Waveforms for Stimulating Magnetic Cores

My assigned topic is test waveforms for magnetic cores, but I'm going to provide a little background, which touches on topics covered by other presenters here:

1) The need for empirical data; there are no remotely adequate theories for predicting magnetic core losses from a few basic measurements.

2) Difficulties in obtaining good data; the results of 1990-1992 round robin tests.

3) Waveforms for testing; with relevant alternatives to the sine wave.

4) A quick survey of some available core loss test methods.

5) Testing ac losses under dc bias; general loss increases, and magnetomechanical resonance losses and related effects.

6) Additional research required; "bulk" eddy current losses in large MnZn ferrite cores.

BRUCE CARSTEN ASSOCIATES
Power Conversion Consulting & Research

The Need for Empirical Data

Unlike eddy current losses in conductors, ferromagnetic characteristics are *moderately to highly non-linear*.

These ferromagnetic characteristics (permeability, loss, saturation) can vary dramatically from one material to another, and with:

1) Flux density (loss not $\propto B^2$)
2) Frequency (loss not $\propto f$)
3) Temperature
4) Excitation voltage waveform

Difficulties in Obtaining Good Data

Ferromagnetic cores are by nature 'inductive'.

Flux sense winding voltage and excitation current can approach 90° out of phase, leading to large wattmeter errors.

There can be significant phase shift errors between voltage and current.

Excitation current can be distorted.

Variations with temperature can be large, and core self-heating can be an issue.

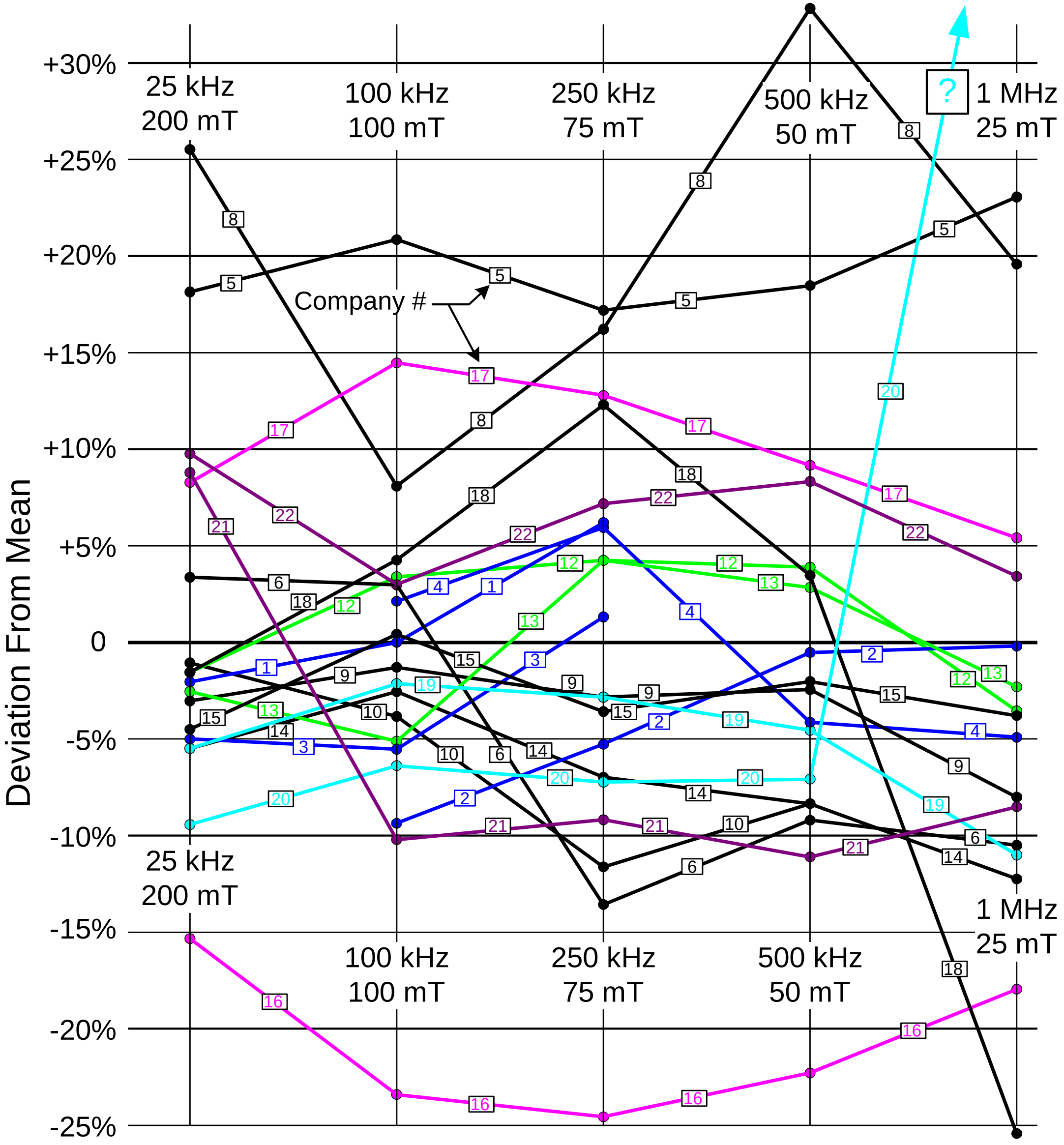
Excitation winding losses are included with some measurement methods.

These problems are illustrated by the results of Round Robin tests of two Magnetics "P" material toroidal cores in 1990 - 1992

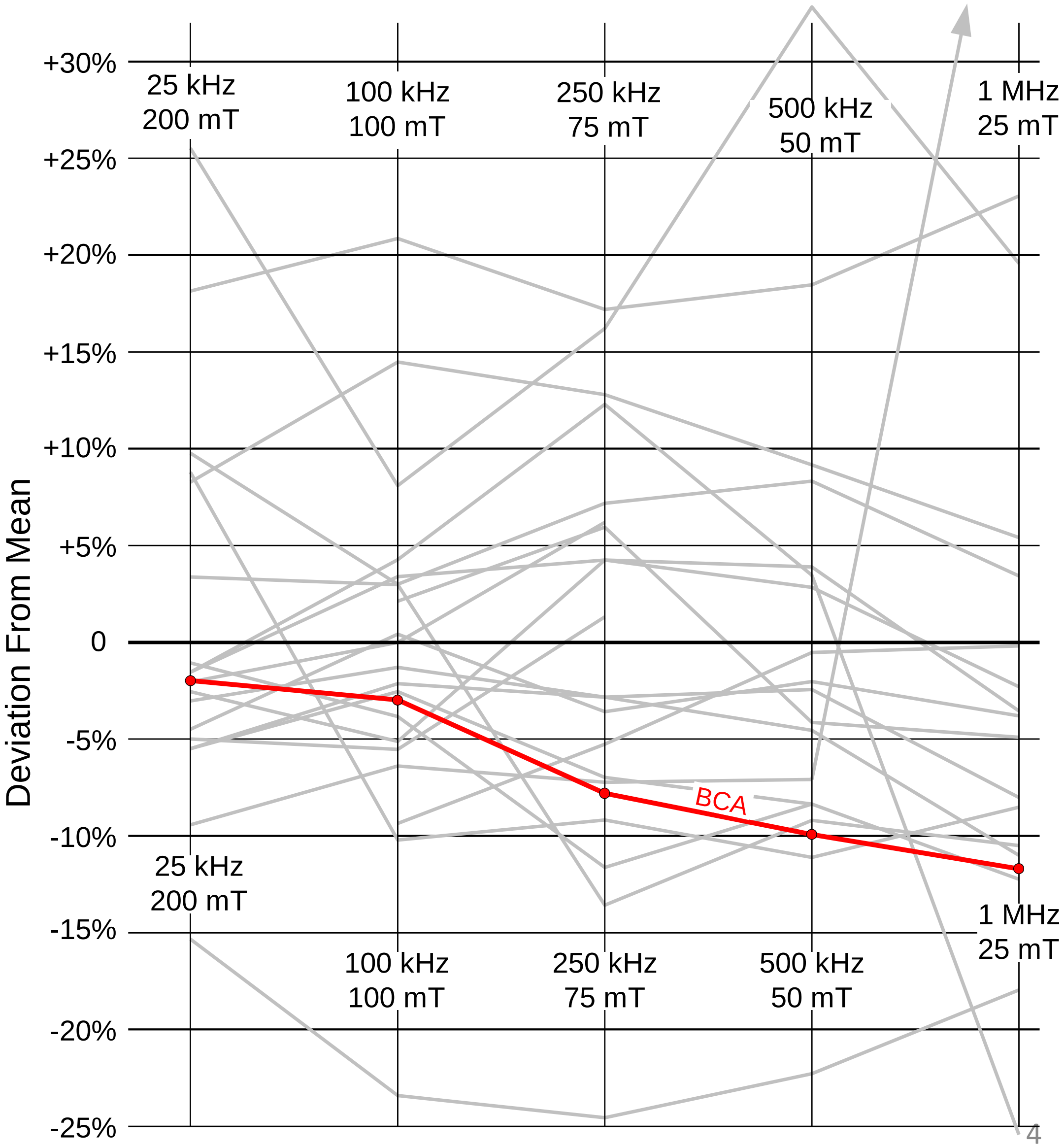
Round Robin Core Loss Testing, Magnetics "P" Cores

Deviation From Mean of 20 Measurements; Toroid #1

(Multiple tests by the same company are in the same color)

