device. Small changes in the contact resistance during calibration swamped the results since the resistance due to the ferrite losses was estimated to be as small as 10^{-4} Ohms. The curves we generated for the imaginary component of the permeability are probably not reliable below values of 0.1 This was unfortunate since the magnetic Q and losses of the ferrite are of great interest, especially in the higher power density machines.

Another difficulty with this measurement technique is obvious from the graph showing the impedance of the empty coax line. Figure 3 shows this baseline measurement over frequency which is subtracted from the ferrite numbers to give the change in inductance and resistance due to the ferrite. The complex impedance data was modeled as a series R and L combination shunted by a capacitor. One would expect the reactive elements to remain flat over the frequency range, while the resistance increased as a function of frequency. The inductance does remain fairly flat, varying by several tenths of a nanohenry over the band. The resistance is very small below 4 MHz, and is at the limits of the device measurement capability. Above this frequency, the resistance rises rapidly until about 85 MHz where the circuit passes through a resonance. The existence of this resonance corrupts the baseline measurement because the model no longer gives an accurate description of the element values. A small divergence in the baseline inductance measurement can also be seen here. Why the impedance indicates a series resonance at this frequency is not clear since the fixture alone is dimensionally much too small to explain the result. This series resonance phenomena is repeated in the raw data for the ferrite loaded fixture, though the effect is, unfortunately, not canceled out. This is because of a shift in frequency of the anomaly due to the ferrite. The effect is clearly visible in the u" data for G-510, resulting in a nonphysical dip in this component of the permeability at high frequencies.

This fixture could, of course be improved, but analysis has shown this will probably not be worthwhile. Because the magnetic Q of the ferrites appears to be greater than 5×10^3 , this type of measurement apparatus would have a large error associated with making such a measurement. The problem, obviously, is in trying to measure a very small number. A different type of test fixture would be better suited to accurately measure these quantities as well as other parameters such as the complex permittivity, and the response of the ferrite under high power or increased temperature. Curves with all this information will be necessary for effective design.

Several useful qualitative aspects of ferrites can be deduced from these curves. It is evident, for these materials, that below 1MHz there is not a significant improvement is loss properties under bias. The relative reduction in losses appears to increase with frequency. It is also apparent that the ferrites need to be biased well above saturation to reach the minimum permeability. To push the real part of the permeability below 2 requires significant increases in bias since the permeability is asymptotically approaching unity.

7. Alternative Measurements.

Measurement of material permeabilities and permittivities at microwave frequencies has been done using many different techniques. A common method is to place the sample in a section of waveguide or coaxial line and perform a two-port analysis with a network analyzer. In such a scheme the transmitted and reflected signals are analyzed as S-parameters to give information about the sample. This type of device also has many difficulties associated with it, such as error

