Massachusetts Institute of Technology

Power Electronics Research Group

Measurements and Application Considerations of Magnetic Materials at High- and Very-High Frequencies

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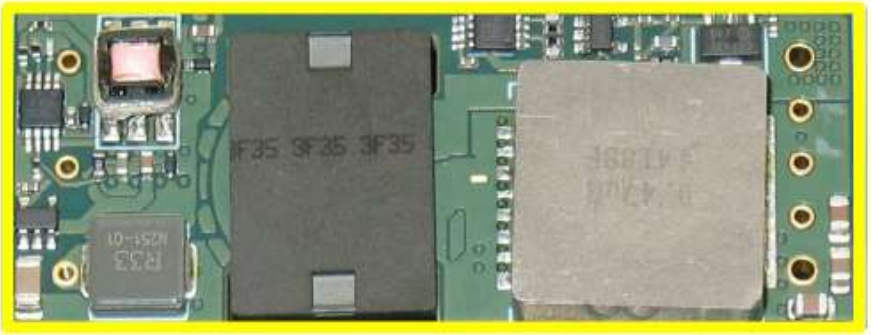
Presented at:

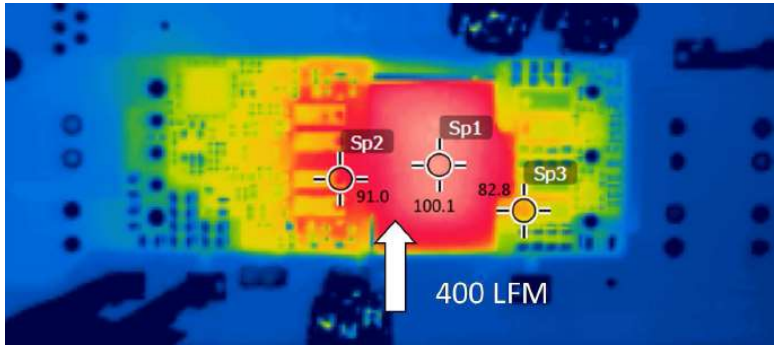
PSMA Magnetics Workshop

Power Magnetics @ High Frequency – Solving the Black Magic!

March 19, 2016

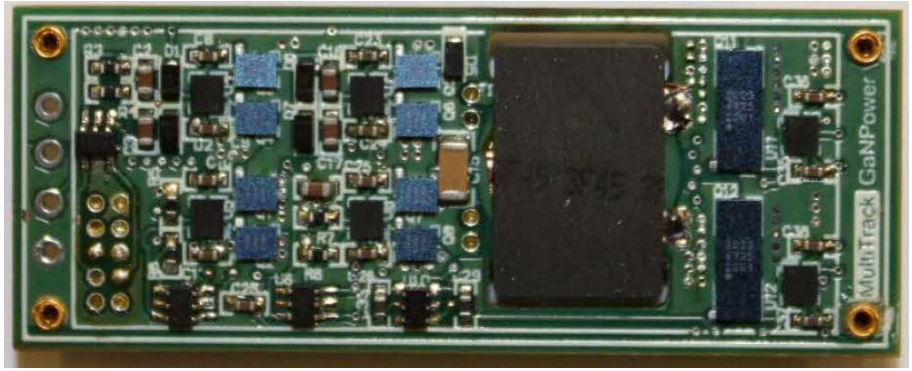
Converter Examples from ECCE 2015

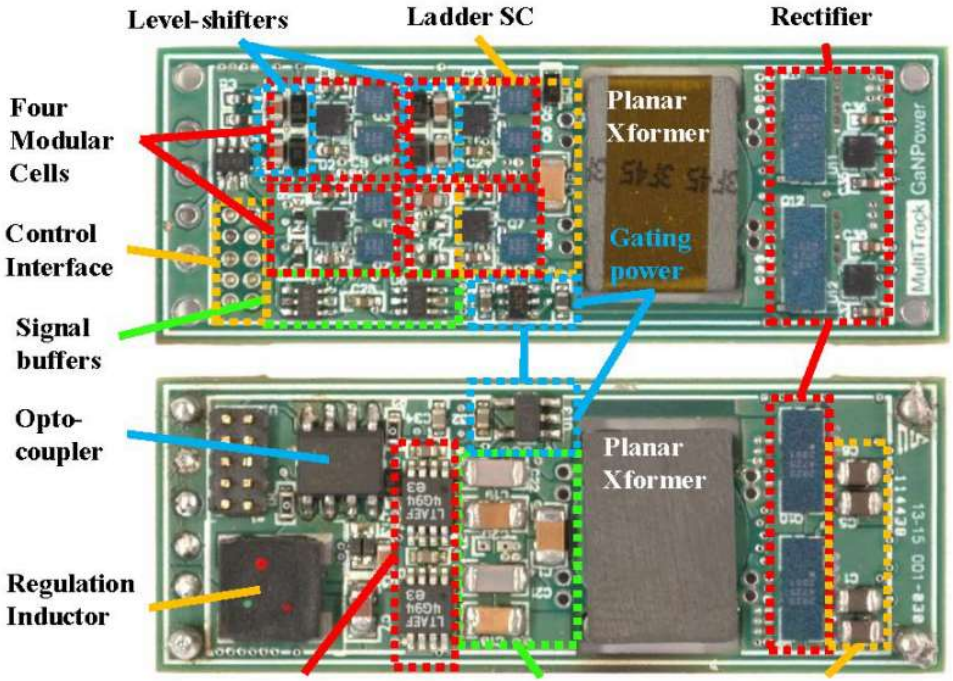




EPC demonstration – 300 kHz design

Magnetics ~48% of loss, 45% of area





Minjie Chen (MIT) – careful 1 MHz design

Magnetics ~35% of loss, 35% of area

Background and Questions

- We seek improved design methods, models and materials for power magnetic components at high frequency (High Frequency, HF, 3-30 MHz)

Key questions:

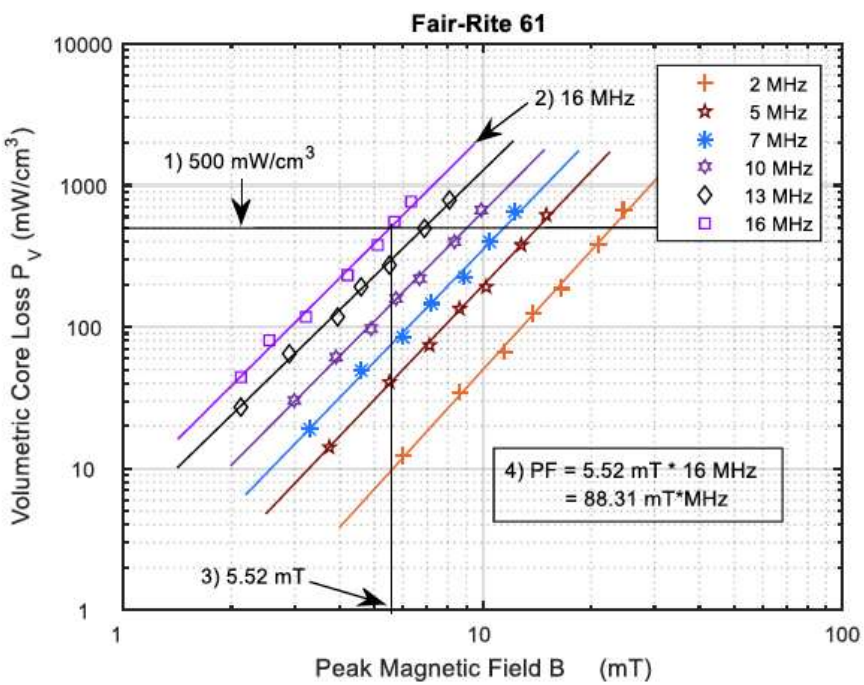
- What is the best way to characterize magnetic materials at high frequencies?
- What capabilities do high-frequency materials really have?
- What are the design considerations for using low-permeability HF materials?

Scaling of Magnetics Size with Frequency

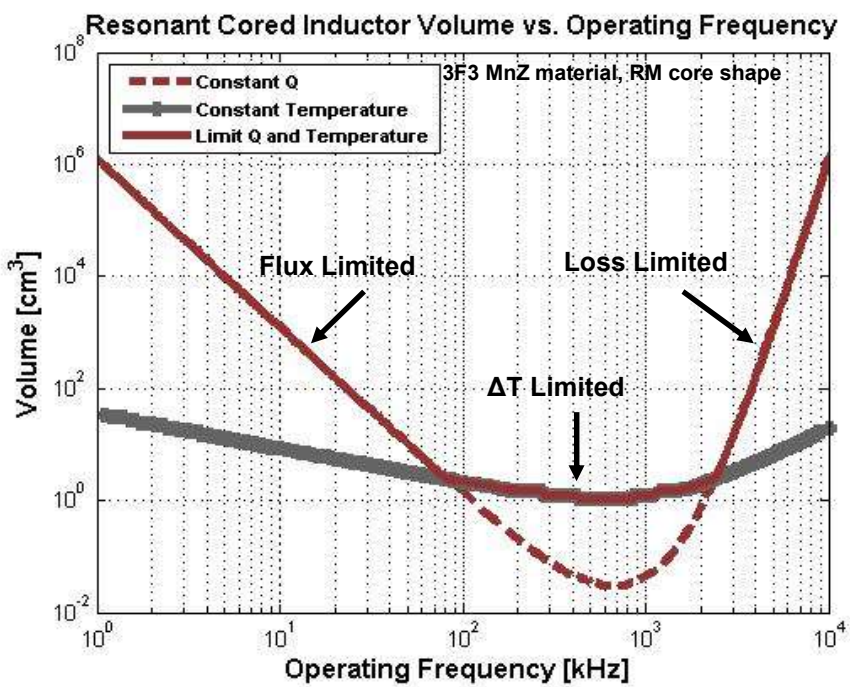
- **Increasing *f* yields smaller L,C for same impedance**
  - **required *energy storage* decreases inversely with *f***

$$Z_L = j\,L\omega$$

- **Component size *can* decrease with frequency, but only over a limited frequency range**
  - **Limited by core loss**
  - ***Core materials are critical!***



Example: Resonant inductor providing |Z| = 10 Ω (1.6 uH at 1 MHz), Q_{min} = 100, ΔT < 75 °C, |Iac| = 0.5 A