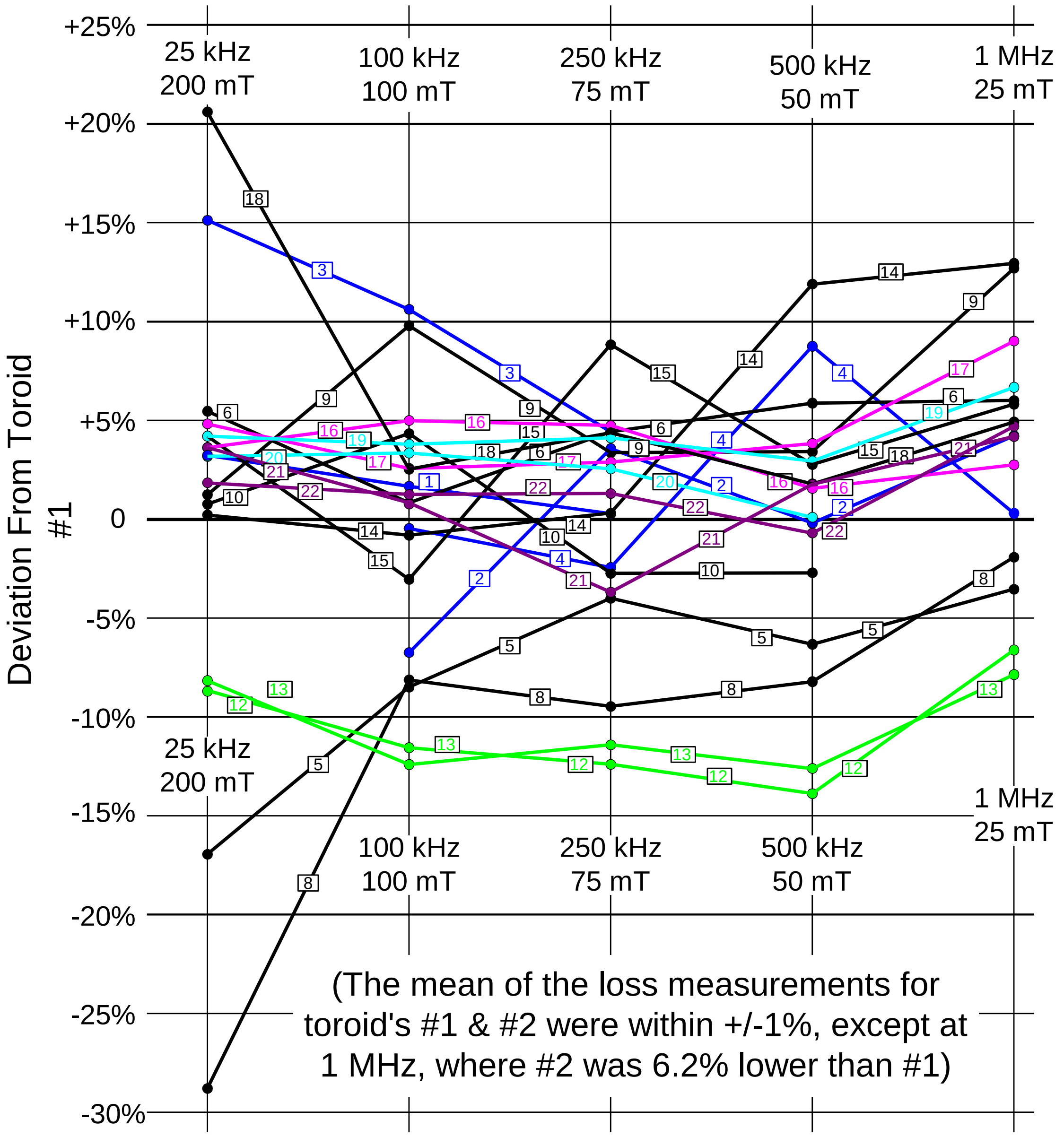


Comparison of BCA Sine Wave Data with Mean of Round Robin Tests, Toroid #1



Round Robin Core Loss Testing, Magnetics "P" Cores

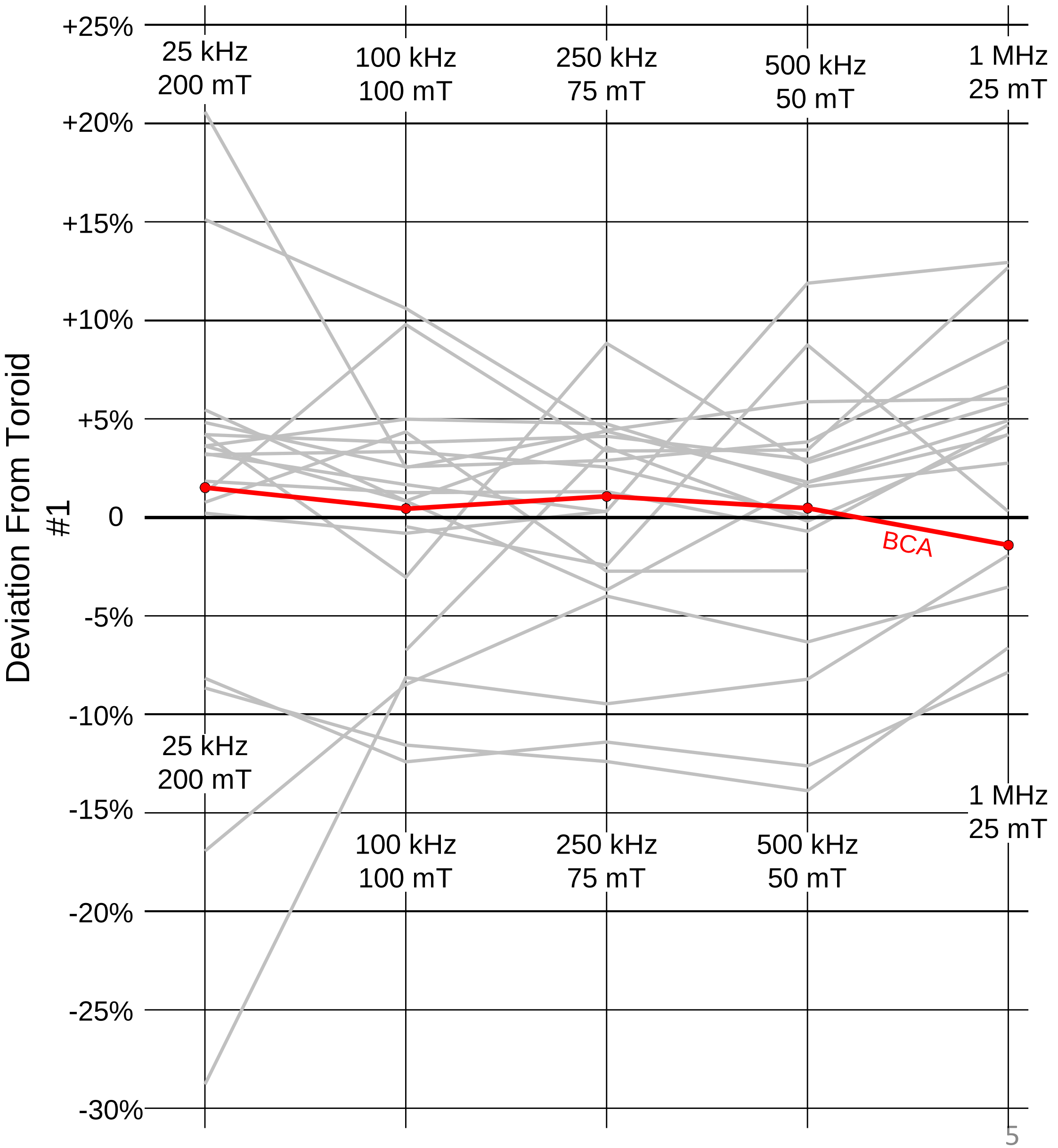
Deviation of Toroid #2 from Toroid #1



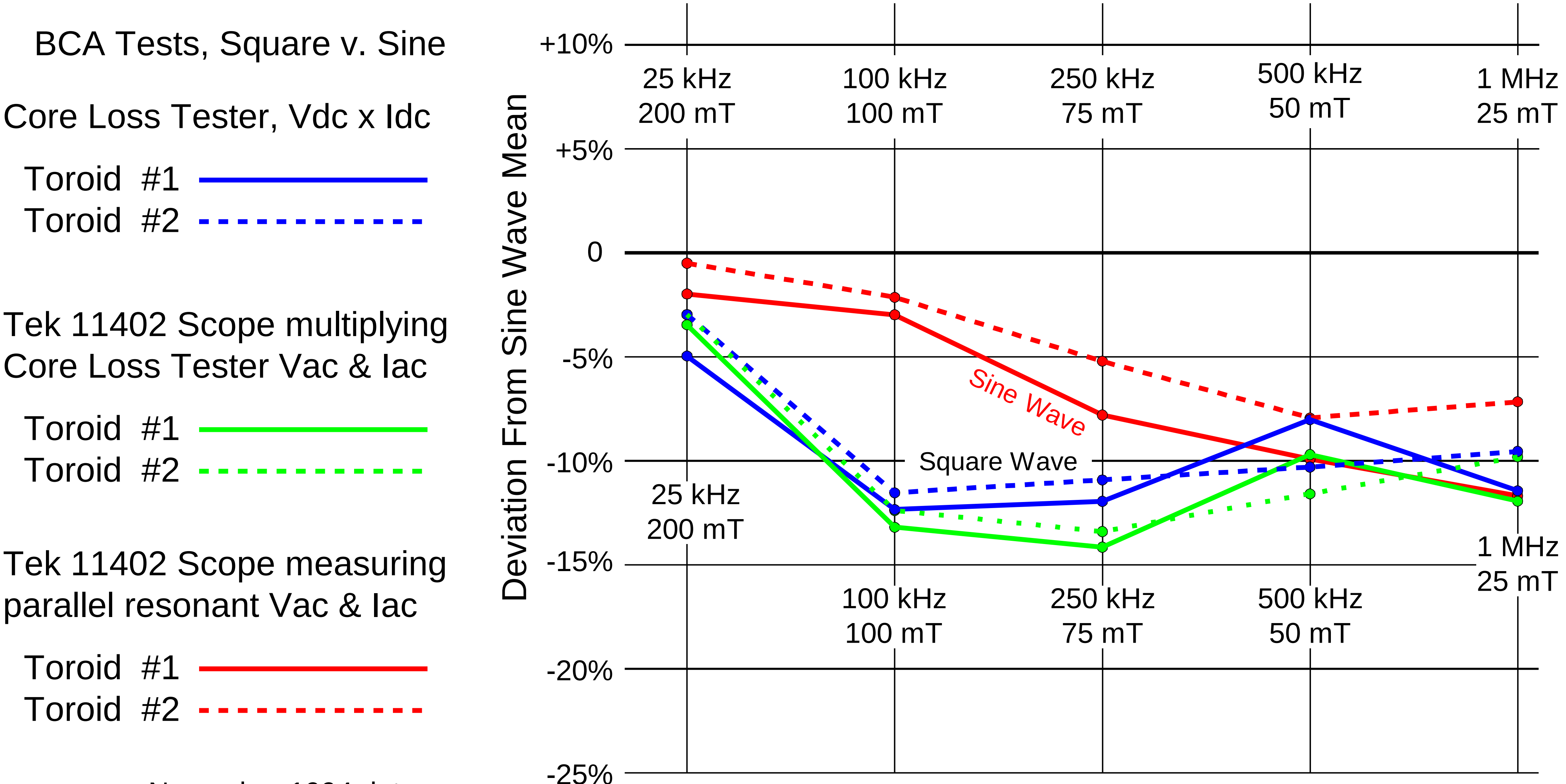
(The mean of the loss measurements for toroid's #1 & #2 were within +/-1%, except at 1 MHz, where #2 was 6.2% lower than #1)

Comparison of BCA Sine Wave Data,

Deviation of Toroid #2 from Toroid #1

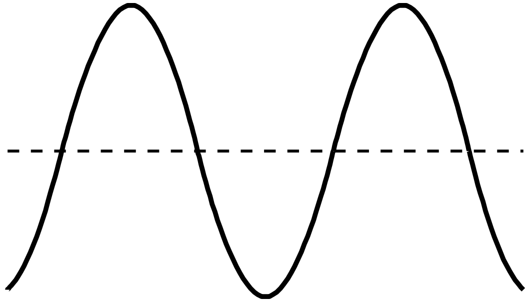


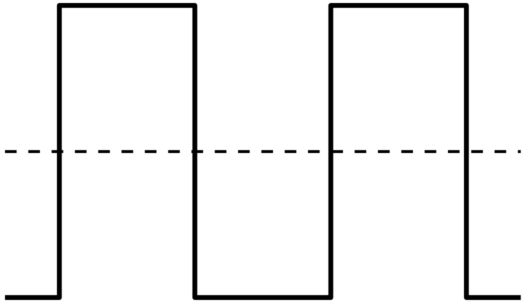
The Steinmetz formula is inadequate for several reasons; among others,the waveform matters:

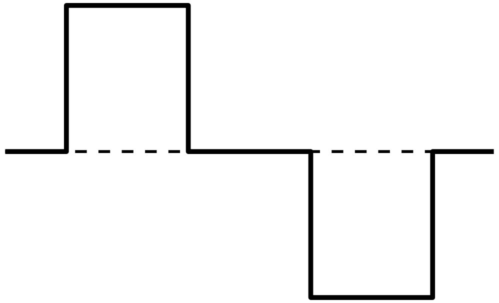


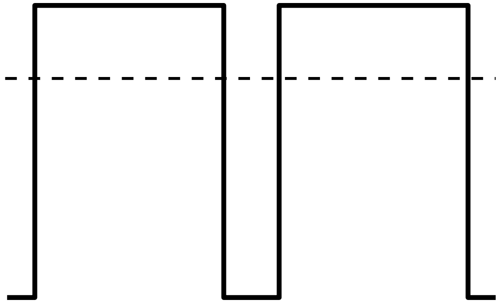
November 1994 data

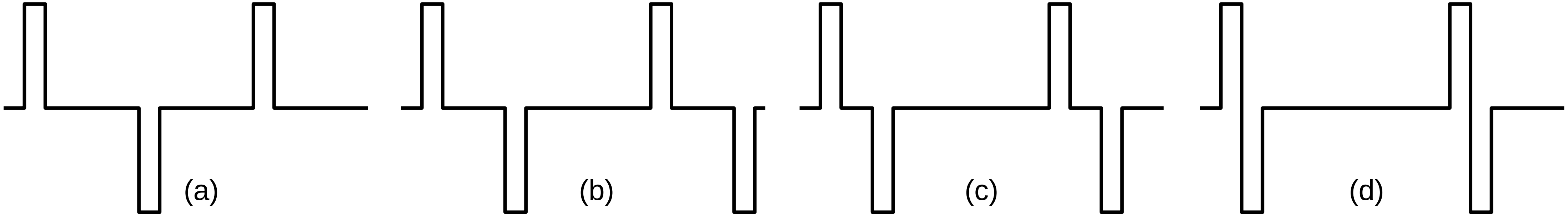
Voltage Drive Test Waveforms for Measurement of Core Losses


Legacy Sine


Square


Symmetric Bipolar pulse,
Variable Duty Cycle D


Rectangular


(a) (b) (c) (d)

Symmetric to Increasingly Asymmetric Delay Bipolar Pulses, Low D

Note that waveform (d) can occur in the inductor of various "soft switching" converters

Available Ferromagnetic Core Loss Methods

1) B-H Loop
2) Wattmeter
3) Impedance
4) Calorimetric
5) L-C Resonance with low loss capacitor
6) High Efficiency Square Wave Driver (adaptable to bipolar pulse wave)
(7) Capacative Cancellation of Bsense Inductive Voltage
8) Negative Mutual Inductance (-Lm) Cancellation of Bsense Inductive Voltage

First, a Quick Survey of the Methods, with Some Pros and Cons at HF

