Technical Note

Gapped ferrite toroids for power inductors

FERROXCUBE

A YAGEO COMPANY

Gapped ferrite toroids for
power inductors

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Introduction

Toroids are well known for their magnetic properties. They achieve the highest inductance per unit of volume due to the uniform cross-section and a fluent magnetic path without corners. The latter means that not only the cross-section, but also the flux density is uniform, which is especially important to fully exploit the material saturation level. Also stray flux is very low for a toroid.

FERROXCUBE has introduced a range of gapped ferrite toroids, intended primarily for power inductor applications. They are made from toroids in the high flux, frequency stable material 3C20 by precision machining a small gap. Finally, the core is completely coated with nylon and ready for winding as if it were ungapped.

The gap helps to avoid saturation in applications where there is a large current. This can be either a DC bias current or an AC current swing. For every size of toroid there is a range of gaps, providing a range of A_L values to fit the required inductance value. The high flux, frequency stable material 3C20 has very low power losses, outperforming in this respect iron powder and all metal alloy powders. Even if a slightly larger core is required, ferrite could beat certain metal alloys on price.

Features

· Simple economic shape
· Available in high flux, frequency stable material 3C20
· Range of toroid sizes and A_L values
· Compact and robust product

Applications

These products will mainly be found as power inductors. These carry larger currents and a gap is required to avoid saturation. There are many types of power inductors, in accordance with many types of power converters :
· Output filter inductor in forward or push-pull converter (DC bias)
· Resonant inductor in half or full bridge converter (AC swing)
· Buck or boost inductor in DC voltage converter (DC bias)
· Power factor correction choke (AC bias)
· Differential filter inductor (DC of AC bias)

A possible application is also a fly-back transformer. This is a transformer with such gap that the stray inductance can be used as output filter inductor. For practical reasons, it is often difficult however to realize with a toroid. There can be more than one output winding and the electrical isolation between primary and secondary side must guarantee a distance of separation.

Type number structure

Gapped toroids can be named quite easily.
The general type number structure is explained in figure 1 below.

The inner diameter is determined by the outer diameter, because only standard toroid sizes are used that already exist without gap. In such a way, all too long type numbers are avoided when the toroid is gapped.

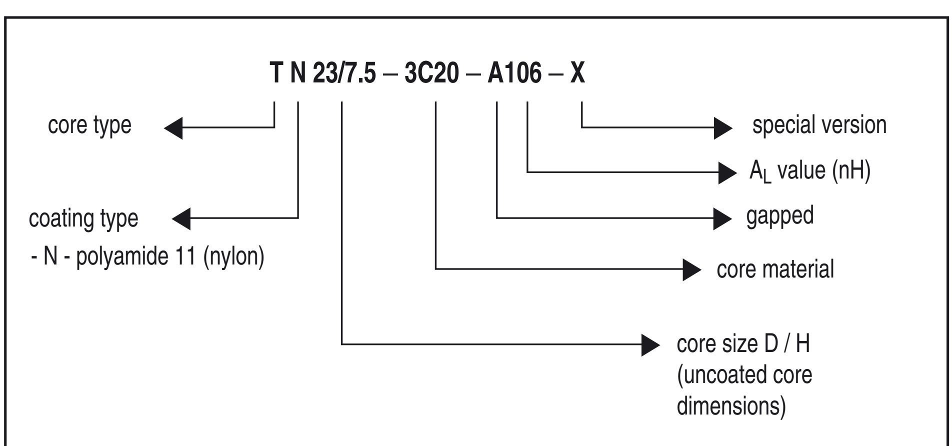
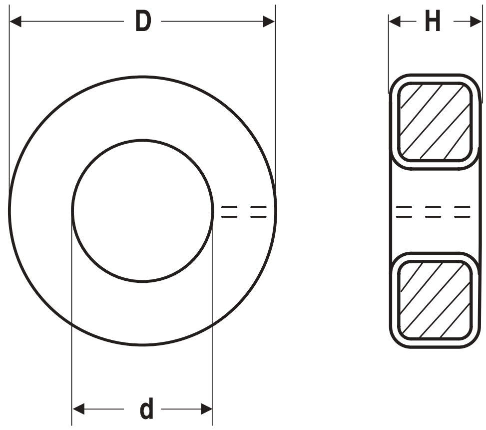


Fig. 1 : Type number structure

Product range and specifications



Core type	B (mT) at	Core loss (W) at	
	H = 1200 A/m f = 10 kHz T = 100 °C	f = 100 kHz B = 100 mT T = 100 °C	f = 100 kHz B = 200 mT T = 100 °C
TN13/7.5/5	≈ 400	≤ 0.033	≤ 0.22
TN17/11/6.4		≤ 0.070	≤ 0.47
TN20/10/6.4		≤ 0.12	≤ 0.80
TN23/14/7.5		≤ 0.16	≤ 1.1
TN26/15/11		≤ 0.33	≤ 2.2

Core type	dimensions (mm)			effective core parameters					
	outside diameter D (mm)	inside diameter d (mm)	height H (mm)	core factor Σ l/A (mm^{-1})	effective volume V_e (mm^3)	effective length l_e (mm)	effective area A_e (mm^2)	mass (g)	isolation voltage (V)
TN13/7.5/5	13 ± 0.35	6.6 ± 0.35	5.4 ± 0.3	2.46	368	30.1	12.2	≈ 1.8	1500
TN17/11/6.4	17.5 ± 0.5	9.9 ± 0.5	6.85 ± 0.35	2.24	787	42.0	18.7	≈ 3.7	1500
TN20/10/6.4	20.6 ± 0.6	9.2 ± 0.4	6.85 ± 0.35	1.43	1330	43.6	30.5	≈ 6.9	2000
TN23/14/7.5	24.0 ± 0.7	13.0 ± 0.6	8.1 ± 0.45	1.69	1845	55.8	33.1	≈ 9.0	2000
TN26/15/11	26.8 ± 0.7	13.5 ± 0.6	11.6 ± 0.5	0.982	3700	60.1	61.5	≈ 19	2000

The cores are coated with polyamide 11 (PA11), flame retardant in accordance with “UL94V-2”, UL file number E 45228 (M). The inner and outer diameters apply to the coated toroid.
Contacts are applied on the edge of the toroid for isolation voltage test, which is also the critical point for the winding operation.