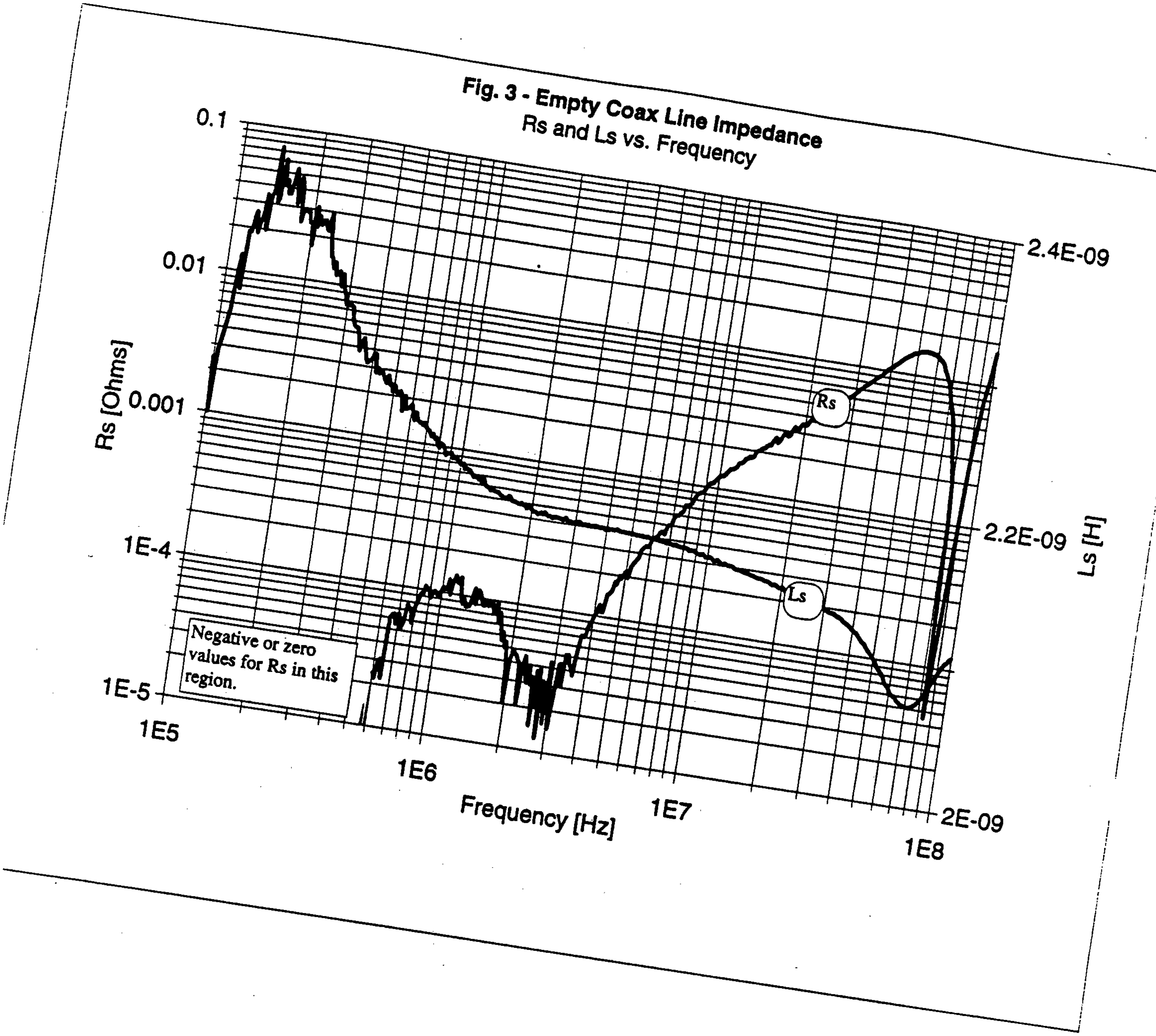


Fig. 3 - Empty Coax Line Impedance
Rs and Ls vs. Frequency
0.1
0.01
0.001
1E-4
1E-5
Rs [Ohms]
2.4E-09
2.2E-09
2E-09
Ls [H]
1E5
1E6
1E7
1E8
Frequency [Hz]
Rs
Ls
Negative or zero values for Rs in this region.

inducing air gaps between the sample and waveguide walls, and making reproducible connections. In the end this type of device is also trying to measure very small numbers when it comes to ferrite losses and will suffer from reproducibility. A better solution to the measurement dilemma is to measure small changes in large quantities, i.e by disturbing a resonant cavity with a small quantity of material. Here the difficulty is in measuring small changes as opposed to tiny absolute values. One advantage to this type of system is the ability to measure both magnetic and electric properties of materials, in addition to higher power density testing. A drawback to this approach is trying to get data across a large frequency range with one cavity. One idea might be to use a superconducting cavity since the losses would clearly be associated with the perturbing sample and any non-superconducting contacts or surfaces. There is a fair amount of literature discussing measurements techniques for this type of parameter, and many useful suggestions can be obtained from these papers. For example, much work has been completed on the advantages of various sample shapes and the best cavity mode to excite when measuring magnetic versus electric parameters in the microwave regime. This information, however, is sometimes of limited utility when you are measuring at the low end of the frequency spectrum (1 MHz). An important issue to consider is the sample shape and size which effects how evenly you can bias the material, and how large an effect the polarization field will have.

Appendix A. Perpendicular and parallel bias permeability.

This section completes the details of a calculation from the paper by Smythe, "Reducing Ferrite Tuner Loss by Bias Field Rotation". The idea is to find the effective RF permeability, given by the partial derivative of B with respect to H, for the two cases of H perpendicular or parallel to the RF variation. (Note, in Smythe's paper, equation (4) has a typo since there should not be an H in the denominator.) Assuming B is parallel to H we can write

$$\vec{B} = \vec{H}\left(1 + \frac{4\pi}{|H|} f(H)\right)$$

where f(H) is a function which describes the magnetization of the particular ferrite, approaching unity at saturation. If we assume the RF field magnitude is small compared to the bias field then the effective RF permeability can be expressed as

$$\mu_{ij} = \frac{\partial B_i}{\partial H_j}$$

If we specify B and H along two orthogonal axes (x and y) and perform the math, we will arrive at a simple expression for the two permeabilities. The general relation between B and H for this example is as follows

$$B = \hat{i}Bx + \hat{j}By = \left(\hat{i}H_x + \hat{j}H_y\right)\left(1 + \frac{4\pi M_s}{\sqrt{H_x^2 + H_y^2}} f(H)\right)$$

the partial derivative of the x-component of B with respect to the same component in H is determined below. This can then be solved for the parallel bias case by substituting in H_y=0, once the derivative is evaluated.

