Preliminary report: PSMA-SMA Phase II Project

Rev. 10 March 2019

Marcin Kacki

Senior Engineer, R & D

SMA Magnetics Sp.z.o.o

Edward Herbert

Co-Chairman

PSMA Magnetics Committee

A study by:

SMA Magnetics Sp.z.o.o

ul. Krakowska 390

32-080 Zabierzow

Poland

Sponsored by:

Power Sources Manufacturers Association

P.O. Box 418

Mendham, NJ 07945-0418

Foreword

The PSMA-SMA Phase II study was started in July of 2018.

The project is jointly funded by PSMA and SMA.

For SMA, the project supports product development, and it has already resulted in new products.

For PSMA, the project furthers our studies of high frequency magnetics.

The project also broadly overlaps with Marcin's PhD studies.

The project is approximately 40% complete. This preliminary report is a snapshot of the progress to date. All data in this preliminary report should also be considered preliminary.

The "background and introduction" section summarizes selected topics from the three PSMA-Dartmouth Core Loss Studies, from the PSMA sponsored High Frequency Magnetics Workshops and other sources. These selected topics influenced the design of the tests for this project, which is why they are included.

Contents

Background and introduction

Edward Herbert, Co-Chairman, PSMA Magnetics Committee

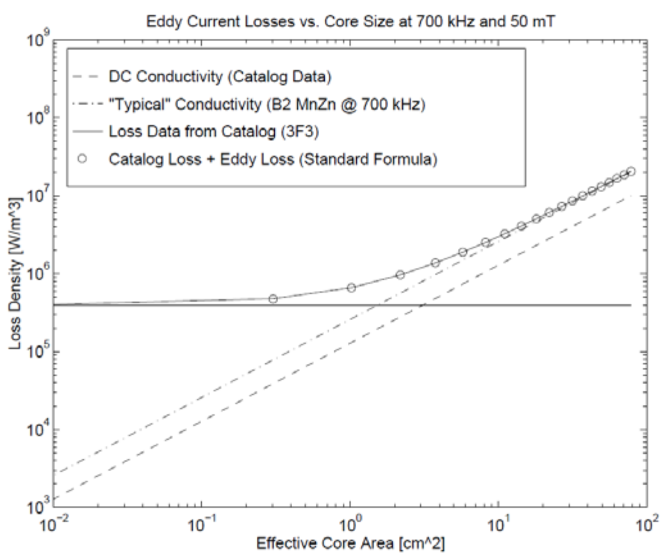
SMA Magnetics wanted to know why large inductor cores performed so poorly compared to published specifications.

PSMA wanted to know more about flux propagation in ferrites and why the performance factor *B*f* was lower and peaked at a lower frequency for larger cores.

Charlie Sullivan recognized that there was significant overlap in these interests. He arranged an introduction, resulting in the Phase I PSMA-SMA core loss study.

Background

An early reference showing that large cores have higher losses is Glenn Skutt's doctoral thesis. Glenn analyzed flux distribution within ferrite cores using wave propagation theory and eddy current analysis.



"High-Frequency Dimensional Effects in Ferrite-Core Magnetic Devices;" Glenn R. Skutt; October 4, 1996; Virginia Polytechnic Institute, Blacksburg, Virginia

Prior PSMA projects

The Power Sources Manufacturers Association (PSMA) sponsored four previous core loss studies, special machined ferrite cores and three workshops.

- 2009 – PSMA-Dartmouth "Pilot" Project
- 2010 – PSMA-Dartmouth "Phase II" Project
- 2012 – PSMA-Dartmouth "Phase III" Project
- 2016 – Power Magnetics @ High Frequency – Solving the Black Magic
- 2017 – Transforming Magnetics 'Black Magic' into Engineering
- 2018 – Power Magnetics @ High Frequency – Eliminating the Smoke and Mirrors
- 2017 – Special Project, Machined cores from Fair-Rite
- 2017 – PSMA-SMA "Phase I" Project

The core loss studies and workshops provided the foundation for the present study, the PSMA-SMA "Phase II" Project. Some aspects of the earlier core loss studies and the workshops are reviewed here. Key items that informed the design of the Phase II PSMA-SMA Core Loss Study and that are helpful for its understanding and analysis are summarized below.

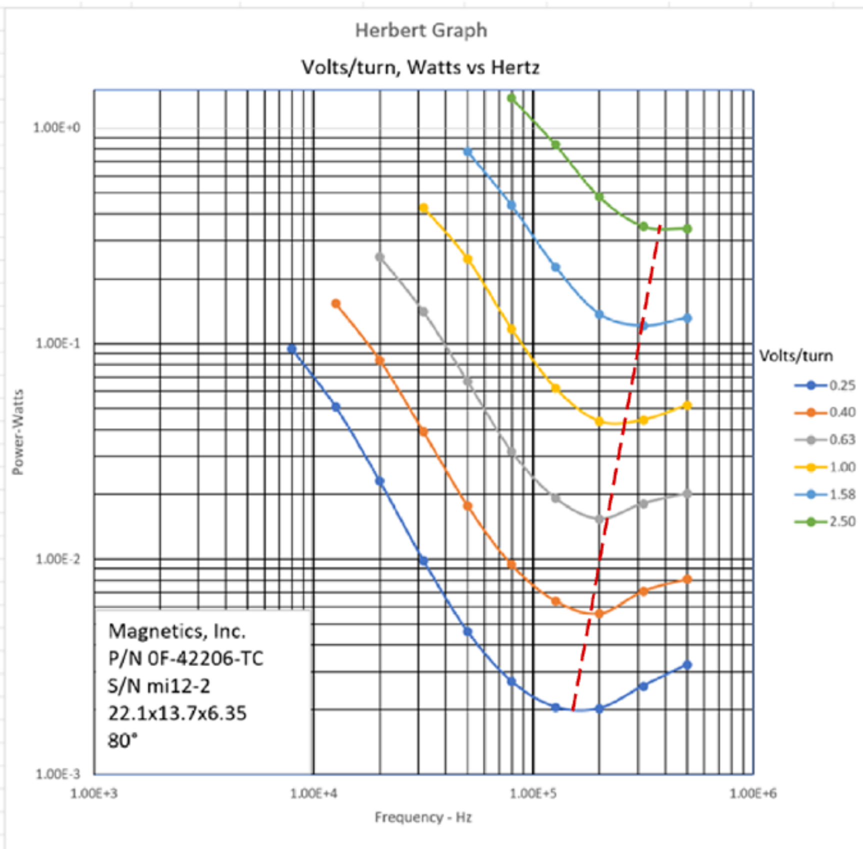
2009 – PSMA-Dartmouth "Pilot" Project

Composite waveform hypothesis

The Pilot Project was approved by PSMA and a purchase order to Dartmouth was issued in the Spring of 2009. Data was taken on one ferrite core and one powdered metal core. The objective of the Pilot Project was to validate the "Composite waveform hypothesis."

The composite waveform hypothesis was partly validated, and shown to be an improvement over other approximations, both for accuracy and for ease of use.

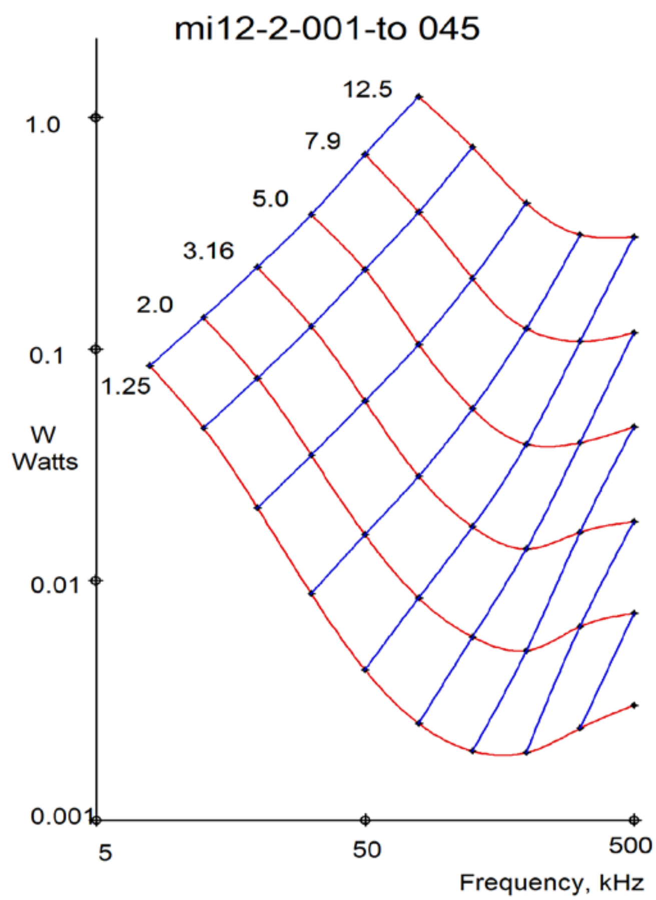
Herbert graph



The curves in the Herbert graph are constant square-wave excitation in volts/turn. To determine the core loss, find the frequency on the X-axis, draw a vertical line to the curve representing the excitation voltage, then draw a horizontal line to the Y-axis. Read the core loss directly, in Watts.

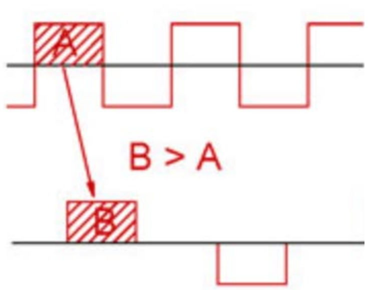
$\hat{B}$ curves

In the graph below, the same points that are used for the Herbert graph can be connected differently to give a graph showing the core losses for curves of constant flux. The blue lines are constant volt-seconds, v-s. They can be scaled to $\hat{B}$ by dividing by A_e.]



Off-time Phenomenon

It was observed that increasing the off-time between excitation pulses increased the loss per cycle.



We hope that we will be able to explain the "Off-time phenomenon" when the Phase II study is done.

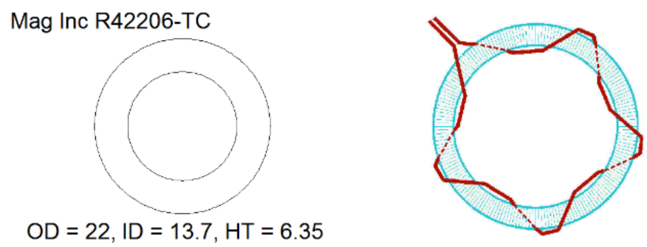
For more information, see Testing Core Loss for Rectangular Waveforms, February 7, 2010 by Charles R. Sullivan and John H. Harris, Thayer School of Engineering at Dartmouth and Edward Herbert.

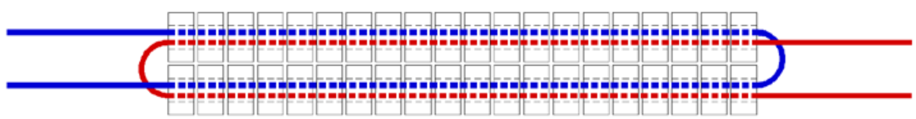
2012 – PSMA-Dartmouth “Phase III” Project

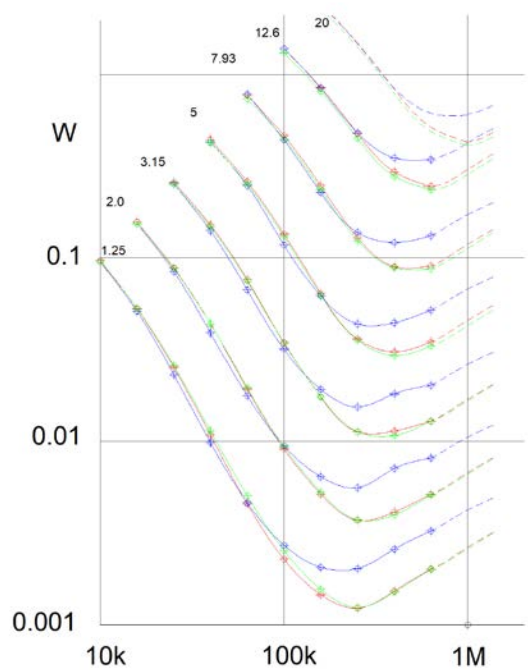
The Phase III Project was approved by PSMA and a purchase order to Dartmouth was issued in the Spring of 2012. The Phase III project had several objectives, but due to equipment problems and the loss of key personnel, few meaningful tests were run.

String of beads tests

A string of small cores having one turn through all can be designed to have the same inductance and core volume as a single toroid having multiple turns, in this example, five turns. A rigorous test would require specially machined cores, but an approximation was tested using stock cores. Unfortunately, only three test runs were run, one as a baseline and two experiments. With so little data, the results are suggestive but cannot be considered conclusive.





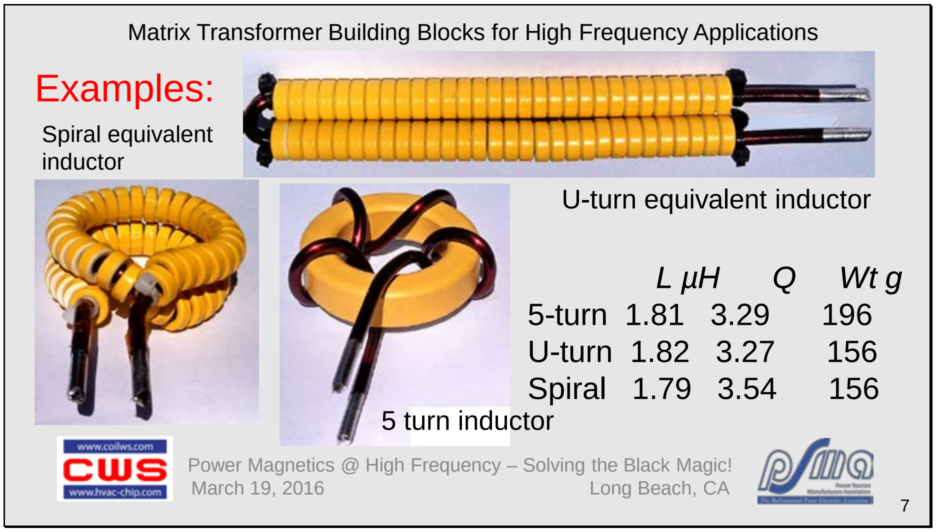


The test results can be found in [Phase III Supplemental Report: The String of Beads Experiment]() by Edward Herbert.

2016 – Power Magnetics @ High Frequency – Solving the Black Magic

String-of-beads inductors

James Lau of CWS introduced the string-of-beads inductor.

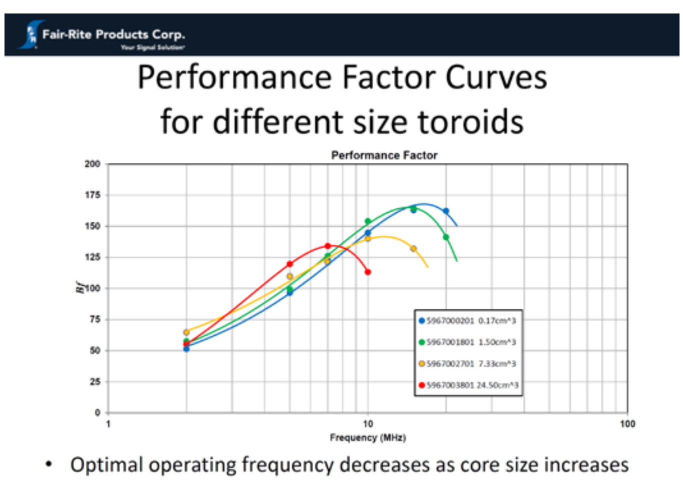


Matrix Transformer Building Blocks for High Frequency Applications.pdf

2017 – Transforming Magnetics 'Black Magic' into Engineering

*B*f* curves vary with core size

John Lynch of Fair-Rite showed us that the *B*f* performance factor varies significantly with core size. Larger cores have a lower *B*f* value, and their *B*f* curve peaks at a lower frequency.

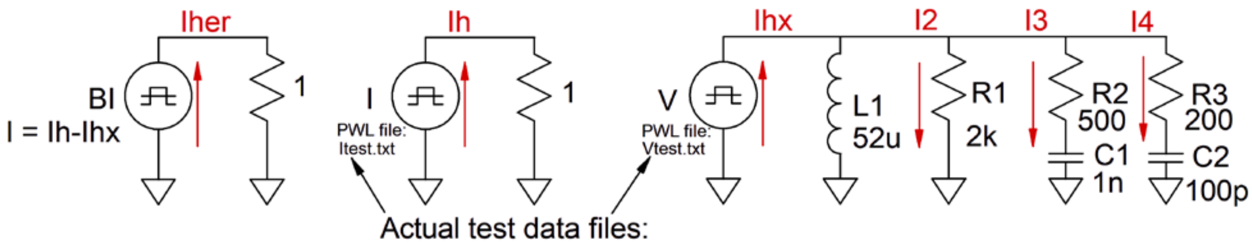


Developing Materials and Geometries for High Frequency Power Magnetics (John Lynch, Fair Rite)

Extracting parameters for SPICE models

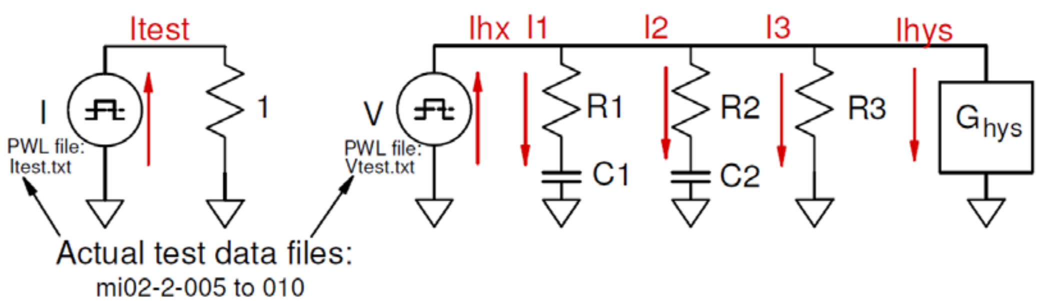
Ed Herbert showed that hysteresis loop data can be used to extract parameters for SPICE models.