Core type	A_L (nH)	eff. perm.
TN13/5-3C20-A40	40 ± 15 %	90
TN13/5-3C20-A56	56 ± 15 %	125
TN13/5-3C20-A67	67 ± 15 %	147
TN13/5-3C20-A72	72 ± 15 %	160
TN13/5-3C20-A79	79 ± 15 %	173

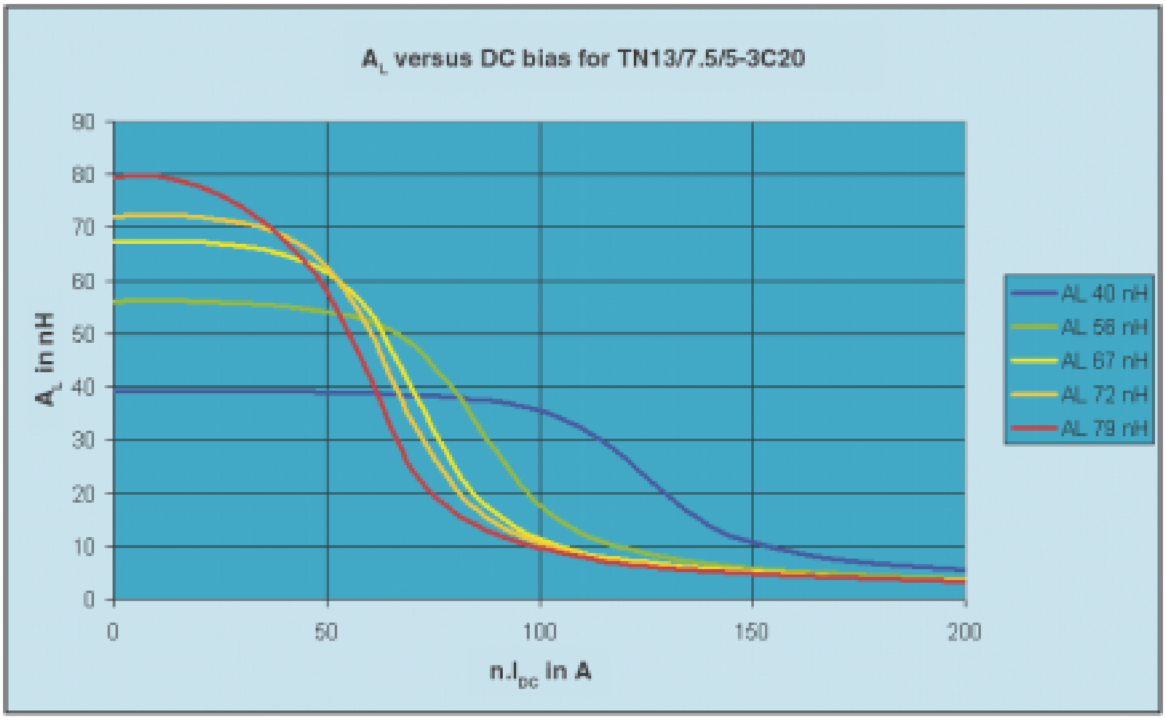
Core type	A_L (nH)	eff. perm.
TN20/6.4-3C20-A68	68 ± 15 %	125
TN20/6.4-3C20-A81	81 ± 15 %	147
TN20/6.4-3C20-A87	87 ± 15 %	160
TN20/6.4-3C20-A96	96 ± 15 %	173
TN20/6.4-3C20-A109	109 ± 15 %	200

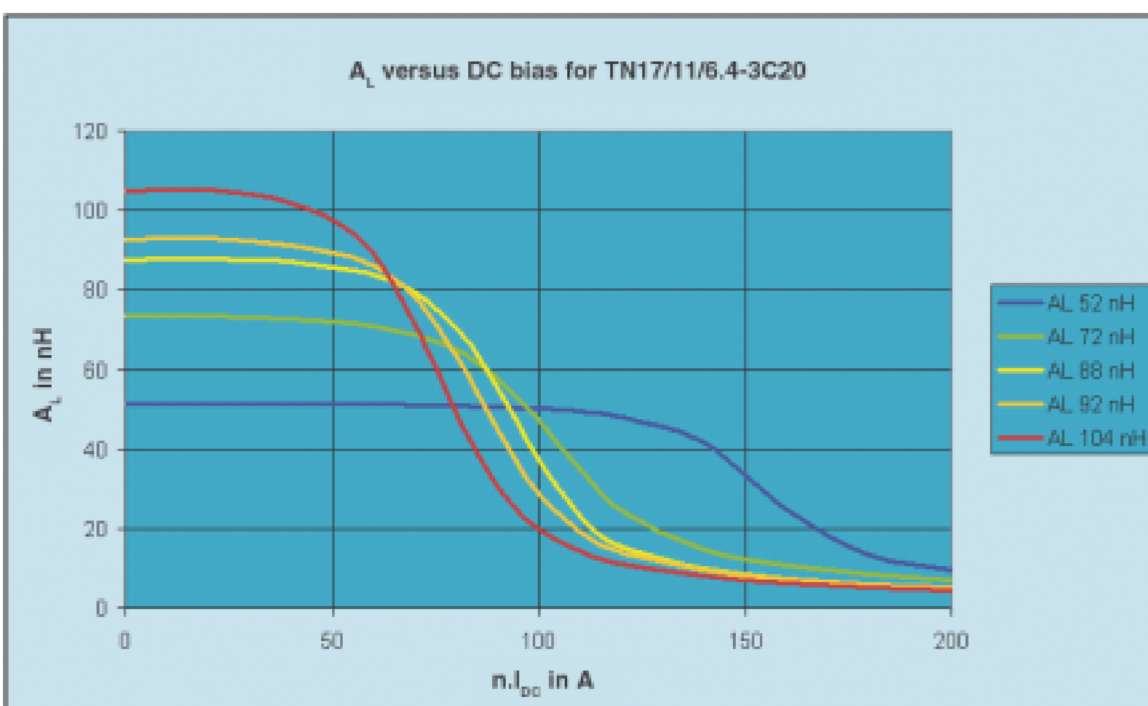
Core type	A_L (nH)	eff. perm.
TN26/11-3C20-A113	113 ± 15 %	90
TN26/11-3C20-A157	157 ± 15 %	125
TN26/11-3C20-A185	185 ± 15 %	147
TN26/11-3C20-A201	201 ± 15 %	160
TN26/11-3C20-A217	217 ± 15 %	173

