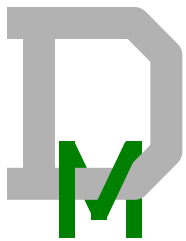# Power Magnetics Design and Measurement of Power Magnetics

Charles R. Sullivan, charles.r.sullivan@dartmouth.edu

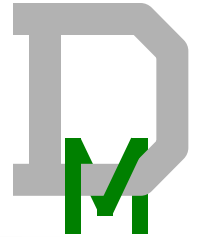Copyright 2011

Dartmouth Magnetics and Power
Electronics Research Group

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http://power.engineering.dartmouth.edu

High-performance high-frequency power magnetic design

- Select winding configuration.

- Approximate analytical models for winding loss, core loss, and thermal resistance.

- Co-optimize magnetics design with circuit design:
    - Switching frequency
    - Inductance value
    - Magnetic component geometric parameters
    - Goal: efficiency vs. size tradeoff (thermal constraint)

- Fine tune design with finite-element analysis.

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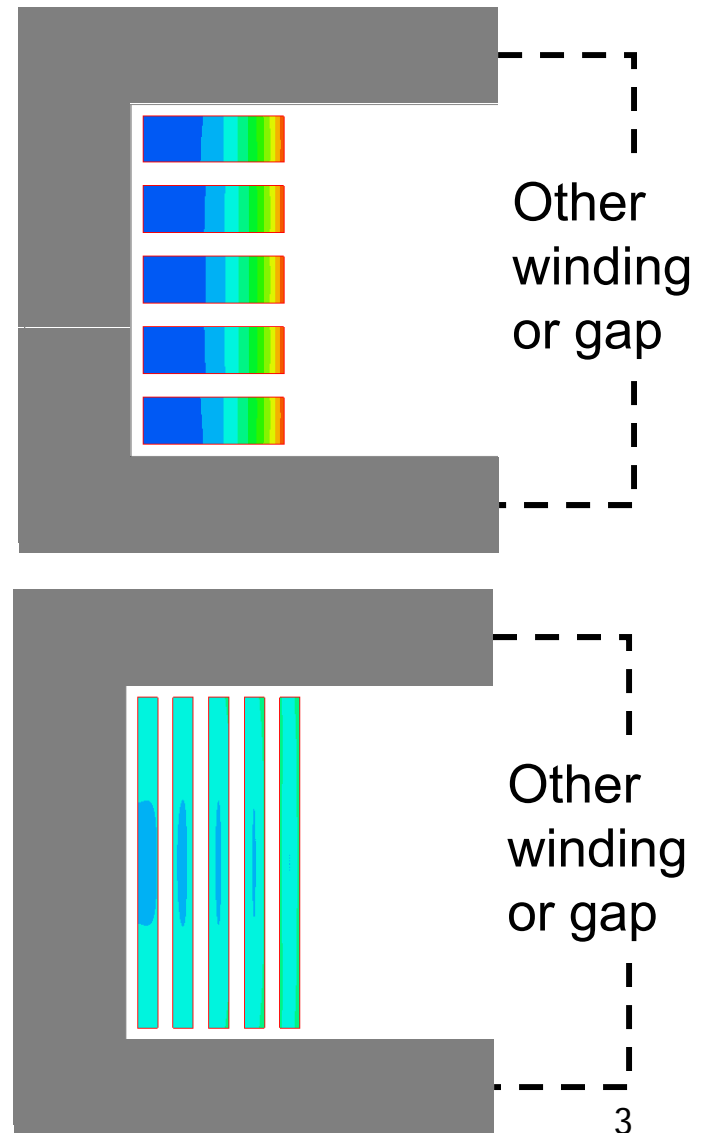ENGINEERING
AT DARTMOUTH
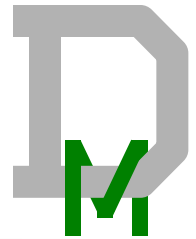1867

Select winding configuration
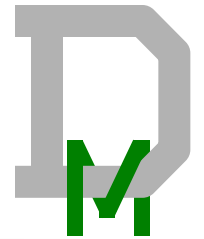
Options for low ac resistance:

- Single-layer winding
  - Can be much thicker than a skin-depth with no ac-resistance penalty.

- Multi-layer winding
  - Layer thickness is critical.
 - Typically need $d \ll \delta$, not just $d < \delta$ (δ = skin depth).

Other winding or gap

Other winding or gap

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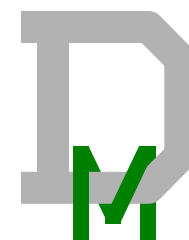AT DARTMO

Rough Performance Estimate

- **Optimum layer thickness with** p **layers** (Dale, 2006): $\dfrac{1.3\delta}{\sqrt{p}}$

  (if all equal thickness)

- **Improvement in ac resistance vs. single-layer winding:**

$$\frac{1.013}{\sqrt{p}}$$

  - For this example:
    - Theoretical 0.45
    - Actual 0.41

Other winding or gap

Other winding or gap

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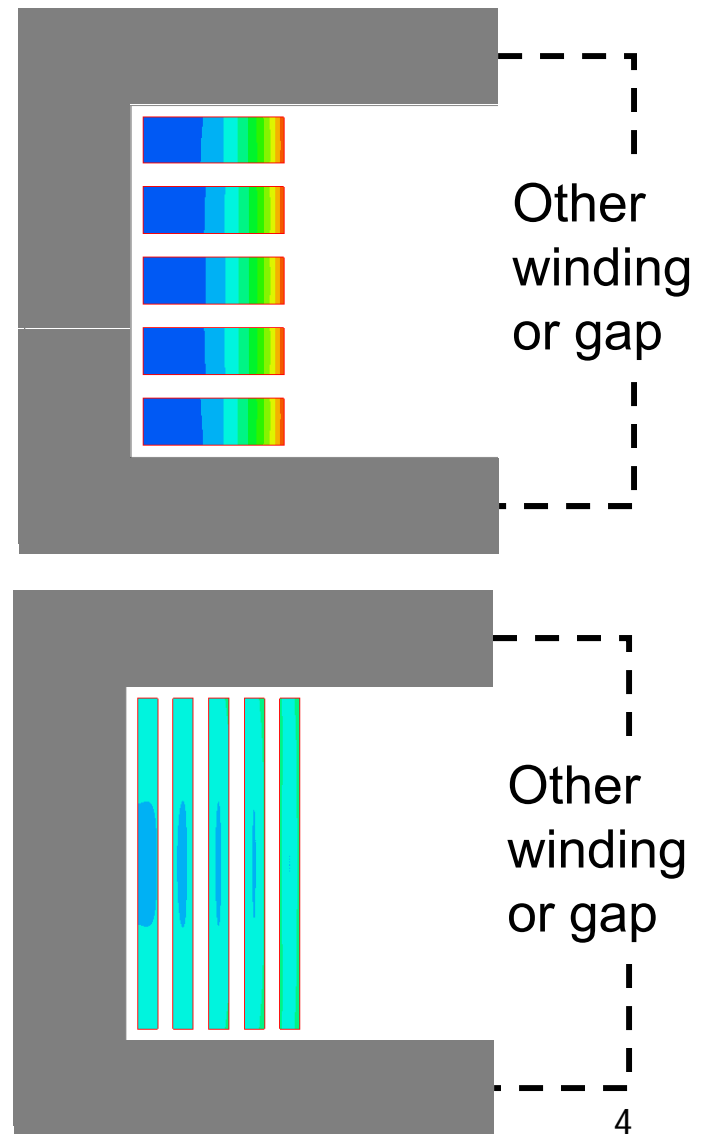
Practical winding-loss issues

- Multiple layers *in parallel* might not share current equally.

    - Twisting in litz wire
    - Interchange foil positions

- Gap effects: current likes to flow near gap.

    - Space away from gap ≥ ¼ width or gap pitch (Hu, 2001).
    - Gap length has only a second-order effect on winding resistance.