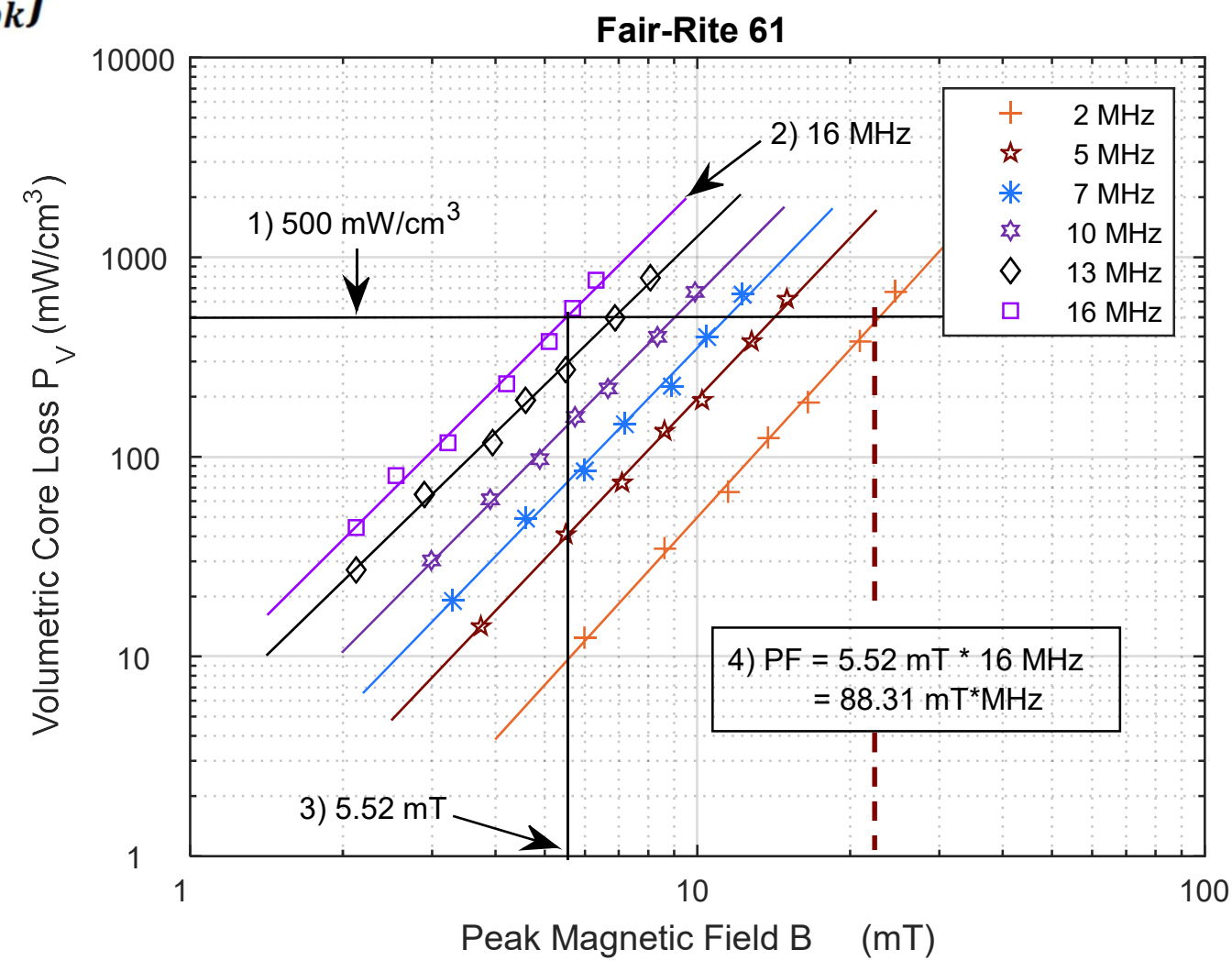
Performance Factor

- "Performance Factor" is *approximate* measure of power handling per unit volume of a material $\mathcal{F} \propto \frac{P}{\text{core volume}} \propto \frac{V_{pk} I_{pk}}{A_C l_C}$
- For a given (fixed-size) core, we might imagine that there is a limited $N \bullet I$ (Ampere-turns) that can be applied, owing to winding area, winding loss, etc. (so treat $N \bullet I$ as fixed)
- Voltage amplitude |V| is $N \bullet B \bullet f \bullet A_C$ (B is core flux density)
- (reactive) power handled is proportional to $|V| \bullet |I|$, so for Fixed $N \bullet I$, then, is proportional to $B \bullet f$
- To see how a core material performs across frequency, we adopt a "performance factor" $B \bullet f$ *, where the value of B at each frequency is selected to provide the same core loss density* (e.g., 500 mW/cm^3)

Calculating Performance Factor

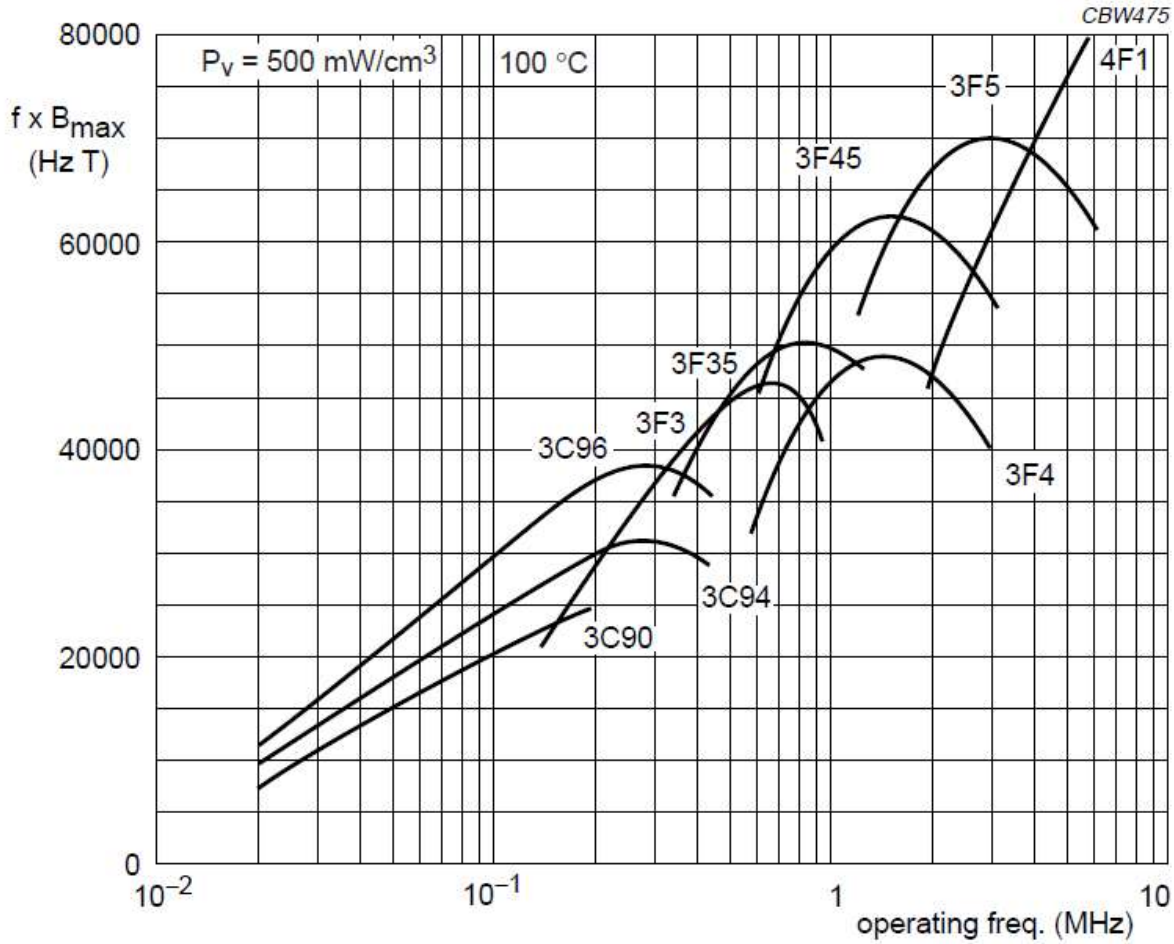
- choose a frequency f and a design core loss density (e.g., 200-500 mW/cm^3) and find the allowable flux density B_{pk}.

$$\mathcal{F}_1 = B_{pk} f$$



Magnetic Material Performance Factor

- The **"performance factor"** is meant to capture the power handling per unit volume of a magnetic material

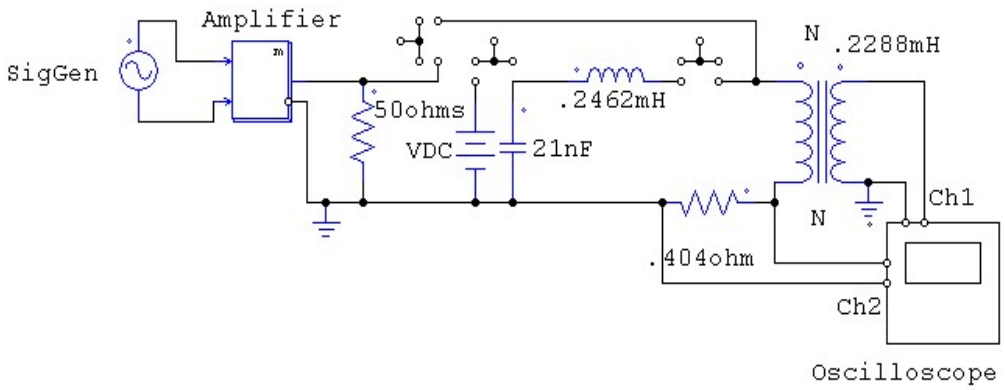


Source: Ferroxcube

Fig.19 Performance factor ($f \times B_{max}$) at PV = 500 mW/cm^3 as a function of frequency for power ferrite materials.