The LTSice model below approximates the high frequency characteristics of the core.



Itest.txt is actual current data from the PSMA-Dartmouth Core Loss studies as a pwl file. Vtest.txt is the actual excitation voltage from the same test run. Ihx is the current simulated by the model with the Vtest stimulation applied. It is compared to the actual data and the difference is Iher.

To capture low frequency characteristics, the inductor must be replaced with a hysteretic inductor model, which is quite complex. The losses in a hysteretic inductor cannot be simulated with inductors and resistors.



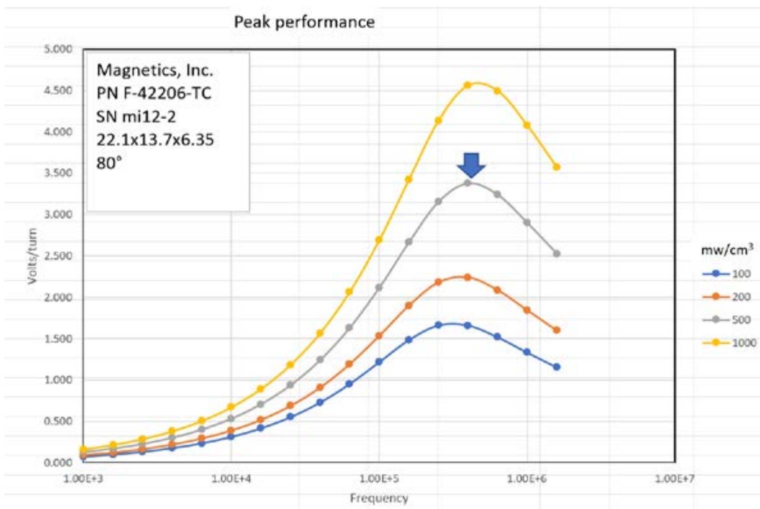
[Parameter Extraction (Data Crunching) (Ed Herbert, PSMA)]

[Spice Models for Core Losses (Ed Herbert, PSMA)]

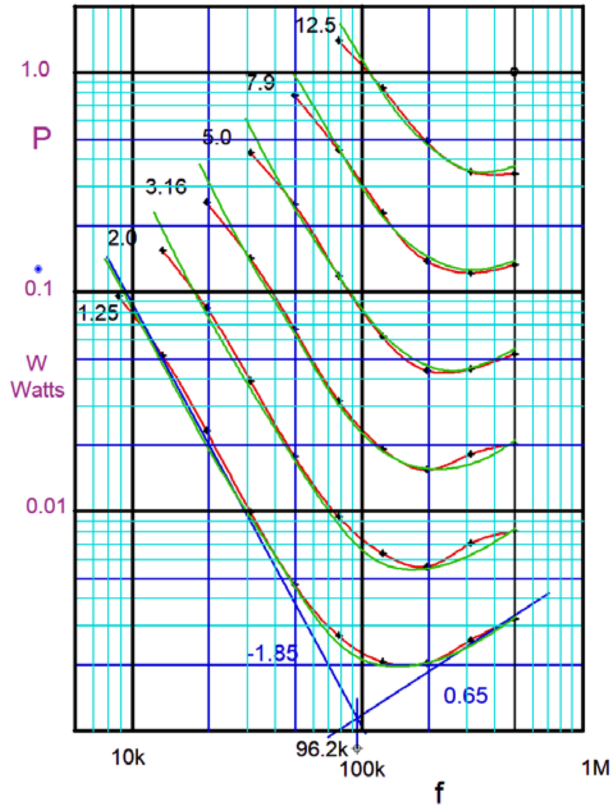
2018 – Power Magnetics @ High Frequency – Eliminating the Smoke and Mirrors

Ed Herbert proposed that the *B*f* curve for a core provides the most visual method of determining the frequency at which the core will operate most efficiently for a particular power or power density. The peak of the *B*f* curve is the "Prime point."

If other considerations constrain the design to operate at a different frequency, it is likely to be some point along the same power or power density curve. After all, most high frequency magnetic designs are constrained by thermal considerations.



Note that the Y-axis is "volts/turn." *B*f*, if resolved, reduces to volts/turn. *B* equals volt-seconds. Frequency *f* equals 1/seconds. Combining and cancelling, volts is what is left.



Herbert Approximation

The following equation gives a good fit for core loss over the whole range.

$$P_c = k * f^{\delta} * \left(1 + \left(\frac{v}{V_b}\right)^{\alpha} * \left(\frac{f_b}{f}\right)^{\beta}\right) * v^2$$

The green lines and dots are data, and **the red dashed lines are the approximation.**

k	4.200E-07	β	2.500E+00
δ	6.500E-01	V_b	1.250E+00
α	1.000E+00	F_b	9.615E+04

The approximation is strictly a curve-fitting exercise. k is determined by curve fitting.

δ is the slope of the higher frequency asymptote

β is δ minus the slope of the lower frequency asymptote, that is, 0.65 – (-1.85) = 2.5.

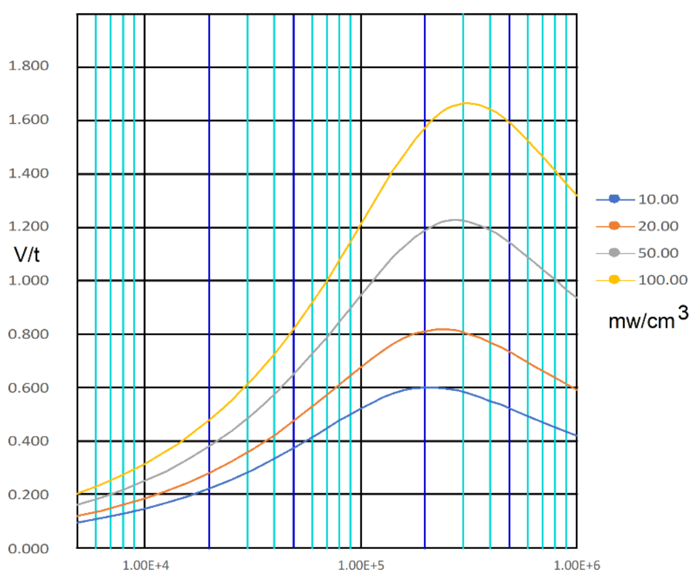
F_b is the frequency at the intercept of the asymptotes.

V_b is the baseline voltage per turn.

α is always 1, so it may not be needed.

The peaks of the $B*f$ curves align with the minima of the core loss curves of comparable power density.

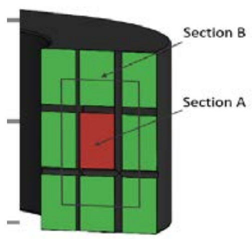
Peak performance



[Generic Specification for Ferrite Cores (Ed Herbert, PSMA)](#)

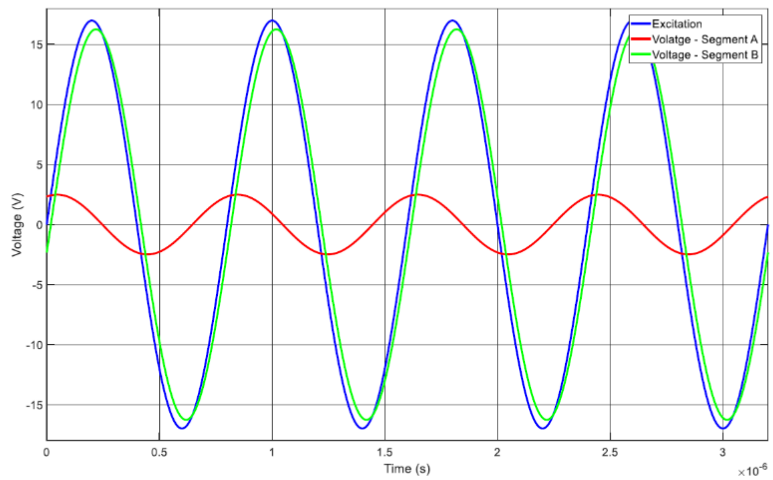
2017 – PSMA-SMA "Phase I" Project

In the Phase I project, holes were drilled in cores so that windings could be inserted to determine the voltage and flux in internal segments. The graph on the right is an example.



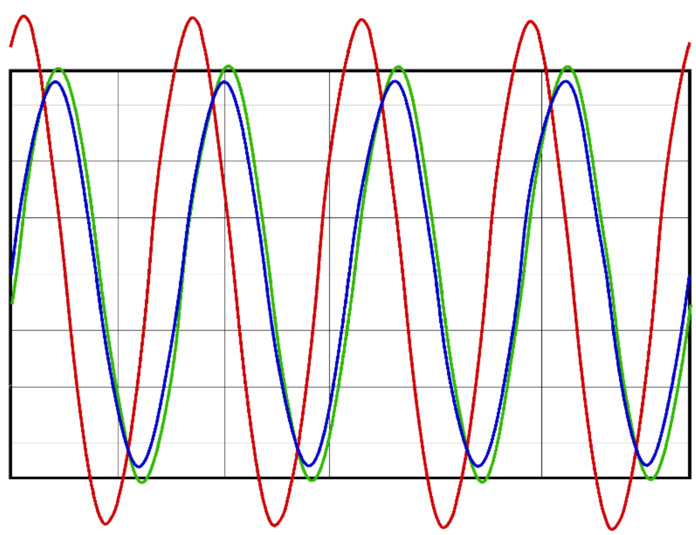
f = 1250 kHz

Blue – Excitation voltage, Red – Section A, Green – Section B



At 1.25 MHz, the flux, and therefore the voltage, in the center of the core was expected to be significantly attenuated. Considering that segment A is 1/9 the area of the whole, equal flux density would suggest a voltage of 1/9 of the excitation voltage, or about 1.9 volts. Instead, it is about 2.5 volts. Further, it leads the excitation voltage by approximately 90º.

In the graphon the right, the voltage curves were copied into CAD and the red and green curves were scaled inversely by their respective areas (9/1 and 9/8), so that the graph represents the flux density compared to the excitation.



Because flux is the integral of the voltage with respect to time, and the integral of a sine wave is a cosine wave, which has the same shape, it is valid to compare voltage curves and voltage density (V/A_e) to asses flux density.

The flux density of the center (red) is higher than the excitation and leads it by about 90º.

It is apparent that we need to learn a lot more about flux propagation in magnetic materials.

TX50/30/16.3, Ferroxcube 3E10,

From Phase I report

Link:
[Study on flux propagation and complex impedance in NiZn and MnZn ferrites - SMA Magnetics Phase I Report]

Looks as expected with classical analysis.

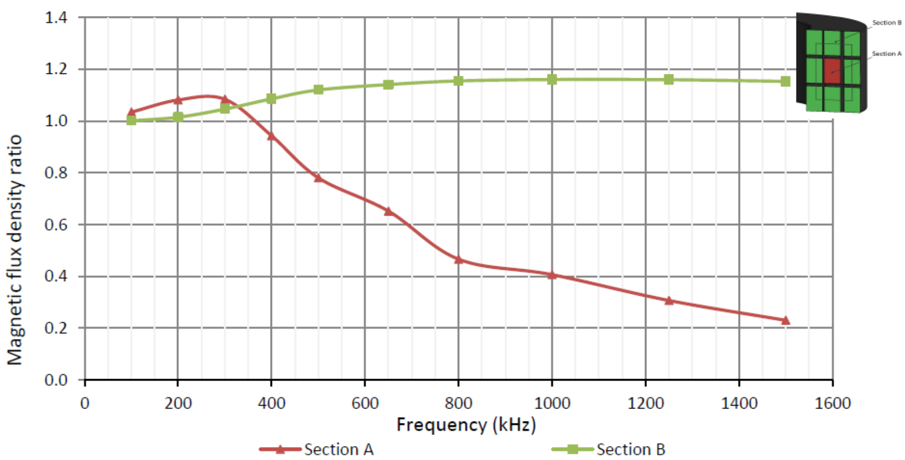
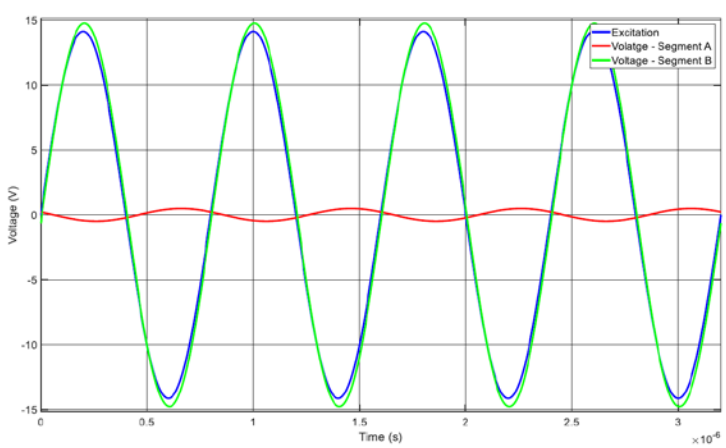


Figure 9. Magnetic flux distribution in the each section of 3E10 TX50 ring core.

At 1250 kHz, the voltage is attenuated, but lead excitation by almost 180º.

f = 1250 kHz

Blue – Excitation voltage, Red – Section A, Green – Section B



Voltage at the center is attenuated, and leads by 150º or so.

TX50/30/16.3, Ferroxcube 3C11

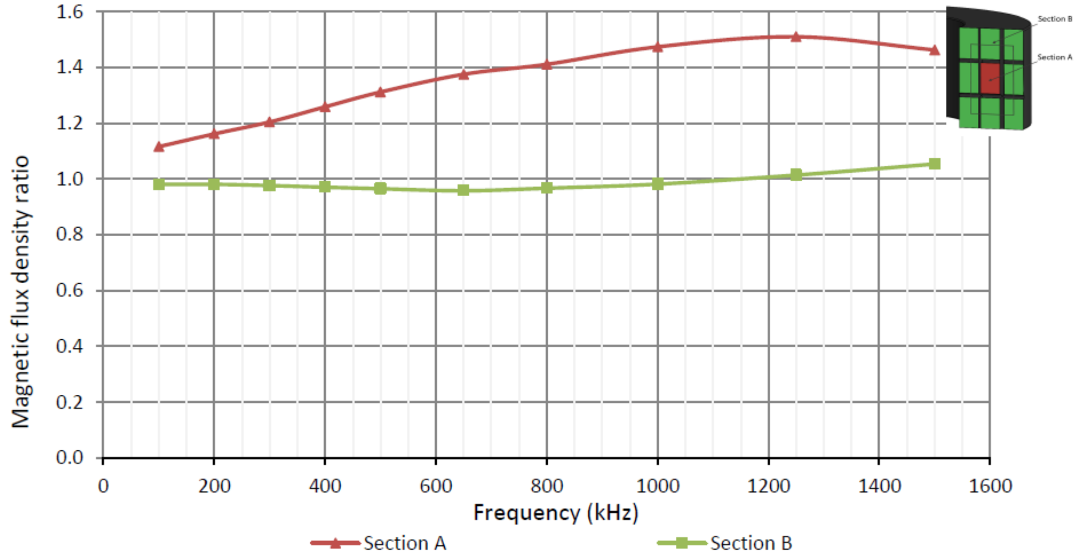
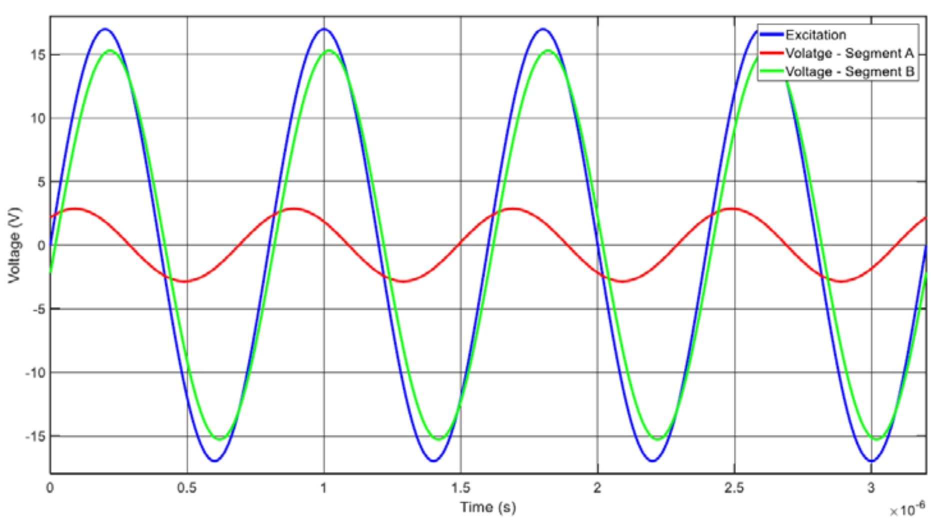


Figure 17. Magnetic flux distribution in the each section of 3C11 TX50 ring core.

Flux peaks at 1250 kHz or so

f = 1250 kHz

Blue – Excitation voltage, Red – Section A, Green – Section B



The voltage at the center is larger than expected, and leasds by about 70º.