4X higher loss

1.22X higher loss

4s

s

1.09X higher loss

2s

s

4s

2s
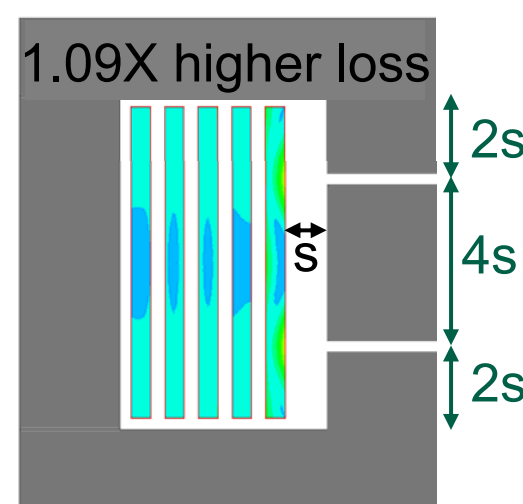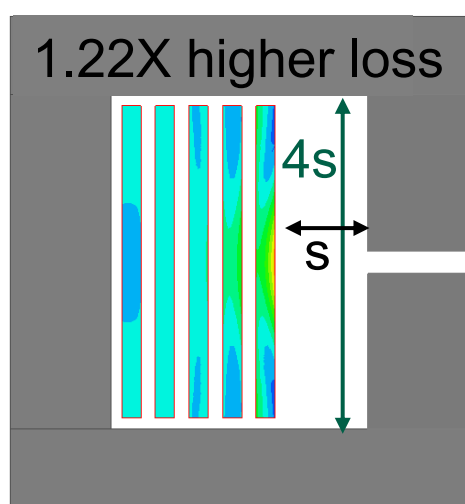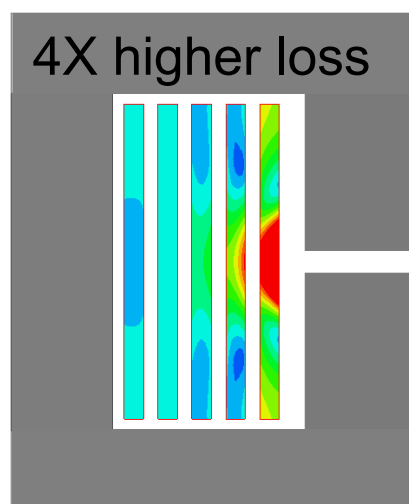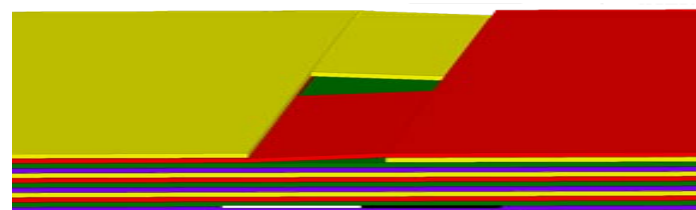
Low loss high-frequency windings: standard is litz wire

- Available improvement

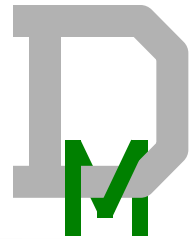$$\frac{P_{ml}}{P_{sl}} \approx 0.584 \left(\frac{d_{min}}{\delta} \right)$$

Frequency	60 Hz	20 kHz	200 kHz	1 MHz	10 MHz
Skin depth	8.5 mm	0.467 mm	0.148 mm	66 μm	21 μm
d = δ	AWG 0	AWG 24	AWG 35	AWG 42	AWG 51
d for 3.5X improvement	AWG 6	AWG 30	AWG 41	AWG 48	AWG 57

- Need alternatives above ~ 1 MHz

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Accurate models for winding losses
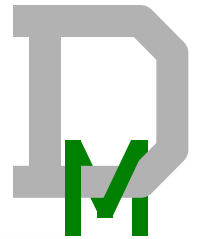
- Transformer AC resistance model: Matrix including mutual resistance terms (Spreen, 1990)

$$P = \frac{1}{2} \begin{bmatrix} i_1 & i_2 \end{bmatrix} \begin{bmatrix} R_1(f) & R_{12}(f) \\ R_{12}(f) & R_2(f) \end{bmatrix} \begin{bmatrix} i_1^* \\ i_2^* \end{bmatrix}$$

- Finding $R_{ij}(f)$ accurately over wide frequency range:
  (Switching-frequency harmonics require wideband model.)
  - Measurements
  - Numerical solutions
  - 1-D foil: Dowell model (e.g., Spreen, 1990)
  - Round wire, 1-, 2- or 3-D: Bessel function is not accurate for packed wire. Better: (Nan, 2004, Zimmanck, 2010).

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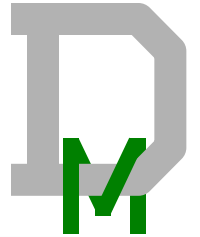
Modeling Core Loss

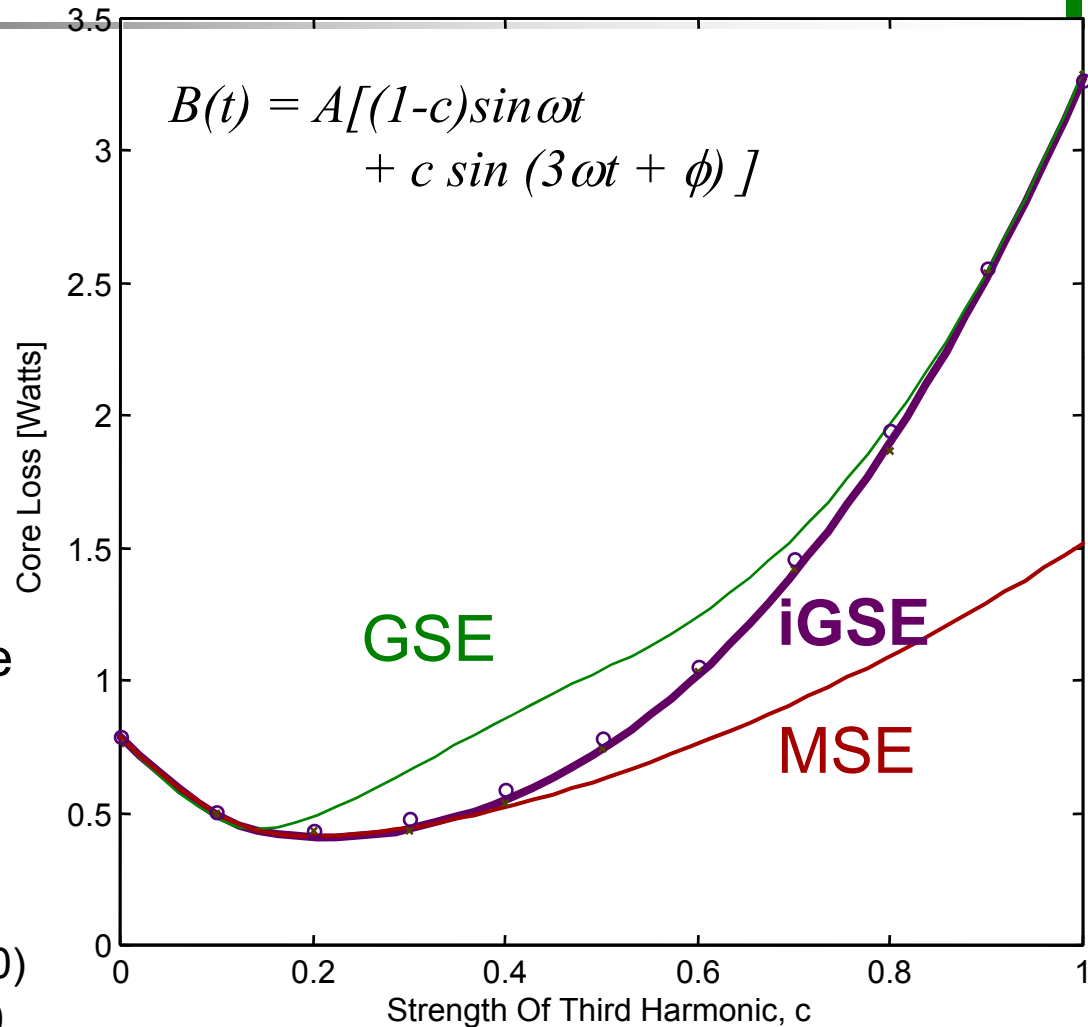- **Thin-film alloys and laminations:**
  - Classical eddy-current
    - At high frequency, with thin dielectric, capacitance may allow additional eddy current (Yao 2009)
  - Hysteresis loss
  - Anomalous loss: model based on domain-wall motion. (Bertotti, 1998)
- **Ferrites: Steinmetz curve fit to measured data….if excitation is sinusoidal.**

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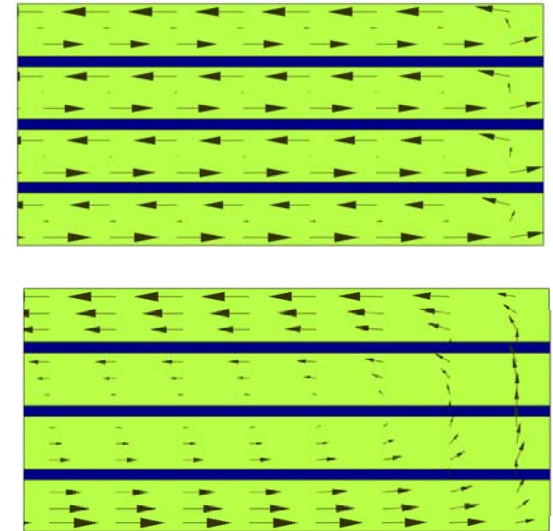
Ferrites with non-sinusoidal waveforms
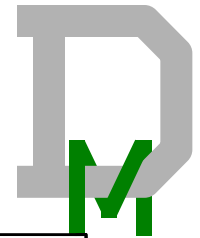
- Improved Generalized Steinmetz Equation (iGSE, Venkatachalam 2002) is more accurate than alternatives.

- Easy to use with basic piecewise linear (PWL) waveforms.