Note: methods 4 to 8 avoid the need for a low phase shift measurement of excitation current, although methods 4, 5 & 6 do include drive or excitation winding losses, which are typically not significant with higher permeability ferrite cores.

(1) B-H Loop Measurement

This classical "graphical" method integrates the sense winding voltage to obtain "B", which is used to plot the B-H loop. Among other information, the core loss can be measured as the area within the B-H loop of a Core Under Test (CUT).

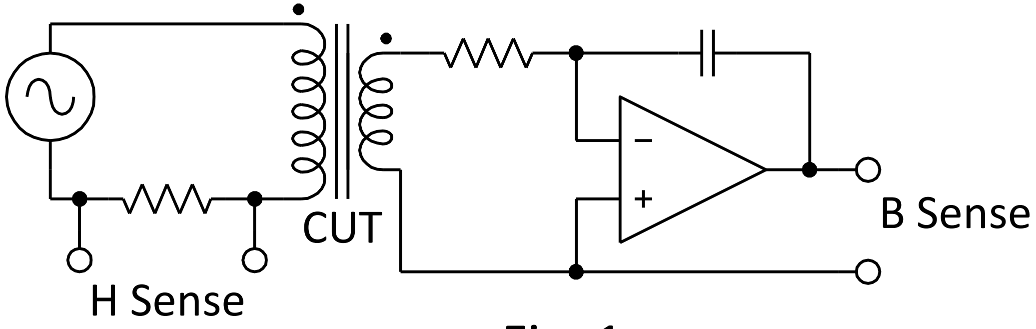


Fig. 1a

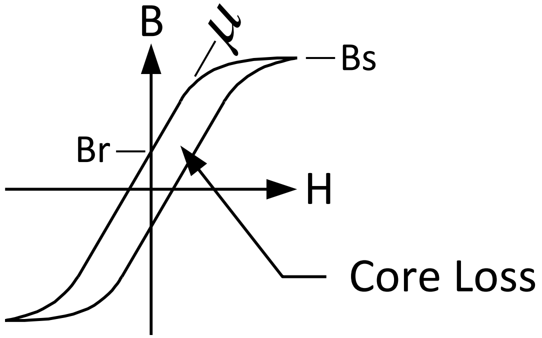


Fig. 1b

Pro: Can also be used to measure Bs, Br, and μ

Con: Requires a precision integrator
B-H loop area *still* needs to be measured
Full excitation V-A must be supplied by the driver

(2) Wattmeter Measurement

The drive current and sense winding voltage are multiplied and averaged. Suitably scaled by the winding turns ratio, the power loss is obtained

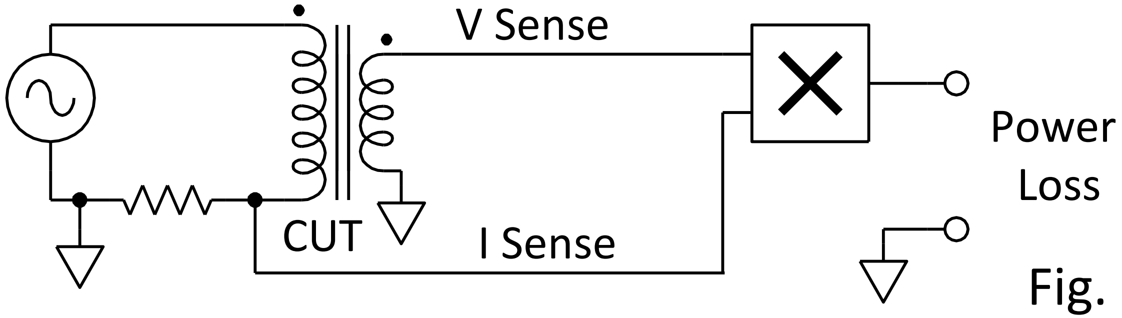


Fig. 2

Pro: Ideally, measures core loss directly

Con: Requires a precision wattmeter, increasingly difficult at higher frequencies
Requires current sensing with minimal phase shift from voltage sensing
Full excitation V-A must be supplied by the driver

The phase shift problem becomes more severe at higher frequencies, particularly with low perm, low loss cores. For example, assume a core loss "Q" of 200; the voltage and current will have a phase angle of 89.714°, or 0.286° less than 90°. At 1 MHz, this is only 800 ps; a time/phase difference of 80 ps in V and I represents a 10% loss error.

