R.F. Ferrites

These notes are a draft, not a finished work. Please do not copy on.

Specification of Parameters:

A core’s magnetic characteristics are sometimes given as Permeability (μ) [1] and power loss in Watts per Kilogram under specified conditions and frequency. This is usually the case for low frequency power transformer cores but it is not so useful when looking to incorporate the losses into a circuit model.

A more useful way at r.f. is to express the permeability as a complex (vector) quantity. This has the advantage that simple relations can be found connecting the electrical characteristics of coils with the real and imaginary components of the permeability of their cores. These will then specify both the inductance and loss resistance of the winding. The term complex permeability is defined in an article written by K. A. MacFadyen (1). This still gives a useful account of complex permeability, for those who can access a copy.

The real part of the permeability is conventionally written as μ’ and the imaginary part as μ’’. It may take a small amount of trust to accept that the real part gives the inductive permeability and the imaginary part gives the resistive loss factor. A full proof of this is lengthy and will not be given here. See e.g. ref (2) which gives a more modern account of vector permeability.

The parameters are most often given as μ’s and μ’’s which are the equivalent series circuit values. Parallel values are more often used in transformer models and conversion at a given frequency is not difficult.

Not all manufacturers make complex permeability information available: Fair-Rite does (3), and so does Ferroxcube (4), probably others do too. Some manufacturers quote μ’s and tanδ, the latter is the ratio μ’’s/μ’s but often only spot values of tanδ are given rather than plots against frequency, which are then less useful.

Variation of Loss factors with Frequency:

Both terms of the complex permeability are frequency dependent. Examination of a manufacturer’s data will show curves similar to Fig 1, which is for the popular type 43 material:

[1] Throughout this note Permeability is the relative permeability μ_r i.e. the value relative to air. This is the figure normally quoted by manufacturers.

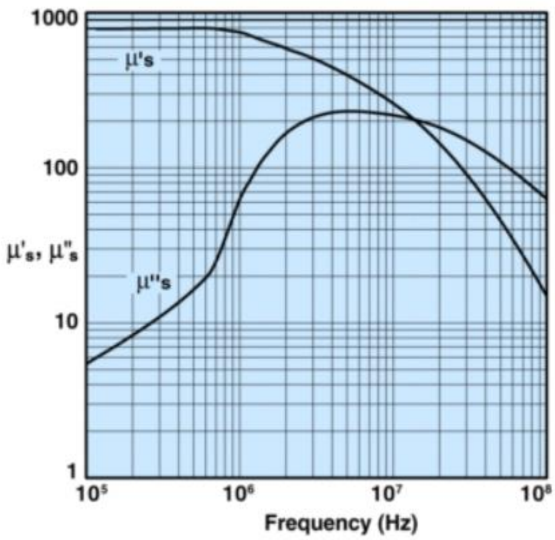


Fig 1. Fair-Rite Type 43 material

For the 43 material, the permeability is constant up to 1MHz and then falls. This means that the inductance for a given number of turns will also fall. The resistive loss factor rises sharply with increasing frequency to as much as 50 times its low-frequency value.

An important point to note is that the manufacturer's Al value, usually given in uH/turn^2 or nH/turn^2 and used to calculate the inductance of a winding, is typically measured at 10kHz. At 14MHz a winding on a -43 material core will exhibit only 1/4 of its low-frequency inductance.

Always check the permeability-frequency graphs where Inductance at a specific frequency is important and measure the finished component.

One parameter which can immediately be derived from these graphs is the maximum possible Q for a winding at a specific frequency (excluding wire loss). It is the ratio μ's/ μ''s (also equal to 1/tanδ).

Application to Specific Cores:

The information in the μ's and μ''s curves cannot be used directly. They give properties for the bulk material, not for a specific core size or shape.