T105/75/15; Fair-Rite 78

From Phase I report

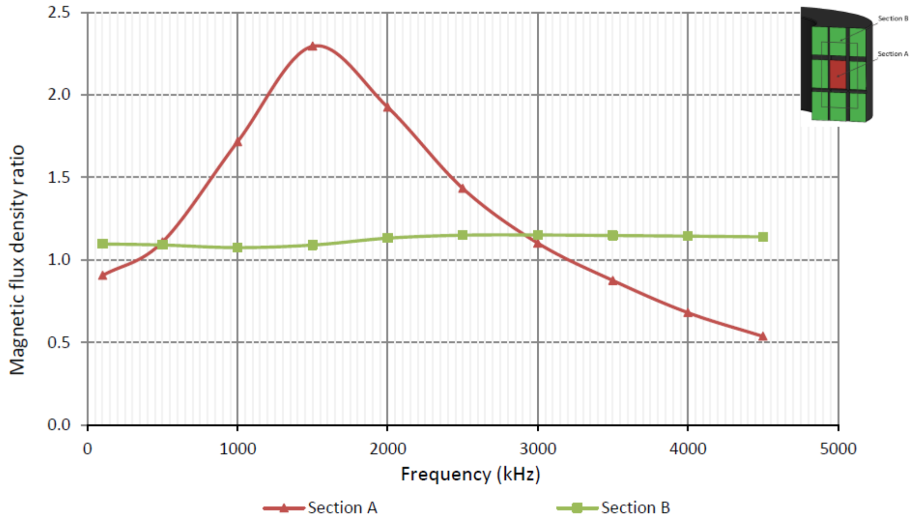
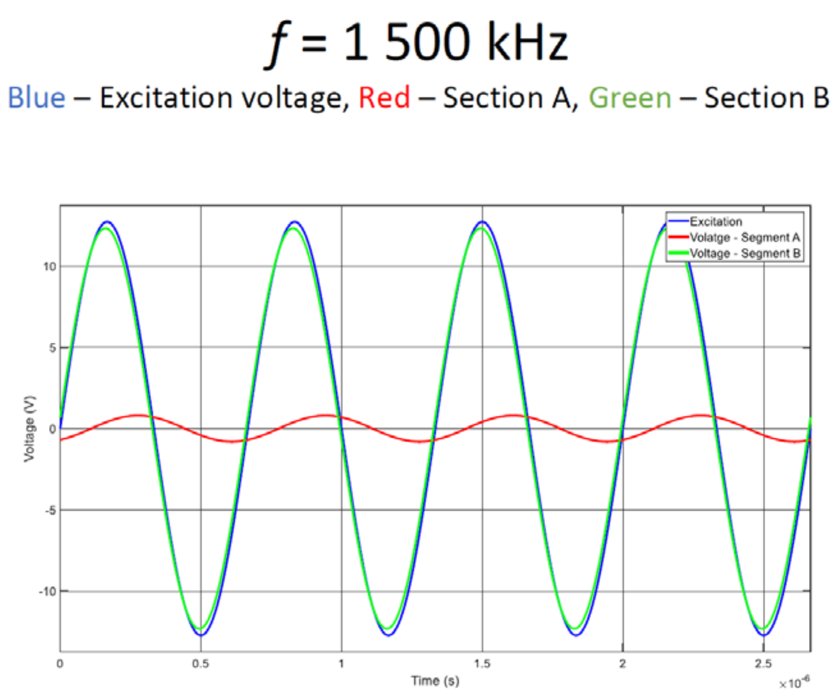


Figure 23. Magnetic flux distribution in the each section of FR78 TX105 ring core.

Big peak at center at 1500 kHz.



Voltage at the center is larger than expected, and lags by about 80 º.

In the Phase I report, most illustrations show a lead, so the polarity may be wrong.

Frame core, Fair-Rite 78.

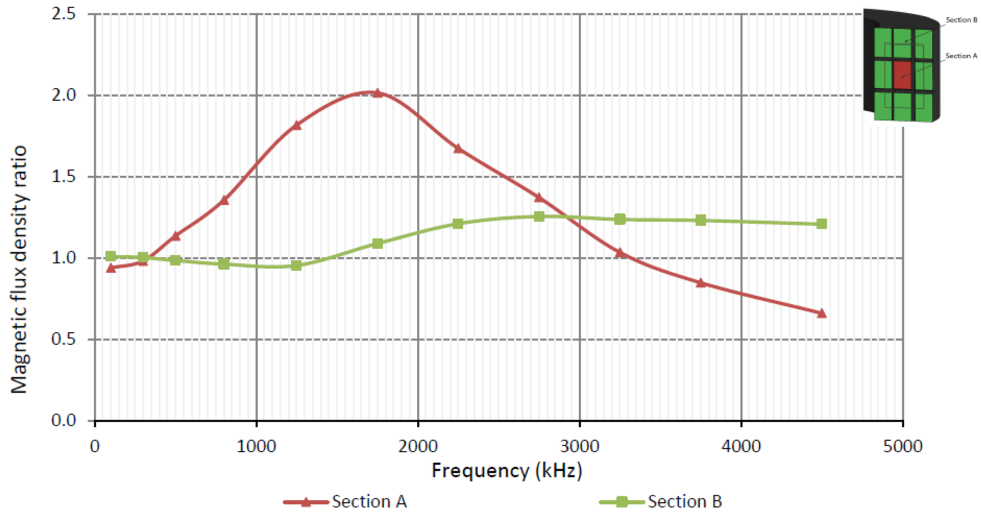
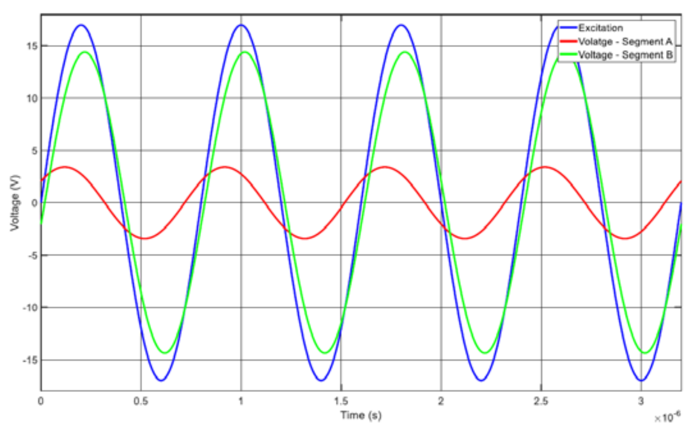


Figure 31. Magnetic flux distribution in the each section of FR78 frame core.

Peak at 1800 kHz.

f = 1 250 kHz

Blue – Excitation voltage, Red – Section A, Green – Section B



Expected behavior of NiZn toroid:

In this core, the flux distribution is very uniform, being almost as high in the center as in the periphery.

Ferroxcube 4S60

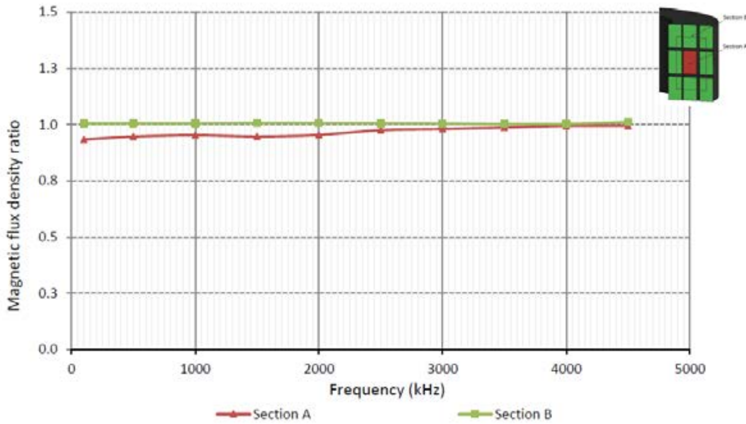


Figure 19. Magnetic flux distribution in the each section of 4S60 TX50 ring core.

And the same is true here

Ferroxcube 4A11

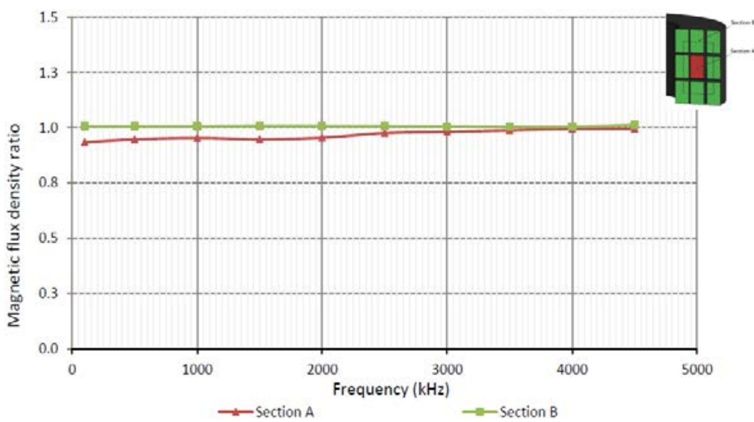


Figure 21. Magnetic flux distribution in the each section of 4A11 TX50 ring core.

What is going on here?

Fair-Rite 61.

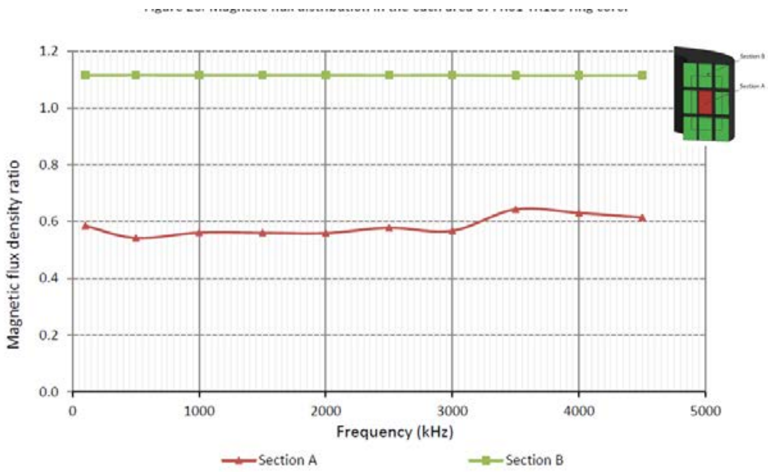


Figure 27. Magnetic flux distribution in the each section of FR61 TX105 ring core.

The flux in the center of the core is only about 60% of what it is in the periphery.

What is shielding the center from having full flux?

Fair-Rite 67

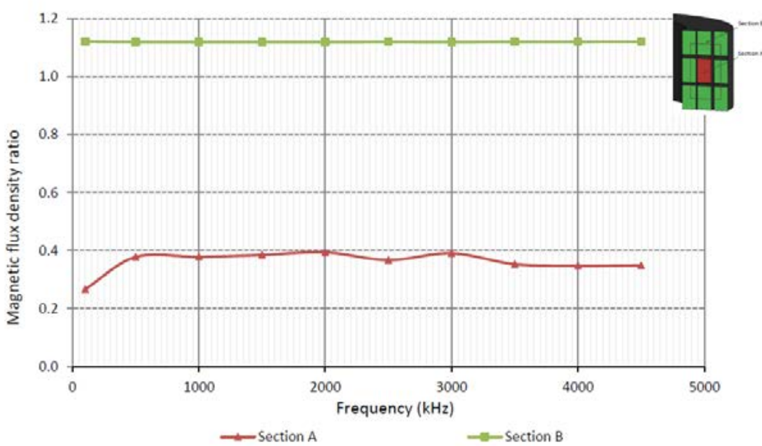


Figure 29. Magnetic flux distribution in the each section of FR67 TX105 ring core.

In the Fair-Rite 67 material, the effect is even more dramatic. The flux in the center is about 40% of what it is in the periphery.

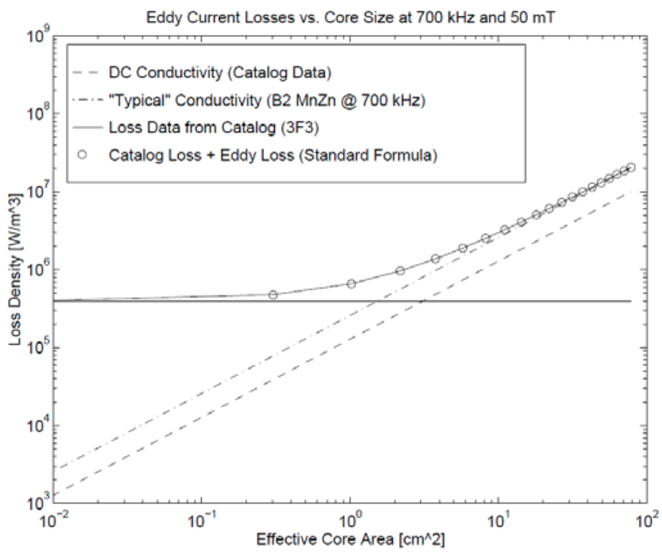
Is there some kind of "skin effect"?

Study on flux propagation and complex impedance in NiZn and MnZn ferrites - SMA Magnetics Phase I Report

The Phase II tests.

Phase II test objectives

Referring to Glenn Skutt's graph of increased loss with large core size, we want to know what is happening at the inflection point. Also, we need to use large cores for some applications. Can we move the inflection point to higher frequency?



The tests

1. Laminated cores

2. Longer, thinner cores and "Strings-of-beads"

3. Resistivity, permittivity and permeability

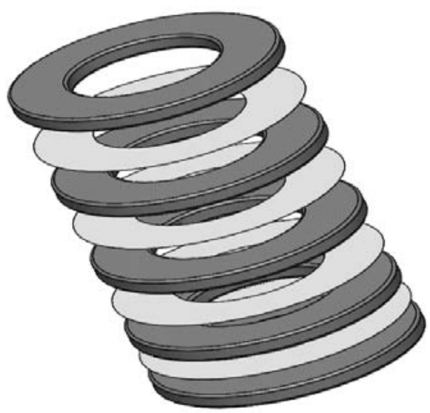
4. Three cores of the same material but different sizes

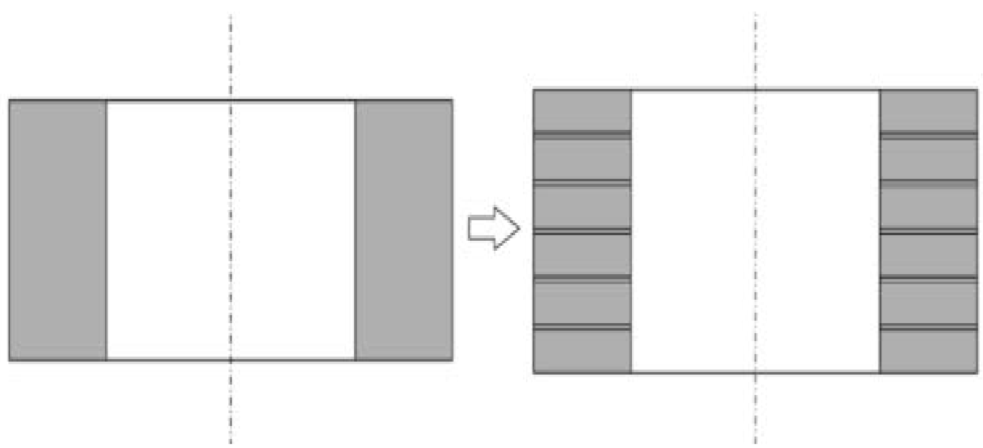
5. The "Research core"

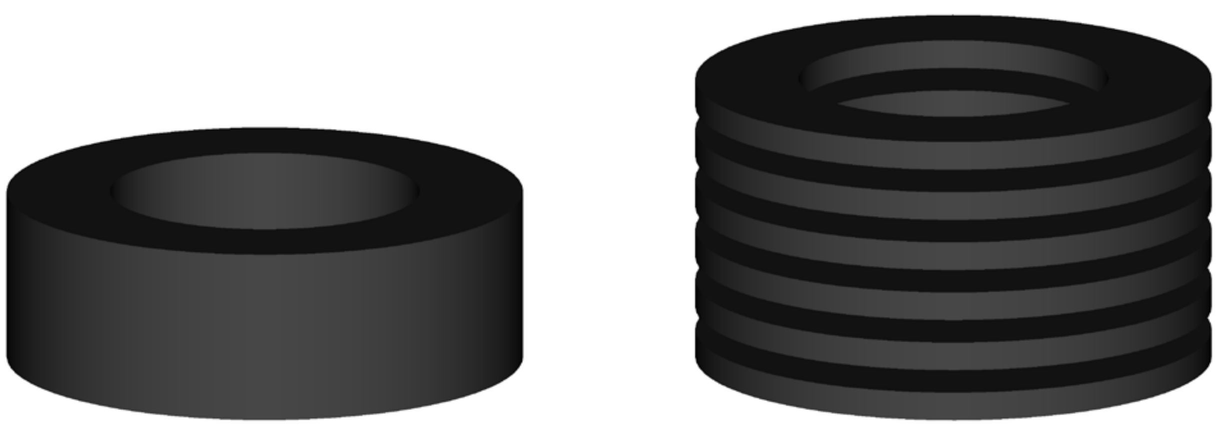
6. Current analysis

7. Machined cores of the same size but different material

1. Laminated cores.



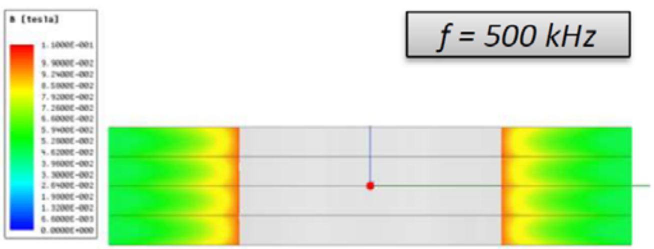


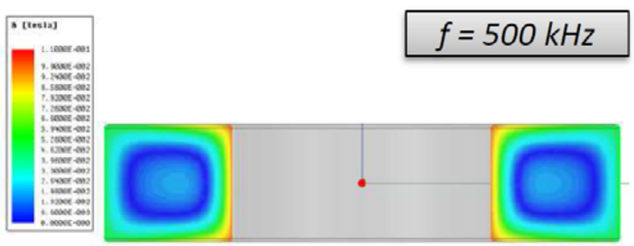


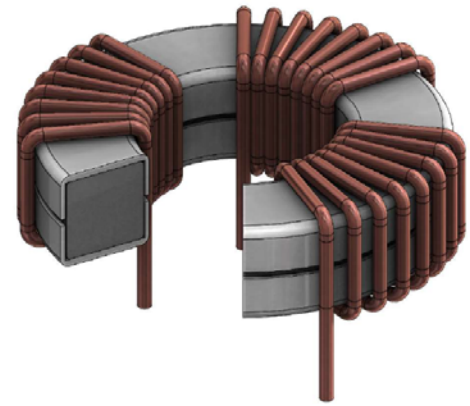
Unequal flux distribution – Laminated ferrite core