(3) Impedance Measurement

Impedance is measured as V/I, providing Z and θ. Impedance meters are designed to operate at higher frequencies than "V x I" wattmeters, to 1 GHz or more.

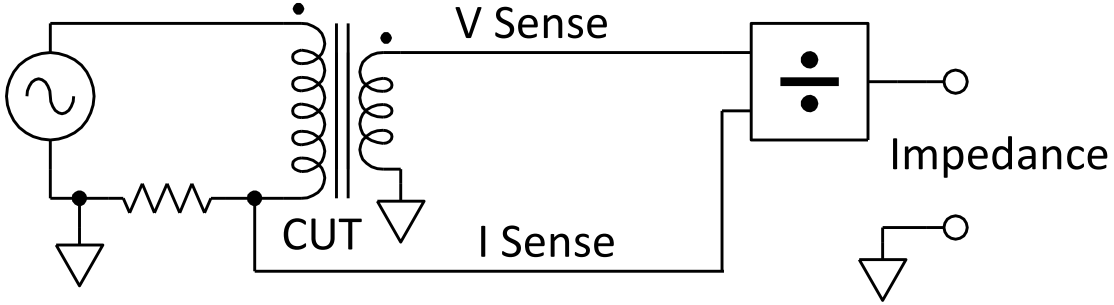


Fig. 3

Pro: In principle, core loss can be derived from Z, θ and V or I
Impedance changes only slowly with excitation level

Con: Most impedance meters supply their own excitation, at a low signal level
Requires current sensing with minimal phase shift from voltage sensing
Full excitation V-A must be supplied by the driver

(4a) Calorimetric Measurement 1

The core is placed in a thermally isolated bath (typically a vacuum bottle), and the temperature rise with time measured to establish rate of heat generation.

Pro: Classical, going back at least to Joule's 1845 measurement of the heat equivalent of work.

Con:
- Slow, very time consuming
- Technically very difficult to minimize errors
- Winding losses measured along with core losses
- Eddy current losses can occur in a water bath
- Dielectric losses can occur in an oil bath
- Full excitation V-A must be supplied by the driver

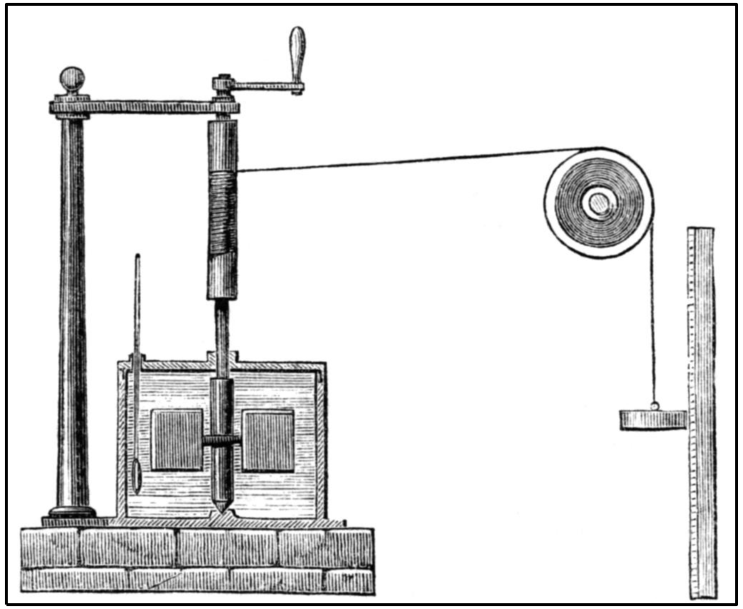


Fig. 4

Joule's apparatus for measuring the mechanical equivalent of heat

Joule's value: 4.155 J/cal, changed to 4.186 J/cal in 1920 (impressively accurate work)

(4b) Calorimetric Measurement 2

In principle, the winding loss (and bath loss) problems can be overcome by operating the core in a vacuum, with the winding thermally isolated from the core, and measuring the temperature rise of only the core with time

Pro: Overcomes many error sources in the classical method

With enough power loss, and a fast temperature rise, the method may work well enough in still air.

Con: Still fairly slow

The core temperature will need to be "reset" between measurements, slowing down measurements further

Full excitation V-A must be supplied by the driver, unless a resonant capacitor is used

(5) L - C Resonance Measurement

High driver V-A requirements, and the phase angle problem, can be overcome by resonating the CUT with a low loss capacitor.

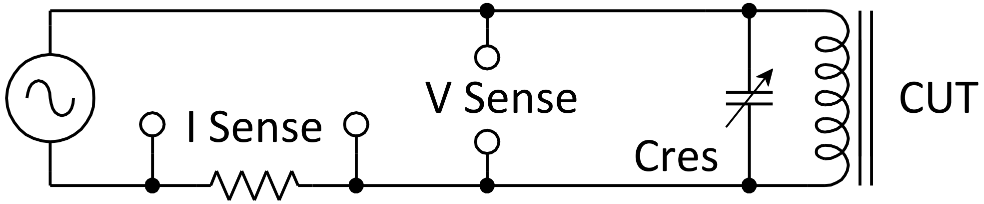


Fig. 5

Pro: A simple measurement, requiring little equipment

Eliminates the "phase angle" problem

Only the core loss needs to be supplied by the driver

Can be used above 1 MHz

Con: Only suitable for higher perm cores, where winding losses are minimal

The resonating capacitance value changes dramatically with frequency, and even with flux density; it's difficult to measure core loss at a desired frequency

Difficult to find the large low loss capacitors needed at lower frequencies

(6) High Efficiency Square Wave Driver

Core loss can sometimes be measured by driving the excitation winding with a very high efficiency half or full bridge "chopper" circuit, allowing core losses to be measured as the dc input power. FET conduction losses are minimized with large, low resistance FETs, and switching losses largely eliminated with "zero voltage switching"(ZVS).

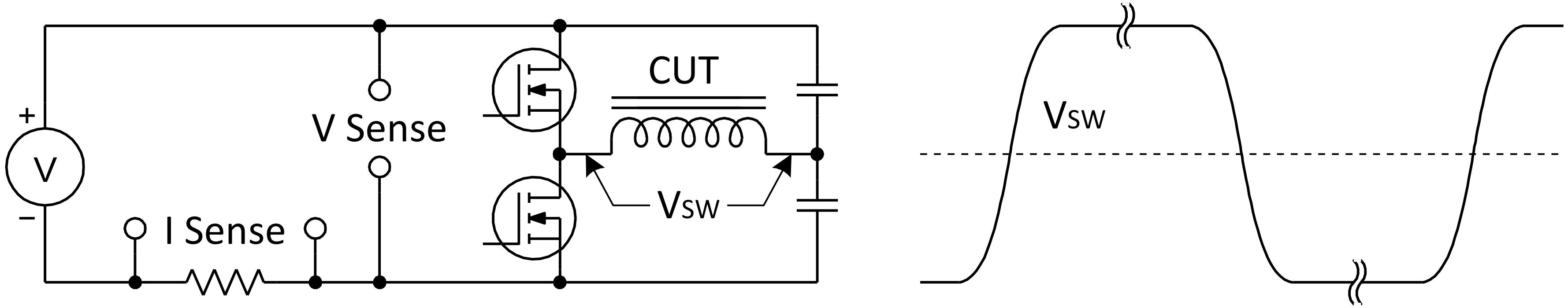


Fig. 6

Pro: Eliminates the "phase angle" problem, with power measured at dc
Only the core loss needs to be supplied by the driver
Core loss can be quickly measured over a wide range of B and f

Con: Only suitable for higher perm cores, where winding losses are minimal
With high perm cores, upper frequency limited to about 1 MHz for ZVS
Can only measure loss with square wave (or bipolar pulse) excitation

(7) Capacative Cancellation of Bsense Inductive Voltage

The sense winding's inductive component can in principle be removed with a low loss series resonant capacitor (may need verification)

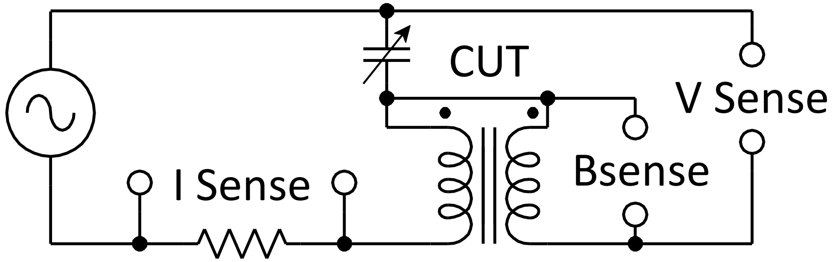


Fig. 7

Pro: A simple measurement, requiring little equipment

Removes winding losses from the measurement

Eliminates the "phase angle" problem

Only the core loss needs to be supplied by the driver

Can be used above 1 MHz

Con: The resonating capacitance value changes dramatically with frequency, and even with flux density; it's difficult to measure core loss at a desired frequency

Difficult to find the large low loss capacitors needed at lower frequencies

Difficult to measure the Q of very low loss capacitors at high frequencies

(8) -Lm Cancellation of Bsense Inductive Voltage

The sense winding's inductive component can *in principle* be removed with a "negative mutual inductance". (Ideally, the mutual inductor's winding resistances do not affect the 90º phase shift between the primary current and *unloaded* secondary voltage.)