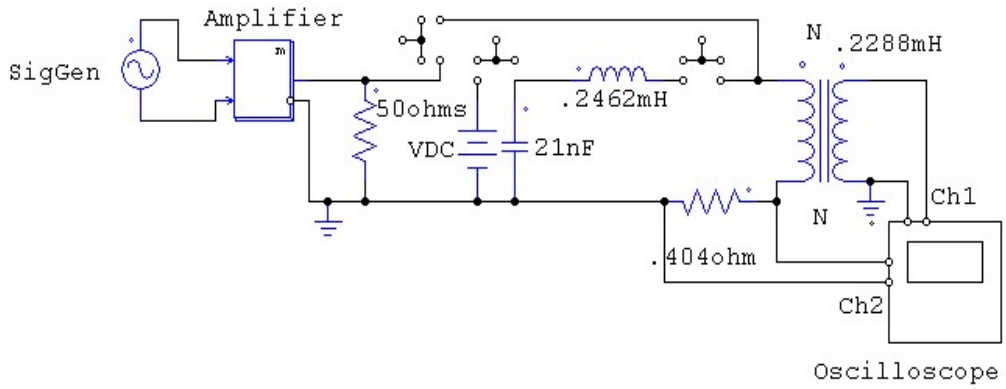
Core Loss Data at HF (3-30 MHz)

- **Core loss data is generally not available at HF (3-30 MHz)** on manufacturer datasheets, even for materials designed for HF operation. Why?
  - Many HF materials have been developed for applications other than power conversion
  - Traditional core loss measurement techniques do not work well at HF owing to phase shift sensitivity
    - No commercial equipment works above 10 MHz



Preconditioning and Measuring Apparatus consistent with International Standard IEC 62044-1, 2, 3

Traditional Core Loss Measurement Method

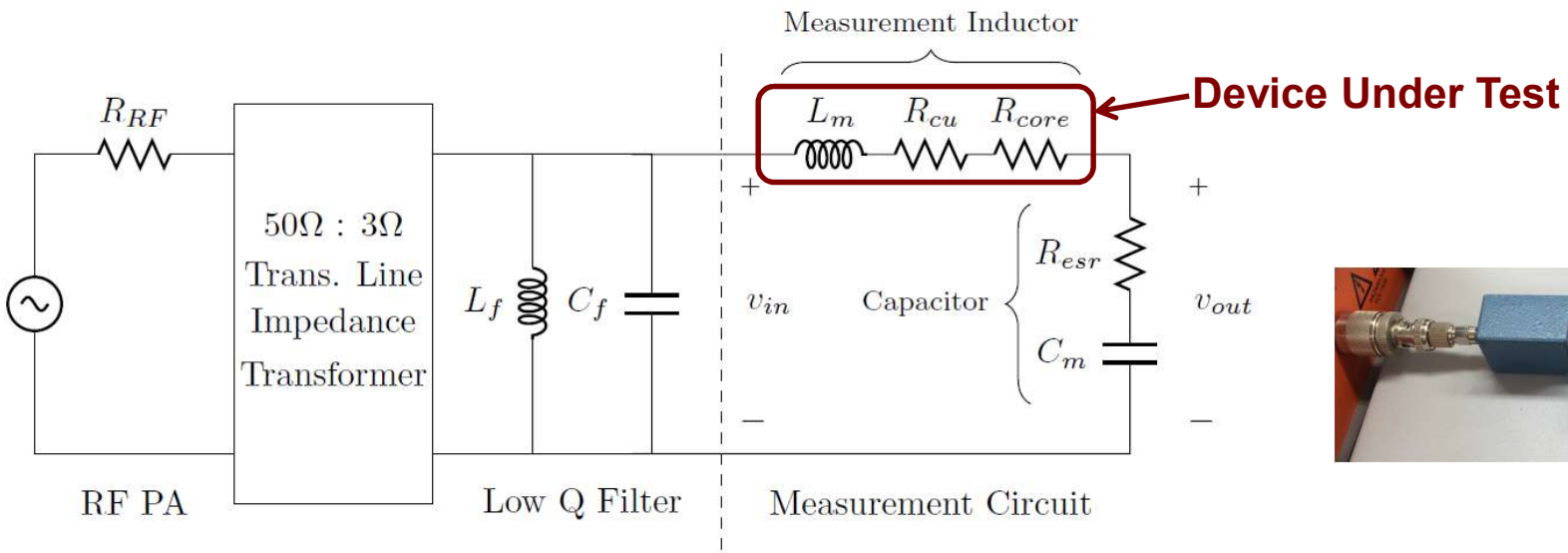


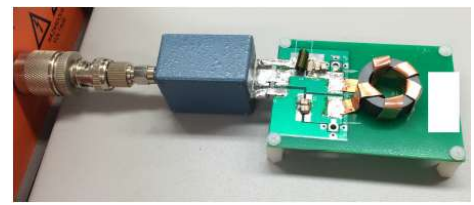
Preconditioning and Measuring Apparatus consistent with International Standard IEC 62044-1, 2, 3

- **Conventional methods difficult at HF/VHF**
  - **Measurements very sensitive to parasitics, phase shift**
- **Instead, use simple method to directly determine the quality factor Q_L of an RF inductor**
  - **Extract the core loss from the measurement of Q_L**
- **The new technique (by Han) is tedious but works well**

Y. Han, et. al., Evaluation of Magnetic Materials for Very High Frequency Power Applications," *IEEE Transactions on Power Electronics*, Vol. 27, No. 1, pp. 425-435, Jan. 2012.

Measurement Circuit and Principles





At the resonant frequency $f_s = \frac{\omega_s}{2\pi} = \frac{1}{2\pi\sqrt{LC}}$ $\quad \omega_s L = \frac{1}{\omega_s C}$

$$\frac{V_{out-pk}}{V_{in-pk}} = \left|\frac{V_{out}(j\omega_s)}{V_{in}(j\omega_s)}\right| = \left|\frac{\frac{1}{j\omega_s C}}{R_{core}+R_{cu}}\right| = \frac{\omega_s L}{R_{core}+R_{cu}} = Q_L$$

- The approach of (Han et al.) enables power loss calculation using a *ratio* of voltage amplitude measurements

Y. Han, et. al., Evaluation of Magnetic Materials for Very High Frequency Power Applications," *IEEE Transactions on Power Electronics*, Vol. 27, No. 1, pp. 425-435, Jan. 2012.

Extraction of Core Loss From Q_L

- Core loss extraction: $Q_L = \frac{V_{out-pk}}{V_{in-pk}} = \frac{2\pi f_s L}{R_{core} + R_{cu}}$

$$R_{core} = \frac{2\pi f_s L}{Q_L} - R_{cu}$$

$$P_V = \frac{I_{L-pk}^2 R_{core}}{2V_L}$$

- Copper loss (R_{cu}) estimation: an air-core inductor with the same dimension is fabricated and measured using an impedance analyzer. From Finite Element simulation results, this estimation of R_{cu} has up to 30% error
- In our experiments, the core loss is controlled to be at least 5 times larger than the copper loss to reduce the error caused by R_{cu}

Estimation of Errors

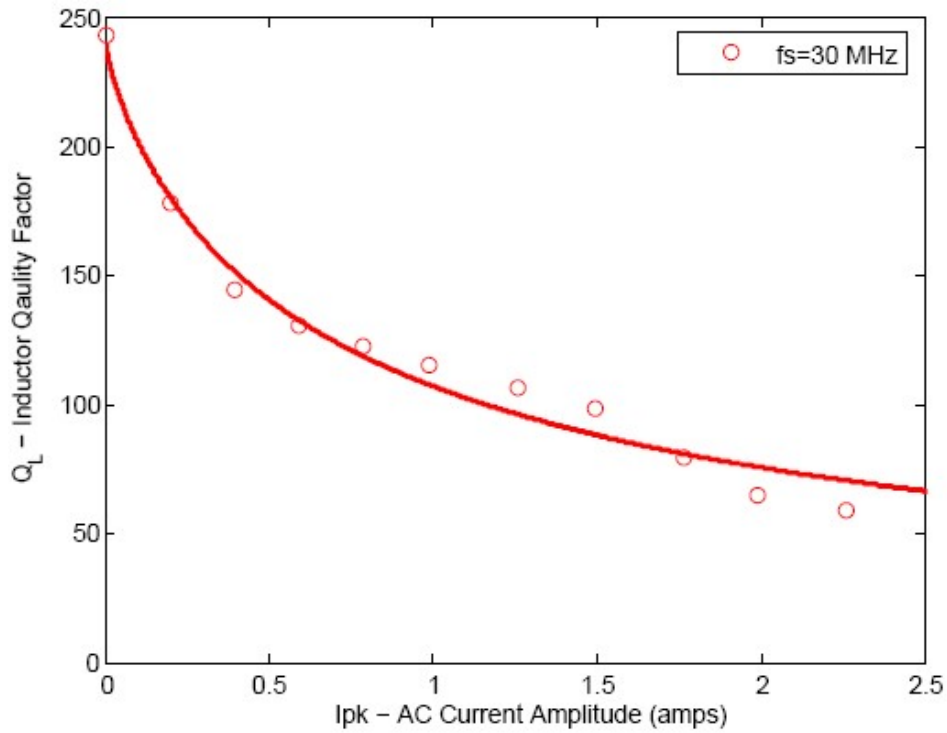
- Error caused by the capacitor ESR
- Error caused by circuit parasitics
- Error caused by copper loss
- Error caused by the measurement frequency
- Error caused by uneven flux density:

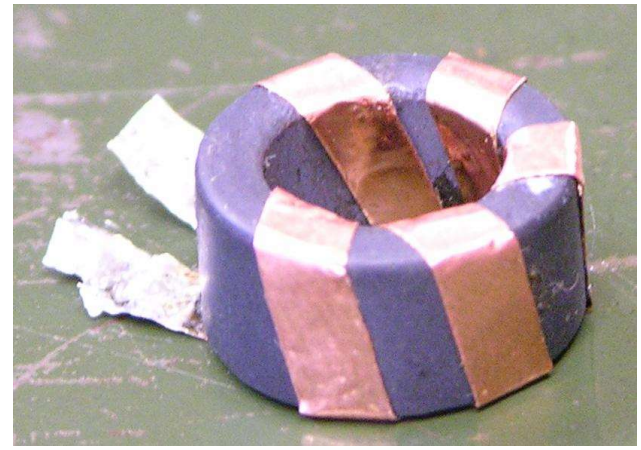
- The total error: less than 20%

Details shown in the Han paper:

Y. Han, et. al., Evaluation of Magnetic Materials for Very High Frequency Power Applications," *IEEE Transactions on Power Electronics*, Vol. 27, No. 1, pp. 425-435, Jan. 2012.