$$\frac{\partial B_x}{\partial H_x} = \frac{\partial}{\partial H_x}\left[H_x\left(1 + \frac{4\pi M_s f(H)}{|H|}\right)\right]$$

$$= \left(1 + \frac{4\pi M_s f(H)}{|H|}\right) + H_x \frac{\partial}{\partial H_x}\left(\frac{4\pi M_s f(H)}{\sqrt{H_x^2 + H_y^2}}\right)$$

$$= \left(1 + \frac{4\pi M_s f(H)}{|H|}\right) + H_x 4\pi M_s \left[\frac{-f(H) H_x}{(H_x^2 + H_y^2)^{-3/2}} + \frac{1}{\sqrt{H_x^2 + H_y^2}} \frac{\partial f(H)}{\partial H_x}\right.$$

$$= \left(1 + \frac{4\pi M_s f(H)}{|H|}\right) + H_x\left[\frac{-4\pi M_s f(H) H_x}{(H_x^2 + H_y^2)^{-3/2}} + \frac{4\pi M_s}{\sqrt{H_x^2 + H_y^2}} \frac{\partial f(H)}{\partial |H|} \frac{\partial |H|}{\partial H_x}\right]$$

$$= 1 + \frac{4\pi M_s f(H)}{|H|} - \frac{H_x^2 4\pi M_s f(H)}{|H|^3} + 4\pi M_s \frac{H_x}{|H|} \frac{\partial f(H)}{\partial |H|}\left(\frac{\partial |H|}{\partial H_x}\right)$$

the last derivative in this expression is given as

$$\frac{\partial|H|}{\partial H_x} = \frac{\partial}{\partial H_x}\sqrt{H_x^2 + H_y^2} = \frac{H_x}{|H|}$$

and when substituted into the main expression gives

$$= 1 + \frac{4\pi M_s f(H)}{|H|} - \frac{H_x^2 4\pi M_s f(H)}{|H|^3} + 4\pi M_S \left(\frac{Hx}{|H|}\right)^2 \frac{\partial f(H)}{\partial|H|}$$

$$= \frac{4\pi M_s f(H)}{|H|}\left(1 - \left(\frac{H_x}{|H|}\right)^2\right) + 1 + 4\pi M_S \left(\frac{H_x}{|H|}\right)^2 \frac{\partial f(H)}{\partial|H|}$$

if we then assume that the bias field H is only x-directed in this derivative, we arrive at the permeability expression for the parallel case.

$$\left.\frac{\partial B_x}{\partial H_x}\right|_{H_y=0} = 1 + 4\pi M_S \frac{\partial f(H)}{\partial|H|}$$

We can make a further simplification of this expression by realizing that

$$\frac{\partial B}{\partial H} = \frac{\partial}{\partial H}(H + 4\pi M_S f(H)) = 1 + 4\pi M_S \frac{\partial f(H)}{\partial|H|}$$

which leads to the simplified relation for parallel bias.

$$\left.\frac{\partial B_x}{\partial H_x}\right|_{H_y=0} = \frac{\partial B}{\partial H}$$

Graphically this can be interpreted as the slope of the tangent point on the B-H curve.

If we assume instead, that the DC field is y-directed only, we arrive at an expression for permeability in a perpendicularly biased system.

$$\left.\frac{\partial B_x}{\partial H_x}\right|_{H_x=0} = 1 + \frac{4\pi M_s f(H)}{|H|} = \frac{B}{H}$$

As indicated, this is simply the ratio of B to H which is graphically interpreted as the slope of the line from the origin to a point on the B-H curve.

The results are summarized for the general case given two orthogonal coordinates i,j where th H-field is applied in the i direction only.

parallel bias $\mu_{ii} = \frac{\partial B_i}{\partial H_i} = \frac{\partial B}{\partial H}$

perpendicular bias $\mu_{jj} = \frac{\partial B_j}{\partial H_j} = \frac{B}{H}$

Appendix B Measurement technique using a coaxial test fixture.

This type of measurement technique is fairly common. A reference for this procedure can be found in *Review of Scientific Instrumentation*, vol 58, no. 4, April 1987, p.624. This section is transcribed from a lab notebook kept during this research.