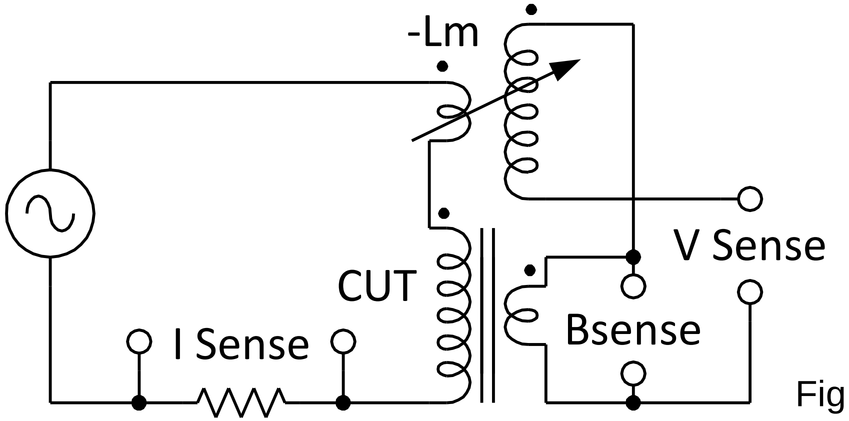


Fig. 8

Pro: A relatively simple measurement in principle, requiring little equipment
Removes winding losses from the measurement
Eliminates the "phase angle" problem
Can be used above 1 MHz

Con: -Lm needs to be adjustable, but not over a wide range with frequency;
-Lm needs to be of very high"purity", with the secondary voltage very close to leading the primary current by 90º; a bit of a technical tour-de-force
The full excitation V-A needs to be supplied (more on that later)

Increase of ac Core Losses under dc Bias

AC core losses are known to increase under dc bias, but by how much?

A Bdc bias is more relevant than an Hdc bias, particularly for inductors, but is not as easy to establish.

My 2006 measurements showed a huge increase (Fig. 13), but later Craig Baguley and I found much lower effects (Fig. 5) in the same material with different loss and bias measurement techniques.

Why is this?

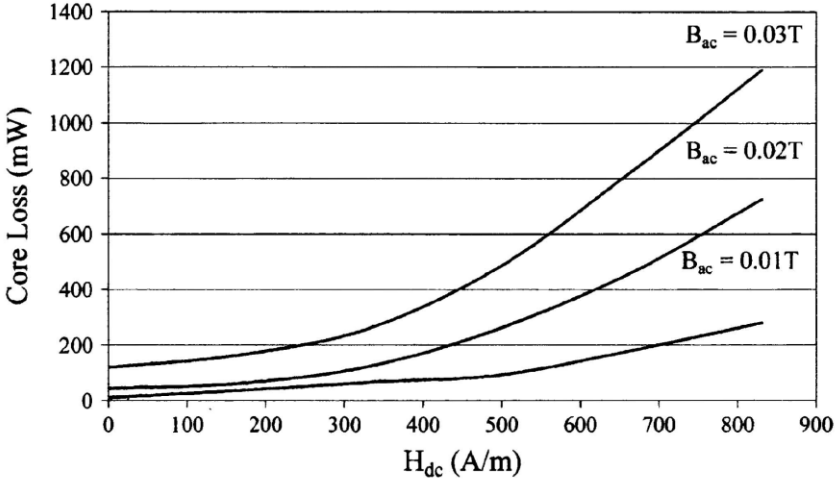


Fig. 5. Core loss measurements made under dc bias conditions.

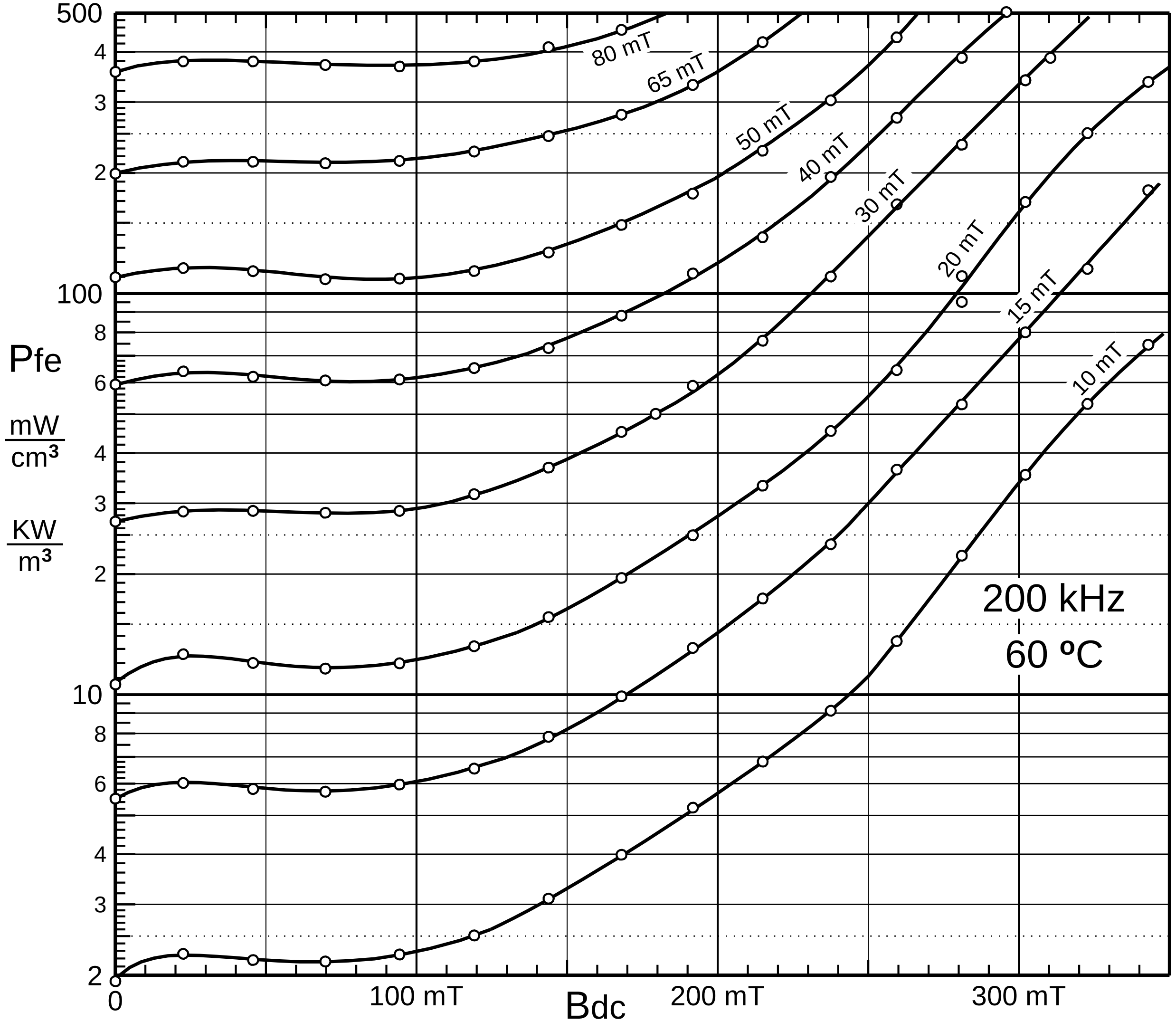


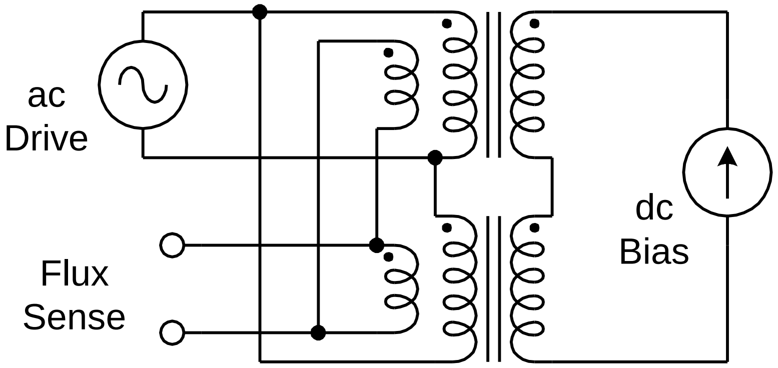
Fig. 13

F49 Core Loss v. dc Flux

Applying a dc Bias to Core Flux

There are two alternatives for applying a dc bias to test cores.

Two "identical" cores with two windings can be used:

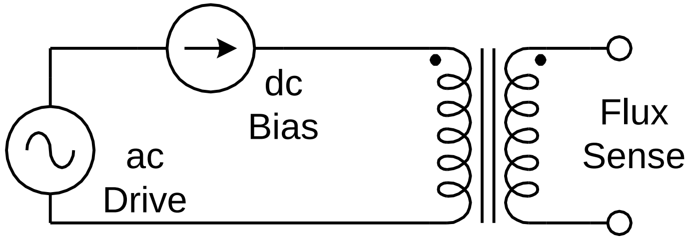


The excitation voltage is applied to the two "ac" windings in "anti-parallel" so that they have the same ac flux, while a current is applied to the "dc" windings in series so that they have the same "H" field. This configuration ideally cancels the ac voltage applied to the dc current source.