Example



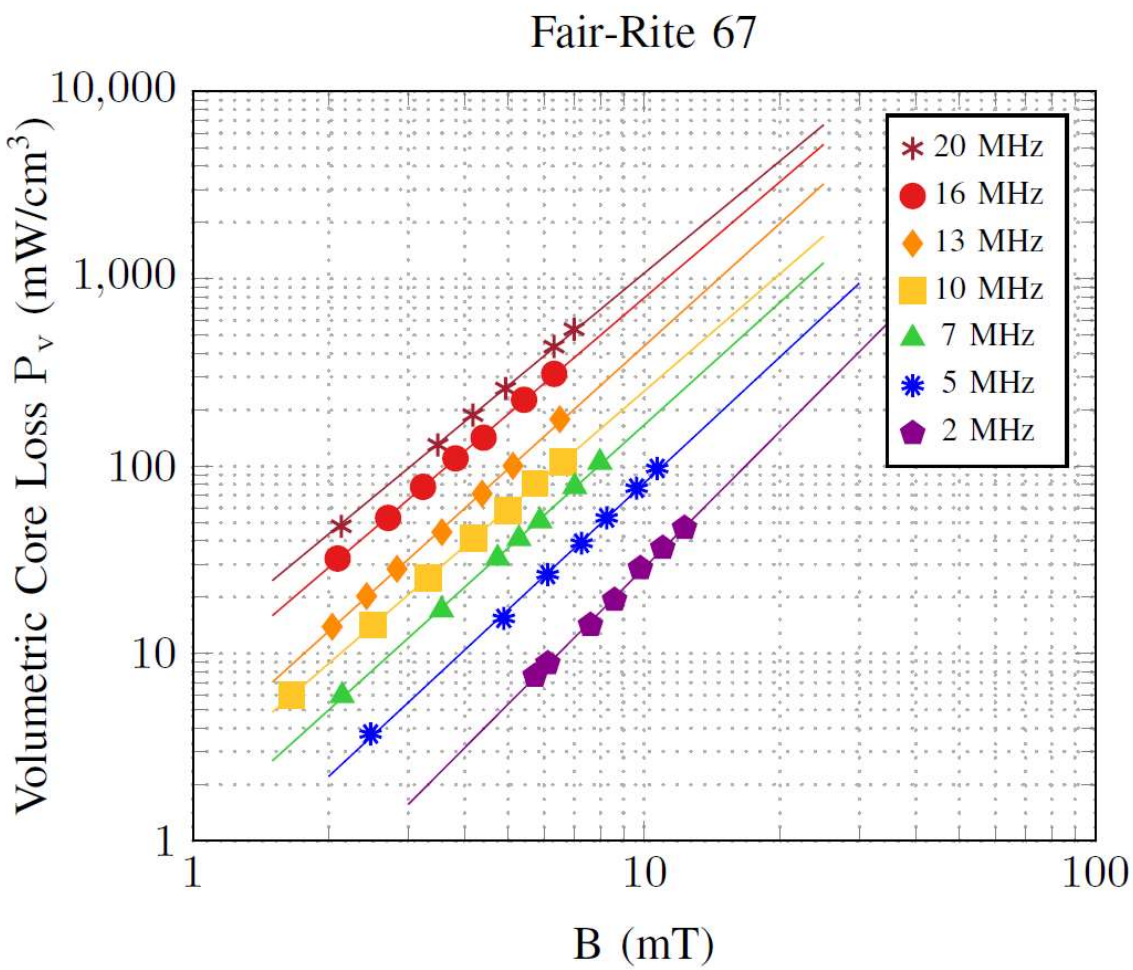


Example inductor fabricated from copper foil and a commercial magnetic core M3-998.

The Q_L of inductor fabricated with an M3 toroidal core (OD= 12.7 mm, ID= 7.82 mm, Ht= 6.35 mm) having N = 5 turns, and L = 190 nH

- **Q_L measurement only depends on the ratio of voltage amplitudes**
- **Eliminates the influence of parasitics & phase shifts**
- **Yields an accurate means to find loss density of a core material as a function of flux density at VHF**