The general expression for the impedance of an inductive element in free space is given by

$$Z = j\omega L_0$$

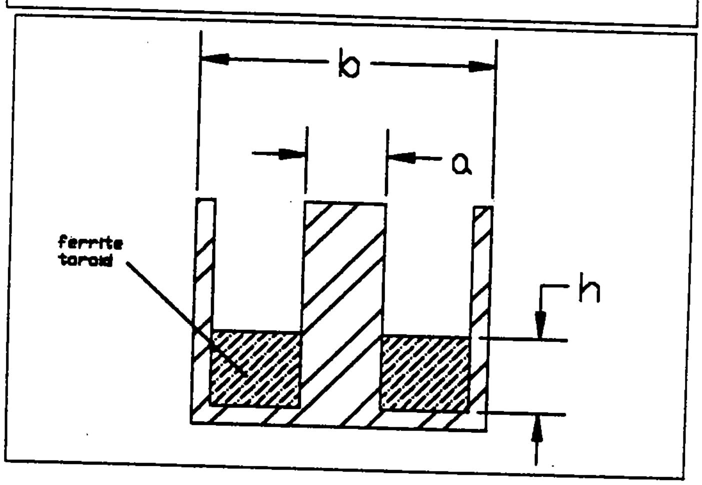
where L_0 is the inductance of the element in free space. For the same element in a media of relative complex permeability μ_r the impedance is written

$$Z = j\omega L_0\left(\mu_r' - j\mu_r''\right) = j\omega L_0 \mu_r' + j\omega L_0 \mu_r''$$

The second term of this expression corresponds to the resistive component of the impedance.

For a shorted section of coaxial transmission line, we can infer the value of the complex permeability by measuring the impedance of the line. A crossectional view of the transmission line section is shown in the accompanying figure.

Figure 1. - Crossection of coaxial test fixture.



The resistance of the empty fixture is simply due to losses in the coaxial line. When the line is partially filled with a toroid of ferrite material the total resistance is equal to the line section resistance plus the resistance derived from losses inside the ferrite material. The difference then, between the measured resistance of the line with and without the ferrite is simply the losses due to the ferrite material . The difference is written below as

$$\Delta R = \omega L_a \mu_r''$$

where La is the inductance (in air) of the section of transmission line of length h. This is simply the inductance of the ferrite if it had a relative permeability of one. Using the closed form expression for the inductance of a coaxial line we can rewrite the expression for ΔR to define the imaginary component of the permeability in terms of the measurable quantities

$$\mu_r'' = \frac{\Delta R}{hf\mu_o \ln\left(\frac{b}{a}\right)}$$

Similarly, the inductive component of the measured impedance can be used to determine the real component of the complex permeability. The total inductance of the coaxial section when filled with the ferrite is given by the sum of the inductance of the ferrite section and the empty length of line above the toroid. This sum is written as

$$Ls = \mu_r' La + L_f$$

where μ_r' is the real part of the ferrite permeability, L_a is the equivalent inductance of the air space occupied by the toroid, and L_f is the inductance of the space above the toroid. The inductance of the empty line is written as