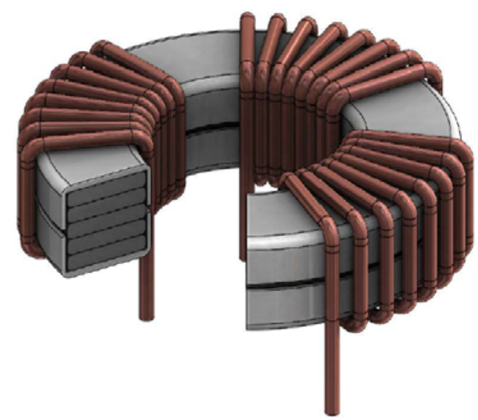
Construction details:

Paremeter	Unit	Bulk	Laminated
Material	-	Mn-Zn 3E10	Mn-Zn 3E10
Dimensions OD x ID x H	mm	80 x 45 x 17.5	80 x 45 x 3.5 x 5 5 lamination
Core total cross section	mm^2	324	324
Core volume	cm^3	62.55	62.55



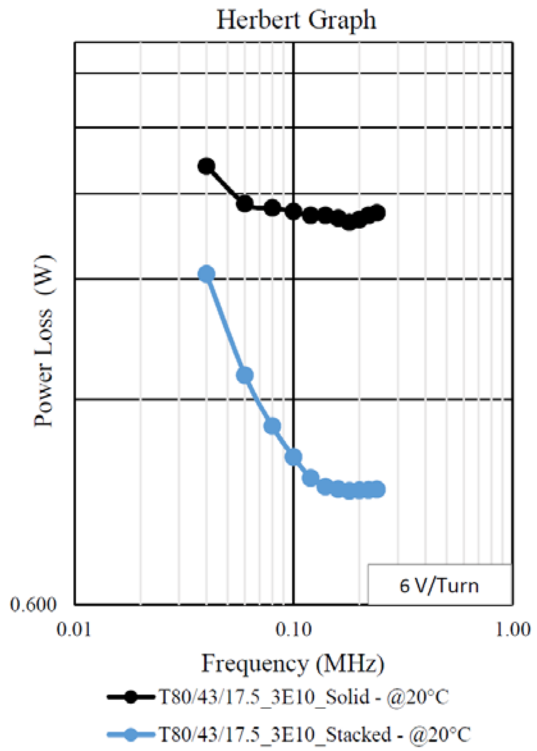


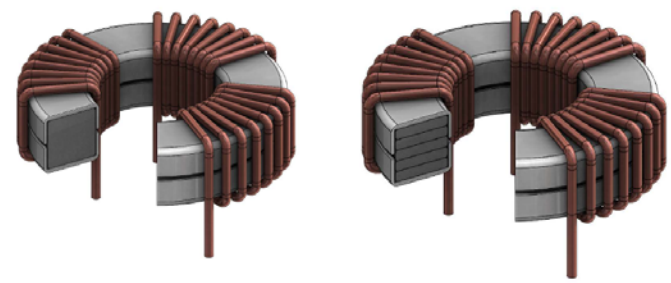


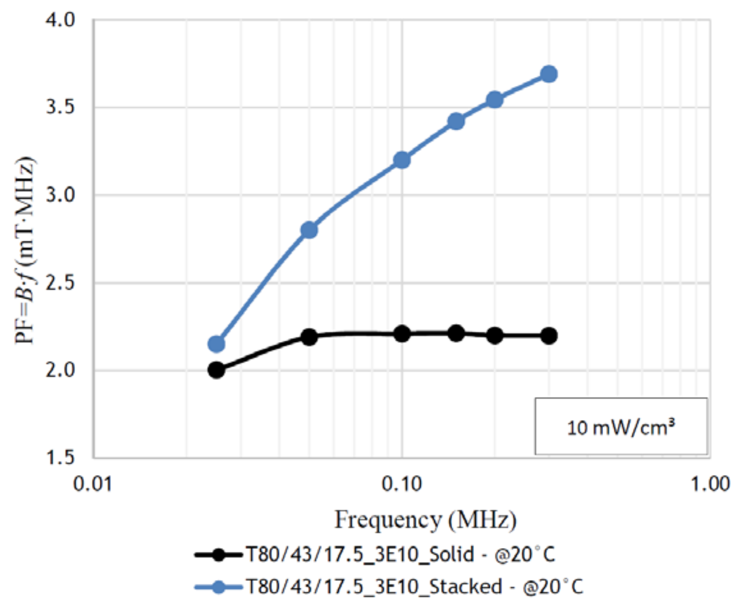


Unequal flux distribution – mitigation ideas

Power loss comparison:

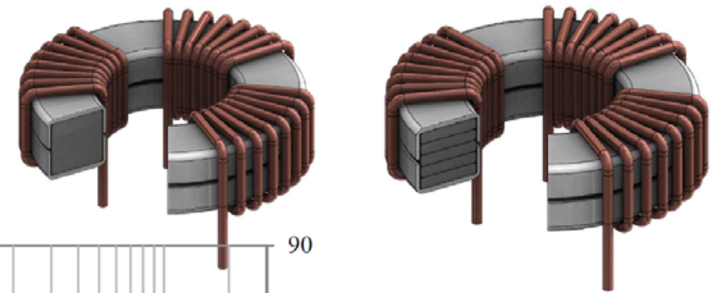


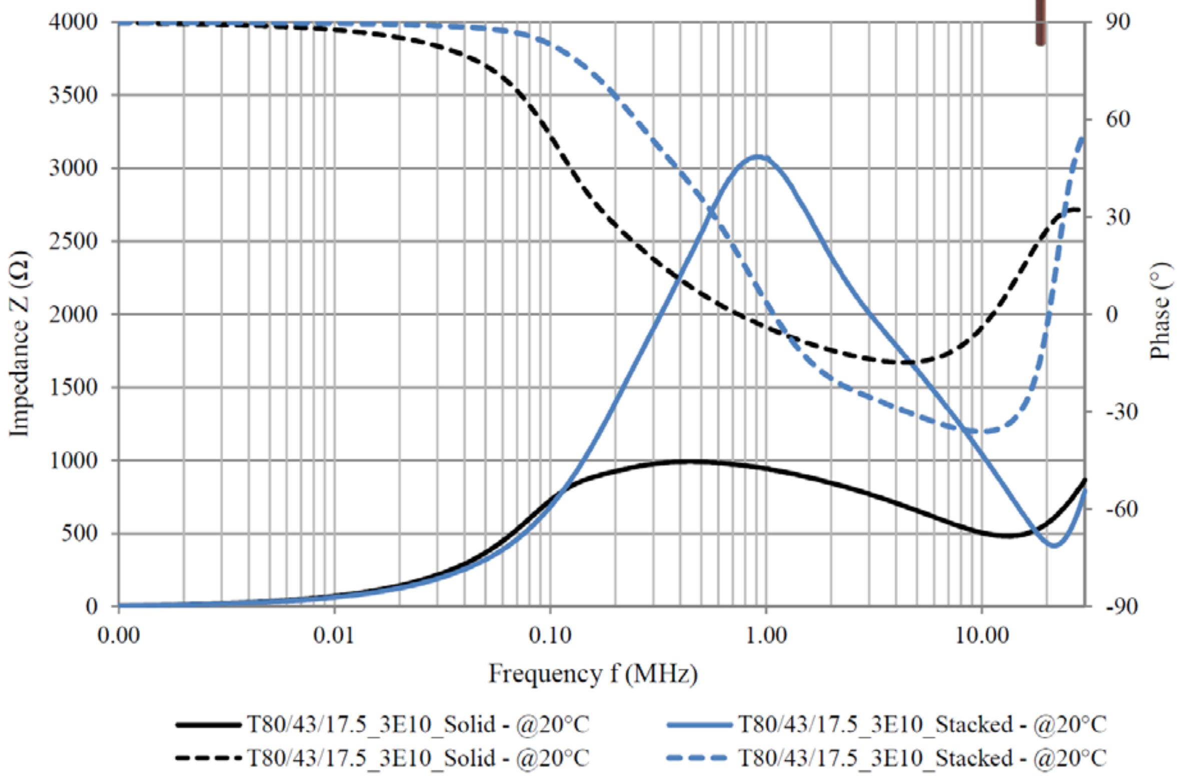




Unequal flux distribution – mitigation ideas

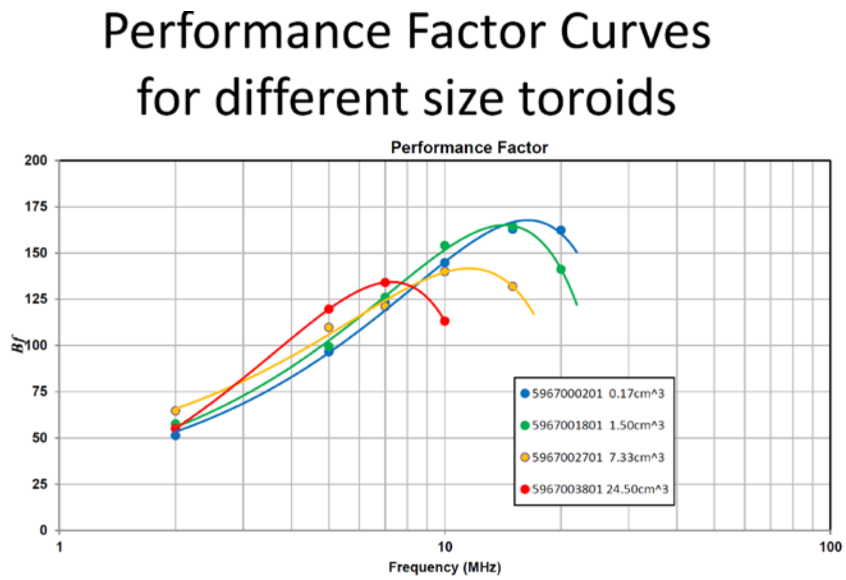
Frequency characteristic:





2. Longer, thinner cores and "Strings-of-beads"

It is known that different sized cores of the same material have different loss profiles, with larger cores having their B*f peak at a lower frequency, with a lower peak value.



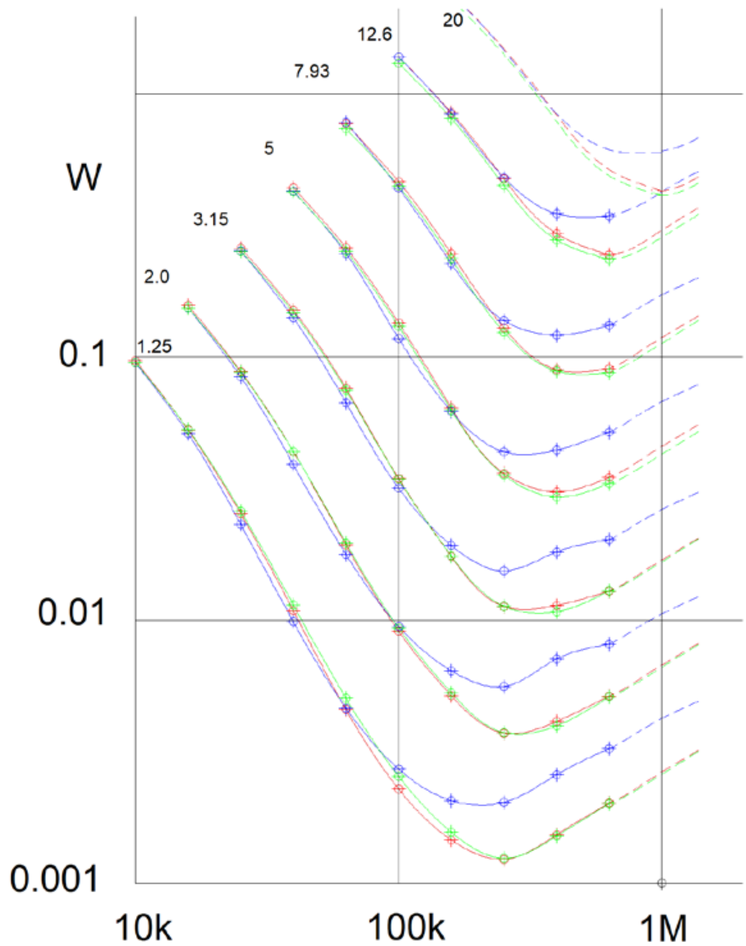
This graph is by John Lynch of Fair-rite, and shows the performance factor for four sizes of 67 NiZn material.

The hypothesis is that if you make a composite core of equal volume and inductance using multiple smaller cores, the superior B*f performance of the smaller core will be preserved in the composite core.

Note: With square wave excitation, B*f equals volts/turn. B = v * t. f = 1/t. Combining and cancelling, B*f = v. So the B*f curve shows the maximum volts per turn that you can get from a core at a particularly power density. The higher the B*f curve, the lower the losses and the greater the efficiency.

Background: PSMA-Dartmouth study

A comparison of a toroid with five turns with a “string of beads” core having the same volume and approximately the same low frequency losses appears to have significantly lower losses at high frequency. There were problems with the data for that test, so, for now, it has to be taken as “suggestive.”



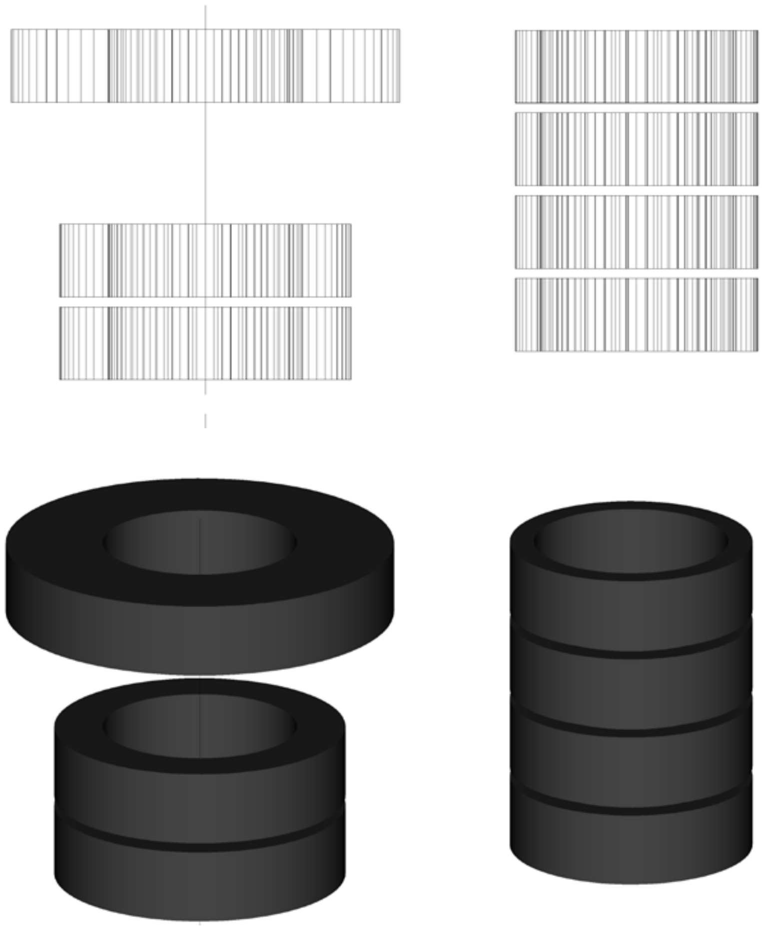
Note. The valley of the loss curve is the same frequency as the peak of the B*f curve.

Cores machined from Ferroxcube TX80/40/15

The reference core is a Ferroxcube TX80/40/15

Two more TX80/40/15 will be machined, reducing their ODs to 60 to make two TX60/40/15 cores.

Four more TX80/40/15 will be machined, reducing their ODs to 50 to make four TX50/40/15.



The three sets all have equal A_e, so that they will have approximately the same B with the same number of turns and excitation. The machined cores are expected to have lower eddy current losses.

The core loss of each set will be measured and compared.

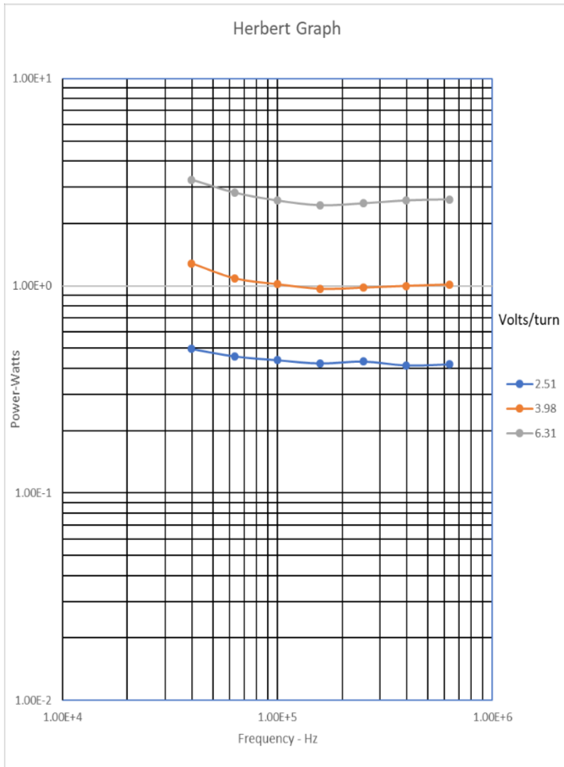
The two machined core sets have slightly lower volume, so they will have lower losses due to that effect. With the same B, they should have about the same W/m^3, but with lower volume, they should have lower loss. Also, there should be less B gradient, ID to OD, which should be more efficient.

It is also noted that heat removal should be much better, so the temperature rise should be substantially less.