Measured Data



Each curve can be described by Steinmetz parameters k, β

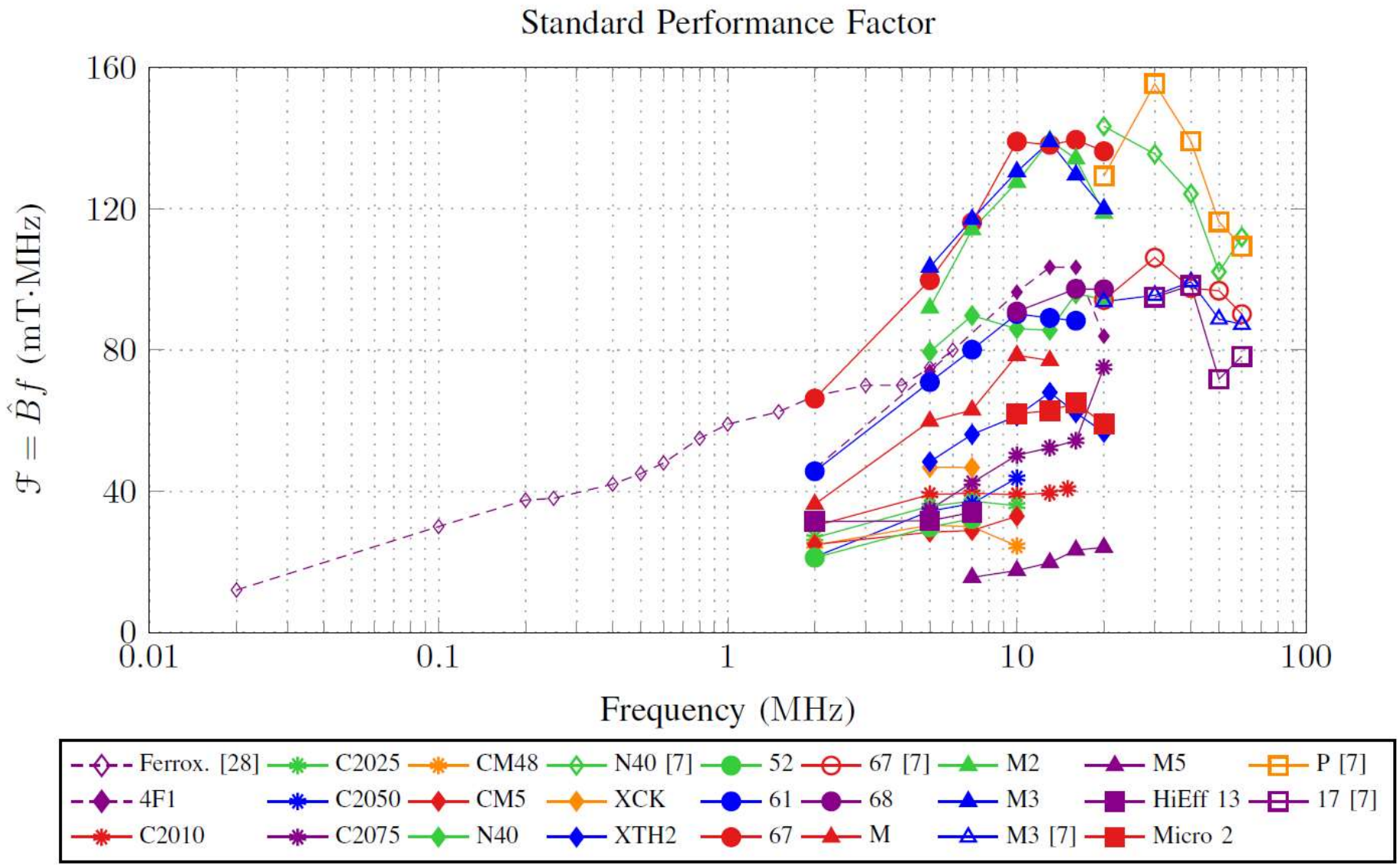
$$P_V = kB_{pk}^{\beta}$$

20 Materials Tested

- All measured data was fit to the Steinmetz equation: $P_V = kB_{pk}^{\beta}$

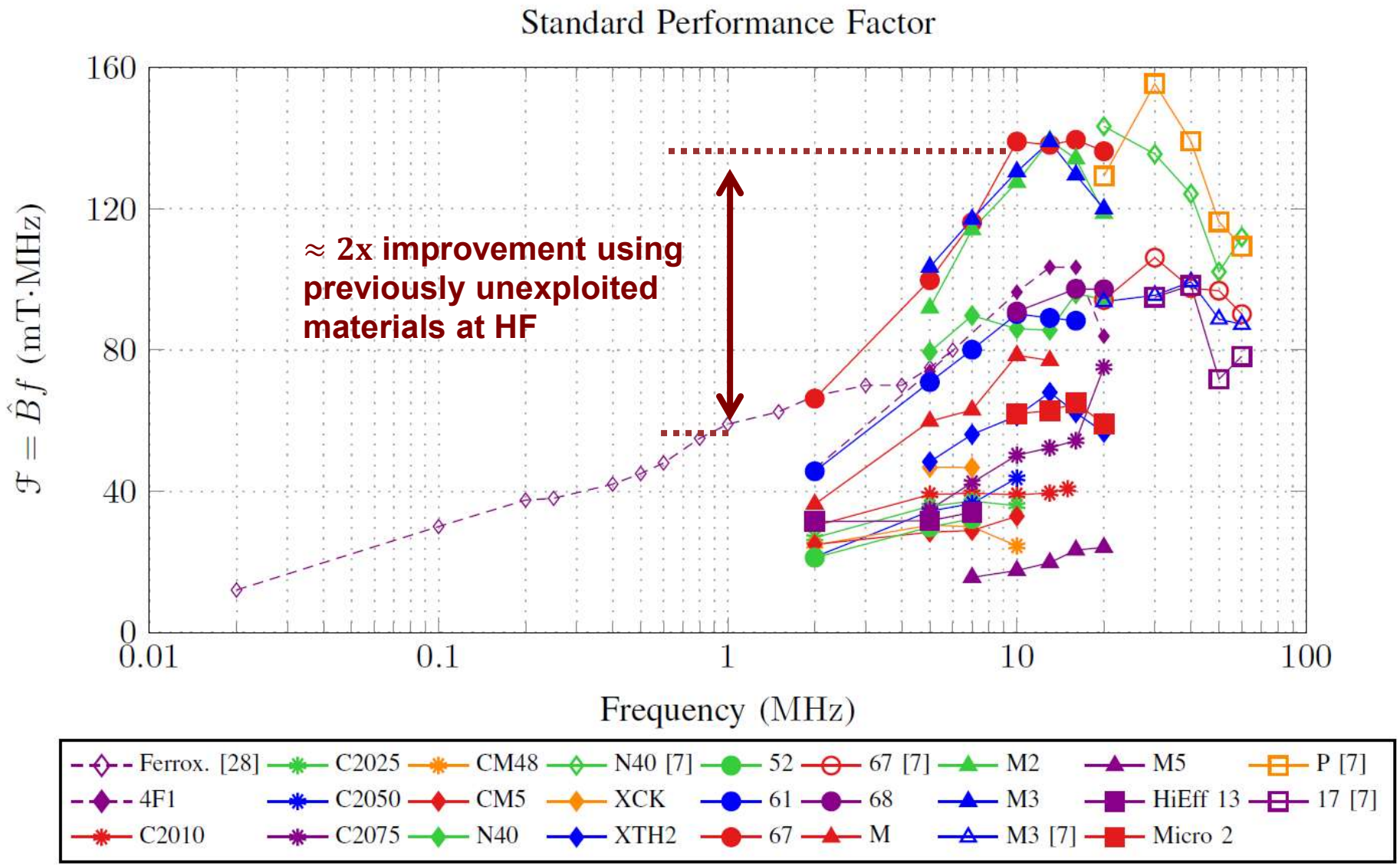
Frequency→		2 MHz		5 MHz		7 MHz		10 MHz		13 MHz		16 MHz		20 MHz	
Material	μ_r	k	β	k	β	k	β	k	β	k	β	k	β	k	β
Ceramic Magn. C2010	340	0.20	2.89	2.61	2.56	10.61	2.23	22.23	2.29	51.55	2.04	-	-	-	-
Ceramic Magn. C2025	175	0.49	2.67	3.14	2.58	11.33	2.27	30.15	2.20	-	-	-	-	-	-
Ceramic Magn. C2050	100	0.52	2.9	2.47	2.75	5.25	2.76	12.44	2.50	-	-	-	-	-	-
Ceramic Magn. C2075	50	-	-	2.31	2.77	3.42	2.77	5.81	2.76	11.88	2.69	20.67	2.61	19.57	2.45
Ceramic Magn. CM48	190	0.59	2.68	7.49	2.33	21.5	2.17	80.01	2.05	-	-	-	-	-	-
Ceramic Magn. CM5	290	0.61	2.66	9.42	2.29	22.55	2.19	42.04	2.08	-	-	-	-	-	-
Ceramic Magn. N40	15	-	-	1.52	2.09	3.04	2.00	6.61	2.01	11.09	2.02	12.47	2.06	21.20	2.04
Ceramic Magn. XCK	210	-	-	1.07	2.75	4.86	2.44	-	-	-	-	-	-	-	-
Ceramic Magn. XTH2	80	-	-	0.83	2.82	1.72	2.72	3.86	2.68	7.07	2.57	15.20	2.57	42.00	2.38
Fair-Rite 52	250	0.46	2.97	5.44	2.53	14.44	2.32	-	-	-	-	-	-	-	-
Fair-Rite 61	125	0.08	2.79	0.42	2.67	0.83	2.62	1.80	2.56	4.31	2.47	6.66	2.53	-	-
Fair-Rite 67	40	0.10	2.44	0.69	2.20	1.11	2.18	2.09	2.08	2.91	2.18	6.06	2.04	10.95	1.99
Ferroxcube 4F1	80	0.15	2.57	1.11	2.27	-	-	2.86	2.28	6.53	2.09	10.89	2.05	23.20	2.14
Fair-Rite 68	16	-	-	-	-	-	-	3.92	2.2	-	-	11.71	2.08	22.67	1.96
Metamagnetics HiEff 13	425	0.11	3.06	10.44	2.10	12.69	2.32	-	-	-	-	-	-	-	-
Micrometals 2	10	-	-	-	-	-	-	10.97	2.09	19.32	2.07	28.79	2.04	57.09	2.00
National Magn. M	125	0.03	3.36	0.45	2.83	1.35	2.69	2.52	2.57	5.23	2.56	-	-	-	-
National Magn. M2	40	-	-	0.41	2.44	0.69	2.36	1.45	2.3	2.85	2.18	5.39	2.13	12.58	2.07
National Magn. M3	20	-	-	0.85	2.10	1.66	2.03	2.55	2.05	4.87	1.95	7.54	2.01	14.44	1.98
National Magn. M5	7.5	-	-	-	-	90.34	2.14	147.6	2.17	198.3	2.21	225.1	2.12	335.1	2.15

Performance Factor at HF



A. Hanson, J. Belk, C.R. Sullivan and D.J. Perreault, "Measurements and Performance Factor Comparisons of Magnetic Materials at MHz Frequencies," *2015 Energy Conversion Congress and Exposition, Sept. 2015 (Also to appear, IEEE Transactions on Power Electronics)*

Performance Factor at HF



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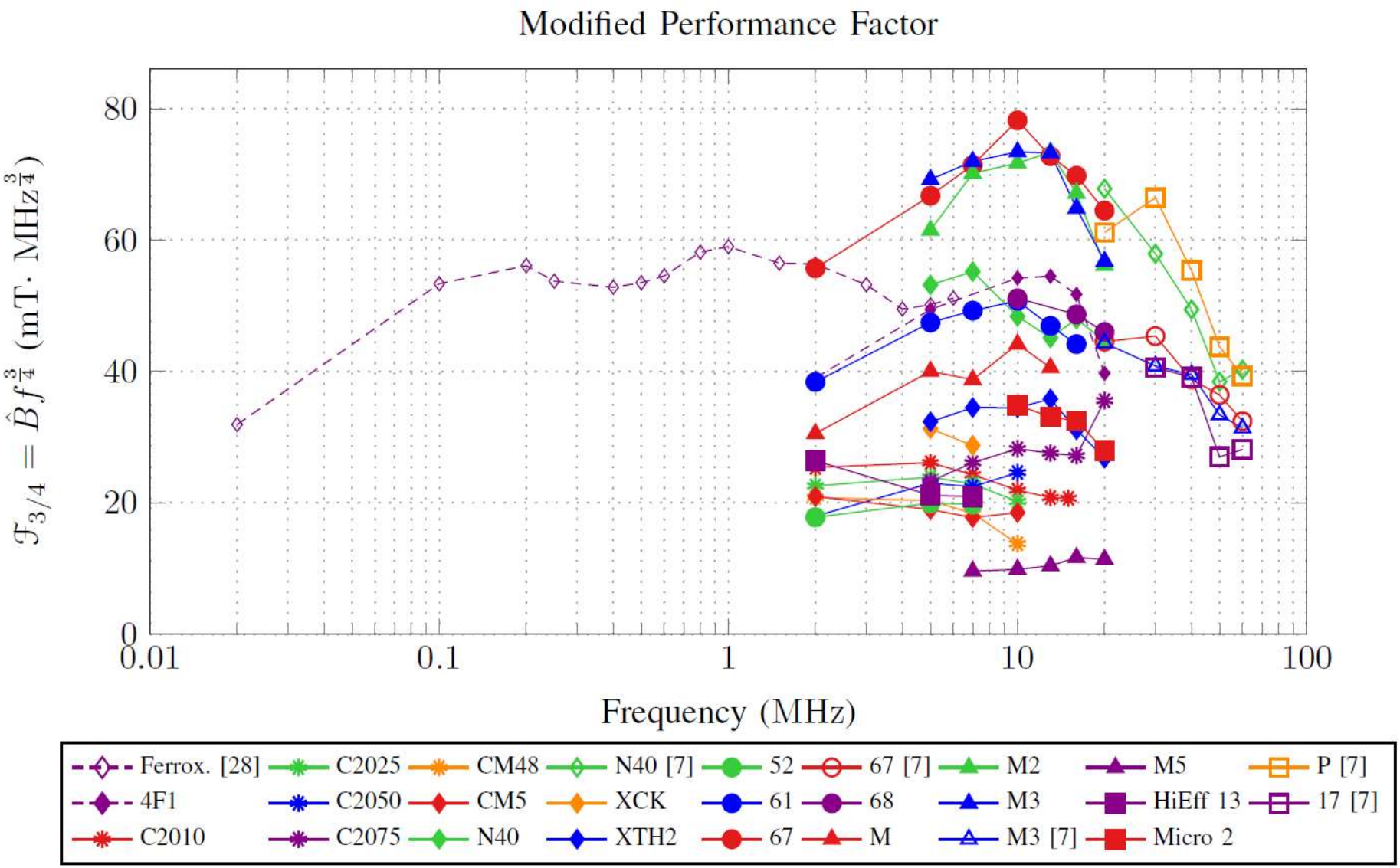
Modified Performance Factor

- Traditional Performance Factor $\mathcal{F}_1 = B_{pk}f$ assumes a fixed (N•I) as a function of frequency (winding loss is independent of frequency)
- As frequency increases, high frequency winding effects become significant, making the current handling of the windings frequency dependent
- For example, skin effect makes the effective resistance $R \propto \sqrt{f}$ To maintain constant I^2R winding loss across frequency, current handling must drop as $f^{-1/4}$, changing the performance factor to:

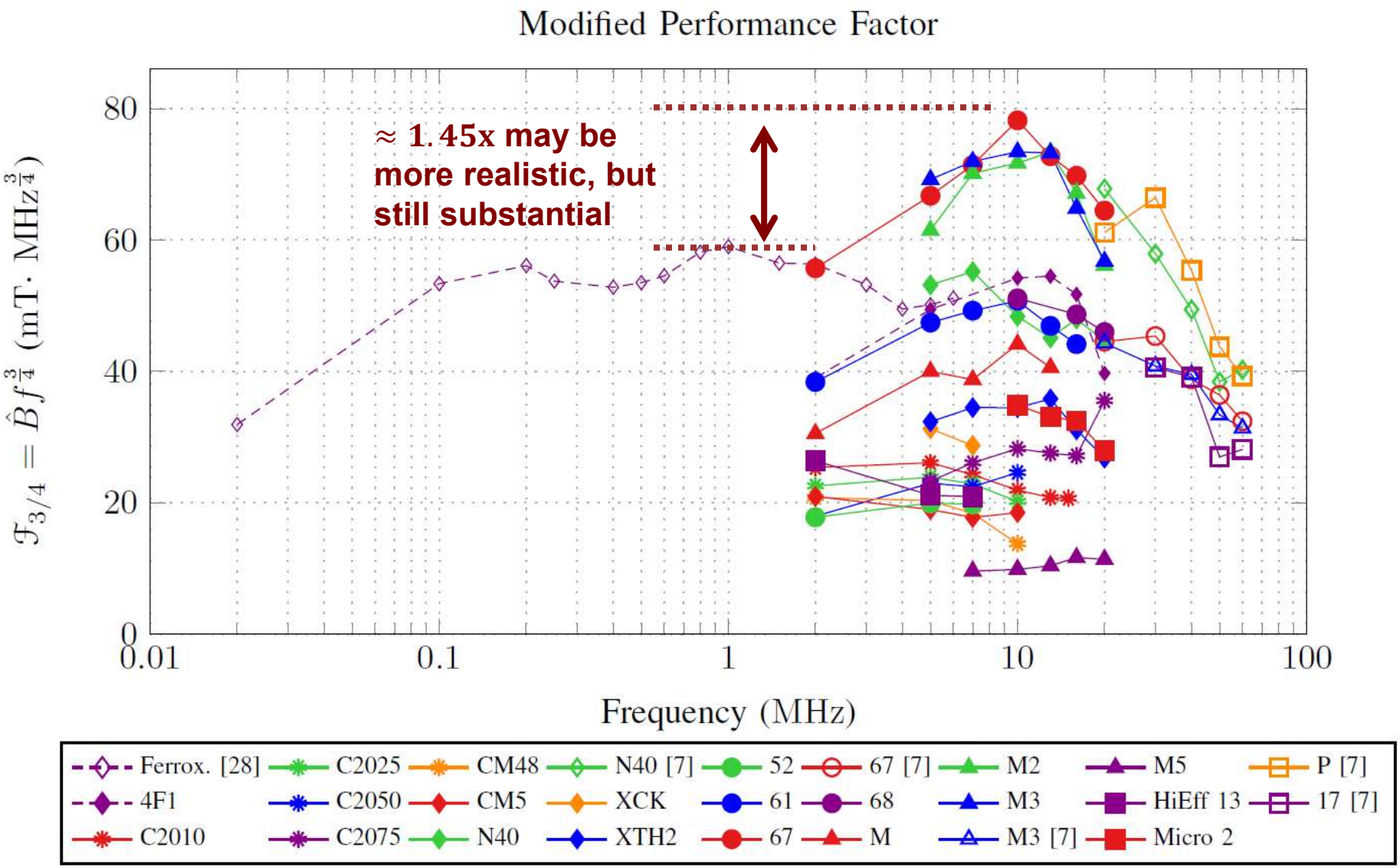
$$\mathcal{F}_{\frac{3}{4}} = \underbrace{\left(B_{pk}f\right)}_{\text{(Voltage)}} \cdot \underbrace{\left(f^{-\frac{1}{4}}\right)}_{\text{(Current)}} = B_{pk}f^{\frac{3}{4}}$$