- Better alternative: measure loss with square waves and generalize to any rectangular waveform. (Sullivan 2010)

- Other effects:
  - DC bias (Mühlethaler, 2010)
  - "Relaxation" (Sullivan 2010, Mühlethaler, 2011)

$$B(t) = A[(1-c)\sin\omega t + c\sin(3\omega t + \phi)]$$

GSE   iGSE   MSE

Core Loss [Watts]

Strength Of Third Harmonic, c

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Design

- Easy way to get a mediocre inductor:
  - Large L for small ripple.
  - Can tolerate large R_{ac} with small ripple—wind for low dc resistance.
  - Saturation is more important than core loss (see Pollock, 2011 for a model)
- Path to a better inductor:
  - Optimize L and $f_{switching}$ with inductor design.
  - $\rightarrow$ Lower L, higher ripple
  - Requires low R_{ac} … and requires circuit tricks for light-load efficiency.
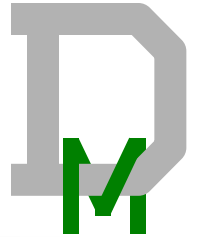
Output of optimization
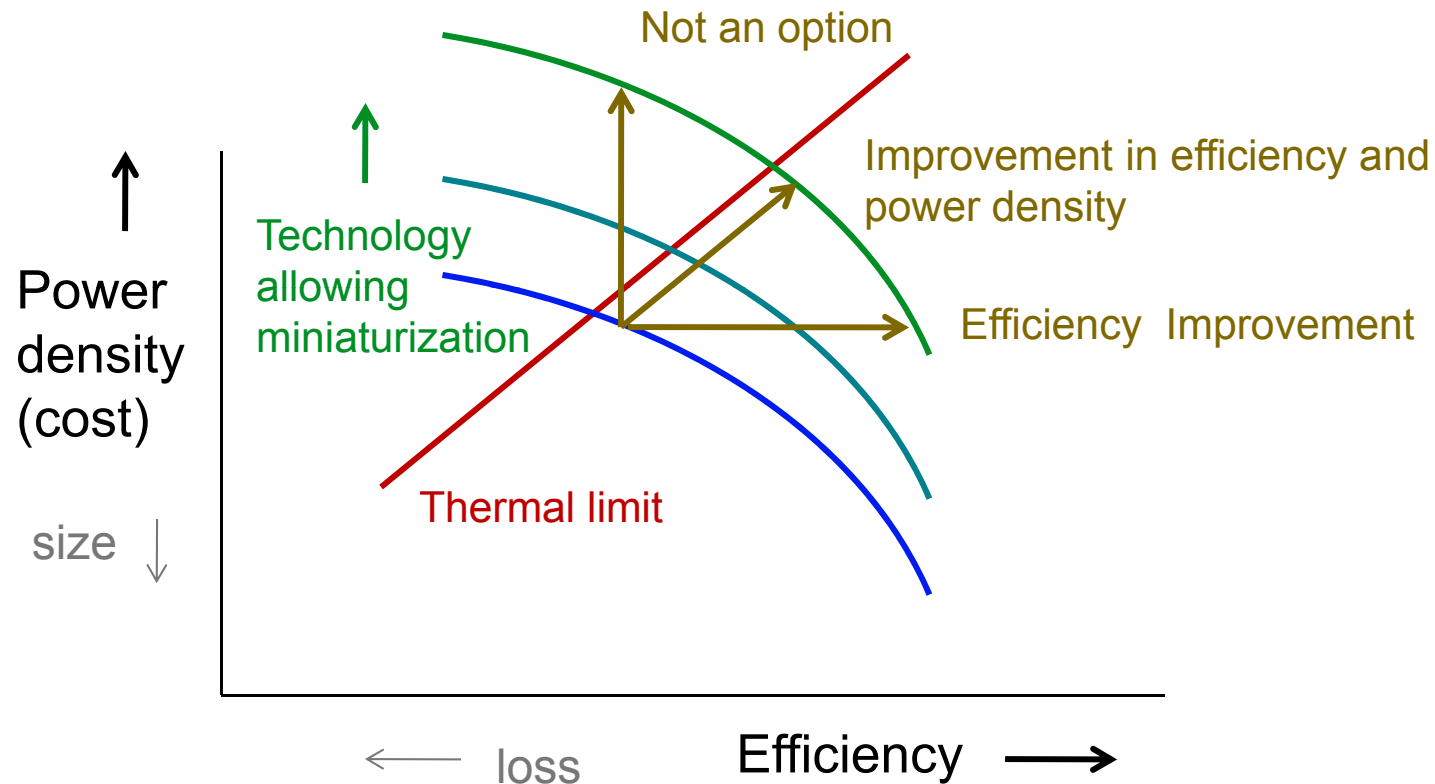
- Plot of efficiency vs. power density shows the range of attractive options.
- Progress on cost, size, or efficiency can be used to improve all of the above.
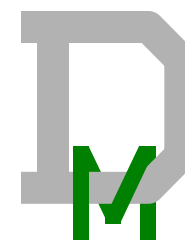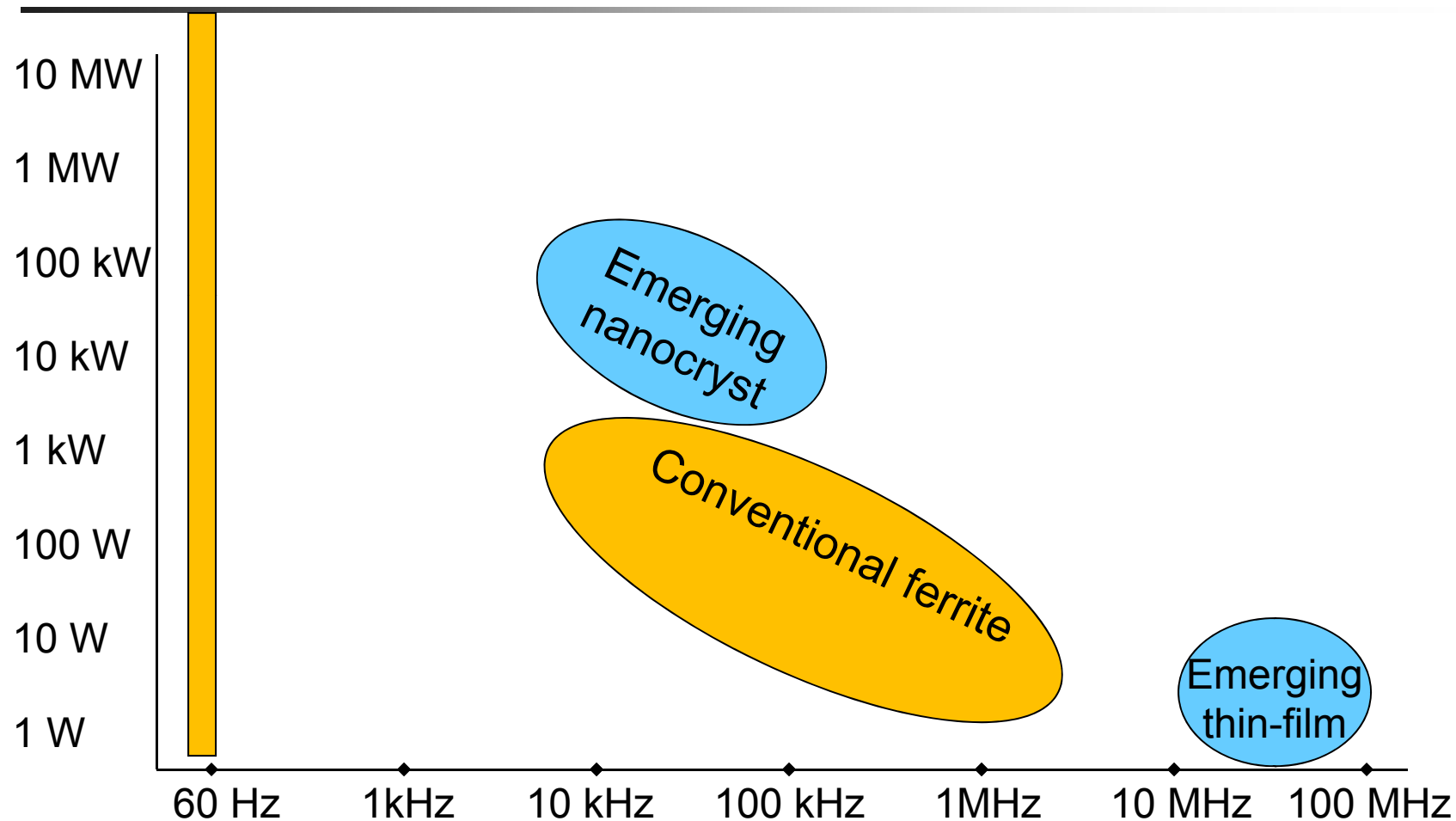
Options to consider

- Integrate multiple components (e.g. inductor, transformer) on a single core.

- Circuit designs that utilize coupled magnetic components.

- Hybrid windings for components with ac and dc or high-frequency and low-frequency current (e.g., litz wire and solid wire) (Valchev, 2005; Schaef 2012).