Core type	A_L (nH)	eff. perm.
TN17/6.4-3C20-A52	52 ± 15 %	90
TN17/6.4-3C20-A72	72 ± 15 %	125
TN17/6.4-3C20-A88	88 ± 15 %	147
TN17/6.4-3C20-A92	92 ± 15 %	160
TN17/6.4-3C20-A104	104 ± 15 %	173

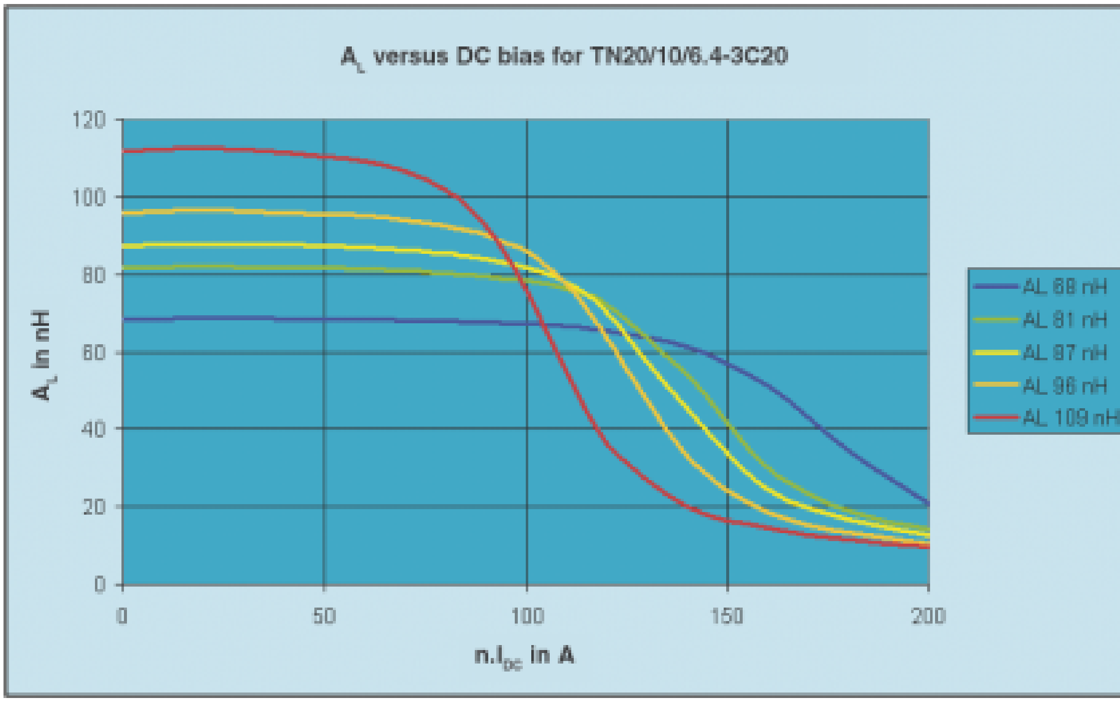
Core type	A_L (nH)	eff. perm.
TN23/7.5-3C20-A65	65 ± 15 %	90
TN23/7.5-3C20-A90	90 ± 15 %	125
TN23/7.5-3C20-A106	106 ± 15 %	147
TN23/7.5-3C20-A115	115 ± 15 %	160
TN23/7.5-3C20-A124	124 ± 15 %	173