To calculate the actual Inductance and loss resistance for a winding on a specific core we need calculate:

$$Rs = 2 * \pi * f * \boldsymbol{L_0} * \mu''s$$ Ohms/turn^2 ---------------- (1)

And:

$$Ls = \boldsymbol{L_0} * \mu's$$ Henrys/turn^2 ---------------------------------- (2)

$\boldsymbol{L_0}$ is the inductance the coil would have without the ferrite core, i.e. if air-cored.

The above two formulae are applicable to any closed core shape, but not to cores with air gaps, or ferrite rods.

Note that the series Inductance Ls is proportional to the square of the number of turns, which is common knowledge, and that the series a.c. loss resistance, perhaps counter-intuitively, also scales as the square of the number of turns.

The standard formula for the inductance of an air-cored toroid is:

$$L_0 = \frac{\mu_0 * h * N^2}{2 * \pi} \ln\left(\frac{b}{a}\right)$$ Henry

Where μ_0 is the permeability of free space: 4*π*10^{-7} Henry/Metre

h is the height of the toroid

N is the number of turns on the toroid

a is the inner *radius* of the toroid

b is the outer *radius* of the toroid

Remember to keep everything in S.I. units i.e. metres if you use this.

This standard formula for the Inductance of an air-cored toroid does not yield answers which match measurements. To check, a Delrin toroid was machined with dimensions which match a Fair-Rite 140 series core. The calculated inductance for 12 turns was 400nH, whereas the measured Inductance, using an H.P. 4342A Q-meter was 800nH. With 50 turns, the calculated inductance was 2.8uH , while the measured value was 3.4uH. The current sheet approximation used to derive the standard formula is thus not accurate for small numbers of turns of round wire spaced over the circumference. Rosa (7) discusses this further. If seeking an accurate value of inductance, measurement is necessary.

It is possible to read µ''s and µ's from the manufacturers graph and use those values, plus the calculated value of L_0 to calculate the series Inductance and series resistance of a winding on a core, remembering to use N^2 in both cases. A spreadsheet helps to maintain sanity if many values are to be processed.

The ready availability of modestly priced network analysers makes such calculations unnecessary for many purposes.

Be aware of resonances due to self-capacitance.

Below is a set of calculated values for the FT140-43, a core suited to high-frequency use.

FT140-43

Outer Diameter (mm)	35.6
Inner Diameter (mm)	22.9
Height (mm)	12.7
L0 (Henries/turn^2)	1.12e-9

From the Manufacturer's graph for 43 material:

F(Mhz)	1	3.5	7	14	30	50
u's	750	500	300	200	95	40
u''s	56	210	210	200	154	100

Calculated values, for the 140 size core, using formulae (1) and (2), above:

Ls/turn^2	8.42E-7	5.61E-7	3.37E-8	2.24E-7	1.07E-7	4.49E-8
Rs/turn^2	0.395	5.18	10.34	19.7	32.5	35.2

<u>Core Temperature Rise:</u>

Core temperature rise is difficult to calculate. Empirical formulae exist but experience suggests these are not reliable for small objects.

To get some idea, a 2mm square platinum resistance thermometer was glued to an FT140-43 core. The core was heated to 100 Celsius and a cooling curve plotted. It is possible to infer the heat transfer from the surface with this measurement, since the reduction in internal energy must equal the energy loss from the surface. For the FT140-43 the result averaged about 10 degrees Celsius per watt. For the larger FT240-43 the figure was 6 degrees per watt. No good measurements have been made on FT50- series cores as they are so small: a figure of 40 degrees per watt is assumed on the basis of core volume. High accuracy cannot be claimed for these figures, but they should serve as a working approximation. The power dissipated in the ferrite can be calculated using the equivalent circuit resistance and this power is then multiplied by the thermal resistance, in degrees per watt, to give the temperature rise.