- Aluminum wire: enables lower loss than copper under weight or cost constraints (but not under size constraints). (Sullivan, 2008)

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Existing magnetics

Chart axes — Vertical (power): 10 MW, 1 MW, 100 kW, 10 kW, 1 kW, 100 W, 10 W, 1 W

Horizontal (frequency): 60 Hz, 1 kHz, 10 kHz, 100 kHz, 1 MHz, 10 MHz, 100 MHz

Regions labeled: Emerging nanocryst, Conventional ferrite, Emerging thin-film
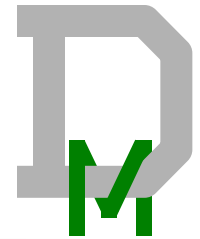
Needed with new semiconductors
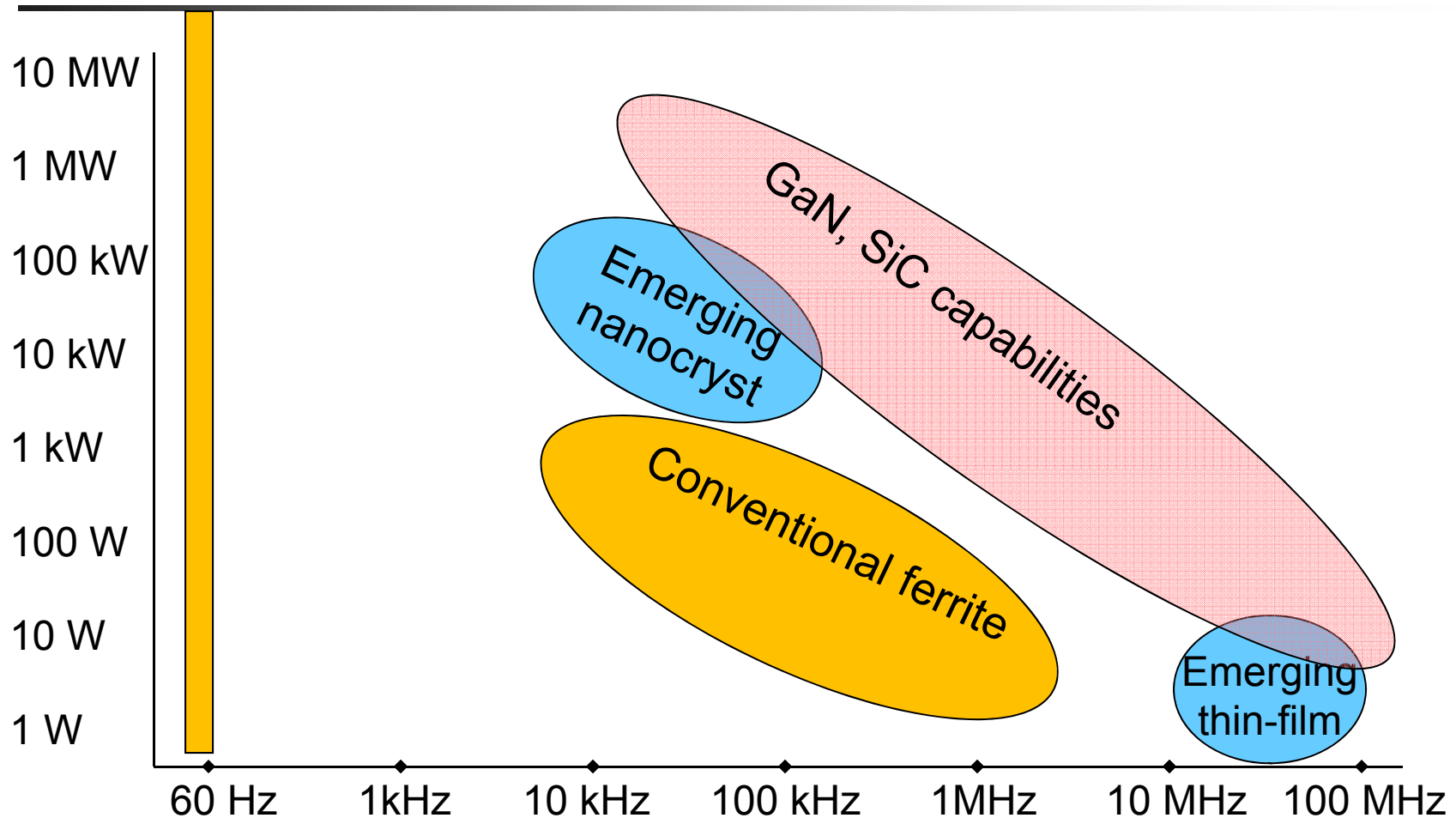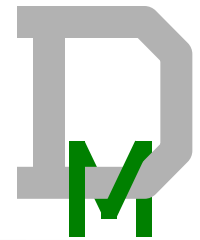
The challenge for magnetics: extending capabilities

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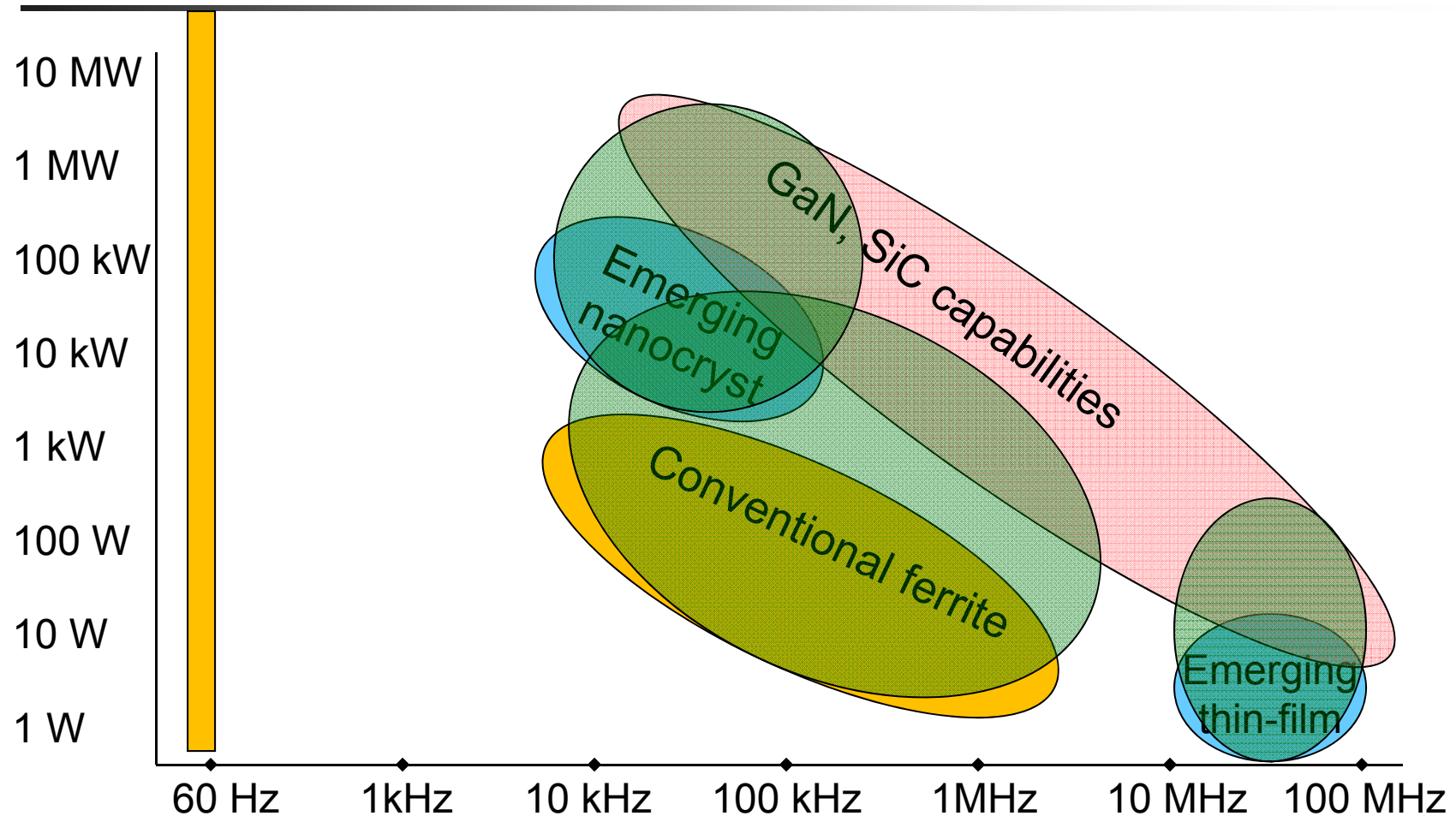ENGINEERING
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Even bigger challenges: breakthroughs needed

Conductors, magnetic materials?

Better ferrites?
Thick thin-film materials?

GaN

Emerging nanocryst

Conventional ferrite

Emerging thin-film

?

?