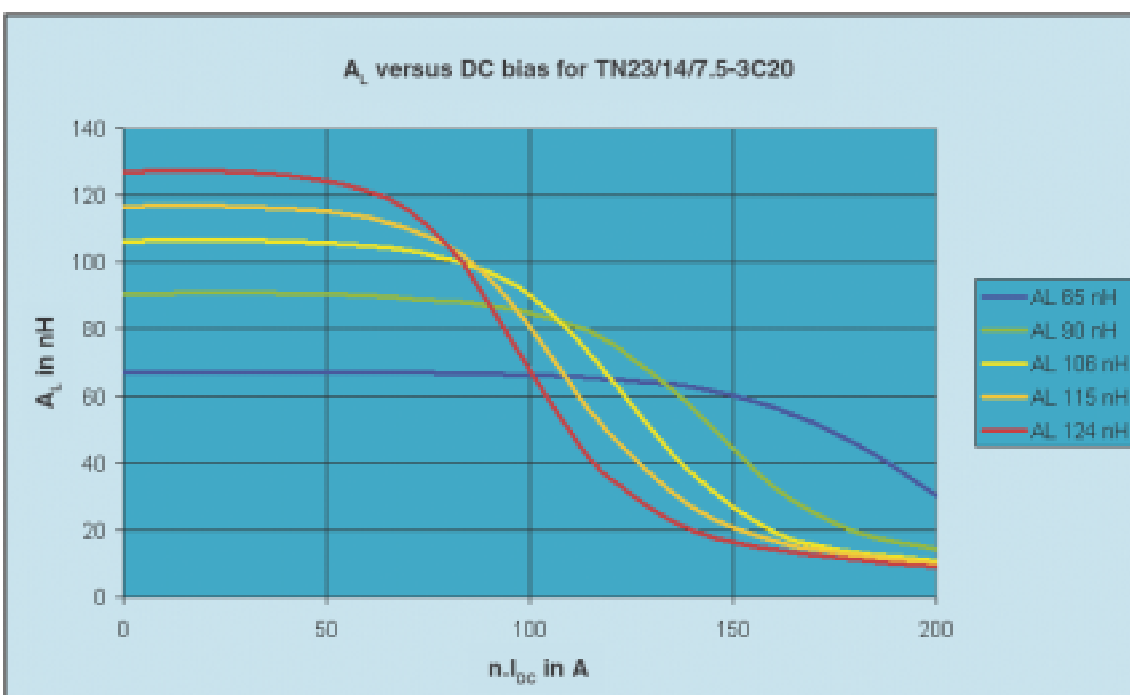
A_L versus DC bias curves



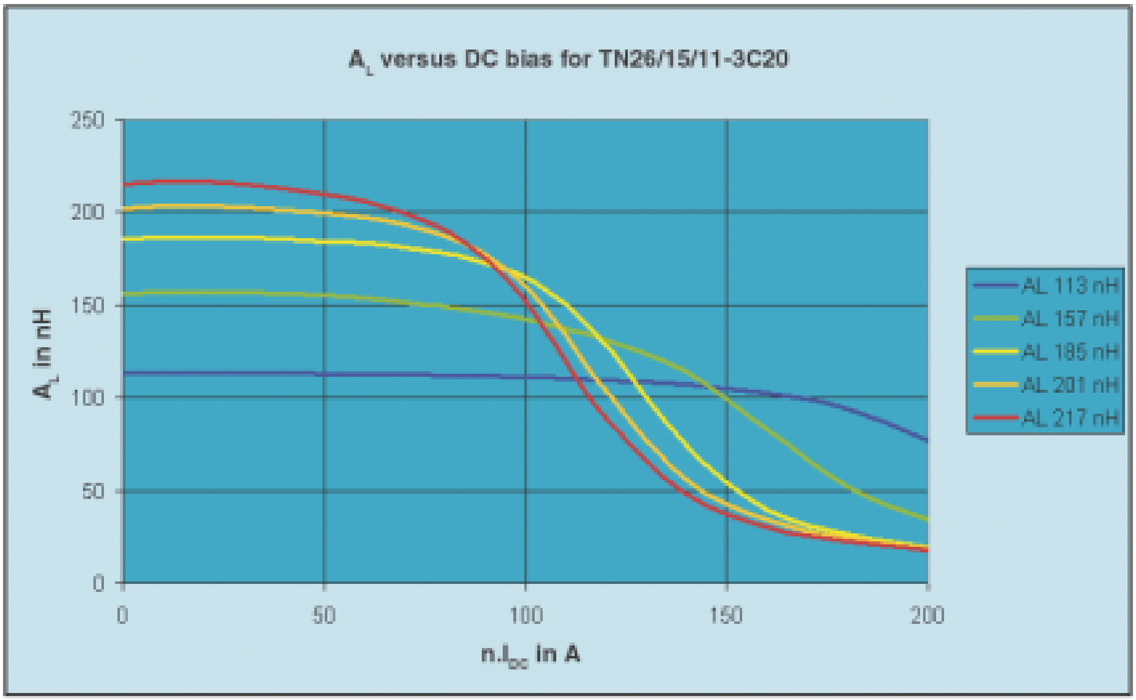


A_L versus DC bias curves (continued)



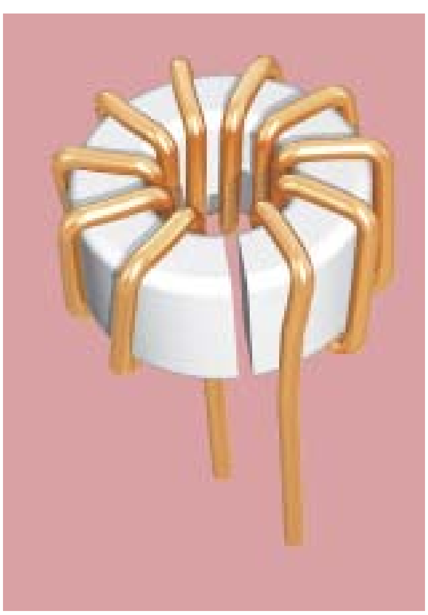


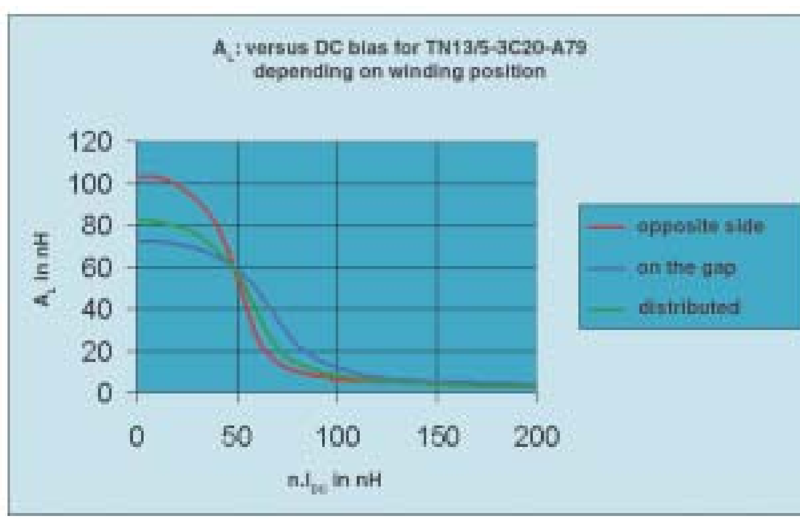
A_L versus DC bias curves (continued)