$$Le = La + L_f$$

The difference of these two measurements is simply

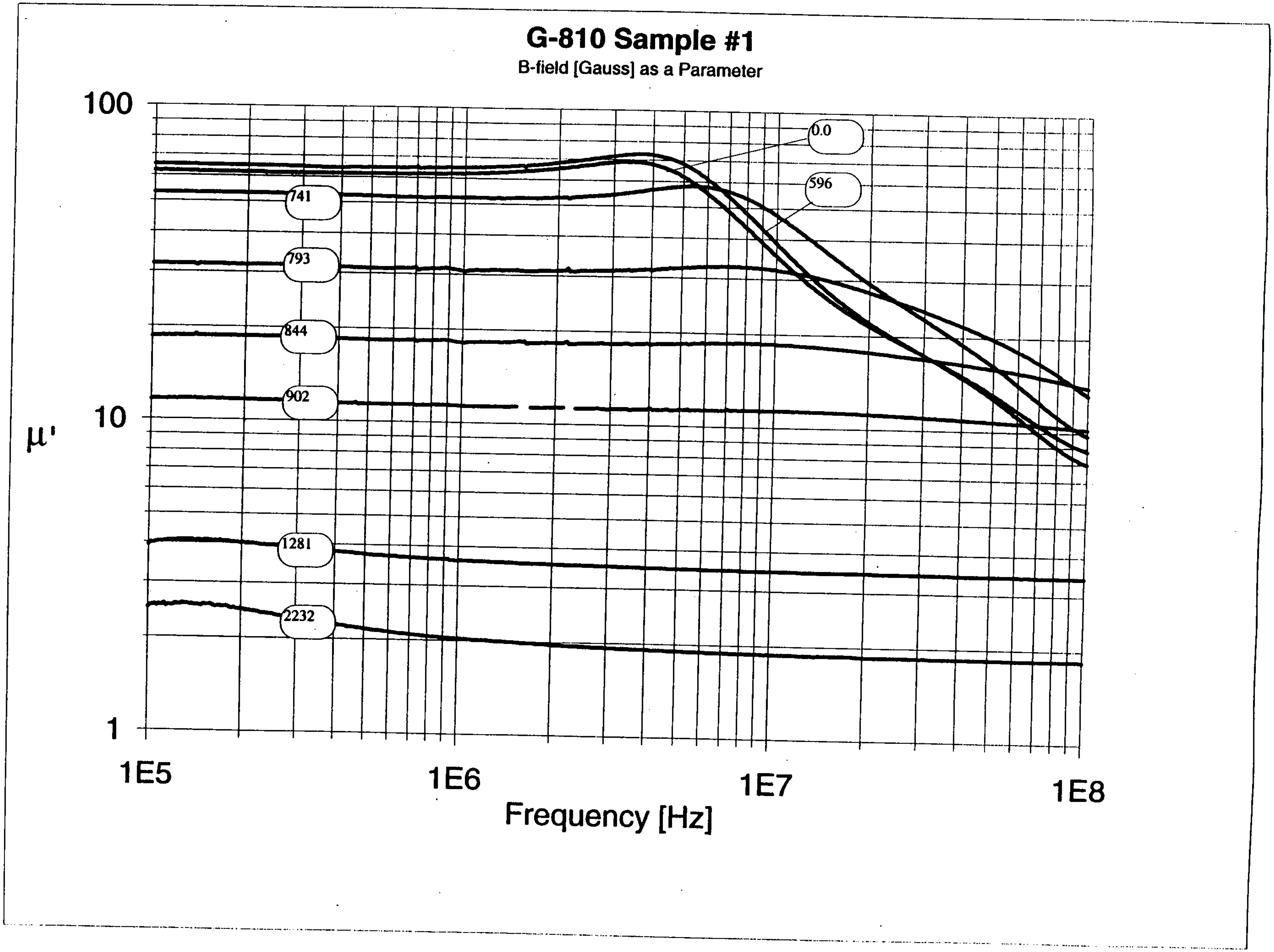
$$\Delta L = La(\mu_r' - 1)$$

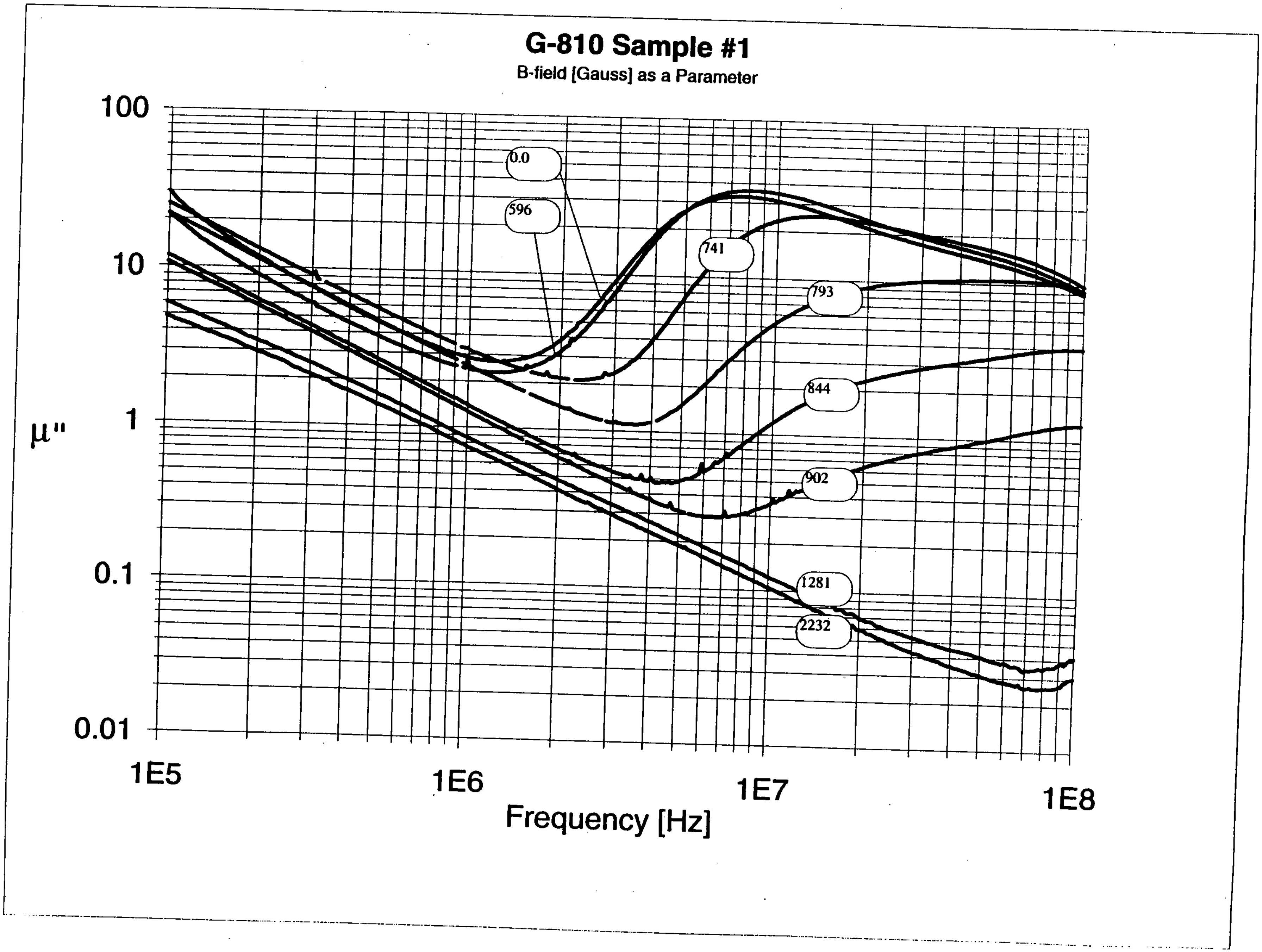
As in the previous calculation of losses, the