Power axis: 1 W, 10 W, 100 W, 1 kW, 10 kW, 100 kW, 1 MW, 10 MW

Frequency axis: 60 Hz, 1kHz, 10 kHz, 100 kHz, 1MHz, 10 MHz, 100 MHz

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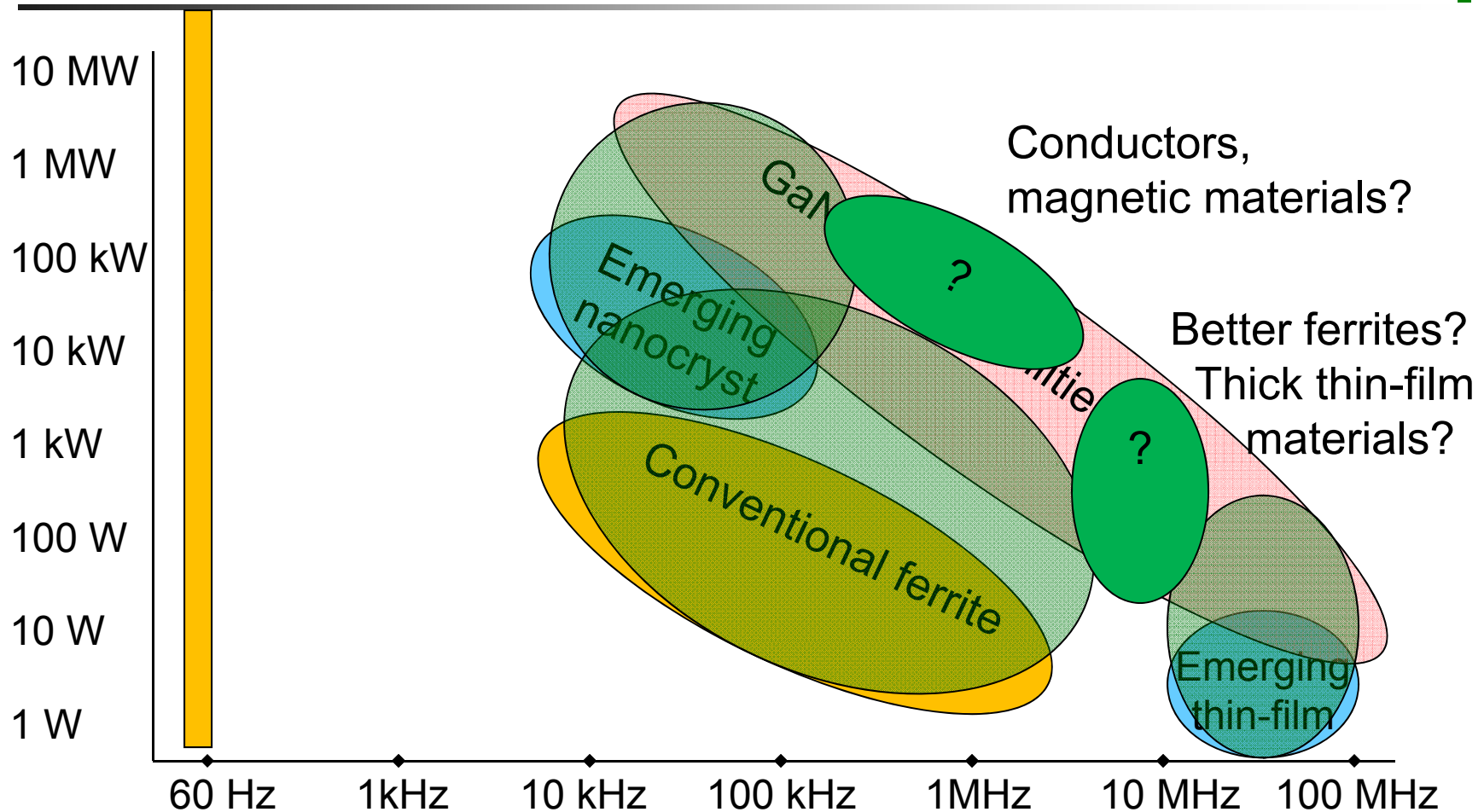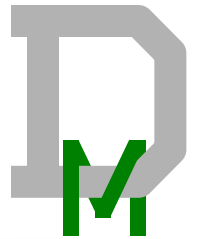
Measurement Challenges

- Accurate loss measurement of low-loss components

- Nonlinearity of core loss

- Connecting instruments with low residual impedance

- Separating core and winding losses

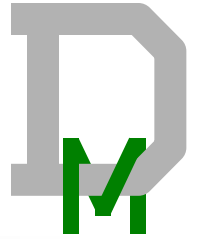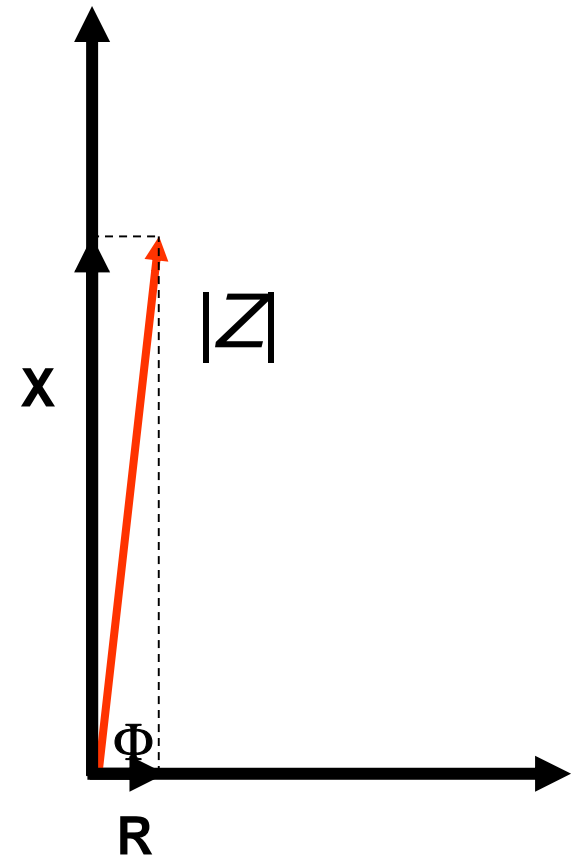- Magnetic material measurement without making components

Accuracy with High *Q*:

- Loss ⟺ Real(*Z*) (ESR)
- Good power components:
  - Real(*Z*) << |*Z*|
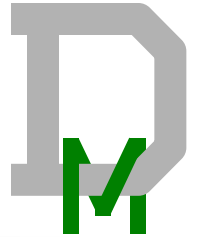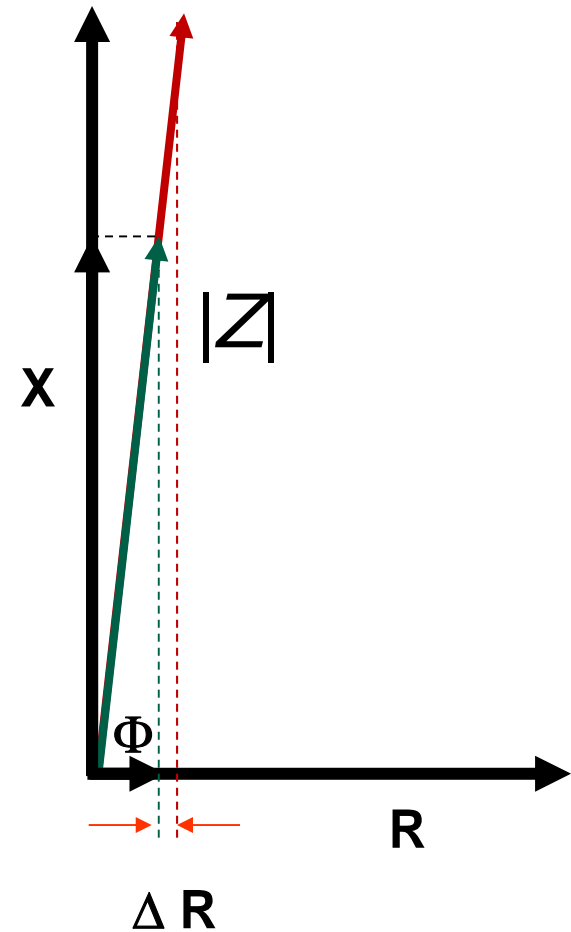 - But it's still important to measure Real(*Z*).

Accuracy with High *Q*:

- Loss $\Leftrightarrow$ Real(*Z*) (ESR)
- Good power components:
  - Real(*Z*) << |*Z*|
  - But it's still important to measure Real(*Z*).
- Small error in |Z|
  - $\Rightarrow$ Small error in Real(Z)
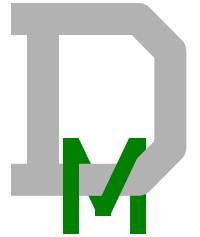
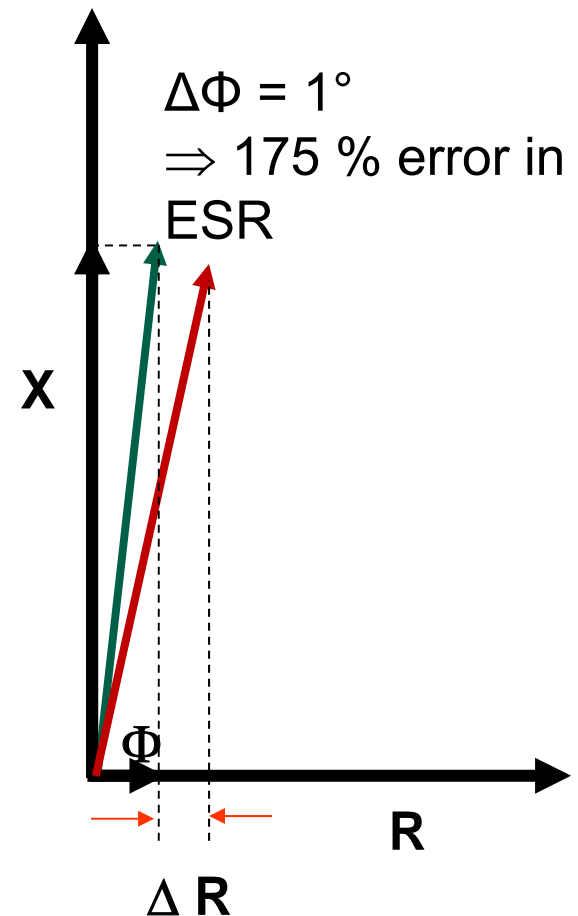THAYER SCHOOL OF
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Accuracy with High *Q*:

- Loss ⇔ Real(*Z*) (ESR)
- Good power components:
  - Real(*Z*) << |*Z*|
  - But it's still important to measure Real(*Z*).
- Small error in |Z|
  - ⇒ Small error in Real(Z)
- Small error in ∠(Z)
  - ⇒ Large error in Real(Z).
  - Example: *Q* = 100. ΔΦ = 0.2° ⇒ 35% error in ESR

ΔΦ = 1°
⇒ 175 % error in ESR

X

Φ

R

Δ R

Accurate measurements with high-Q

- Use an instrument with excellent phase accuracy.