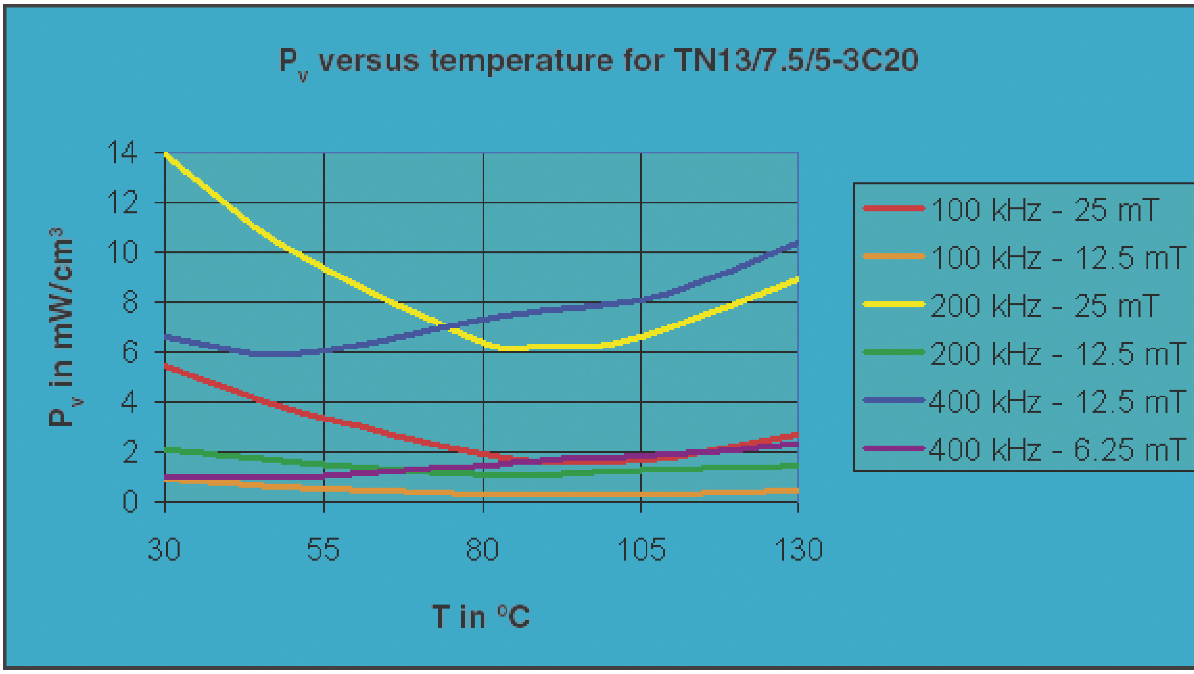
Influence of winding position

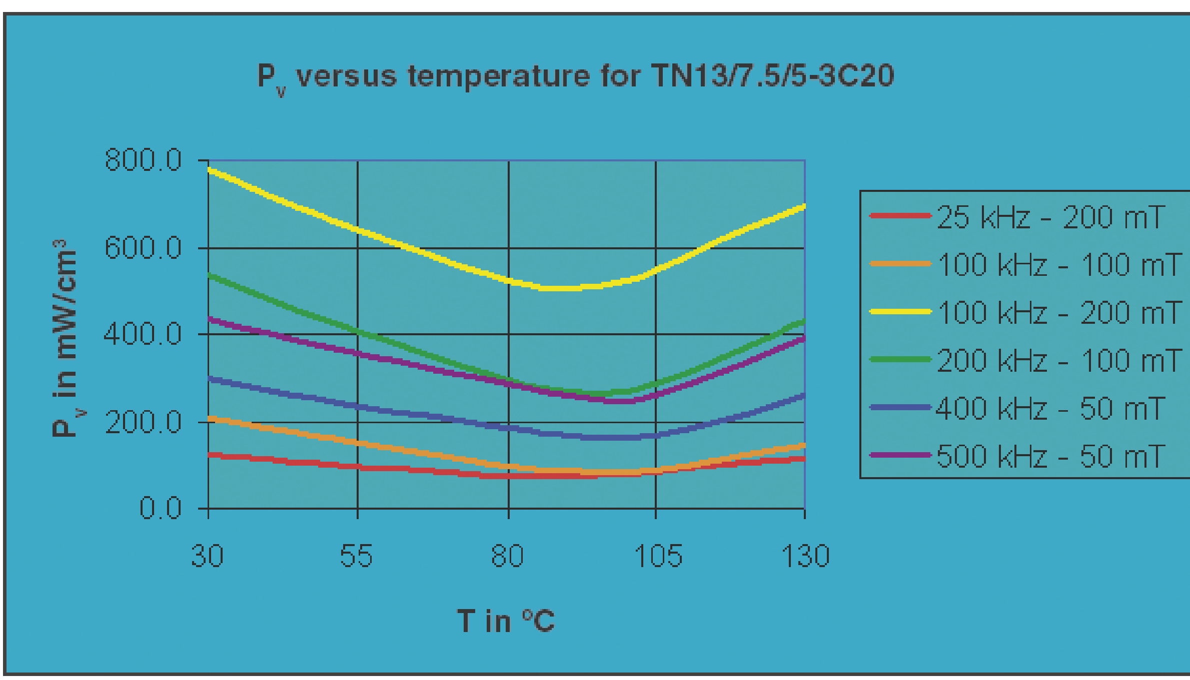
All curves above are for a winding, evenly distributed over the circumference of the toroid.





P_V versus temperature curves





P_V measured on ungapped toroids, see note on page 12.
The same loss density values hold for all A_L values and core sizes.

Comparison with metal powder cores

Several other material categories are used for power inductors. Metal powders form an important group. The metal can be pure iron or an alloy. In the form of a powder they have a distributed gap and don't need to be gapped as a core.

- Pure iron
Composition : Fe 100 %
Permeability : up to 90
Highest saturation flux density
- Molybdenum Permalloy Powder (MPP)
Composition : Ni 80 % – Fe 20 %, some substitution by Mo
Permeability : up to 550 (because of the high intrinsic permeability of permalloy)
Power loss volume density closest to ferrite
- High Flux
Composition : Ni 50 % – Fe 50 %
Permeability : up to 160
Highest saturation flux density of metal alloys
- Sendust (sold under various brand names)
Composition : Fe 85 % – Si 10 % – Al 5 %
Permeability : up to 125
Saturation flux density & power loss volume density intermediate

Ferrite comes into the picture where the limiting condition is power loss rather than saturation, so especially for high frequency and also for resonant inductors (large AC swing). For a certain set of application conditions, the limiting condition for metal powder can well be the power loss, while for ferrite it is the saturation. Even if that leads to a slightly larger core size, the gapped ferrite toroid could be more economical than expensive materials like MPP or high flux.

3C20 has an improved saturation level which makes it well-suited as an inductor material.