expression can be rewritten to give the real part of the permeability of the toroid in terms of the measured quantities.

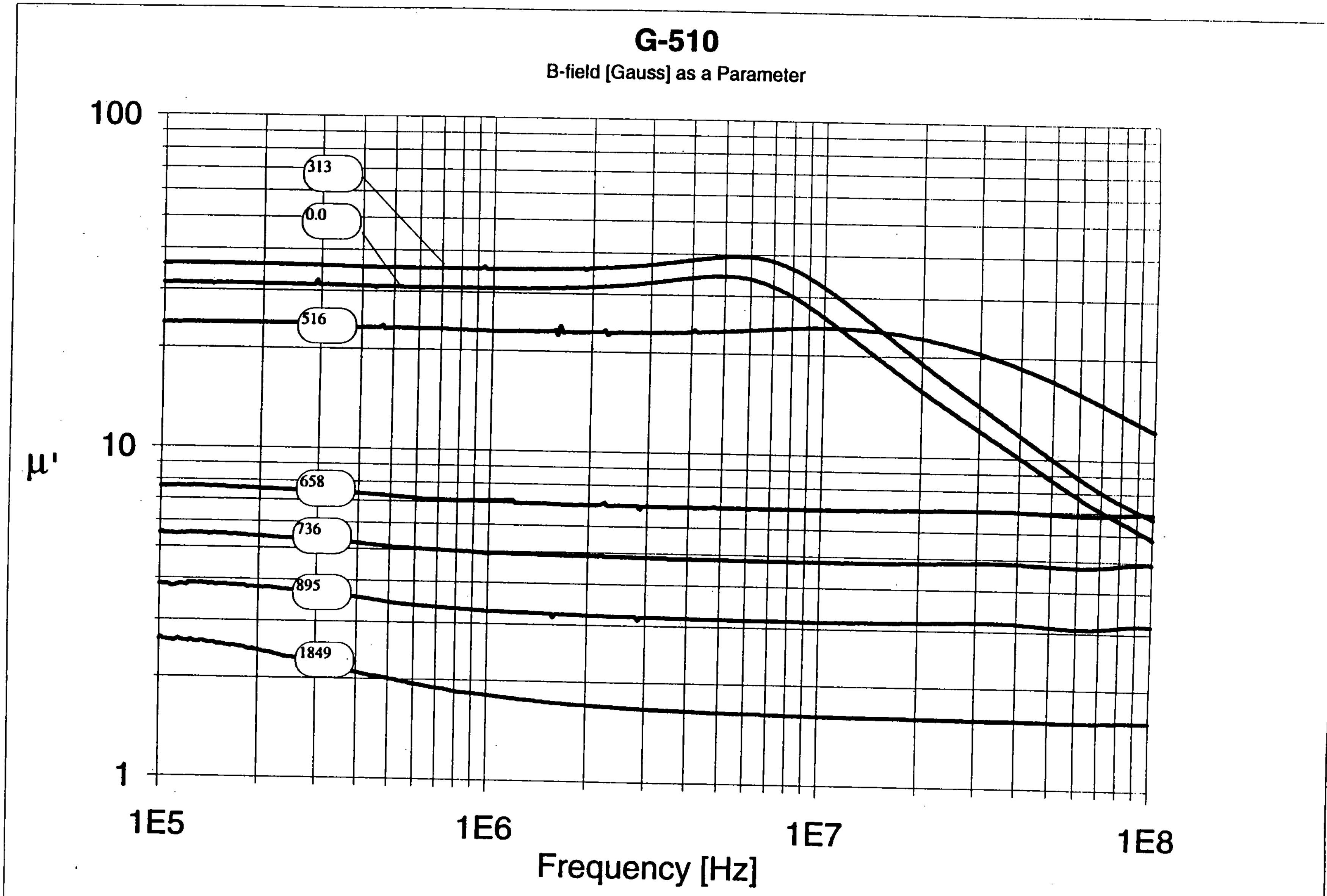
$$\mu_r' = 1 + \frac{2\pi \Delta L}{h\mu_o \ln\left(\frac{b}{a}\right)}$$