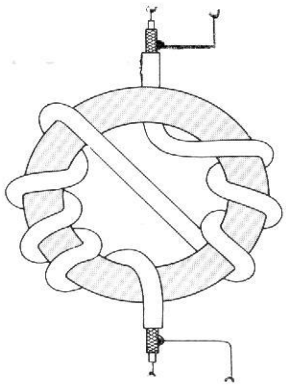
To minimise core heating in power applications, the winding need not be covered with insulation tape. This ensures that the maximum core surface is exposed to the air. The resistivity of ferrites is so high that the insulation on the wire is generally sufficient unless high voltages are expected to develop across the winding.

A note on winding methods:

It is often assumed that toroids have a closed magnetic circuit with no external field, sometimes referred to as self-shielding. This is not the case unless special winding techniques are used.

If, for example, a number of turns are wound in a continuous single layer on a toroid, the turns do form a closed solenoid with a contained circumferential field. However, there is also a net current flow from the start to finish of the winding equivalent to one circumferential turn, which produces an axial field not coupled to the core. This can result in significant leakage flux (leakage inductance) when using a low-permeability toroid with a small number of turns. It can, for example, cause unexpected coupling between the inductors in a filter. This effect can be ignored for most applications. For ten turns on a core with a permeability of 100, the leakage is 0.1%

There are various solutions. See ref (6) for a detailed explanation. One, for a single layer winding, is to lay a single circumferential turn around the outside of the core and then wind the turns back over this, finishing close to the start. Cancellation of the axial field is not perfect, but is already quite good. Another is to wind half the turns around the toroid and then wind the other half back over them to the start, crossing the turns at an open angle if possible to minimise the increase in self-capacitance. Again cancellation is good, but not perfect if there has to be an odd number of turns. This winding method also helps to cancel any electric field around the winding (ref (6) again). The winding method shown in Fig:x also achieves cancellation and has the sometimes useful property of keeping start and finish ends of a winding opposite each other.



In this case the winding is split into two halves. The fields from the halves of the circumferential turn tend to cancel, whilst the field created in the core by the turns adds in the same way as a simple winding. Windings with a few turns could be close-wound over a small part of the core, but this will increase the self-capacitance and is not generally done.

Other Materials:

Carbonyl Iron powder (dust) cores have not so far been mentioned. This is mainly because complex permeability curves are generally not available, so that the methods above cannot be applied. Amidon does publish Q curves, but these are not sufficient to assign values to the two permeability components. Because the Iron particles are coated with an insulating film, they tend to stay magnetically separate, Carbonyl Iron cores have in effect a distributed air gap. This accounts for their low permeability and also makes them less liable to saturate in power applications.

Iron powder cores have very low permeability, often 10 or less, but this is maintained up to 50MHz or more. Their losses are low and may, for many purposes, be neglected. They may be the best choice filters, resonant circuits, antenna tuning units and some flux-coupled transformers *where sufficient inductance can be obtained with the low permeability.* They sit above ferrites in the optimum frequency range of use. Note that they are not the material of choice for broadband chokes, baluns or transmission line transformers where a choking action is needed to suppress unwanted currents.

An important use for iron dust toroids is when a small inductance is required to be wound to moderate accuracy, for use in filters for example. The lowest permeability Nickel-Zinc ferrite from Fair-Rite is the type -68 which winds, on small cores, at about 20nH/turn^2. Thus a 1uH inductor would need only 7 turns. Adding or removing one turn gives either 1.28uH or 720nH. Other values close to these cannot be wound because fractional turns are not possible on a toroid. Iron dust cores have lower permeability and a T50-7 (white) core winds at 4.3nH/turn^2. Thus 1uH would need 15 turns and there is more scope for fine adjustment by adding or removing one turn i.e. 1.1uH or 842nH. Thus Iron dust cores are often used for tuned circuits and filters including antenna matching networks.

Air-Gaps in magnetic components

The question “is it acceptable to glue the pieces of a damaged core back together?” is sometimes asked. This will inevitably introduce a small non-magnetic gap between the parts. An air-gap reduces the effective permeability. If an air-gap is introduced into a toroid, either by accident or design it then:

$$\mu_e = \frac{\mu_r}{\left(1 + \left(\mu_r * \frac{lg}{le}\right)\right)}$$

μ_e is the effective permeability of the gapped core

μ_r is the permeability of the ferrite material

lg is the path length of the gap (twice the individual gap for a broken toroid)

le is the path length of the ferrite: mean circumference for a toroid.