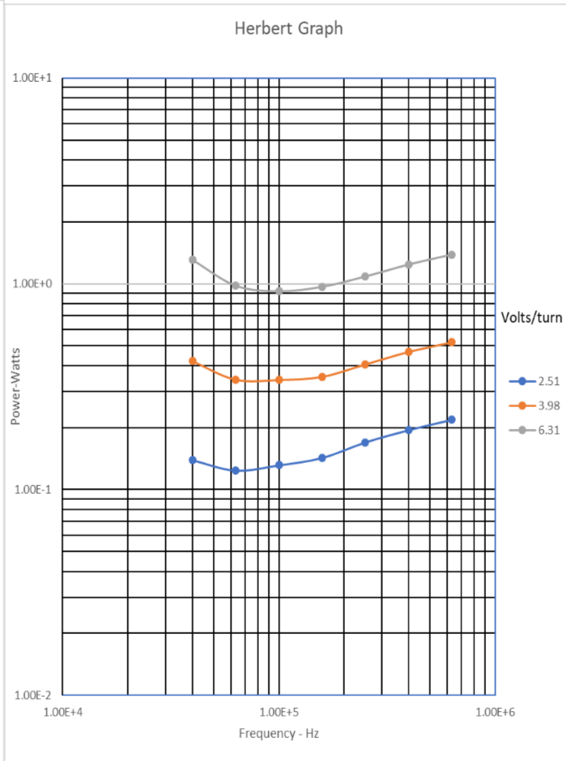
It is also anticipated that the cores will have good performance to a higher frequency, so the $B*f$ performance factor should peak higher and at a higher frequency.

Preliminary test results:

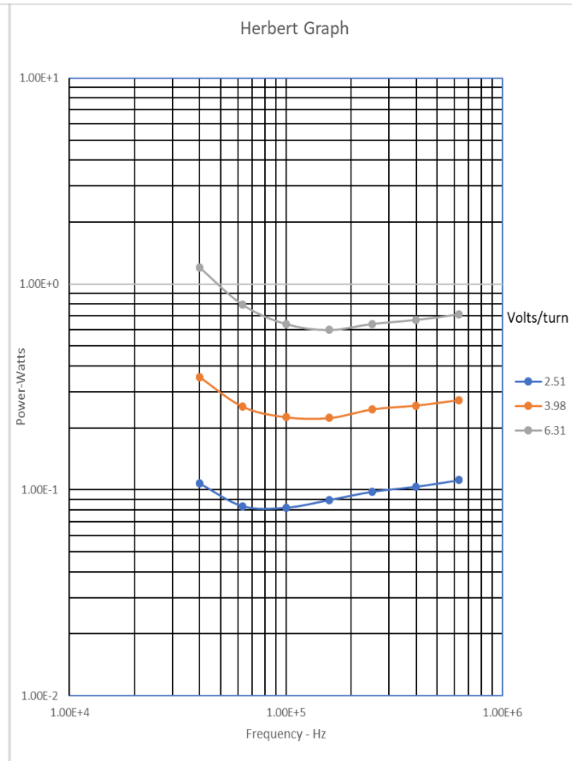
TX80/40/15



Two TX60/40/15



Four TX50/40/15



All of the core sets above have the same ID, the same area and the same excitation, but the longer, skinnier core sets have significantly lower losses.

Looking at the highest voltage curves, 2.51 V/turn, the TX80/40/15 has 2.5 Watts at its minimum, the two TX60/40/15 set has a minimum of 1 Watt, and the four TX50/40/15 set has a minimum of 0.7 Watts, or 72% less than the TX80/40/15 core.

String of beads with TX80/40/15 reference.

A Ferroxcube TX80/40/15 core will be wound with a 5 turn excitation winding, and its losses will be measured.

The ideal single turn string of beads equivalent would be $TX\left[\frac{80}{5}\right]/\left[\frac{40}{5}\right]/(15 * 25)$, or TX16/8/375.

The closest catalog core is the TX14/9/9. Many must be stacked to get the required "height." The ID and OD are far from ideal, so 375/9 won't give a valid core count. Comparing the volumes probably will come closer.

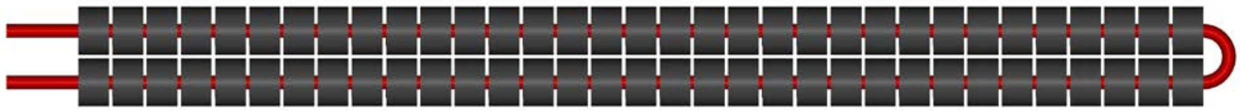
For TX80/40/15, the V_e is 50,200 mm^3.

For TX14/9/9, the V_e is 774 mm^3.

50,200/774 = 65 cores. This is an estimate. To do the tests, the losses of the TX80/40/15 with five turns will be measured. For the string of beads, cores will be added or removed until the low frequency core losses are approximately the same.

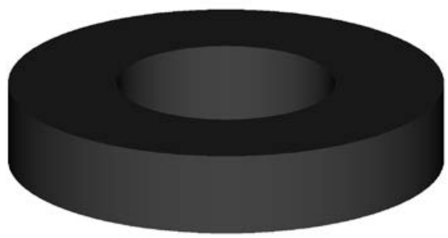
It is anticipated that the high frequency losses will be significantly lower, and that the *B*f* performance factor will be substantially higher and peak at a higher frequency.

For testing, a simple inductor with a double row of cores is suggested. A "hairpin" winding runs through the cores with a sense winding following the same path. The sense winding can be smaller wire.



Hypothetical design examples

For a practical design, the cores can be arranged in any pattern as long as the cores are positioned end to end with the winding through them.



A coil of 65 TX14/9/9 beads in series is compared to the TX80/40/15 core. The core volume is the same, but the physical volume is larger for the string-of-beads inductor. How much larger depends upon the winding design for the TX80/40/15 toroidal core, which is not shown.

Comparative inductance

The TX80/40/15 has an A_L of 4,780 nh/turn^2. With 5 turns, that is 120 uh.

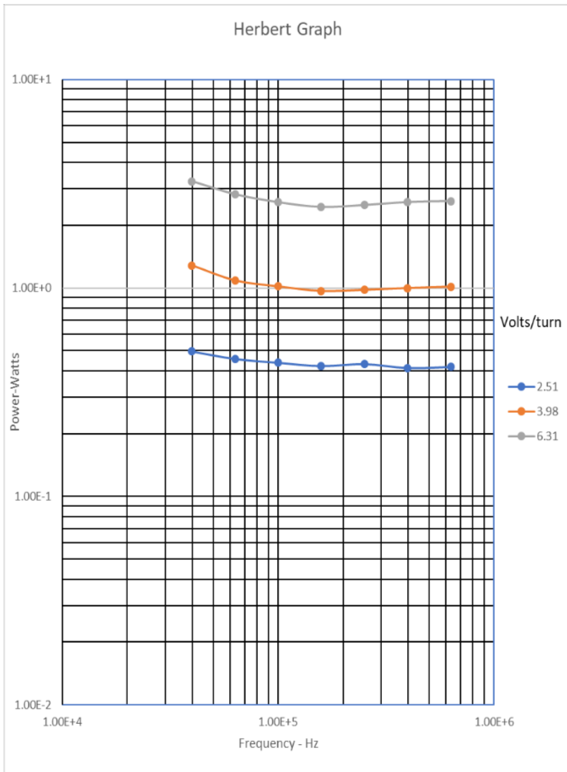
The TN14/9/9 has an A_L of 1,825 nh/turn^2. With one turn and 65 cores in series, that is 119 uh.

However, these values are taken with much different operating conditions and may not predict what happens at high frequency. It is possible that the string of beads will be better, but that remains to be seen.

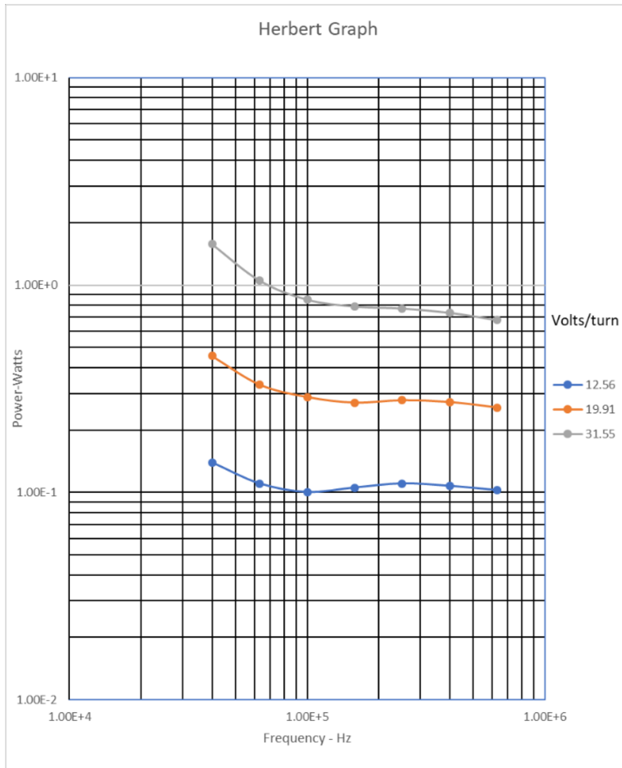
The coil above purposely is open, the concept being that other components could be mounted inside. However, it could be flat, as shown below.

String of beads comparison, preliminary data

TX80/40/15



TX14/9/9 string



The TX80/40/15 has 2.5 Watts at its minimum with 2.51 volts/turn. The string of TX14/9/9 cores has a peculiar curve shape that is not yet understood, but comparing the loss at 150 kHz, the loss is 0.8 Watts., or about 68% less. Because the string core set has only one turn, its volts per turn is five times higher, or 12.5 volts/turn.

While this looks good and it validates that strings of beads of equal volume have lower losses than the solid toroid equivalent, it is not as good as the four TX50/40/15 set.

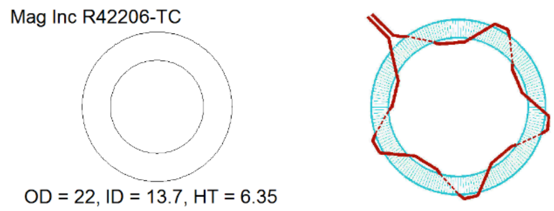
Repeat string of beads test from the Phase III PSMA-Dartmouth Core Loss Studies.

Reference core: Mag Inc. R 42206-TC

Beads: Approximately 40 to 50 cores of Mag Inc. R 40402-TC

See: “Phase III Supplemental Report: The String of Beads Experiment;” By Edward Herbert, Co-chairman, PSMA Magnetics Committee; December 16, 2013

This test has not been done yet in the PSMA-SMA Phase II project.



Ideally, for inductance comparable to a five-turn winding using only one turn, the area Ae should be 5 times and the magnetic length Le should be 1/5. The total volume Ve should be the same.

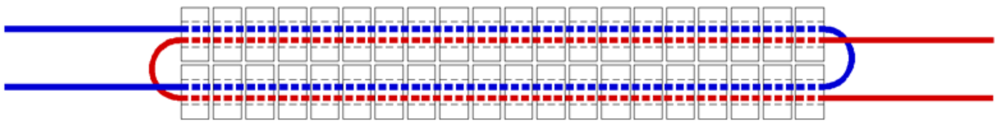
If we keep the ID/OD ratio the same, and meet the above criteria, the ID and OD are divided by 5 and the height is multiplied by 25, so the area Ae is 5 times and the volume Ve is the same. The height of the individual beads is arbitrary as long as the total is correct.

We could not find a combination using standard cores that fit the criteria, but 40 cores of Mag Inc. R 40402 is quite close on inductance using the published values and 87 percent of the volume Ve. To make the volume Ve equal, use 46 cores.

	R 42206		**R 40402**	
Ae	26.2 mm^2	x5 = 131 mm^2	3.08 mm^2	x40 = 123.2 mm^2
Le	54.1 mm	x1/5 = 10.8 mm	10.21 mm	
Ve	1441 mm^3		31.4 mm^3	x40 = 1256 mm^3

Check proportionate inductance L:

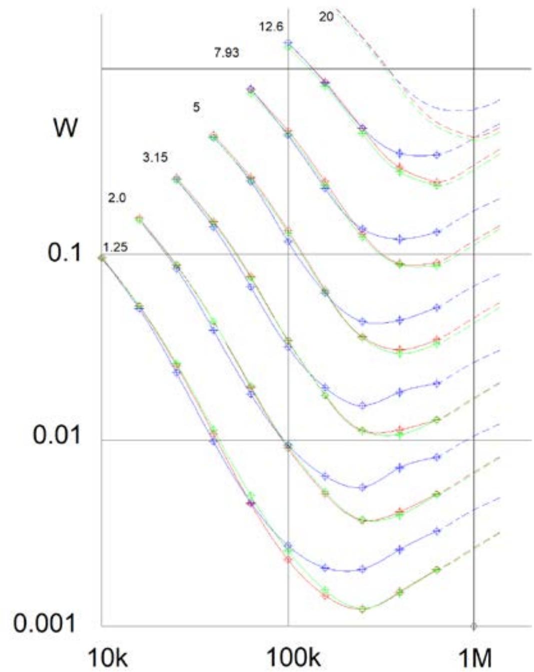
$$L \propto \frac{n^2 * A_e}{L_e} = \frac{5^2 * 26.2}{54.1} = 12.11 \approx \frac{40 * 3.08}{10.21} = 12.07$$



Tests of a “string of beads” of 40 beads and 46 beads were proposed.

Test procedure

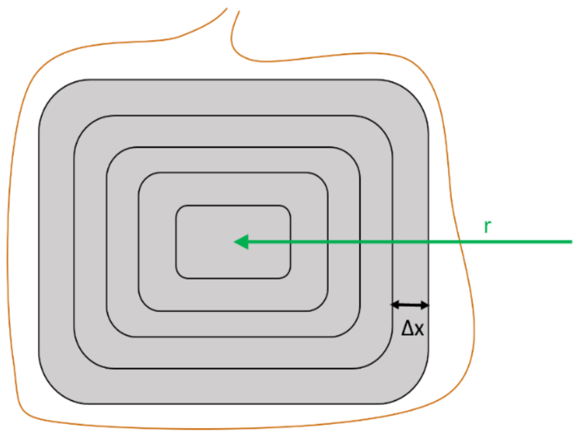
1. Wind a Mag Inc R42206-TC core with 5 turns and measure its core loss.
2. Wind approximately 46 cores of Mag Inc R40402-TC as shown above with a single turn winding and measure its core loss. Add or remove beads so that the core loss is approximately the same as the reference core at low frequencies.
3. Measure the core loss and plot it on the same graph as 1. above.
   The graph may look like this:



4.

3. Resistivity, permittivity and permeability

The objective is to develop a model for a ferrite core using the properties of the ferrite material, resistivity, permeability and permittivity, and its dimensions. The resistivity, permeability and permittivity vary with frequency and are notoriously difficult to measure.

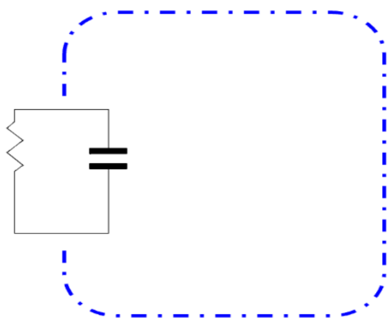


Proposed model

(copied and pasted from C. Sullivan's slides, with some edits).

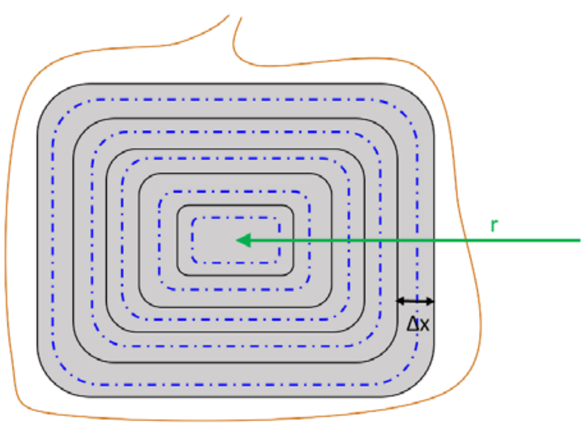
Consider concentric shells of a toroidal core (conceptual only—it's still solid material)

Four shells plus center



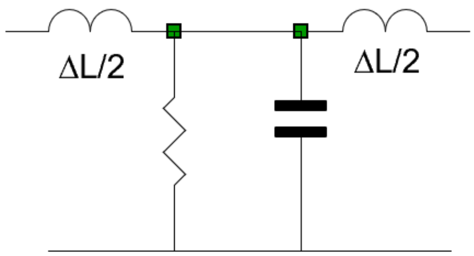
- Each path (blue dashed line) has capacitance and resistance, in parallel:
$R = \ell\rho/A$
$C = \epsilon_r\epsilon_0 A/\ \ell$
- where ℓ is the length of that loop, and A is its cross section, $A \approx (2\pi r)\Delta x$.

[There is series resistance as well.]

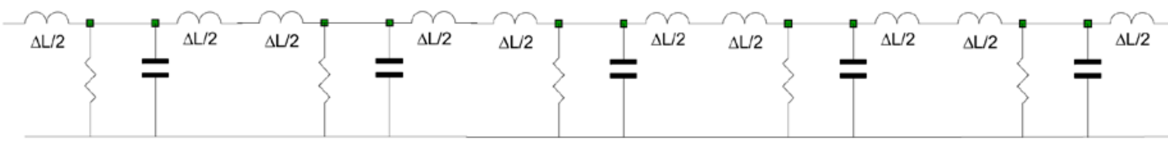


- Each path links a little less flux, as we move from the outer shells to the inner shells.
- The inductance arising from a shell divides half and half: half outside the blue line (not linked) and half inside (linked)
- Inductance of a shell
$\Delta L = N^2 A/(2\pi r) = (\Delta x\ \ell)/(2\pi r)$ (for simplicity assume N =1)

Model for one shell:



Transmission line model for multiple shells



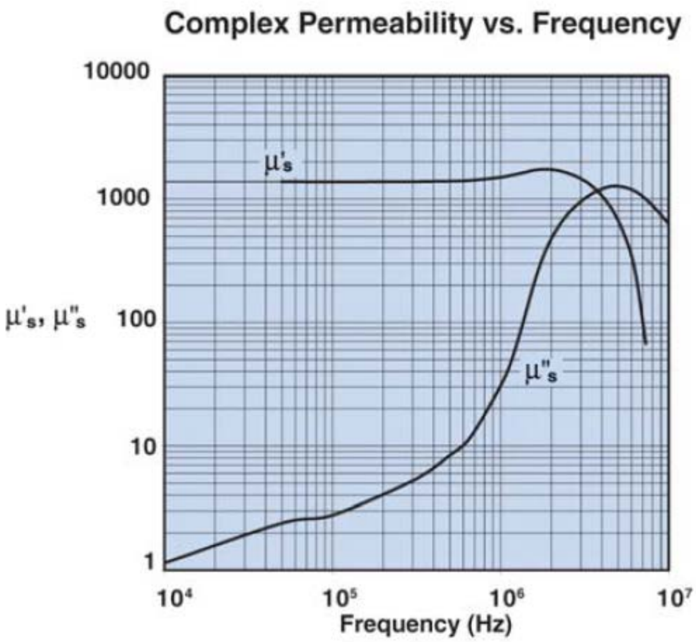
- This is a linear model, but any and all of the components can be made nonlinear and accurately capture nonlinear aspects of the corresponding behavior.
- Add an ideal transformer at the input for N > 1.