- Compensate with a low-loss capacitor to "tune out" indutance (power factor correction) (Han 2008, Mu 2010)

  - Polypropylene/porcelain/mica/air

  - May still need to measure and correct for capacitor ESR, but at least it's linear (except ferroelectrics).

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Two favorite impedance instruments
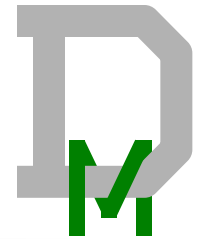
4294A
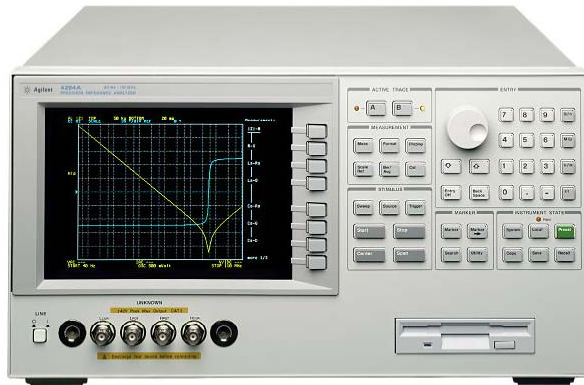
E4991A

- 40 Hz to 110 MHz.

- 4-terminal pair for wide impedance range.

- Best 40 Hz to 10 MHz.

- Phase accuracy can be ~3 m° below 100 kHz.

(Prabhakaran, 2002)
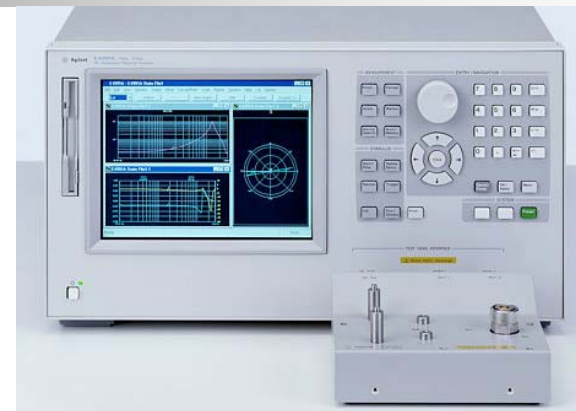
- 1MHz to 3 GHz.

- 7-mm port—best for 0.5 Ω to 5 kΩ.

- Best ≥10 MHz.

- 4-way calibration: open, short, load, and air cap for 90° phase accuracy.

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4 terminal pair configuration
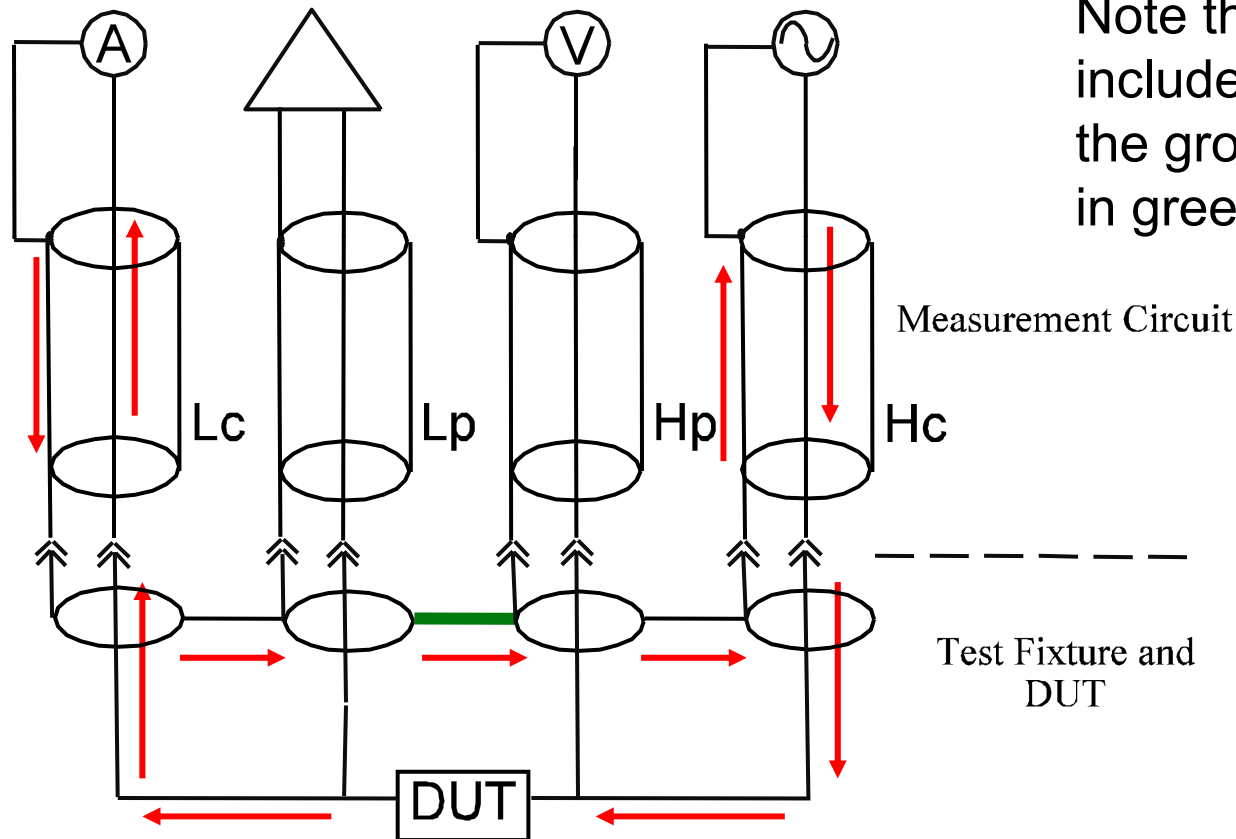
Note the measurement includes the impedance of the ground path highlighted in green.

Measurement Circuit

Lc   Lp   Hp   Hc

Test Fixture and DUT

DUT

High power measurement with a standard analyzer

Current Probe

Differential Probe

Lc   Lp   Hp   Hc

Measurement Circuit

High Power Module

Amplifier

Test Fixture and DUT

DUT
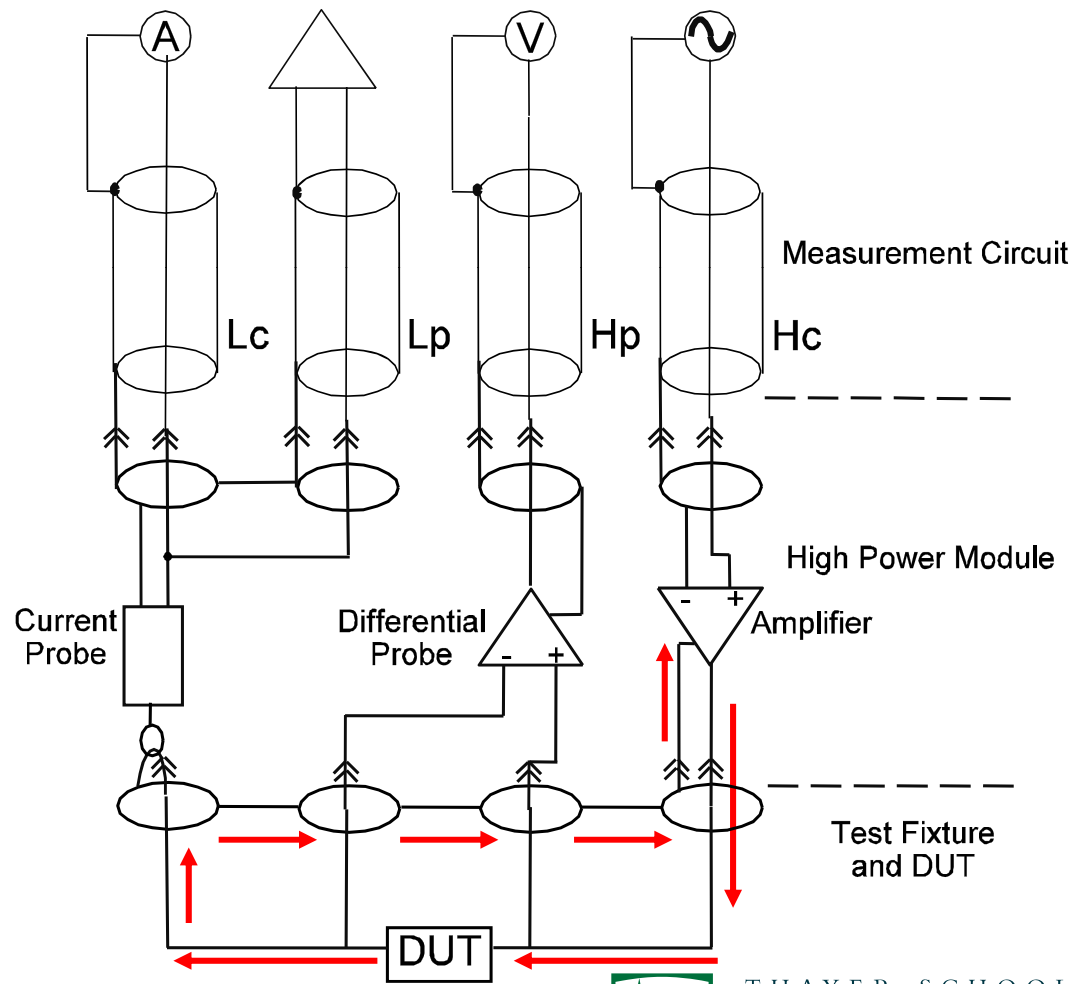
- Needed for nonlinear magnetic materials