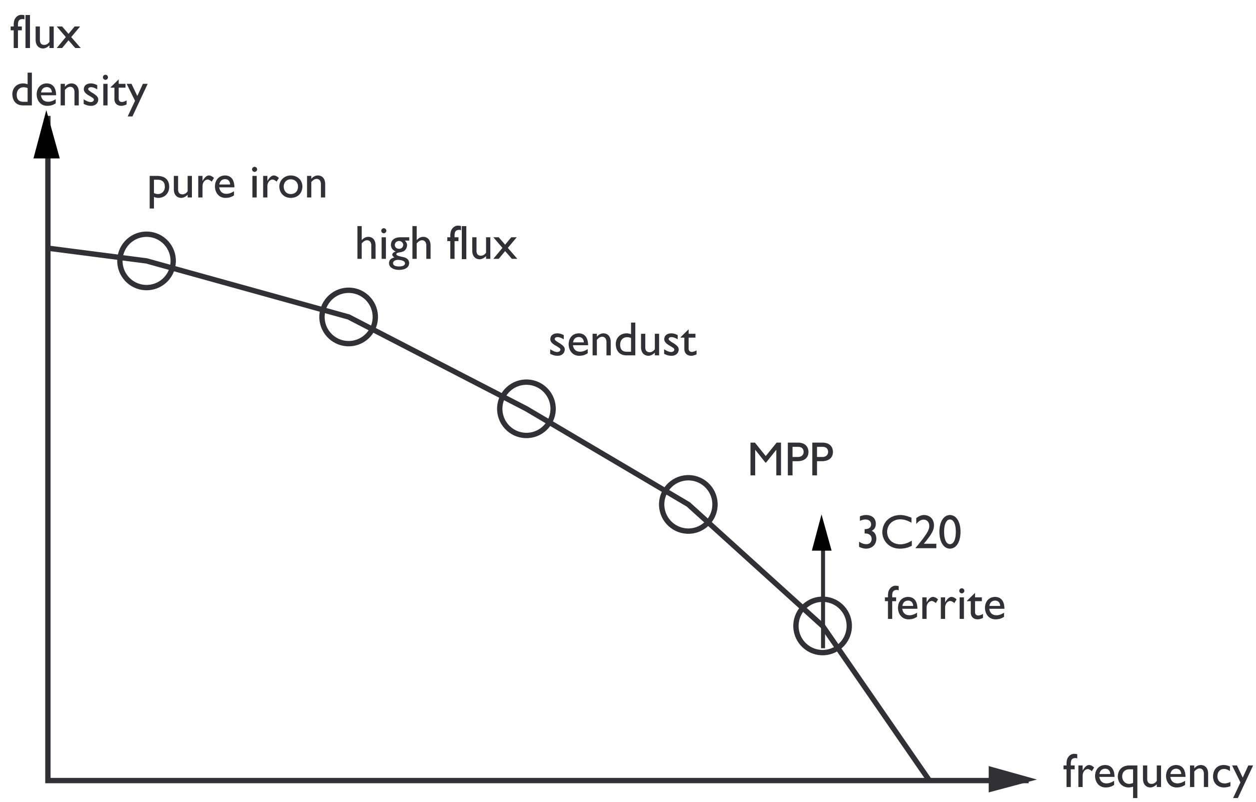
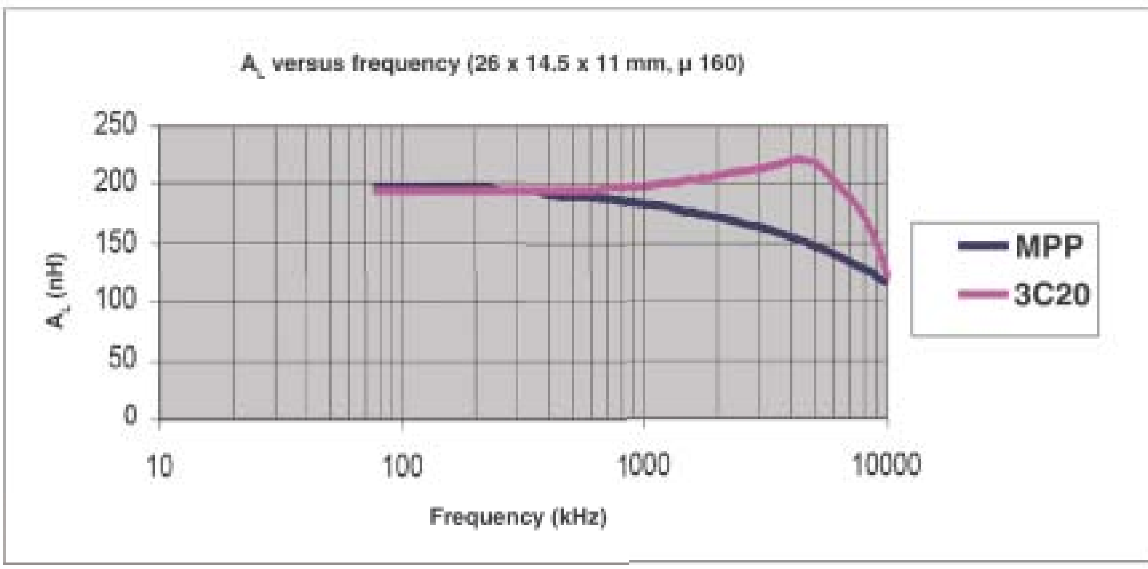


Fig. 2 : Relative position of materials with respect to application conditions

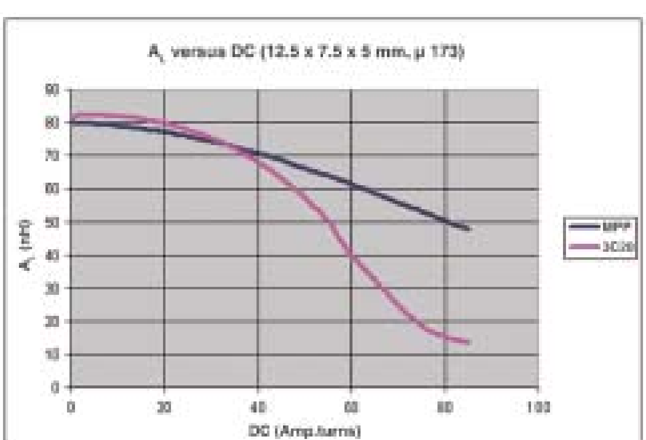
Pure iron, high flux and sendust have a soft saturation curve due to the distributed gap. The permeability starts dropping early, but the slope doesn't increase fast. MPP has a much more abrupt saturation curve due to the very high intrinsic permeability of permalloy. The hysteresis loop is therefore extremely sheared.