Materials characteristics like permittivity and resistivity usually are missing in data published by ferrite manufactures. This test is to define permittivity and resistivity frequency characteristic for various materials and sizes. The characteristic will be measured at three temperatures: 25 °C, 60°C and 110 °C. The measurement approach may become a backbone for future core measurement standards.

The high resistivity ferrite cores are beneficial from an eddy current perspective. The same structure that makes ferrite high resistive also results in high permittivity. Combination of ferrite high permittivity together with high permeability develops core dimensional effect.

Published core permeability vs material permeability

Magnetic material data sheets usually have a curve showing the complex permeability µ’ and µ”. This is NOT the permeability that will be measured on test specimens as a property of the material.

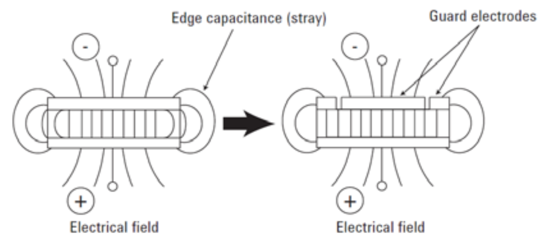
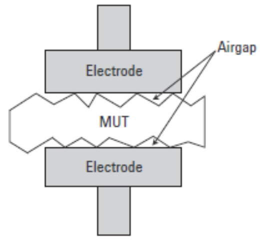
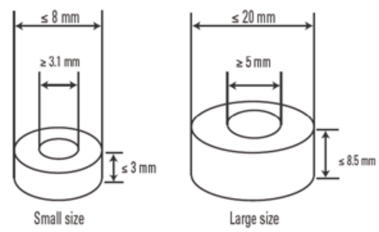


Fair-Rite 79 material

The µ’, µ” curve shows apparent changes of permeability of several orders of magnitude with frequency. The µ’, µ” curve is the inductance measured on winding terminals, not the material properties. This is not the expected behavior of permeability as a material parameter.

A successful model will have the same input characteristics when reflected to an excitation winding.

Permittivity and conductivity measurement challenges:

1	Stray capacitance is formed on the edges of the electrodes and consequently the measured capacitance is higher than the capacitance of the tested material Electrode shape and size should be adapted to measured samples	
2	Air gaps which are formed between tested material and electrodes cause measurement error. Thin materials with high dielectric constant are most prone to this effect	
3	Precise geometry measurement of the samples is a key for the good quality results.	

Possible reasons for poor repeatability:

a. Surface conductivity effects. Possible insulating layer decreases G.
b. Surface contamination on sides could increase conductivity.
c. Thermal coefficients. It may require well-regulated temperature to get repeatable results.
d. Humidity. The material may absorb moisture, which may affect conductivity.

Find a good, easy, repeatable way to make connection to the core.

a. Surface prep (sanding?)
b. Metallization.
c. Elastomeric contacts, such as Zebra W series.
d. Silver epoxy painted.

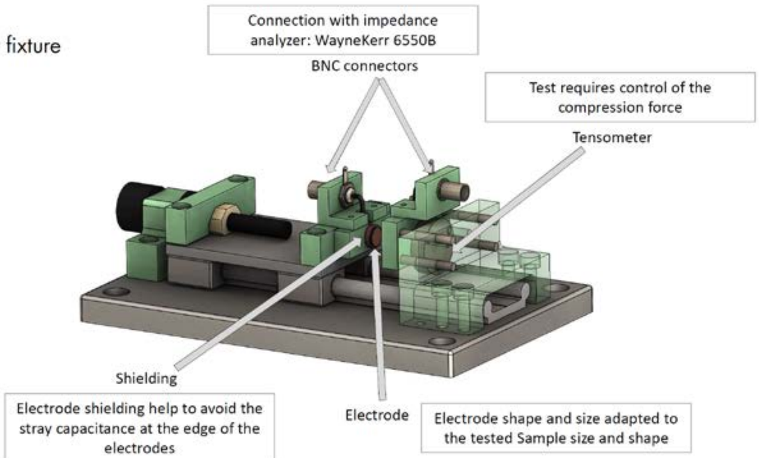
We have various sized slugs. We also have blocks of the same material, so we can review whether a different shape would be better. Maybe slabs of varying thickness.

Valid data requires identifying the parasitics of the specimens and compensating for them.

Test fixture

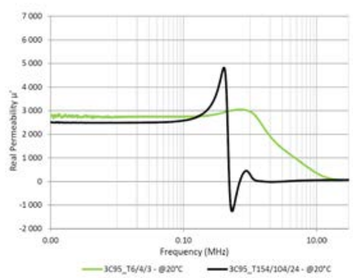
Ferrite dielectric constant and conductivity

Test fixture

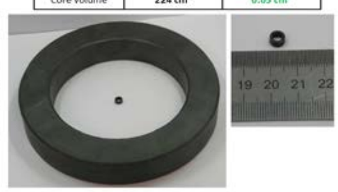


Permeability measurement

Permeability frequency characteristic must be measured on very small ring core.

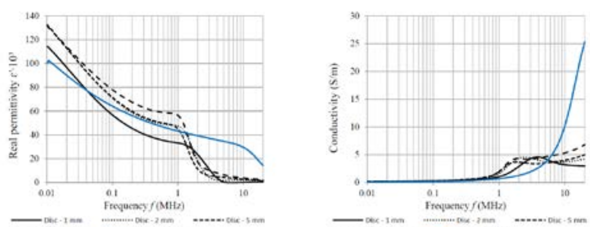


Tested samples		
Martial	3C95	3C95
Dimensions OD x ID x H	**152x104x24 mm**	6x4x3 mm
Core total cross section	**558 mm²**	3 mm²
Core volume	**224 cm³**	0.05 cm³



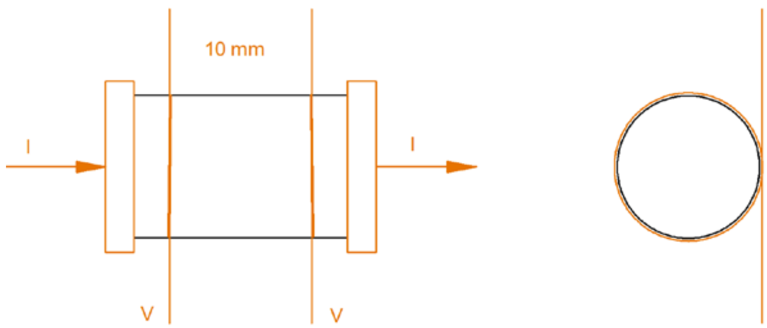
Dielectric constant and conductivity measurement

Materials dielectric constant and conductivity strongly vary with frequency and core size:



We retained blocks of each of the materials used for the machined core tests. If experiments suggest that a different shape may be better, we have material available to try it out. Glenn Skutt use rectangular slabs in his tests, and that shape may have merit.

The first attempts at measuring resistivity were not very successful. There seemed to be significant variation due to contact pressure. A four-wire measurement was used, but the original placement of the sense wires may have captured part of the contact resistance. A new method uses sense wires that wrap 360º around the slug away from the ends.

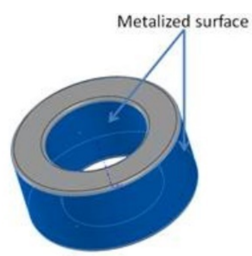


Test specimen parasitics

It is a challenge to ensure that the parasitics of the test specimens do not affect the measurements.

Tests on entire cores

Another test that is planned is to metallize the top and bottom surfaces of a toroid and measure the current flowing top to bottom when a potential is applied.



Another core will be metallized on its ID and OD, and the same current measurement will be done.

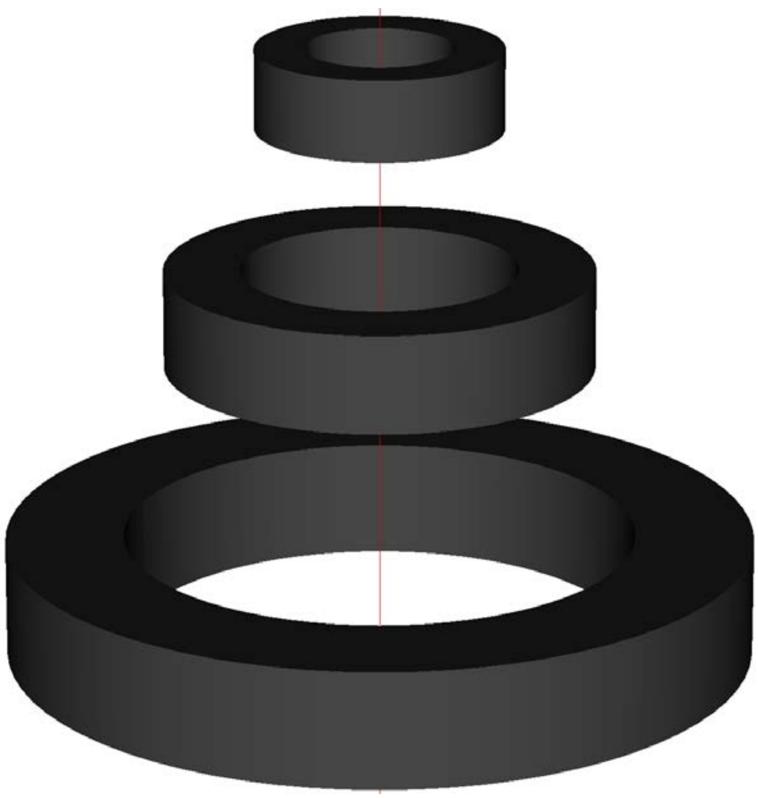
If the currents are confined by skin depth to a thin layer under the surface, the measured currents can be used to figure out the current in the skin depth.

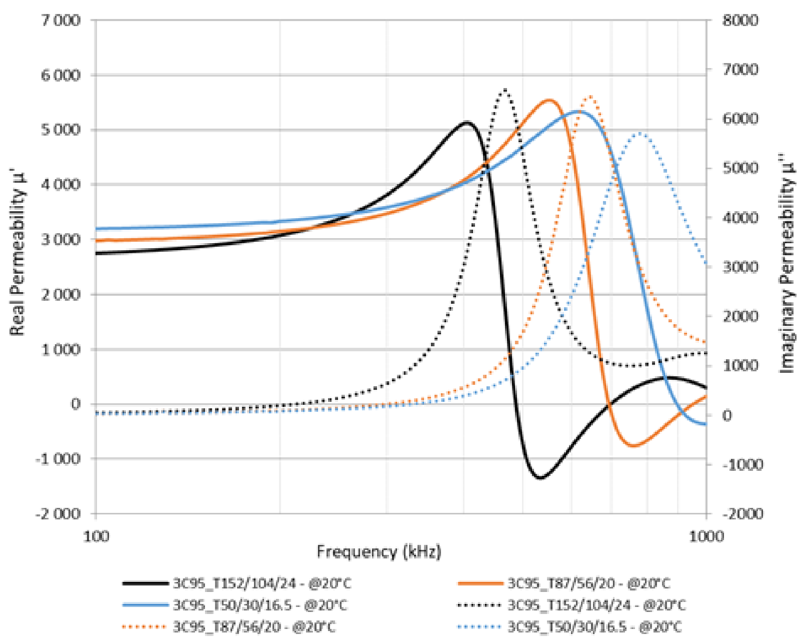
4. Three cores of the same material but different sizes

This test was not among those planned originally. However, SMA built an H-bridge for measuring core loss with square wave excitation, and they used these cores for testing the H-bridge. We did not have a test planned for different sized toroids of the same material, and oversight that this corrected, so the test has been added.

Cores

	A, mm^2	L_{avg}, mm	V, mm^3
T152/104/24	576	402	231.6E3
T87/56/20	310	224.6	69.6E3
T50/30/16.5	150	125.7	20.7E3

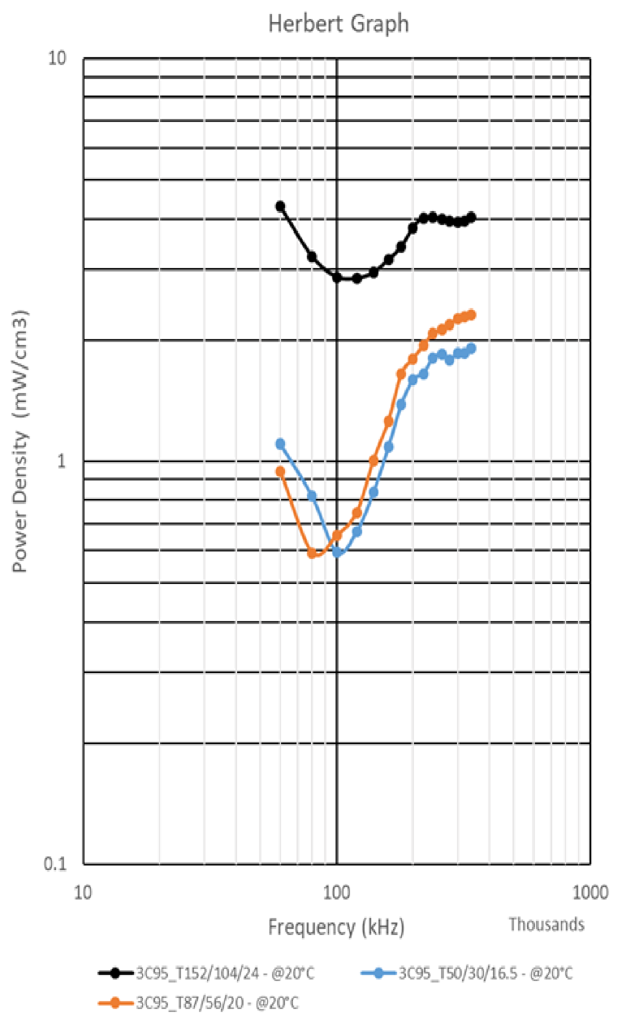




The µ', µ" curves for different sized cores

The µ', µ" curves were taken for three cores of the same material but of different size.

The larger cores break at a lower frequency.



The first test results

Early test data raises several questions. At the left, the curve of the larger core looks as we expected around 100 kHz, but the leveling off at high frequency was unexpected, and we do not yet know if it is real.

The shapes of the lower two curves are misshaped, especially at the lower power densities.

Possible explanation?

From the discussion of skin depth on Wikipedia, it is known that the skin depth becomes approximately constant at high frequencies under some circumstances. Also, ferrite is known to be almost purely resistive at very high frequencies, as seen in suppressor beads.

Excerpts from Wikipedia

https://en.wikipedia.org/wiki/Skin_effect

The general formula for the skin depth is:

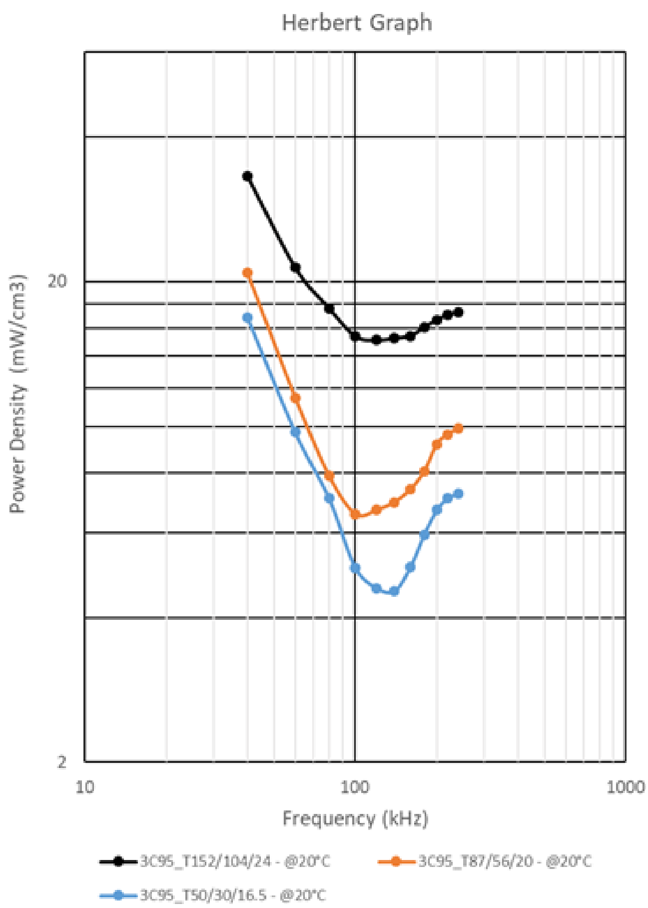
$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}\ \sqrt{\sqrt{1+(\rho\omega\epsilon)^2}+\rho\omega\epsilon}$$

At frequencies much below 1 / ρ ϵ the quantity inside the large radical is close to unity and the formula is more usually given as:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}.$$

However, in very poor conductors, at sufficiently high frequencies, the factor under the large radical increases. At frequencies much higher than it can be shown that the skin depth, rather than continuing to decrease, approaches an asymptotic value:

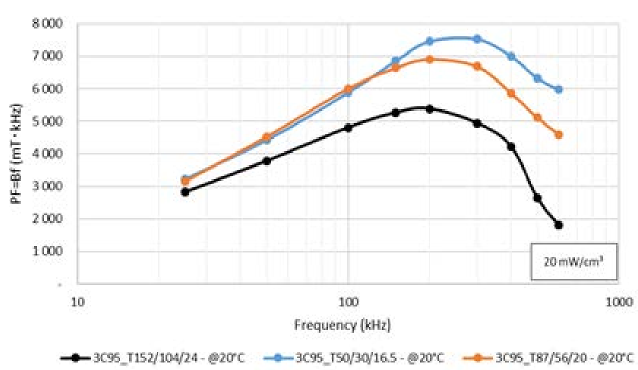
$$\delta \approx 2\rho\sqrt{\frac{\epsilon}{\mu}}$$



Second test results

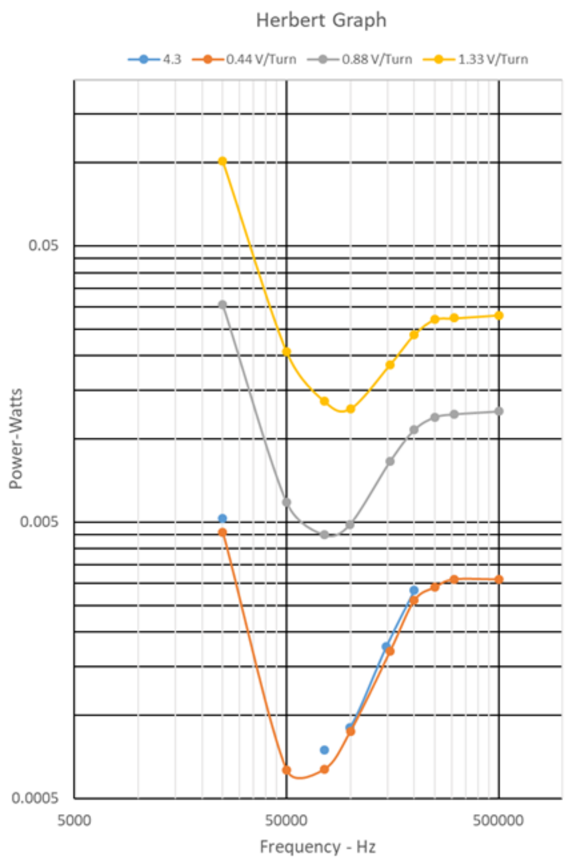
These curves were taken at a higher power level but still the lower power curves show possible distortion. It is suspected that the H-bridge has a small negative power bias, perhaps due to the gate drive coupling through the gate-source capacitance.