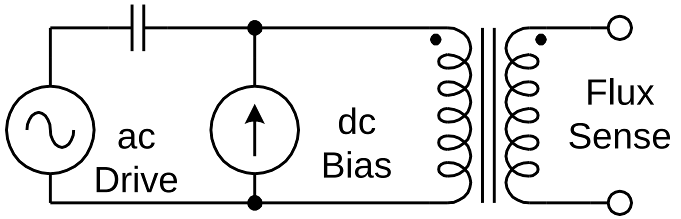
Typically ac windings are placed on each of two toroids, with a single dc winding around both.

Or an ac voltage & a dc current can be supplied to one winding on a single core, from a single source, or paralleled or series connected sources:

(a)



(b)

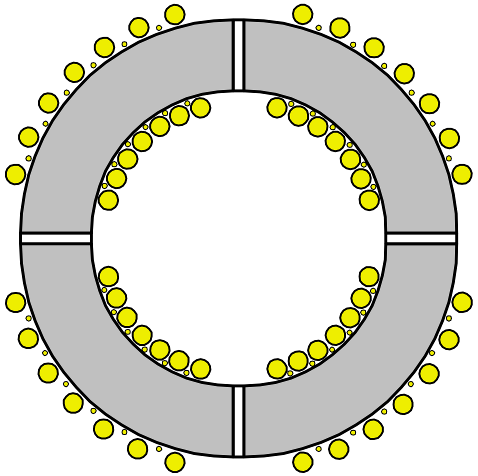


This typically requires that either the ac voltage source provide the dc current, or conduct the dc current from a separate source (a), or that the dc source have sufficient "compliance" for the ac voltage applied to the winding.

Applying a B_{DC} Instead of an H_{DC} Bias to a Core

Again, there are two alternatives for this:

One or more core air gaps can be used, sufficient that B_{DC} does not vary appreciably with core permeability:

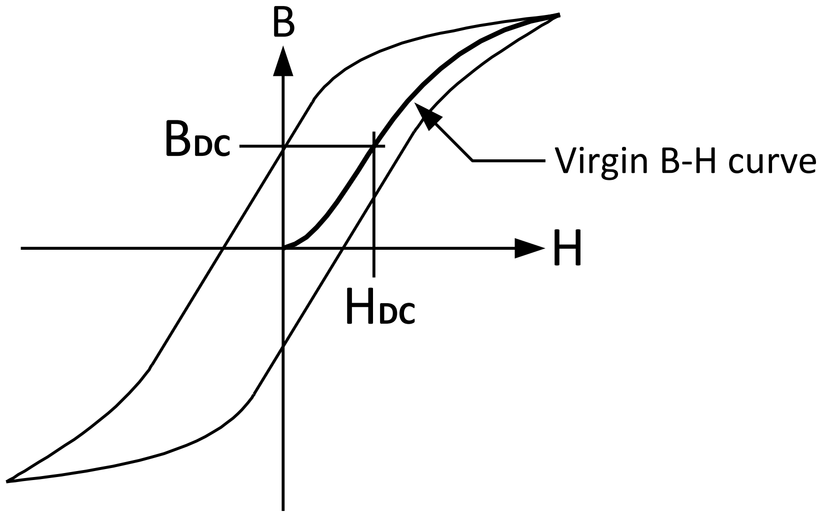


1) Multiple air gaps are recommended to minimize fringing around air gaps (non-uniform core flux)

2) Windings should be kept back from air gaps (fringe field induced winding losses)

3) A very rigid or hard material (e.g., ceramic) should be used in the air gaps should be used to minimize viscoelastic losses (explained later).

Alternatively (and preferably), the virgin magnetization curve of a fully demagnetized core can be measured, establishing the B vs. H relationship for the core:



Then, *after each demagnetization*, a monotonic rise to a given H_{DC} establishes a known B_{DC}, without the air gap problems of fringe fields, high magnetizing currents, and near 90° phase angle between V & I.

Measuring the Virgin B-H Curve

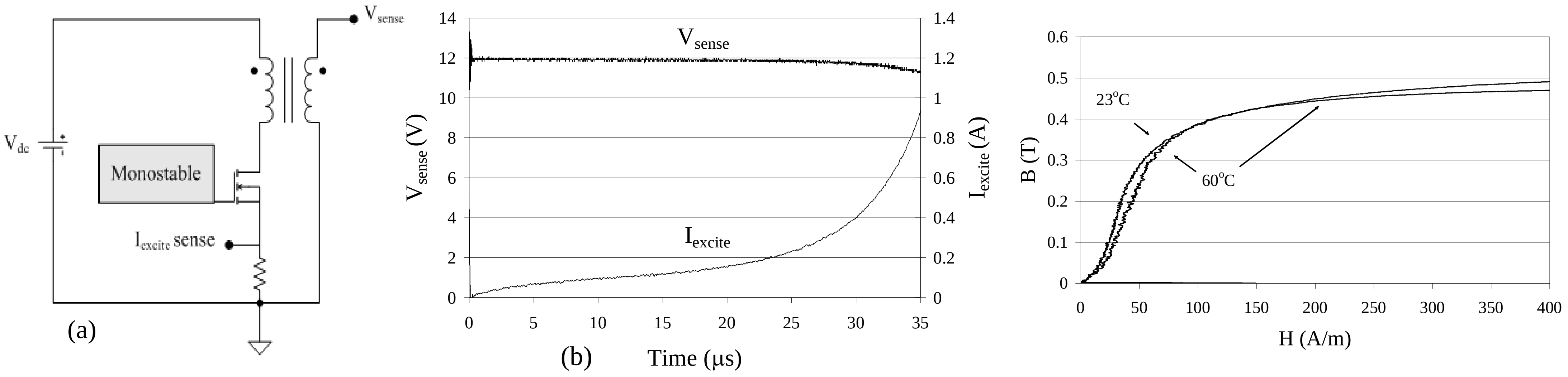


Fig. 1

(a) The magnetization curve measurement circuit,

(b) measured V_{sense} and I_{excite} waveforms,

(c) magnetization curves measured at 23 ^{O}C and 60 ^{O}C.

Figures in this and the next 2 slides extracted from papers by C. Baguley, U. Madawala (Univ. of Auckland) and B. Carsten

Loss Peaking at Certain Frequencies, Increasing with dc Bias

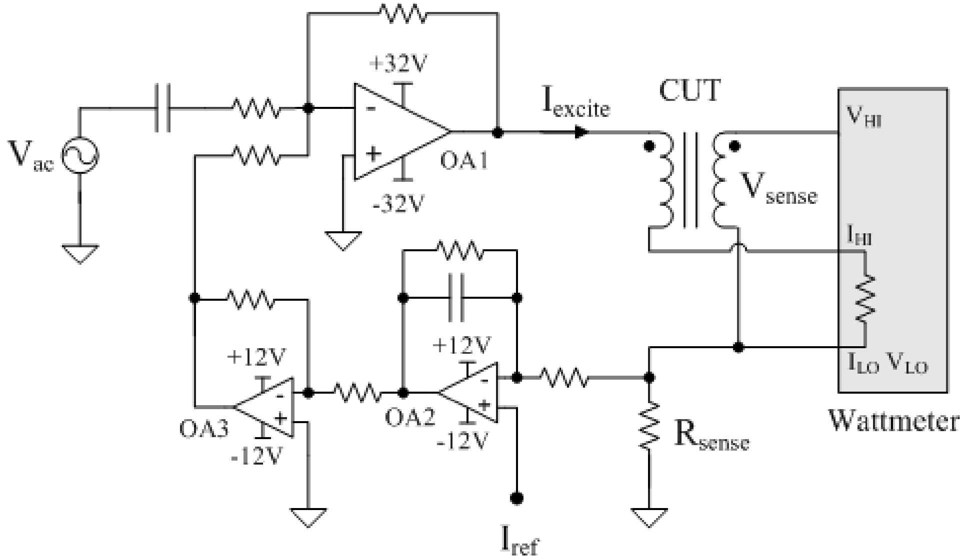


Fig. 2. The core loss test circuit schematic

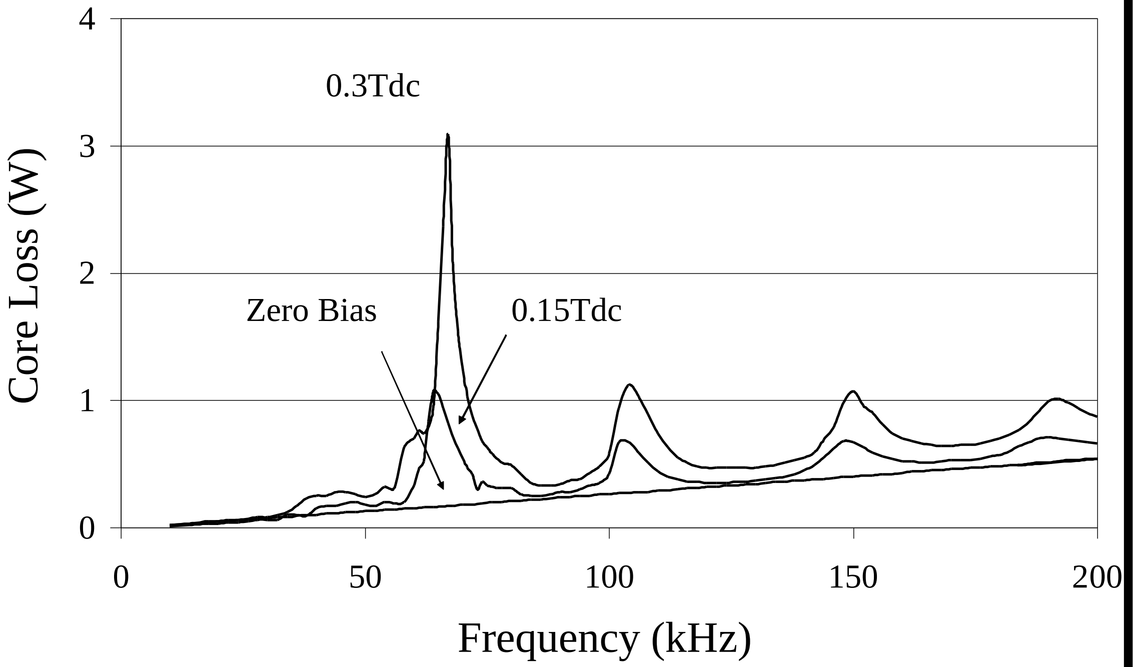


Fig. 8 (a) The variation in core loss with dc bias and frequency for a 30x18x6 toroid