- For other assumptions, it can be shown that $\mathcal{F}_w = B_{pk}f^w \left(\frac{1}{2} < w < 1\right)$ is appropriate. This **modified performance factor**, especially $\mathcal{F}_{\frac{3}{4}}$, is valuable for HF material evaluation

Modified Performance Factor at HF



Modified Performance Factor at HF

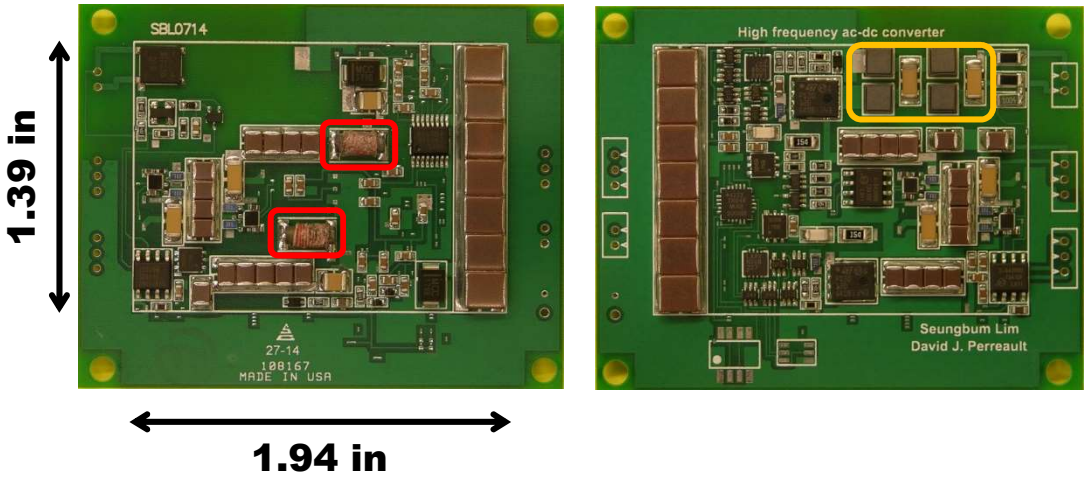


Implications for Power Density

There is great opportunity for power conversion at HF!

- Main power stage (loss-limited) magnetics density: 1.45x – 2x improvement

- Other components (EMI filters, etc.) scale freely with frequency for substantial improvement.

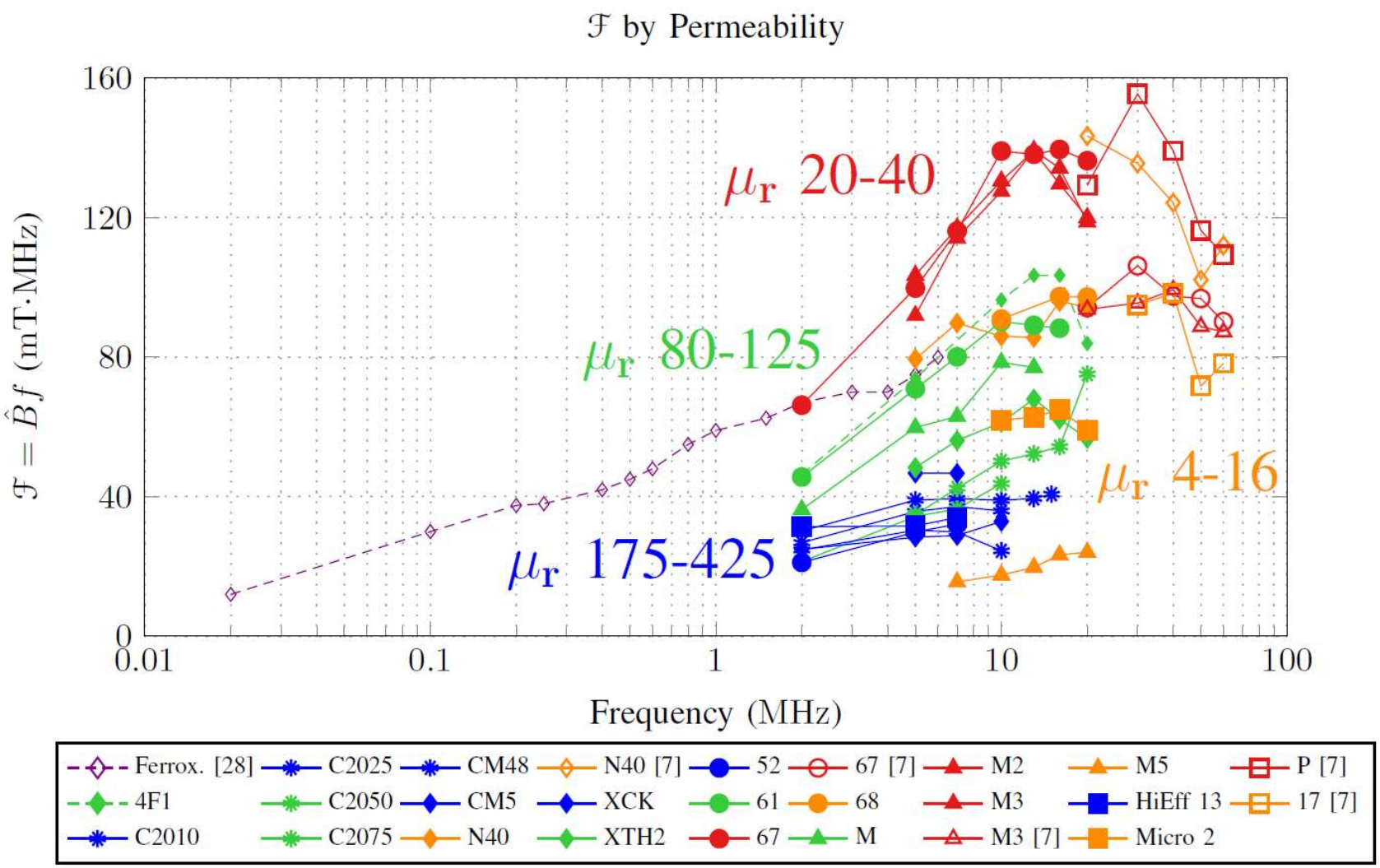


- Inductors
- EMI Filter

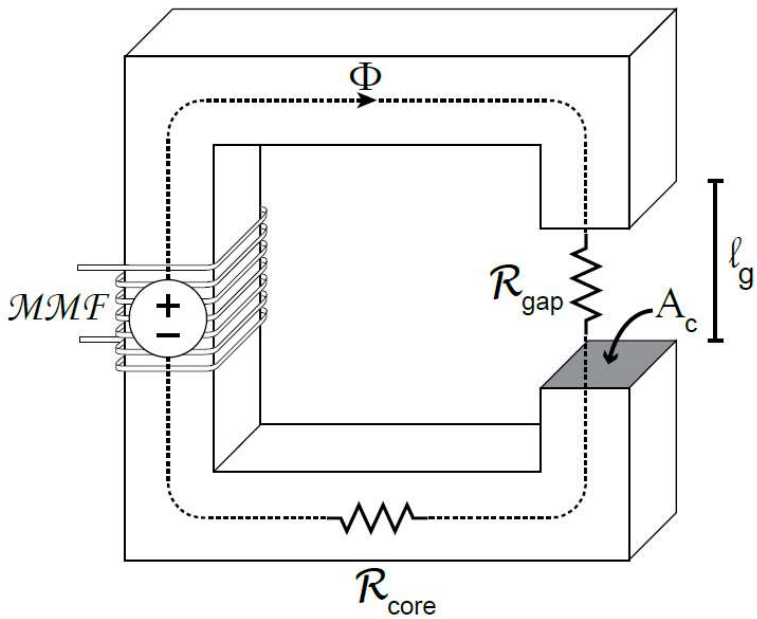
5-10 MHz Off-Line LED Driver (Seungbum Lim, MIT)

What about Permeability?

- Many low-frequency materials have μ_r > 500, but most HF/VHF materials have μ_r in the range of 4 - 425



Permeability Consideration

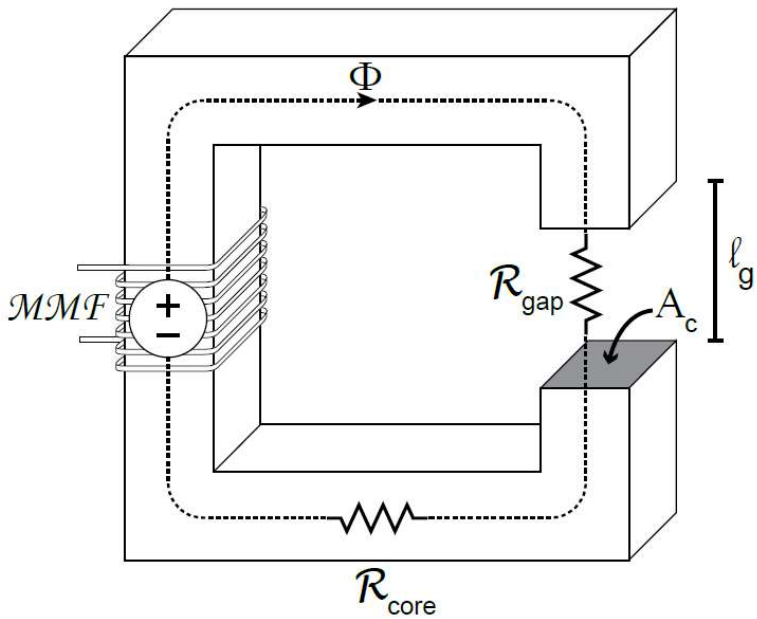


- For an ungapped inductor:

$$L_{ungapped} = \frac{N^2}{\mathcal{R}_C} = \frac{\mu_0 \mu_r N^2 A_C}{l_C}$$

- Couldn't we use high μ_r to reduce the number of turns and decrease total losses?