- Demonstrated 1~300 kHz (Prabhakaran, 2002).

- Under construction: 1~30 MHz, up to 5 A drive current.

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Resonant-circuit high-power testing
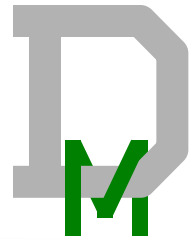
- Find *Q* from two amplitudes—no error from phase shift (Han, 2008).

- Resonance reduces VA requirement at input.

- Matching may still be needed for low-Z series resosnant circuit.
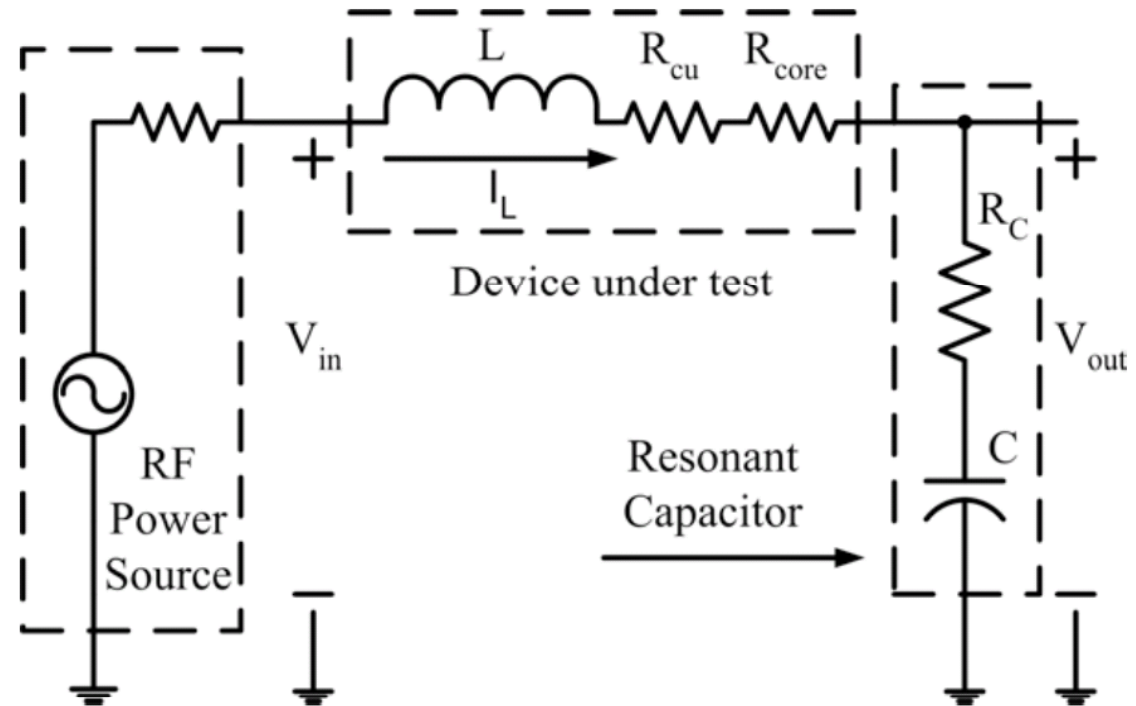
Test Fixtures
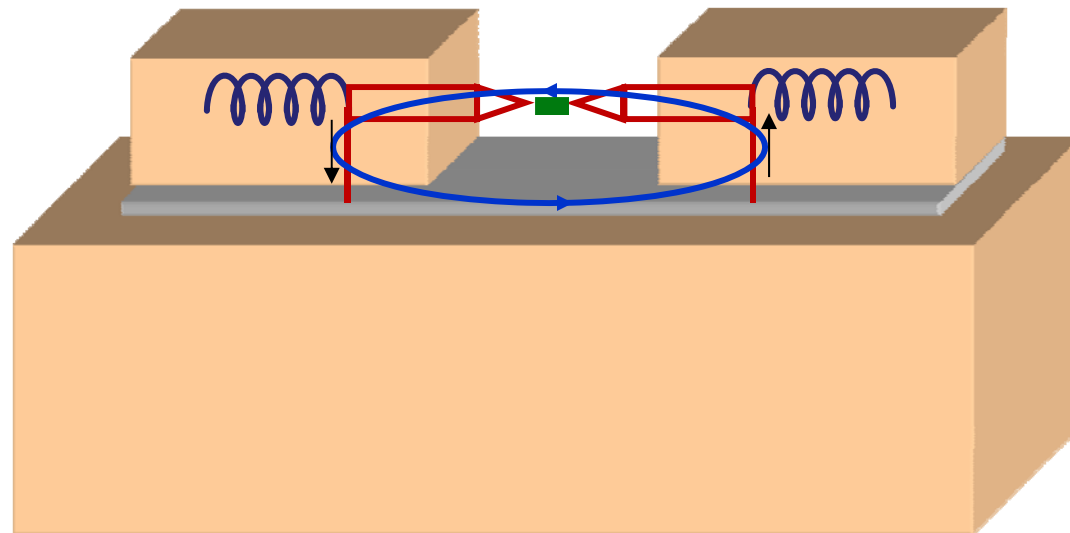
- Disadvantages of commercial fixtures
  - **Large stray** impedance (100 nH)
  - Most have **unrealistic test configuration**
  - Two point contacts have **large series resistance**

Low-stray surface-mount impedance-analyzer test fixture (Prabhakaran, 2002).

A   ▷   V   ~

3 mil (75 μm) polyimide (Kapton)   Ground traces underneath
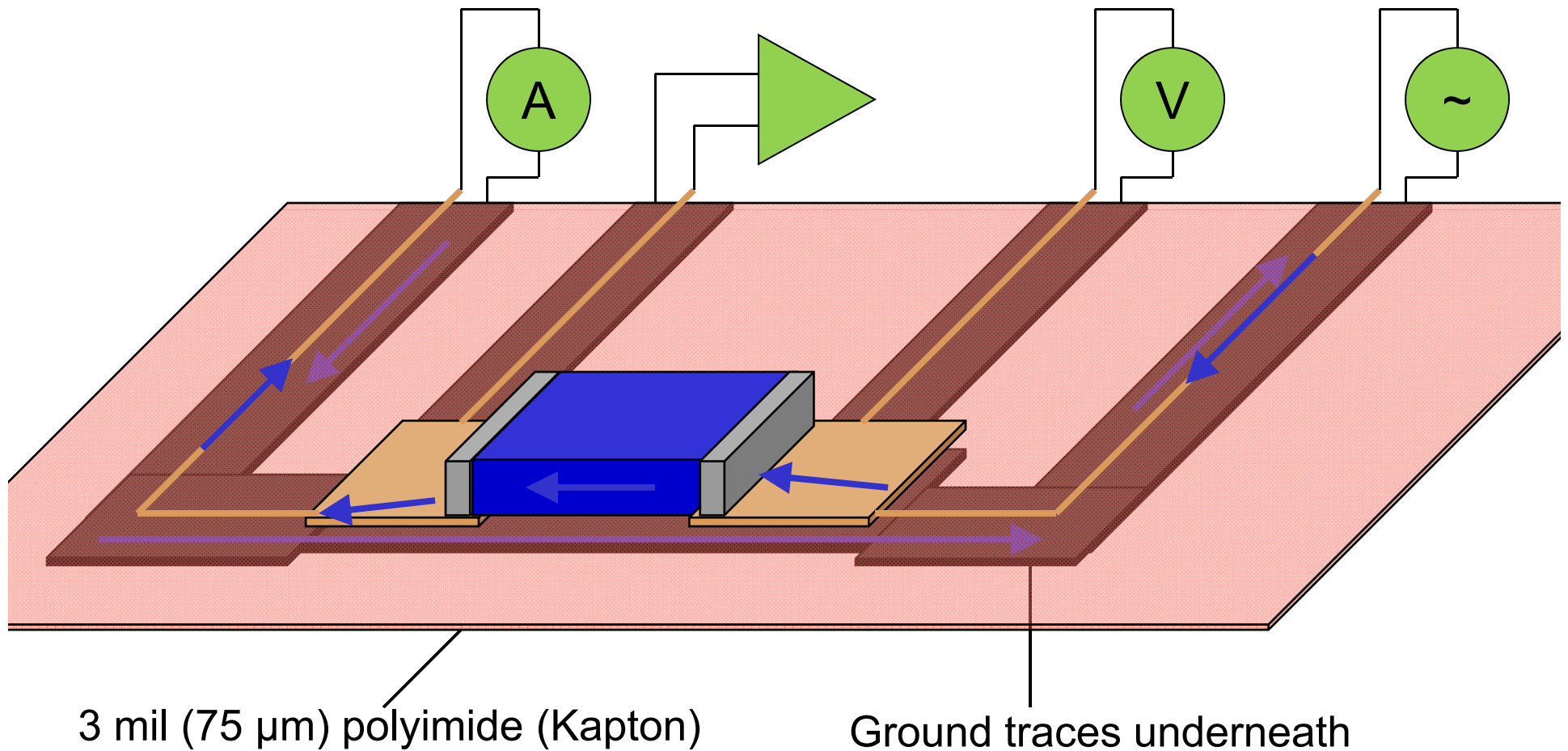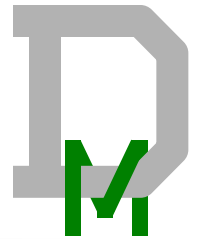
Test fixture performance at 10 MHz