Further testing will be done with the H-bridge loaded to a higher power level.



The *B*f* curves should peak at the same frequency as the minimum in the core loss curves. in the examples at the left, the B*f peaks are significantly higher in frequency. This is unexpected, but the correlation between the loss curves and the B*f curves is fairly fundamental, so we expect that the preliminary data are faulty. It's the best that we have for now.

T26/15/20 core loss



These results don't really belong in this section, but they are included as another example of very early data on the new H-bridge.

There are not enough low frequency points.

We see loss data at three excitation voltages, 0.44 V/t, 0.88 V/t and 1.33 V/t. The core loss increases approximately as the square of the voltage, as expected.

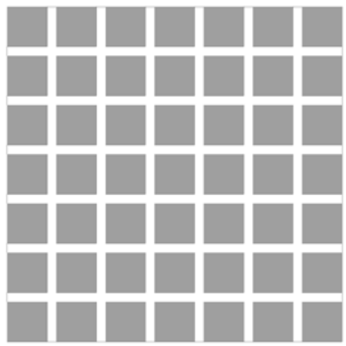
The curves are included here mostly to show another example of the curves going flat at high frequency.

At this time, we cannot be sure that they actually do. It is preliminary data.

5. The "Research core"

The concept for the research core was to drill a cross-hatch pattern of six holes horizontally and six holes vertically, equally spaced, so that test wires could be inserted to measure the voltage around any of the 49 segments. If vertical symmetry is assumed, only 28 measurements are actually needed.

Apparently, a large amount of data has been taken, but it was taken by a technician and has not been verified. There is a tension between releasing data that may be wrong in a timely manner vs ensuring that it is correct and releasing it at a later time.

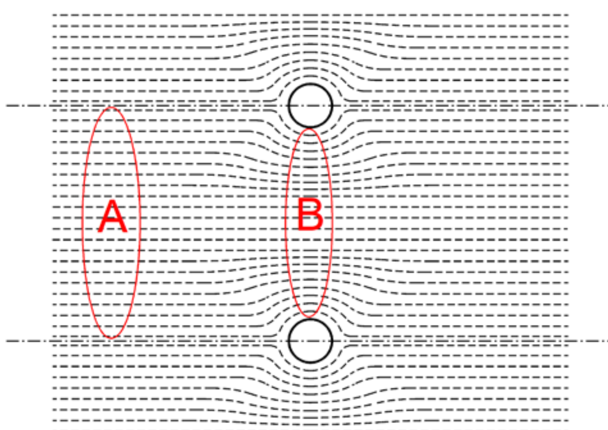


Effect of holes on flux distribution

During the approval of the PSMA Special Project Nomination, questions were raised about the effects of drilling holes in cores and machining cores.

Do drilled holes affect the flux?

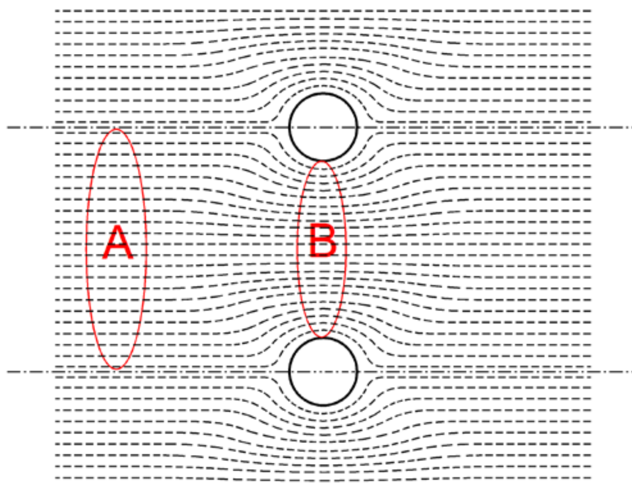
Yes, of course they do. The important question is whether they affect the measured voltage induced by changing flux through the area.



The assumption is that the flux through area A, above, would all pass through area B, so the measured voltage would be the same. The flux density is slightly higher, but the area is smaller, exactly offsetting the difference. This assumes that when flux encounters a hole, it divides at the centerline and goes around it equally on both sides of the hole.

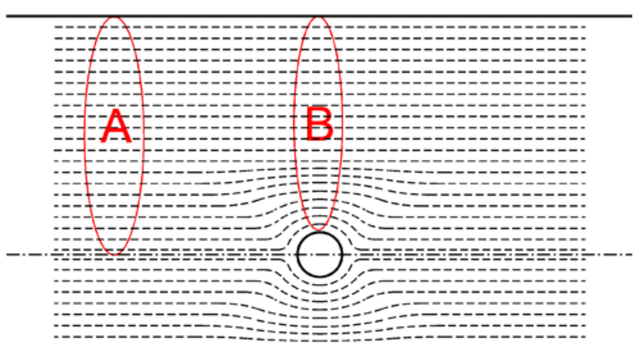
If the hole is too big, and the area of B is reduced enough that saturation begins to occur, that would not be true, but it should be true for small holes used with low flux density.

Even if the hole is bigger, as shown below, as long as the flux separated at the centerline, going around each side of the hole, the voltages should be the same.

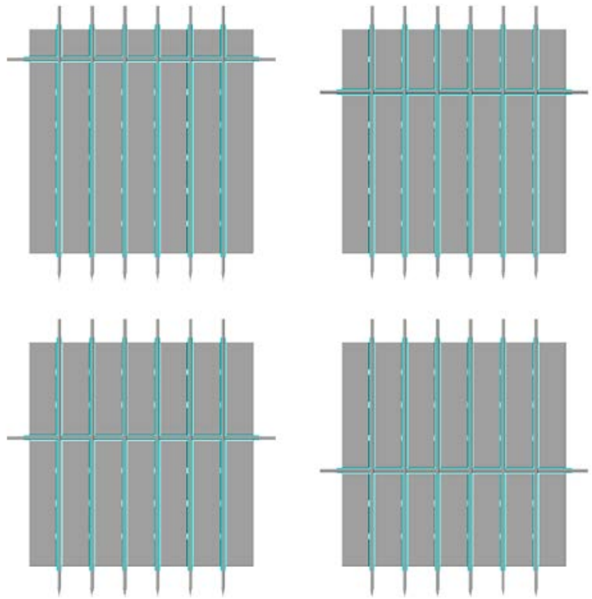


Thus, it is believed that voltage measured in test loops in holes will be representative of what the flux is doing in the bulk core in an area that is defined by the centerline to centerline of the holes as long as the maximum flux density is small compared to saturation.

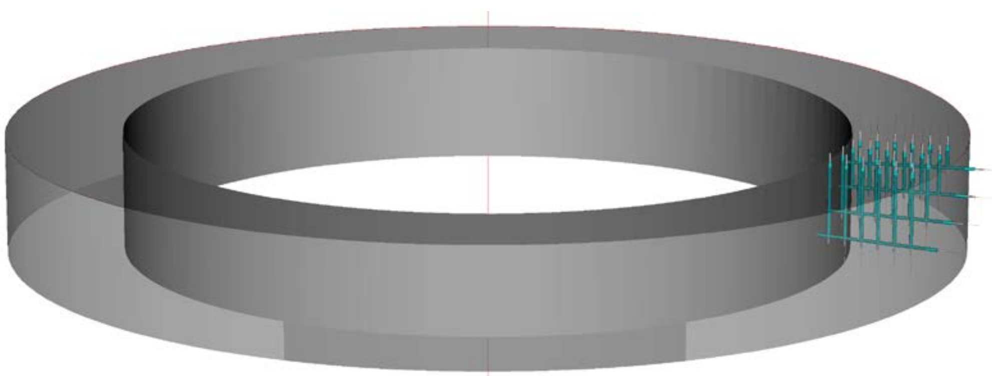
If this assumption is true for hole-to-hole voltage measurements, surely it will hold for hole-to-edge measurements, as shown below.

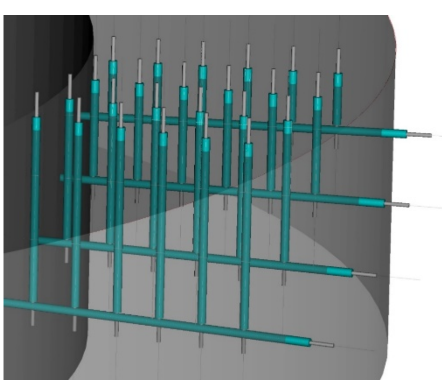


A modified drill pattern is used for the research core. In four planes, one horizontal hole is drilled from the OD to the ID of the core. The holes are spaced 1/7, 2/7, 3/7 and 4/7 of the height from the top of the core.



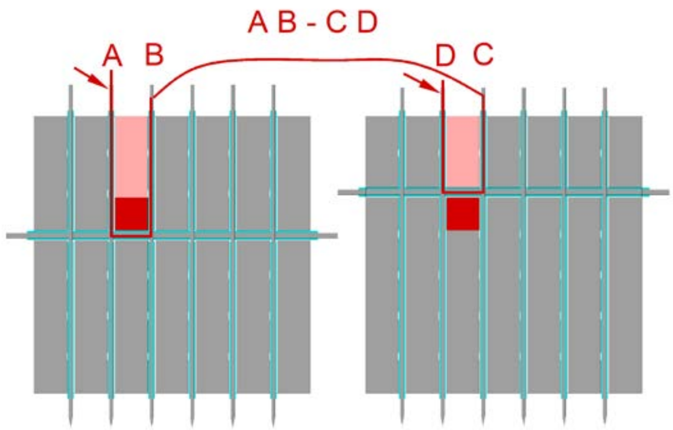
Six vertical holes spaced 1/7 through 6/7 of the width of the core. A wire is placed through each horizontal hole, and the vertical wires intercept the horizontal wires and connect at each intersection.



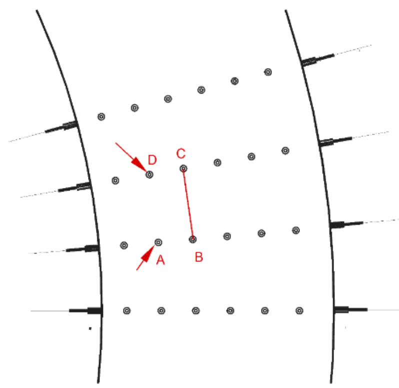


The advantage of this arrangement is that the wires can be permanently installed, so tests can be rerun later or more tests can be done.

To measure the voltage on a segment, for example the red segment shown below, the wiring diagram shown below can be used. The loops A-B and C-D are wound in series opposition so that the voltage of the pink area is cancelled.



A top-view of the wiring is shown below.



This test is planned, but data is not yet available.

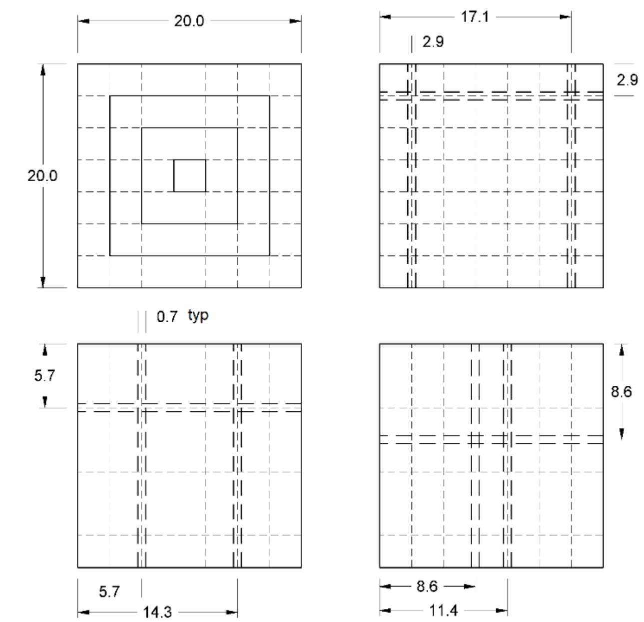
6. Current analysis

There are some flux measurements below, but the current measurements will be taken later.

Data needed for a current analysis

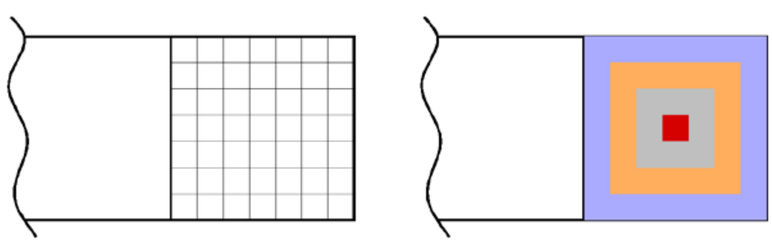
The core is a T80/40/20. The drill dimensions are shown below.

0.7 mm holes are drilled in the patterns below. The patterns are spaced apart around the core.



The proposed tests will measure the voltage at three layers and the center, as shown below on the right.

The excitation winding is n turns around the core. A single turn sense winding around the whole section (blue) is used to measure v1.



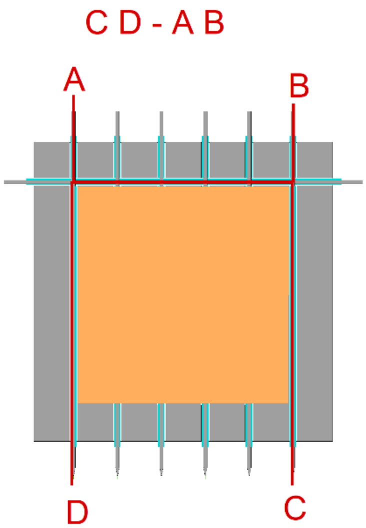
The voltage around the orange section is v2.

The voltage around the gray section is v3.

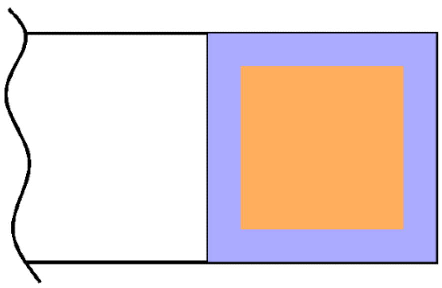
The voltage at the center is v4.

We also measure the excitation current, in ampere-turns.

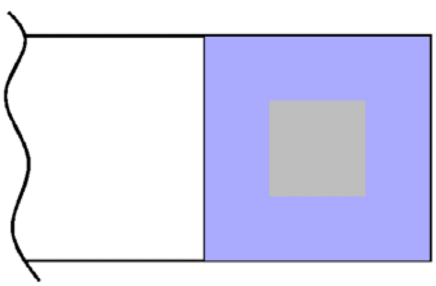
Measuring voltage of an inner segment:



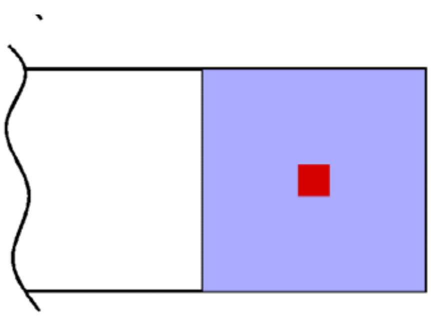
To determine the voltage around the orange segment, measure the voltage from A to B and from C to D. Subtract A B from C D.