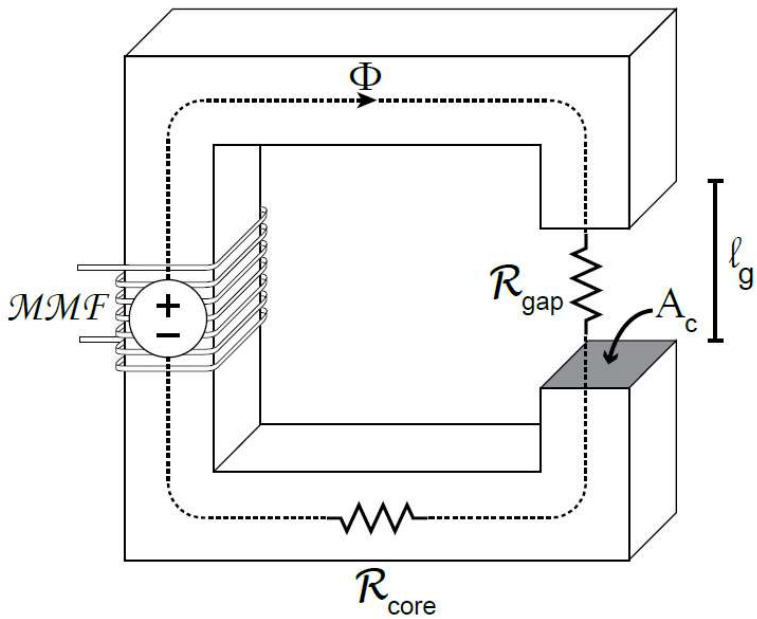
Permeability Considerations



- Power inductors are almost always *gapped* to balance core/copper loss and reduce overall loss
- For a gapped inductor, **permeability trades with gap length**:

$$L_{gapped} = \frac{N^2}{\mathcal{R}_{tot}} = \frac{\mu_0 N^2 A_C}{l_g + \frac{l_c}{\mu_r}} \approx \frac{\mu_0 N^2 A_C}{l_g}$$

Permeability Considerations



As long as permeability is high enough that a gap is required, additional permeability does not affect loss

$$\mu_{r,threshold} = \frac{L l_C}{\mu_0 N_{opt}^2 A_C}$$

→ **Permeability above $\mu_{r,threshold}$ is much less useful**

Conclusion

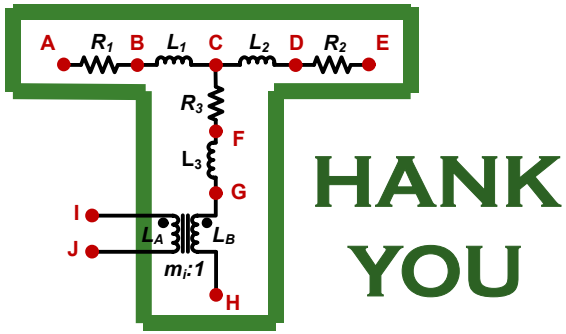
- We have investigated the loss characteristics of many commercial rf magnetic materials for power conversion applications at HF/VHF (> 3 MHz)
- A experimental method to directly measure inductor quality factor has been described
  - Estimate core loss characteristics based on quality factor measurements
- Measurements of many HF materials have been made
- Material "Performance Factor" continues to increase up to at least the high HF range (3-30 MHz)
- Modified performance factor (accounting for ac winding loss effects) also improves to 10+ MHz
- Reduced permeability of HF materials is ok

- Power conversion at HF poses major opportunities!

END

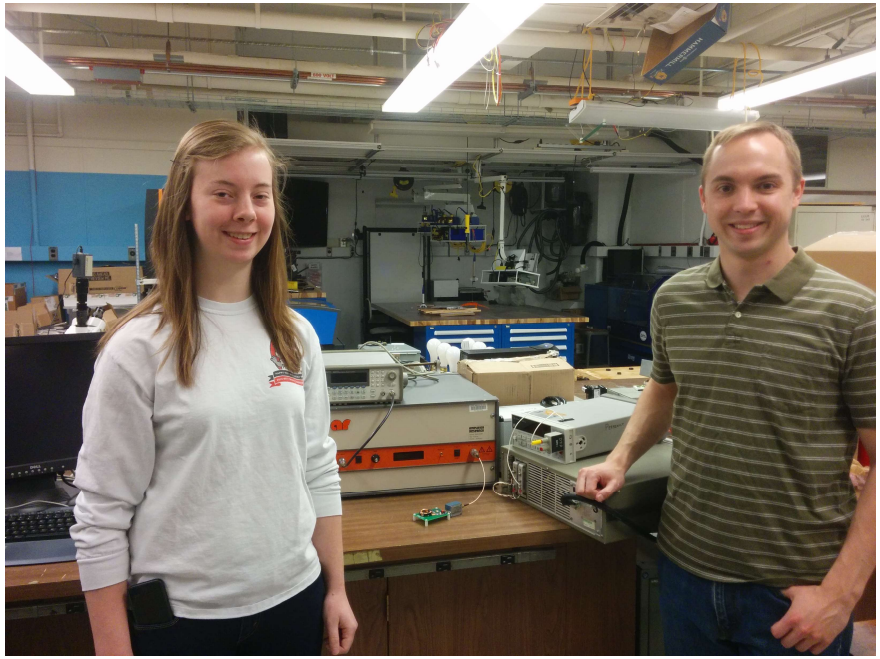
Contributors:

- Alex Hanson
- Julia Belk
- Prof. Charles Sullivan (Dartmouth)
- Dr. Yehui Han



Sponsorship:

- Lockheed Martin
- National Science Foundation
- MIT CICS



Publications:

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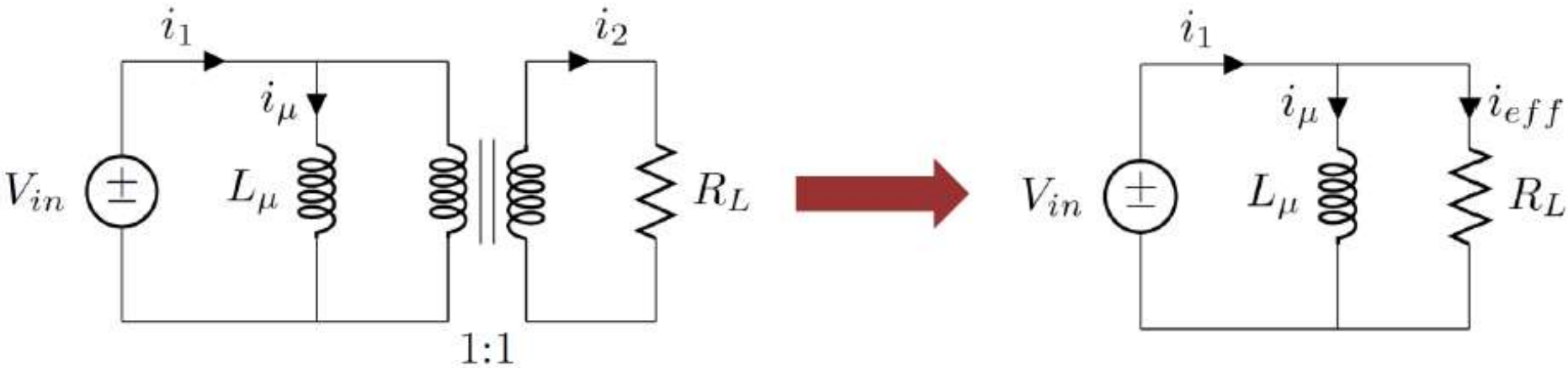
- *(Also to appear, IEEE Transactions on Power Electronics)*

Permeability Needs for Transformers

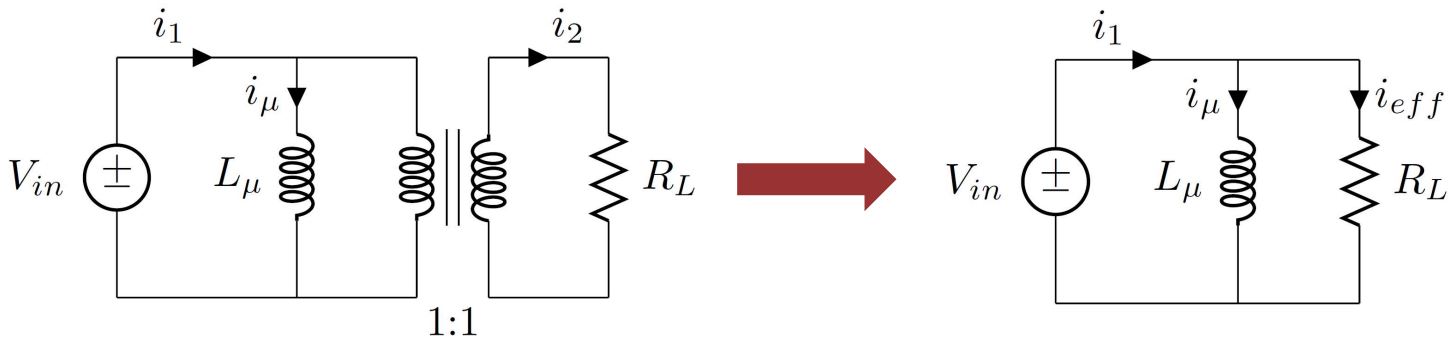
- **Reduced permeability increases the magnetizing current one must drive to magnetize the core**
  - **e.g., in a transformer**
  - **Causes added conduction loss (but current orthogonal to load)**