The above assumes the gap has relative permeability of one, i.e. air or some non-magnetic material. The effect is worse with high permeability materials.

If, for example μ_r is 200 (type 43 material at 14MHz), lg = 0.2 mm (two 0.1mm gaps), and le = 90mm, then μ_e is 138. The permeability and thus inductance are reduced by about 30%.

A ferrite rod already has much of the magnetic path in air. Graphs are available on the Internet showing a rod’s effective permeability against material permeability and rod dimensions (length/diameter is what matters). They may be more amenable to repair.

Given the usually low cost, damaged ferrites should always be replaced by new parts where possible.

A final caution is that ferrites are annealed after manufacture and dropping or grinding a ferrite component can change its properties. Treat ferrites like eggs.

Design aids:

The mini ring core calculator program, available free on the internet is particularly useful, with the caution that it uses the low frequency value for permeability. Ref (9)

Further reading material:

The first edition of Eric Snelling's important and rare book "Soft Ferrites" is available for download on the Internet. See 8. below. It was written in 1969 so does not cover many of the modern materials but gives a good account of the theory including ferrite rod antennas (chapter 10). Use the first PDF option.

1. https://archive.org/details/SNELLING__SOFT-FERRITES__1969

A few of my own calculations. Errors and omissions are entirely possible

		FT240-43					
Outer Diameter (mm		61					
Inner Diameter (mm		35.6					
Height (mm)		12.7					
L0 (Henries)		1.37E-09					
f MHz	0.1	1	3.5	7	14	30	50
us'	800	750	500	300	200	94.9	40
us"	5.8	56	210	210	200	153.5	100
Ls /tn^2	1.09E-06	1.03E-06	6.84E-07	4.10E-07	2.74E-07	1.30E-07	5.47E-08
Rs /tn^2	0.005	0.481	6.317	12.634	24.065	39.578	42.973

		FT140-31						
Outer Diameter (mm		35.56						
Inner Diameter (mm		22.86						
Height (mm)		12.7						
L0 (Henries)		1.12E-09						
f MHz	0.01	0.1	1	3.5	7	14	30	50
us'	1424	1402	1400	590	329	206	115	61.8
us"	10.5	41.6	463	658	444	299	210	152
Ls /tn^2	1.60E-06	1.57E-06	1.57E-06	6.62E-07	3.69E-07	2.31E-07	1.29E-07	6.94E-08
Rs /tn^2	0.001	0.029	3.265	16.239	21.916	29.517	44.423	53.590

		FT240-31					
Outer Diameter (mm		61					
Inner Diameter (mm		35.6					
Height (mm)		12.7					
L0 (Henries)		1.37E-09					
f MHz	3.5	7	14	30	50	60	100
us'	125	125	140	105	60	50	42
us"	0.7	1.2	4	80	75	65	50
Qm	178.5714	104.1667	35	1.3125	0.8	0.769231	0.84
Ls /tn^2	1.71E-07	1.71E-07	1.92E-07	1.44E-07	8.21E-08	6.84E-08	5.75E-08
Rs /tn^2	0.021	0.072	0.481	20.627	32.229	33.519	42.973

		FT140-43					
Outer Diameter (mm		35.56					
Inner Diameter (mm		22.86					
Height (mm)		12.7					
L0 (Henries)		1.12E-09					
f MHz	0.1	1	3.5	7	14	30	50
us'	800	750	500	300	200	94.9	40
us"	5.8	56	210	210	200	153.5	100
Ls /tn^2	8.98E-07	8.42E-07	5.61E-07	3.37E-07	2.24E-07	1.07E-07	4.49E-08
Rs /tn^2	0.004	0.395	5.183	10.365	19.744	32.471	35.257