Our Explanation: Magnetomechanical Resonance

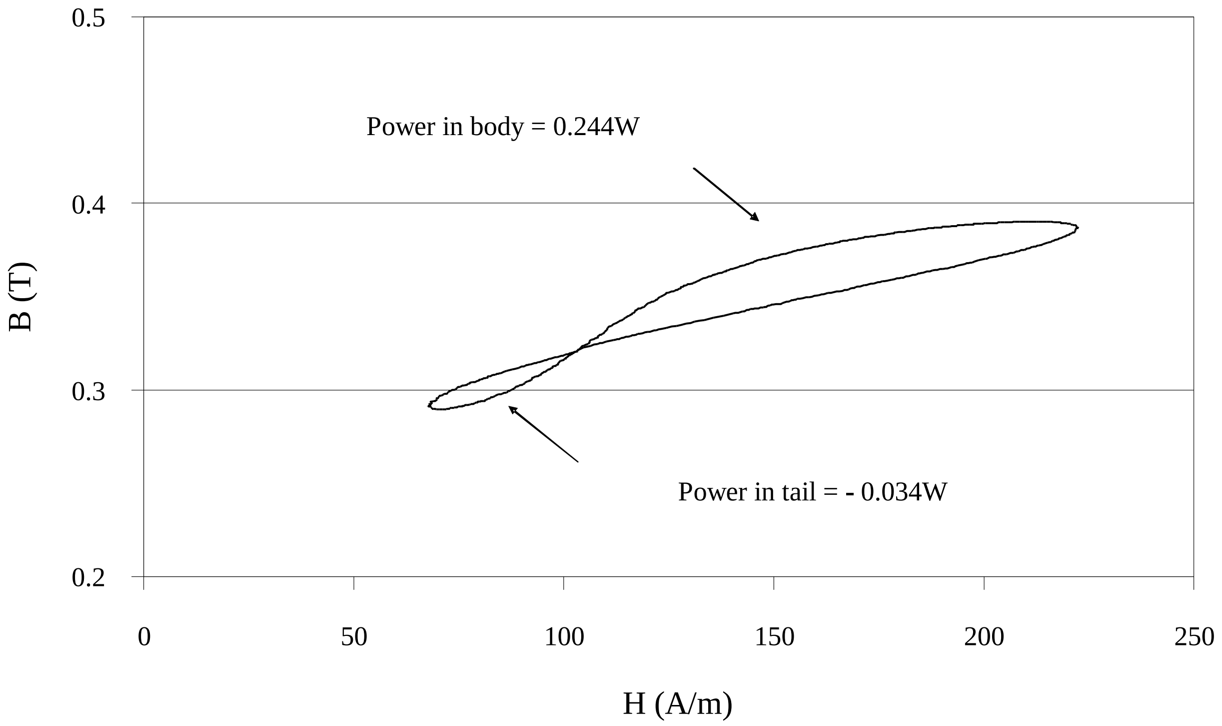
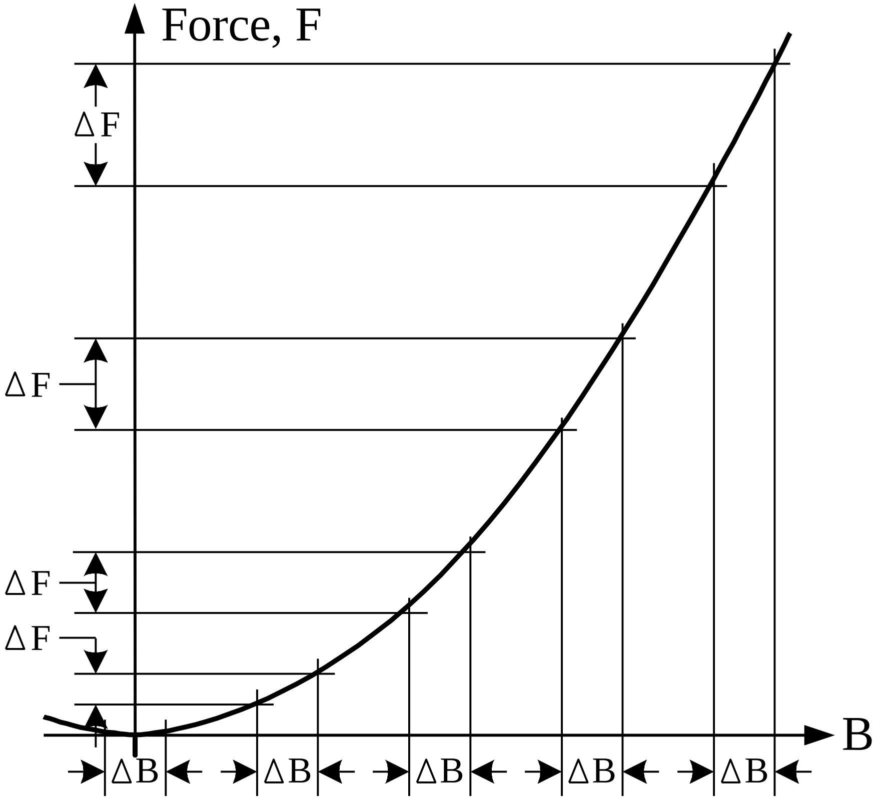


Fig. 11 (a) measured BH loop at 34.8 kHz, 0.35 Tdc



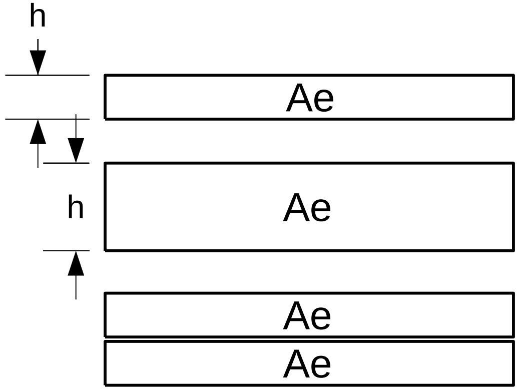
Core ac Force $\Delta F \propto \Delta B^2$

I strongly suspect that the excess core losses I measured in 2006 (slide 18, Fig. 13) were <u>viscoelastic losses</u> in the polyester-fiberglass "air gaps" used.

"Bulk" Eddy Currents in Larger MnZn Ferrite Cores

1) Eddy currents are induced in a conductive material by a changing magnetic field, inducing a voltage around a closed path with $V \propto d\Phi/dt$, or $\propto Ae \bullet Bac \bullet f$.
2) The eddy current loss/volume in ferrites is assumed constant, **but**:
3) Such an eddy current *cannot* be flowing thorough the "bulk" of the material, but must be around the moving domain walls *within each ferrite grain.*

Bulk eddy current loss in a sheet or lamination vary as the cube of thickness "h":



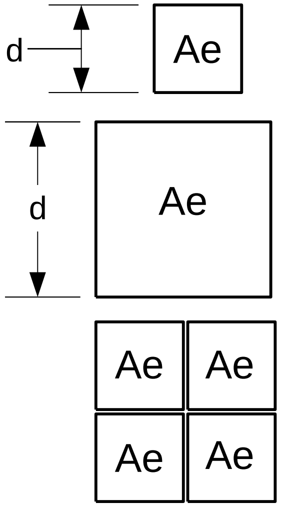
Relative Loss = 1

Relative Loss = 8

Relative Loss = 2

In either case, the eddy current loss/volume varies as Ae^2

While those in a round or square material vary as the fourth power of the diameter or width "d":