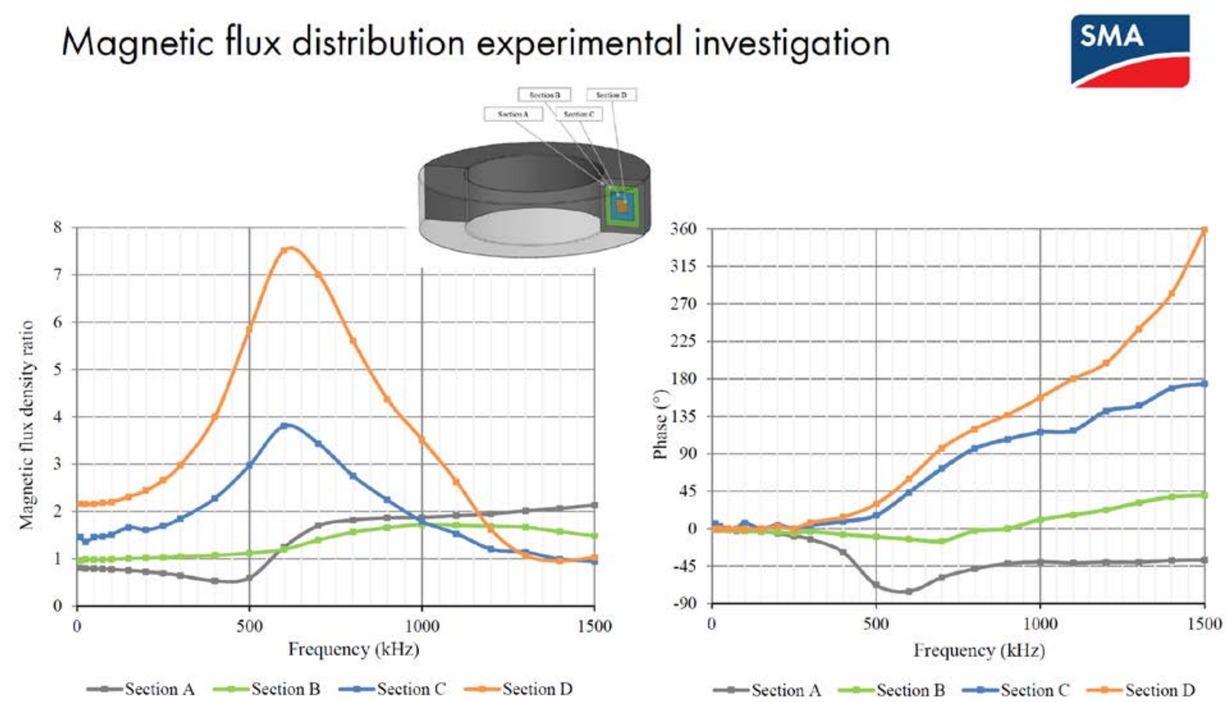
The voltage around the orange section is measured as v2. Assuming that the voltage is reasonably sinusoidal, it is sufficient to record the voltage magnitude and the phase angle with respect to v1.



In the same way, we measure the voltage v3 for the gray segment. Assuming that the voltage is reasonably sinusoidal, it is sufficient to record the voltage magnitude and the phase angle with respect to v1.



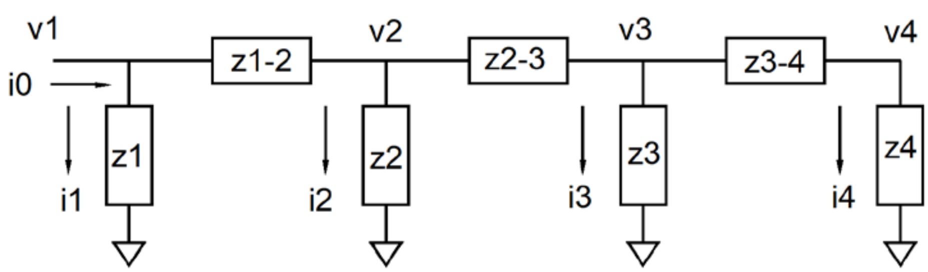
Finally, measure the voltage v4 of the red segment. Assuming that the voltage is reasonably sinusoidal, it is sufficient to record the voltage magnitude and the phase angle with respect to v1.



Building a model reflecting these measurements

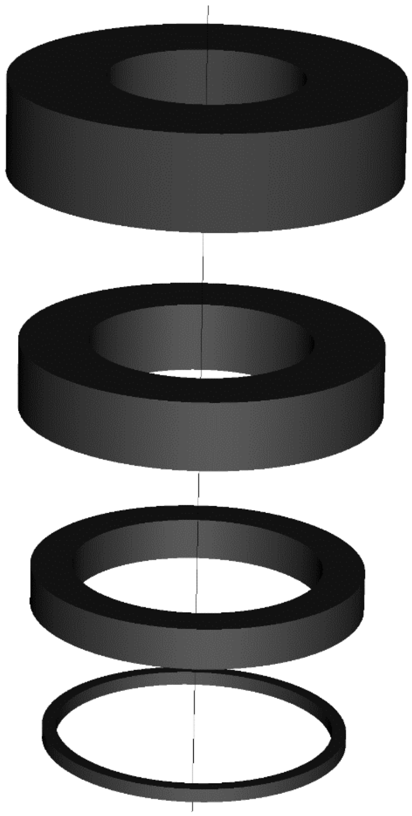
There are several ways to approach a network. The network below is suggested, as the voltages and currents in it are voltages and currents that are planned to be studied in the Phase II Project.

To start, we will try to build a network that will produce the measured voltage at nodes representing four sense windings. With reference to the network below, v1 is a sense winding around the entire core. The voltages v2 and v3 are sense windings around internal segments of decreasing size. The voltage v4 is the voltage around the center.



The voltages v1 through V4 can be measured directly, and we can measure the input current i0. To solve for the impedances, we need the current measurements i1 through i4, but they are internal to the core and cannot be measured directly.

Approximating the currents.



The test core is T80/40/20, as shown on the right.

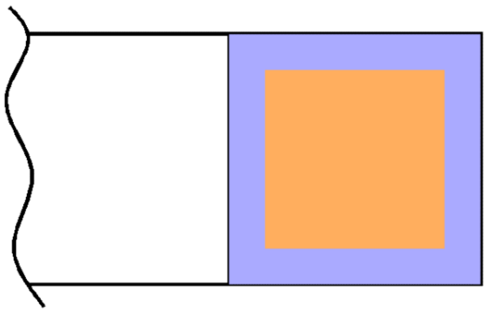
We machine three special cores of smaller section, corresponding to the inner sections of the test core.

A T74.3/45.7/14.3 core is the size of the orange section.

A T68.6/51.4/8.6 core is the size of the gray setion.

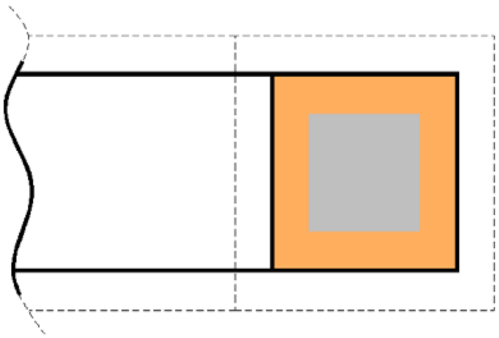
A T62.9/57.1/2.9 core is the size of the red section, the center.

Approximating the currents



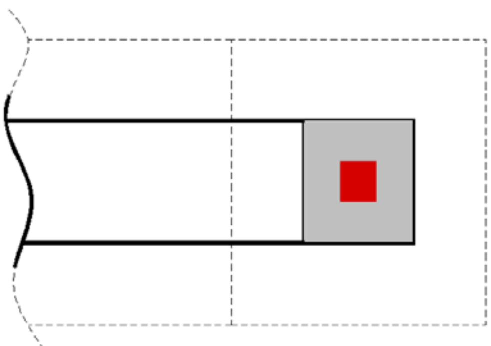
The first step is to apply the excitation to the test core and measure the input current i0 as the excitation current, expressed in ampere-turns.

Next, a core of the same material is machined to the dimensions of the orange segment. This is a T74.3/45.7/14.3 core.



An excitation winding is wound on this smaller core, and it is excited with a voltage equal to v2 volts per turn, with reference to the v2 measured in the test core.

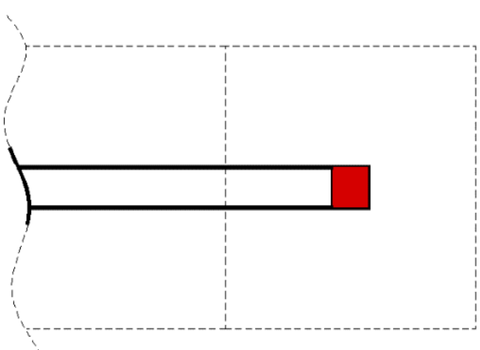
Measure the excitation current in the excitation winding, expressed in ampere turns. This current equals the sum of the currents i2 + i3 + i4. The current i1 can be solved by subtracting this sum from i0, that is,
i1 = i0 – i2 – i3 – i4.



Another core of the same material is then machined to the dimensions of the gray segment. This is a T68.6/51.4/8.6 core.

An excitation winding is wound on this smaller core, and it is excited with a voltage equal to v3 volts per turn.

Measure the excitation current in the excitation winding, as ampere turns. This equals the sum of the currents i3 + i4. The current i2 can be solved by subtracting this sum from i0 – i1, that is,
i2 = i0 – i1 – i3 – i4.



This operation can be repeated one more time to make a core having the dimensions of the red segment. This core is T62.9/57.1/2.9.

Apply an excitation winding of v4 volts per turn. The current i4 is measured.

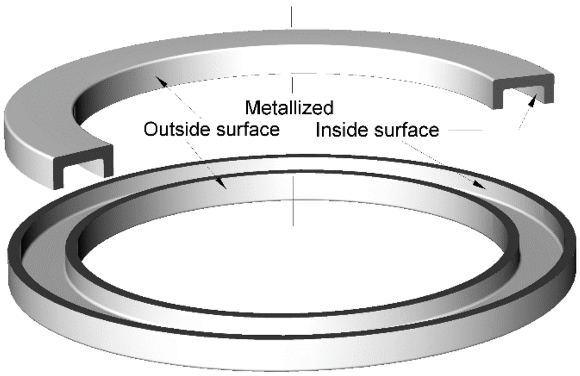
In this way, we can approximate the unmeasurable internal currents of the test core.

Shell capacitance

This test has not yet been done

The series impedances z1-2, z2-3, z3-4 may be related to the capacitance through the respective shells.

This can be measured if a hollowed-out core is metalized on its outside and inside surfaces as shown below, and the capacitance between the surfaces is measured.



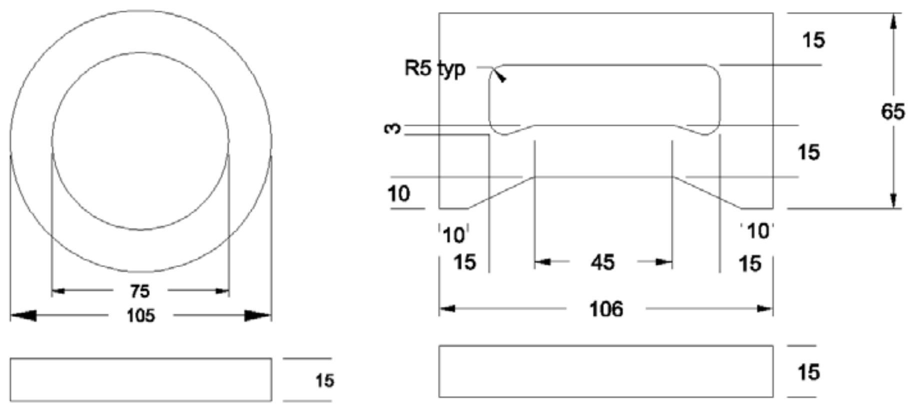
We planned to make a hollowed-out core to test its losses. One half could be metallized, or, preferably, we could make an extra half core and metallize it as shown above. NOTE: The bottom core above picture is the proposed core. The top core in the picture is only to show the cross-section.

Since only half of the shell is represented, the capacitance should be doubled to represent the shell capacitance for a whole core.

7. Machined cores of the same size but different material

Last year, PSMA approved a special project for Fair-Rite to machine eight special cores of four materials and second special project for SMA to do tests on the cores (Phase I). One core of each material is a large diameter toroid, and the second is a special design with straight legs so the effect of varying reluctance with radius is eliminated where the flux is measured.

Two sets were MnZn ferrite, and two were NiZn ferrite. We will have a fifth set from Fair-Rite of a new material 80 that has characteristics that fall between MnZn and NiZn when comparing their B*f curves (a figure of merit).



The recognized parameters of MnZn and NiZn cores are very different, yet for both the transition from inductive to very lossy has a very similar appearance, graphically, except that NiZn transitions about a decade higher in frequency.

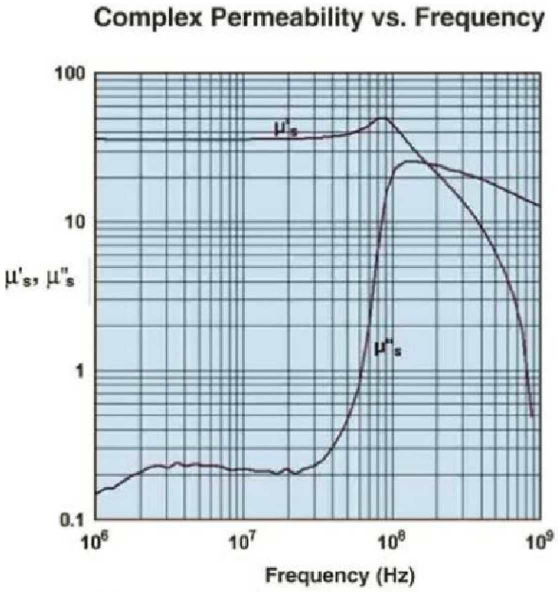
The explanation for this similarity is elusive, as NiZn has a much higher resistivity and much lower permittivity. After the break, the downslope of the μ' curve is slower for the NiZn, but then it falls rapidly about a decade higher in frequency. We wonder if NiZn may transition to be more similar to MnZn at high frequency than published parameters would suggest.

We have not done much testing on NiZn yet, because the higher frequency will require higher bandwidth test equipment.

An important part of this effort is to find practical test procedures for core catalog data and production tests to characterize flux propagation and eddy currents.

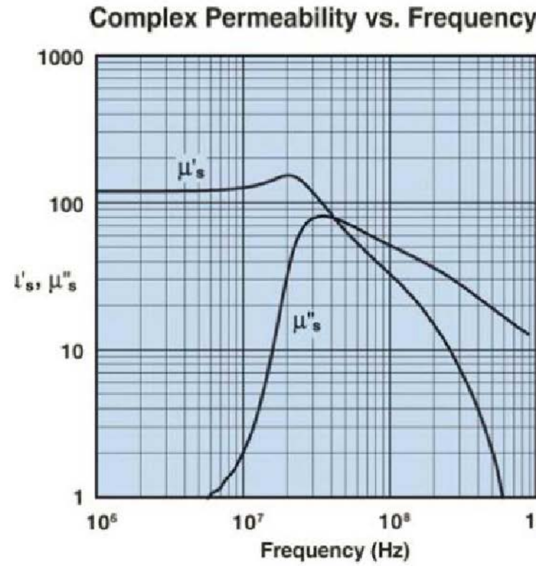
With my encouragement, these tests were put aside in Phase I to work on a Large Core Test as described above.

67



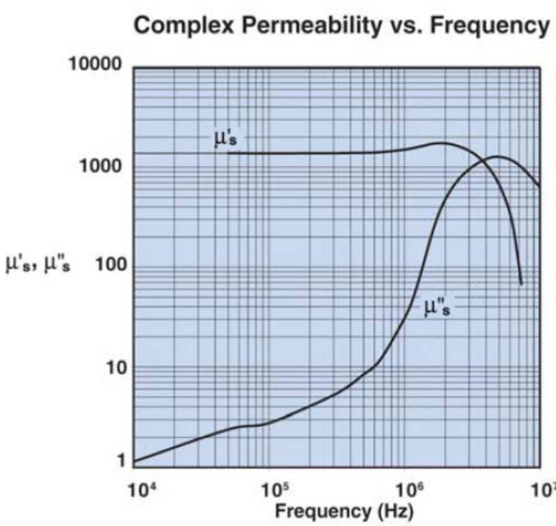
Measured on an 19/10/6mm toroid using the HP 4284A and the HP 4291A.

61

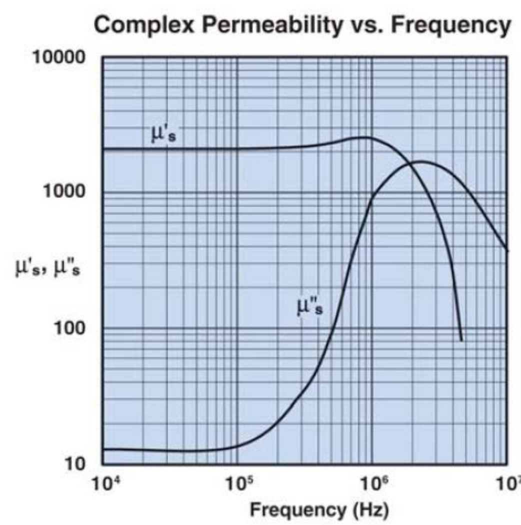


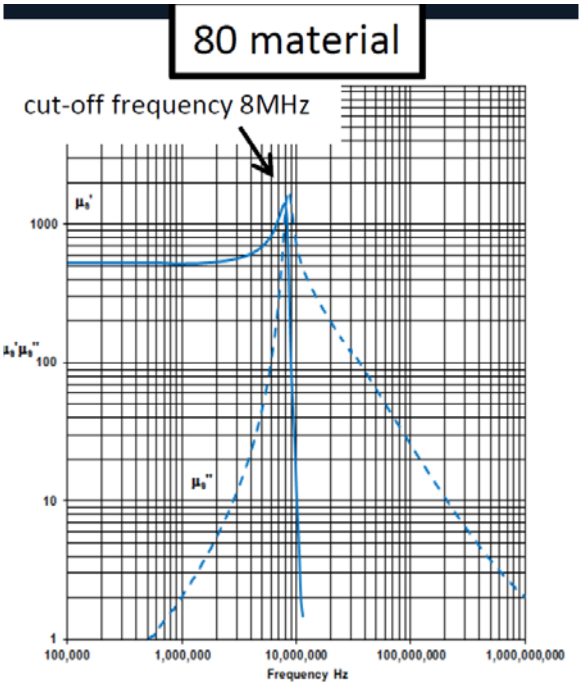
Measured on a 19/10/6mm toroid using the HP 4284A and the HP 4291A.

79



78




80 material
cut-off frequency 8MHz
μ_s'
$\mu_s'\mu_s''$
μ_s''
1000
100
10
1
100,000
1,000,000
10,000,000
100,000,000
1,000,000,000
Frequency Hz