(Prabhakaran, 2002).
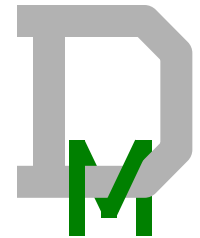
	Shorted		Open
	Stray L	Stray R	
Externally shorted	59 pH – 62 pH	1.35 mΩ - 1.38 mΩ	15 fF
Pre-shorted	43 pH	1.1 mΩ	
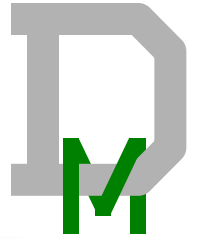
Separating core and winding loss

- ~~Measure winding without core~~ and subtract to get core loss?

- Measure core without winding and subtract?

- Core usually affects winding loss (gap, any asymmetry).

- To find winding resistance, measure small signal impedance and subtract small-signal core-loss effect.

  - Requires complex permeability data or measurement to describe the core.

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Additional notes on winding measurement (added after presentation)
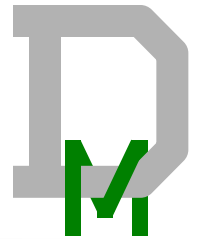
- For a two-winding transformer without much magnetizing current:
  - The most important resistance is for the excitation with no magnetizing current ("leakage excitation" or "transformer excitation"), obtained with equal and opposite amp-turns in the two windings.
  - This resistance can be measured with a shorted secondary (with high enough magnetizing inductance) or, for a 1:1 transformer, with windings connected in series opposition (Hayes 2009).
  - Core loss effects are typically negligible for ferrite cores with leakage excitation, so subtracting core loss is not necessary. (Not true for magnetizing excitation!)
- Stray capacitance leads to a parallel resonance at high frequencies in a typical component.
  - Find C value from resonant frequency.
  - Model including C leads to a difference between winding resistance and the ESR of the component. Using this model becomes important as frequencies approach the resonance.

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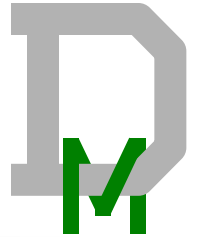
Typical procedure to measure ac resistance of an inductor winding (added after presentation)

- Calibrate analyzer with text fixture.
  - Consider using averaging over the same frequency range to be used in the impedance measurement.
- Measure $Z(f)$, typically using series inductance and series resistance as coordinates.
- Find resonant frequency (which may be outside the range initially scanned in the impedance measurement) and calculate capacitance.
- Measure impedance with closed gap (zero gap) to obtain small-signal core characteristic. If ESR measured in this configuration is much larger than ESR measured with a gap, the loss is mostly due to core loss. If not, see the next slide for alternatives to obtain core loss.
- The small-signal core loss characteristic can be used to calculate the component of the ESR attributable to the core loss. One way to do this is to use the fact that the parallel resistance due to core loss is constant independent of gap length.
- Winding resistance is obtained by subtracting core ESR and correcting for C.

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Core loss measurements: small-signal and large-signal
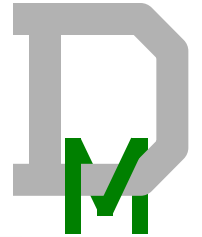
With a closed core (ideally with no gap):

- Classic two-winding measurement:
  - Small-signal or large-signal
  - Beware of capacitance to other winding or core, and of mutual resistance appearing as core loss.
  - Can use capacitor to make high-Q measurement more accurate (Mu, 2010) (important for low-perm cores)
- Subtract winding resistance (Valchev, 2005, Han 2008):
  - Known via modeling.
  - Litz wire in range where it's independent of frequency.
  - Measured…

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Subtracting measured resistance for core loss…
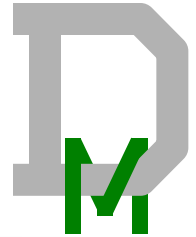
- Requirements:
    - Repeatable configuration.
    - Current distribution unaffected by core.
- Solution: coaxial connector (e.g. "7/16" high-power RF connector) with shorted mating connector.
    - Similar to commercial impedance analyzer "magnetic material test fixture"
    - May be better: full cylindrical symmetry vs. 4-post design.
    - Zero instrument with empty fixture; insert toroidal core.

Core loss measurements with thin-film samples
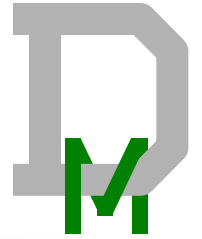
- Low-frequency high-field: BH looper (e.g., SHB Instruments)

- High-frequency low-field: Permeameter (e.g., Ryoawa)

- High-frequency high-field: (Mukadam, 2008)

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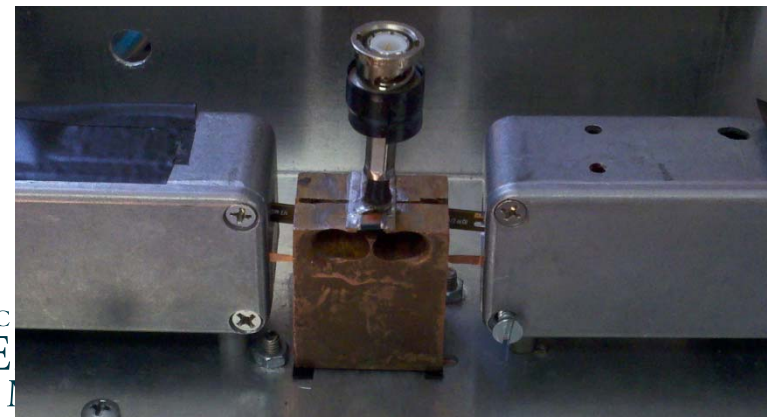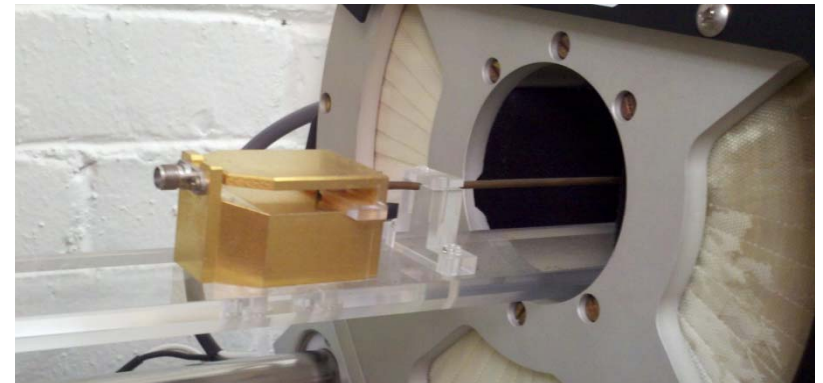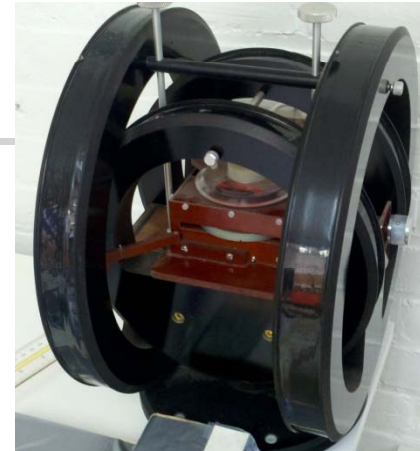
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