The measurement procedure consisted of determining of the impedance of the empty coaxial section, as well as the impedance of the section with the ferrite inserted. These complex impedances were then used to find the circuit elements of the equivalent circuit model for the coaxial line. This gave values for R and L, from which we compute the differences to be used in the previous equations. The circuit model used for this analysis was a series L and R branch shunted by a capacitor. Although the capacitance of the line section is relatively small, it is necessary to include a capacitive component to accurately model the test fixture. A useful feature of the HP Impedance Analyzer was that it could measure the complex impedance and then compute various equivalent circuit parameters directly. A series of data files was created for a given ferrite which contained a list of R and L values versus frequency with the bias current as a parameter.

Appendix C. Trans-Tech G810, G510 biased permeability spectra.

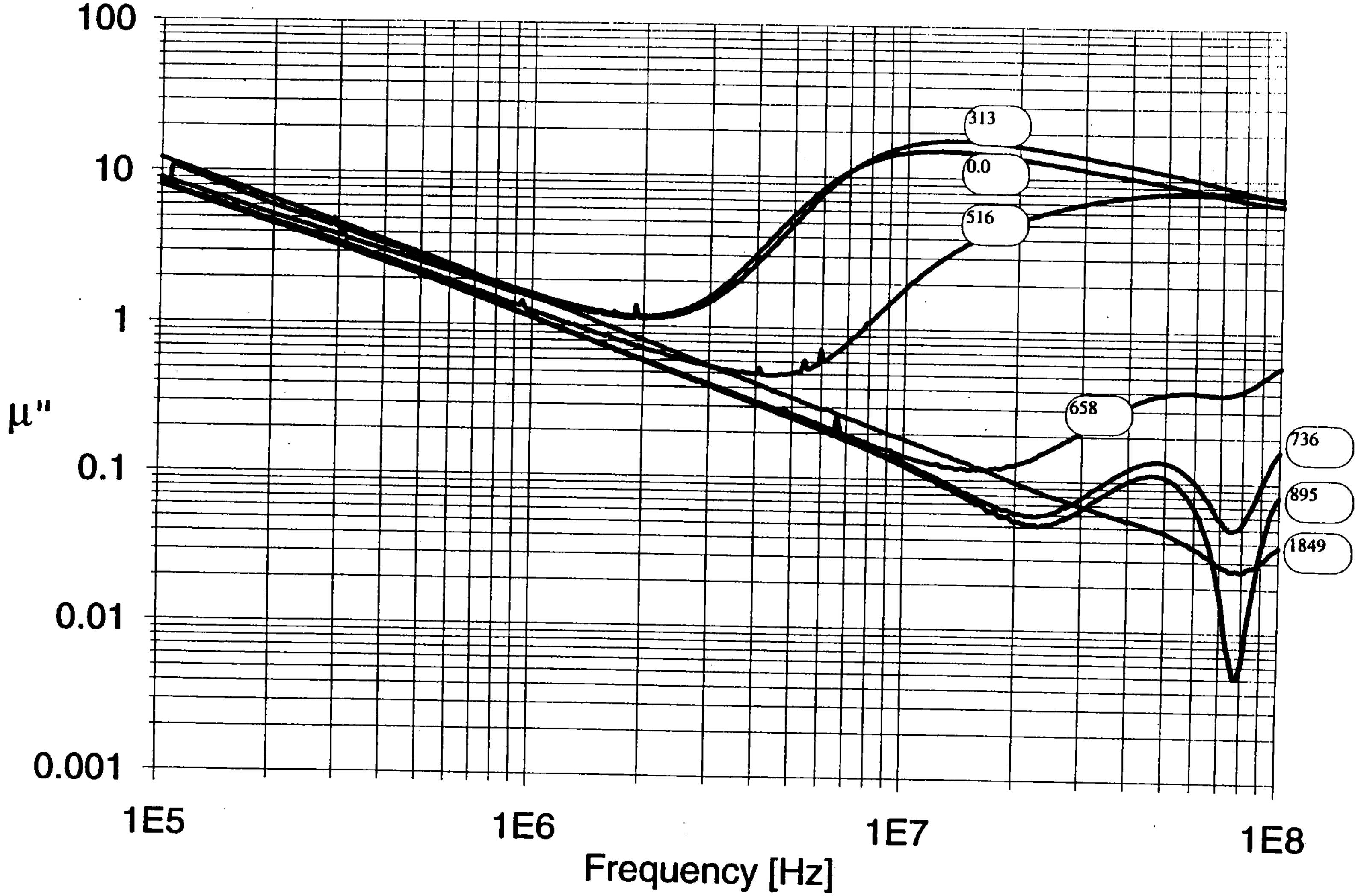

G-810 Sample #1
B-field [Gauss] as a Parameter
100
10
1
μ'
0.0
596
741
793
844
902
1281
2232
1E5
1E6
1E7
1E8
Frequency [Hz]


G-810 Sample #1
B-field [Gauss] as a Parameter
100
10
1
0.1
0.01
μ"
0.0
596
741
793
844
902
1281
2232
1E5
1E6
1E7
1E8
Frequency [Hz]


G-510
B-field [Gauss] as a Parameter
100
10
1
μ'
313
0.0
516
658
736
895
1849
1E5
1E6
1E7
1E8
Frequency [Hz]

G-510

B-field [Gauss] as a Parameter



Appendix D. General Magnetostatics

The following section contains some notes, useful reminders, and definitions.

For materials with residual magnetization:

Ferromagnetic - Neighboring dipoles align parallel.

Antiferromagnetic - Neighboring dipoles align antiparallel.

Ferrimagnetic - Neighboring dipoles align antiparallel, but different types of atoms are present in the lattice, each with differing dipole strengths, resulting in incomplete cancellation. It is also possible to have this incomplete cancellation when the magnetic ions are the same, but they can exist in two different types of sublattice.

For materials without residual magnetization:

Diamagnetic - Response of material to applied magnetic field (H) acts to *reduce* the magnetic flux density within the material.

Paramagnetic - Response of material to applied magnetic field (H) acts to *increase* the magnetic flux density within the material.

Terms used in ferrite data sheets:

Lande g-factor - The constant relating the atomic magnetic moment to the total angular momentum, according to the following relation.

$$\mu = gJ\mu_B$$

where J is the total angular momentum, g is the Lande g-factor, μ is the atomic magnetic moment, and μ_B is the Bohr magneton. Generally, for ferrite materials the magnetic moment is determined by the electron spin (not nuclear) which results in a g-factor approximately equal to two.

Line width - This refers to the resonance line width of the electron spin resonance. This is measured by selecting a constant RF frequency and a constant applied field at which resonance occurs. The line width is measured by varying H, not the RF frequency. Usually the point at which the line width was measured is given, i.e at the point -3dB down from maximum power absorption (resonance).

Spin wave linewidth - This refers to the line width of the spin wave resonance frequency. A spin-wave in ferrites occurs when the spins across a sample do not precess in phase with each other in response to an RF field. Instead, the precession, communicated by exchange forces, transfers from one electron to the next in a wave-like fashion. This is somewhat like an acoustic wave propagating through the material and is explained in text books by analogy to a plasma wave. If the sample length is a multiple of the spin-wave wwavelength, a standing wave will occur, providing a means for measuring this frequency. It appears that this term is used to compare losses for various materials when propagating RF through a ferrite (i.e. as in phase shifters).

Curie temperature - The point at which the thermal energy overwhelms the magnetic exchange forces which create the spontaneous magnetization in a material. At this temperature, the magnetization drops to zero.

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