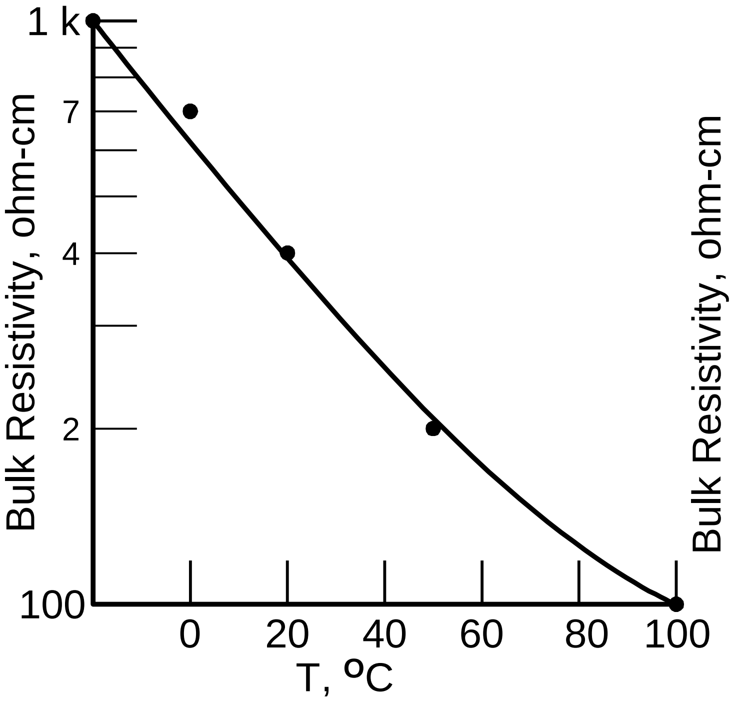
Relative Loss = 1

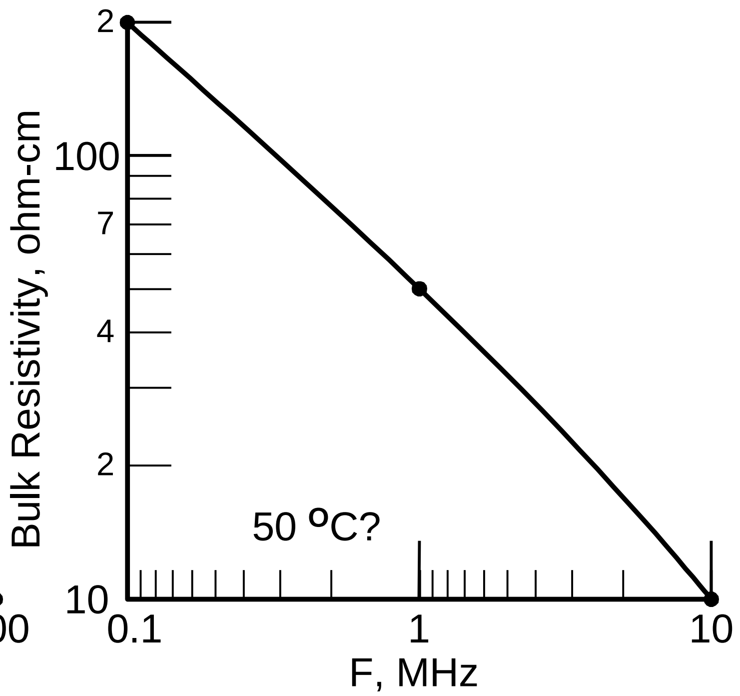
Relative Loss = 16

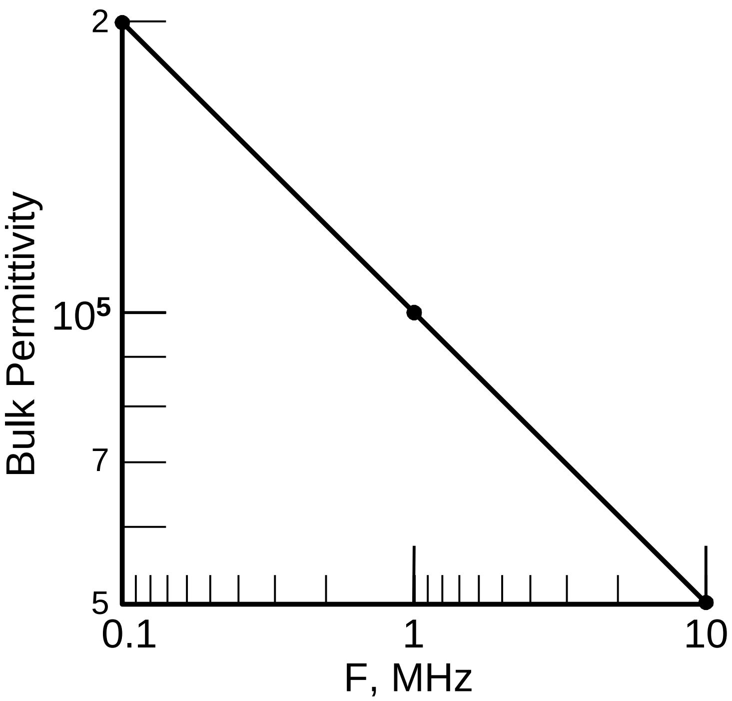
Relative Loss = 4

The Approximate Conductivity and Permittivity of MnZn Ferrites

Per the 2013 Ferroxcube Catalog





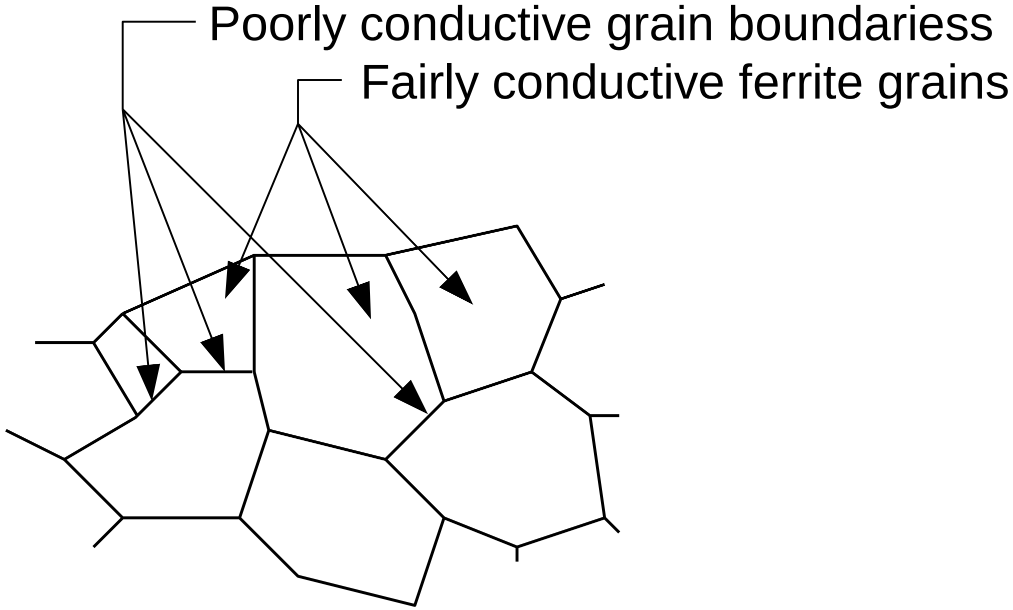


It would be interesting to measure the impedance and loss tangent of representative power ferrites as a function of frequency (and temperature).

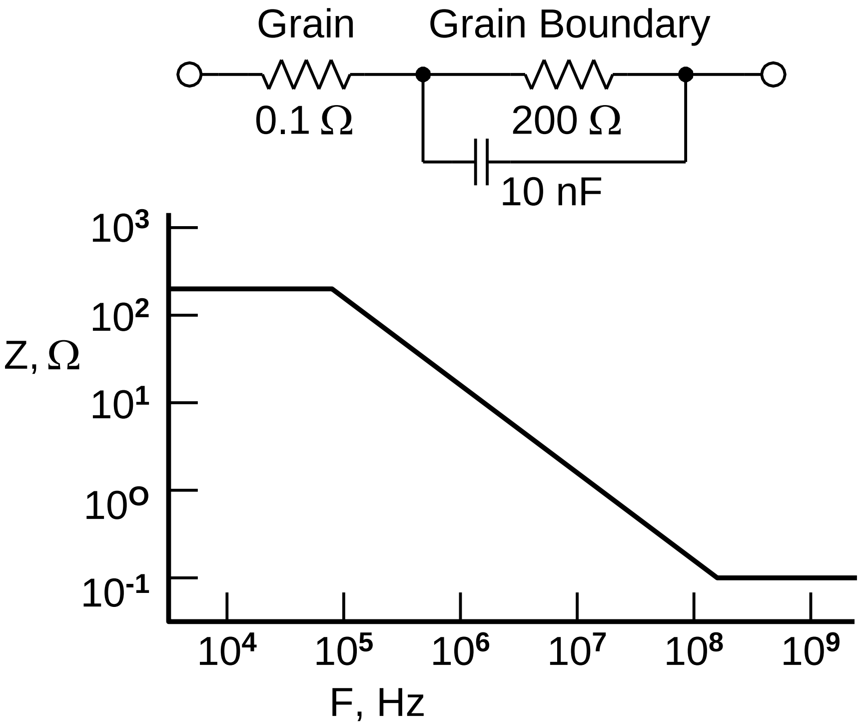
Modeling the Ferrite's Conductivity

A ferrite is basically composed of fairly conductive grains (resistivity on the order of 0.1 ohm-cm) separated by a thin layer of poorly conductive material at the grain boundaries.

This also causes the effective bulk permittivity to be extremely high at lower frequencies, as the 'capacitive dielectric' is extremely thin.



A rough model of the conductance of a 1 cm cube, based on the Ferroxcube info:



Proposed Method to Test for the Bulk Eddy Current Effect

1) Select a few relatively large toroids with a square cross section (e.g., Magnetics 46113-TC; OD: 2.40", ID: 1.40", H: 0.50") with a range of characteristics (e.g., Magnetics "W", "R" & "K" materials).

2) Measure the loss vs. frequency at a moderately low level (to increase relative eddy current loss), perhaps at a constant B x f.

3) Progressively cut the toroids into 2 and then 4 "washers", remeasuring the loss/volume at the same B x f.

If bulk eddy currents do exist, the kW/m³ should progressively drop at higher frequencies with thinner cores.