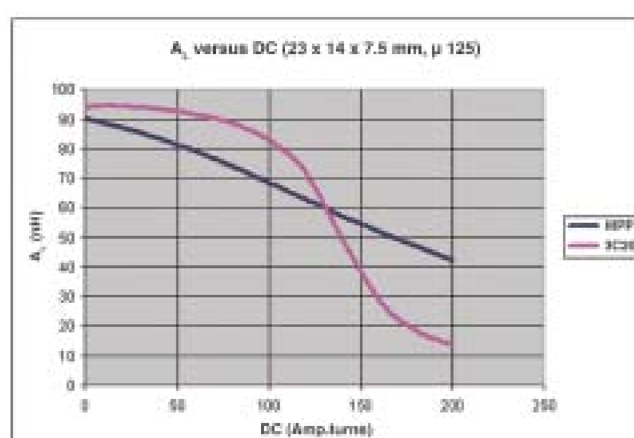
Ferrite toroids have a single gap and the fringing effect compensates the slow intrinsic permeability drop until real saturation occurs.

In the following graph we can see a comparison between a gapped ferrite toroid (TN26/11-3C20-A201) and a powder core (MPP, 26.9x14.7x11.2mm, A201). We can see the frequency behavior of the different pieces. The stability with frequency is better for gapped ferrite than for MPP.

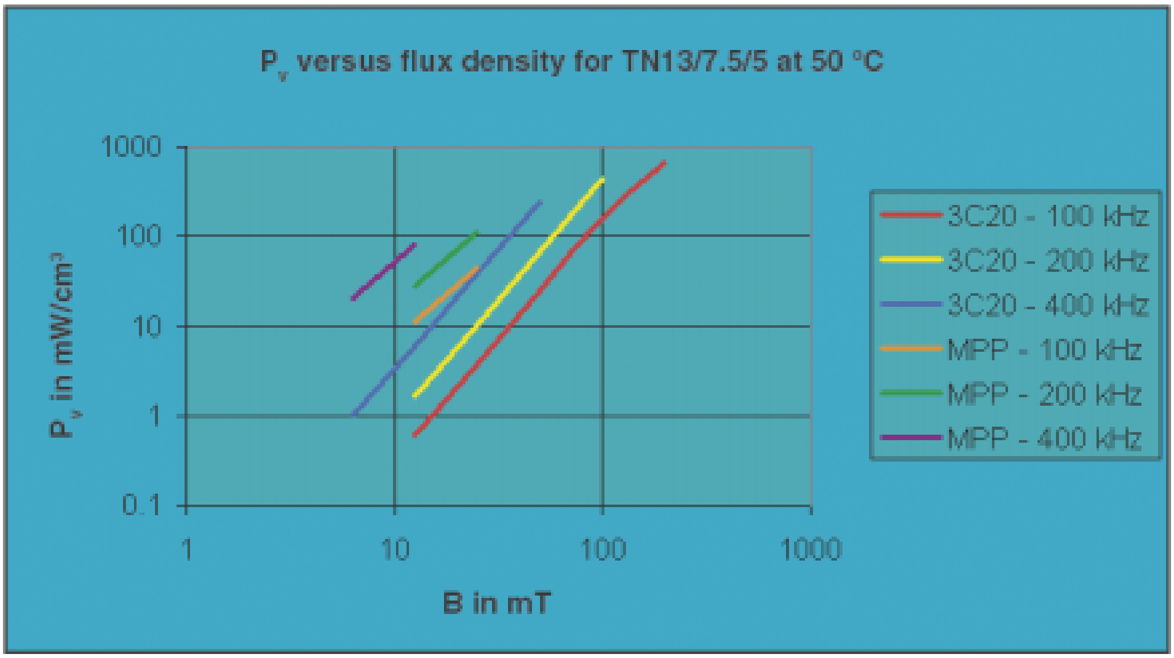


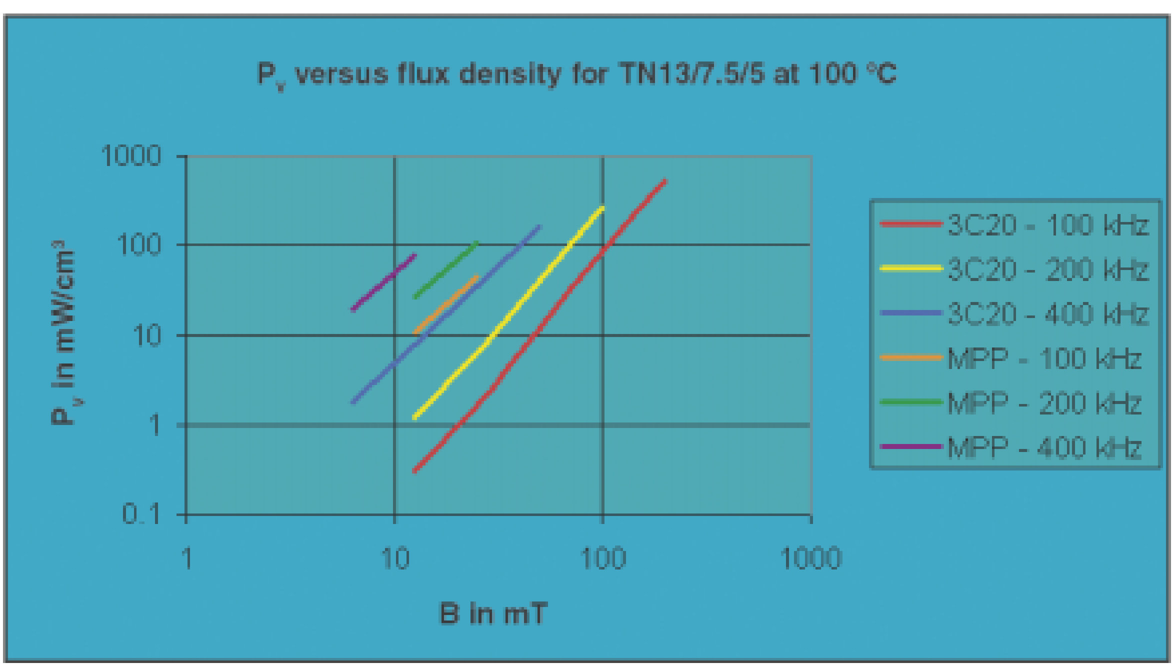
Below 2 graphs comparing the saturation behaviour between a gapped ferrite toroid (TN13/5-3C20-A79) and a powder core (MPP, 12.7x7.6x4.8 mm, A79) for the first graph and TN23/7.5-3C20-A90 and MPP, 22.9 x 14 x 7.6, A90 for the second.





Finally 2 graphs comparing the core losses of a gapped ferrite toroid (TN13/7.5/5-3C20) and a powder core (MPP, 12.7 x 7.6 x 4.8 mm), at 50 and 100 °C. The difference is at least a full decade.





Product performance calculation

With the aid of the foregoing graphs, 2 basic performance parameters can be calculated : minimum inductance (at maximum load) and total core loss.

• The required inductance determines the number of turns : $n = \sqrt{(L_o/A_{L,o})}$
This is rounded to an entire number.

• The bias current determines the A_L reduction : $A_{L,min} = A_L\ (n.I_{bias})$

• The inductance reduces with the same factor : $L_{min}/L_o = A_{L,min}/A_{L,o}$

• Voltage and frequency determine the flux density
for sinusoidal flux and voltage variation : $B_{max} = V_{rms}/(\sqrt{2}.\pi.n.f.A_e)$, $V_{rms} = V_{max}/\sqrt{2}$
for triangular flux and rectangular voltage variation : $B_{max} = V_{rms}/(4.n.f.A_e)$, $V_{rms} = V_{max}$

• Core loss follows from flux density and frequency : $P = P_V(B,f).V_e$

L_o = inductance without bias current
$A_{L,o}$ = A_L value without bias current
L_{min} = inductance with maximum bias current
$A_{L,min}$ = A_L value with maximum bias current

If the minimum A_L value doesn't comply the requirements, then a lower A_L value or else a larger core size is necessary.

Example

Required : output choke with inductance > 5 µH, decrease < 10 % for 15 A bias current.

Starting with the smallest toroid and A_L value leads to the following sequence :

TN13/5-3C20-A40	$n = \sqrt{(5000/40)} = 11.2 \rightarrow 12$ turns $\rightarrow n.I_{bias} = 180$ A.turns	clear saturation
TN17/6.4-3C20-A52	$n = \sqrt{(5000/52)} = 9.8 \rightarrow 10$ turns $\rightarrow n.I_{bias} = 150$ A.turns	decrease < 50 %
TN20/6.4-3C20-A68	$n = \sqrt{(5000/68)} = 8.6 \rightarrow 9$ turns $\rightarrow n.I_{bias} = 135$ A.turns	

remaining A_L value = 62 nH, decrease = 6 nH < 10 %   This is just enough
A_L value 109 nH could reduce the turns to 7 to achieve 5 µH, but would not comply with 15 A bias.

Suppose the choke is driven by a rectangular voltage of 4 V amplitude, switching at 200 kHz.
Taking into account the core effective cross-section 30.5 mm^2 of TN20/6.4, peak flux density will be :
$B_{max} = 4/(4 \ .\ 9 \ .\ 200x10^3 \ .\ 30.5x10^{-6}) = 18.2$ mT.

Ignoring the influence of bias current and non-sinusoidal waveformes,
the graphs of $P_V(T)$ can be taken as reference.
Even for lower temperatures the loss density will be below 10 mW/cm^3.
With an effective volume of 1.33 cm^3, the core loss will only be in the order of 10 mW.

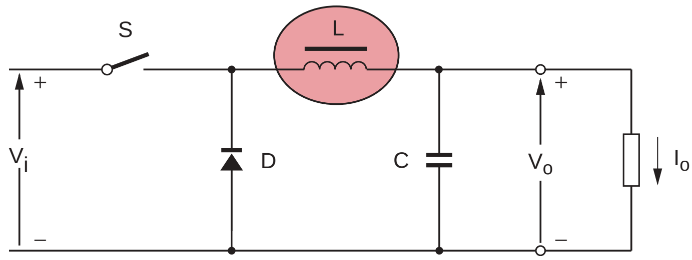


Fig. 3 : Output inductor in forward configuration.

Note on power loss measurement

Power losses as presented in this brochure have been measured on ungapped ferrite toroids, as is common practice for paired core shapes like EFD etc. Gapped cores have a much lower loss tangent tgδ which reduces the loss measurement accuracy :

• Lower loss tangent

$(tg\delta/\mu)_e = tg\delta/\mu$

$tg\delta_e/\mu_e = tg\delta/\mu$

$tg\delta_e = (\mu_e/\mu).tg\delta$

As $\mu_e/\mu < 1$, the loss tangent is reduced by a gap.

• Lower measurement accuracy

$P = V.I.\cos\varphi = V.I.\sin\delta$

$dP/d\delta = V.I.\cos\delta$

$\Delta P/P = (dP/d\delta).\Delta\delta/P = \Delta\delta/tg\delta = 2\pi.f.\Delta t/tg\delta$

μ = permeability without gap
tgδ = loss tangent without gap
tgδ/μ = loss factor without gap
μe = permeability with gap
tgδe = loss tangent with gap
(tgδ/μ)e = loss factor with gap

For a given time accuracy Δt (equipment), the relative loss error ΔP/P increases proportional with frequency f and inversely proportional with loss tangent tgδ (or proportional to quality factor Q).
The above linear calculation holds for small signals, but qualitatively the result is the same for large signals and hysteresis loops.
Measuring with the same flux density B still leads to the same power loss P as for gapped ferrite toroids, apart from the core volume factor $V_g/V_e = (A_e.(l_e-l_g))/(A_e.l_e) = 1-l_g/l_e \approx 1$.
In the case of metal powder cores, it's impossible to measure without the (distributed) gap, but the accuracy is much higher due to the higher loss tangent tgδ.

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