- **Define acceptable loss levels at:** $B = \hat{B}$

$$NI = K = \hat{K} l_c$$

Permeability Extension



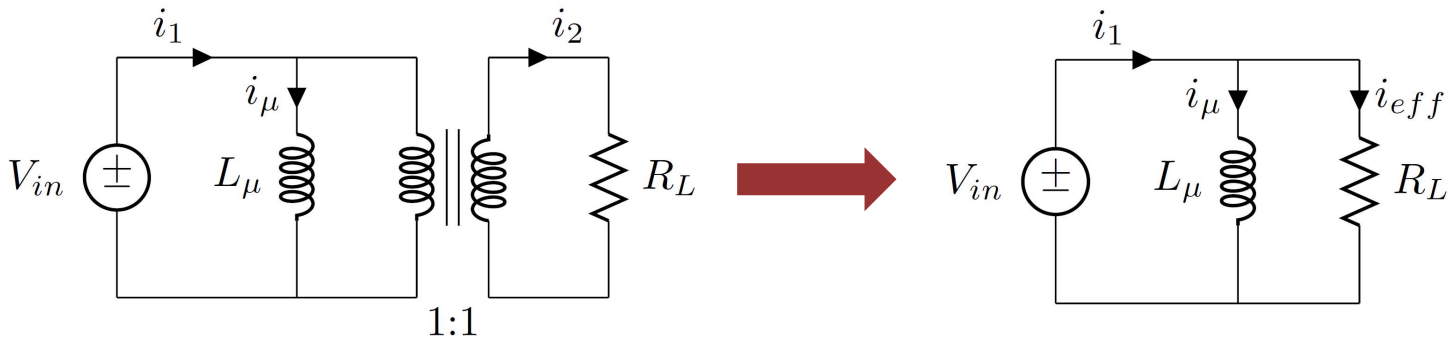
$$P_{DEL} = V_{in} I_{eff} = \frac{1}{2} 2\pi f \cdot N A_C \hat{B} \cdot \sqrt{\left(\frac{\hat{k} l_C}{N}\right)^2 - \left(\frac{l_C}{N^2 \mu_C A_C * 2\pi f}\right)^2}$$

$$= \pi A_C l_C \cdot \hat{B} f \cdot \sqrt{\hat{K}^2 - \left(\frac{\hat{B}}{\mu_C}\right)^2}$$

$$= \left(\boldsymbol{\pi \hat{K}}\right) \cdot \left(\boldsymbol{A_C l_C}\right) \cdot \left(\boldsymbol{\hat{B} f}\right) \sqrt{\mathbf{1} - \left(\frac{\boldsymbol{\hat{B}}}{\boldsymbol{\hat{K} \mu_C}}\right)^2}$$

$$= (scale) \cdot (volume) \cdot (\mathcal{F}_1) \cdot (\mu\, factor)$$

Permeability Extension



- **Modified performance factor can be thought of as an adjustment to $\hat{K}$**
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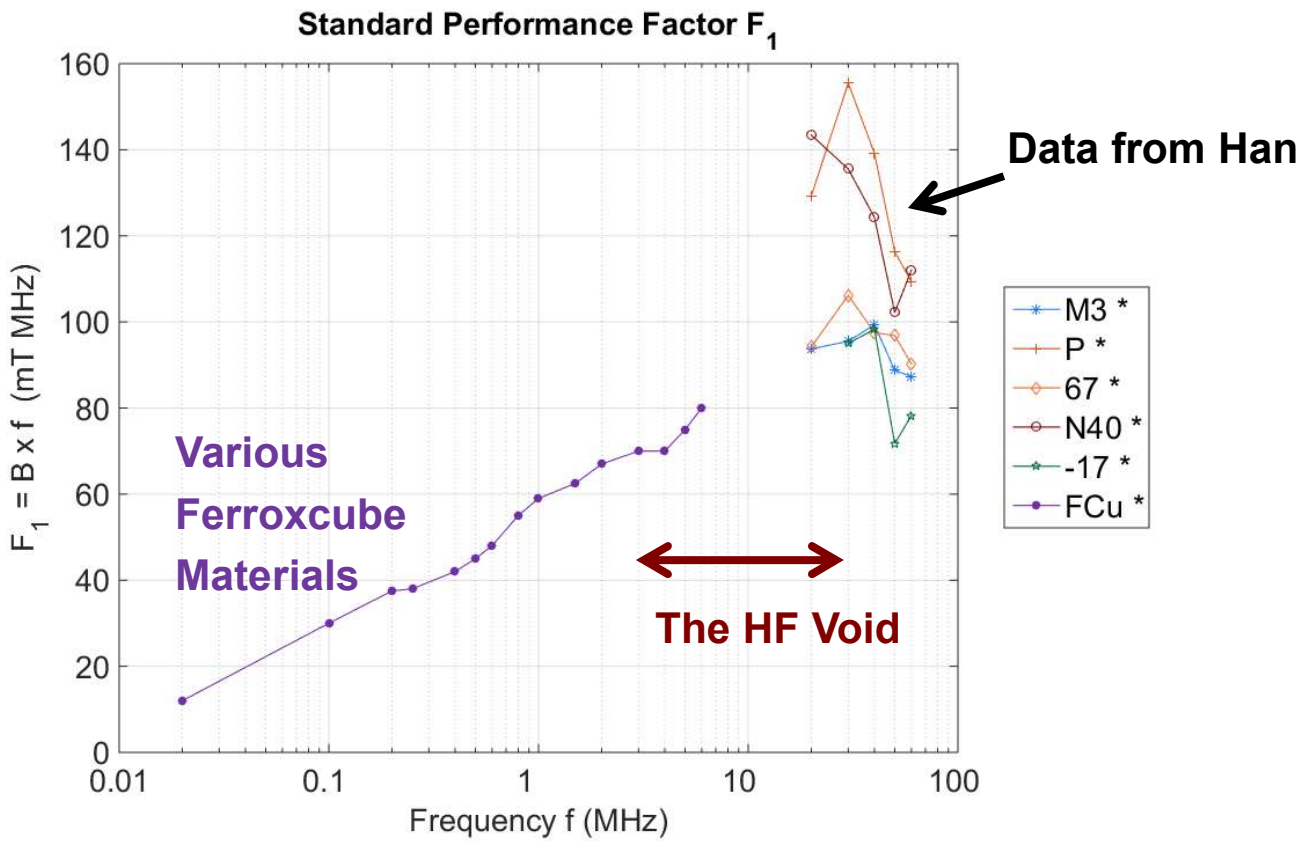
  - **One *needs* less permeability at HF, VHF**

$$P_{DEL} = (\pi\hat{K}) \cdot (A_C l_C) \cdot (\hat{B} f) \sqrt{1 - \left(\frac{\hat{B}}{\hat{K}\mu_C}\right)^2}$$

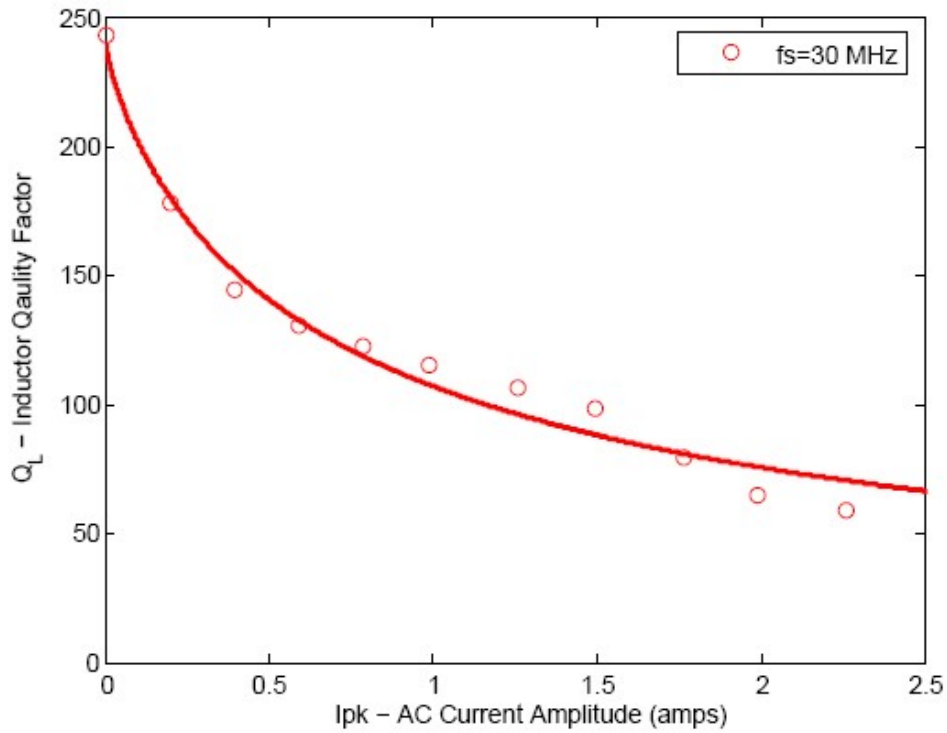
The HF Void

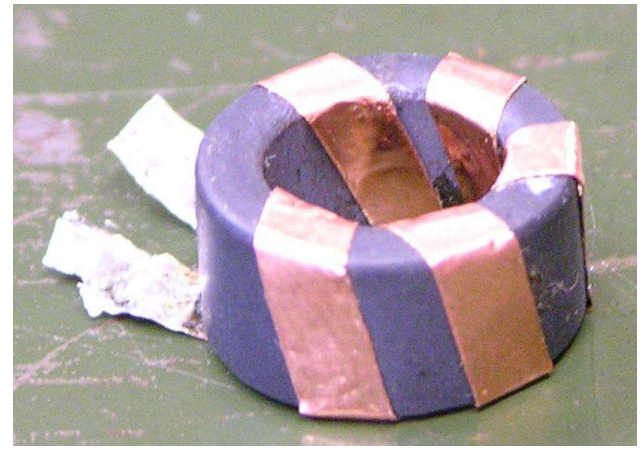
- **Earlier work by Han, et. al., characterized some materials in the (30+ MHz) VHF range, but left out materials suitable for the HF (3-30 MHz) range**
  - **We aim to fill this void**



Y. Han, et. al., Evaluation of Magnetic Materials for Very High Frequency Power Applications," *IEEE Transactions on Power Electronics*, Vol. 27, No. 1, pp. 425-435, Jan. 2012.

Example





Example inductor fabricated from copper foil and a commercial magnetic core M3-998.

The Q_L of inductor fabricated with an M3 toroidal core (OD= 12.7 mm, ID= 7.82 mm, Ht= 6.35 mm) having N = 5 turns, and L = 190 nH

- **Q_L measurement only depends on the ratio of voltage amplitudes**
- **Eliminates the influence of parasitics & phase shifts**
- **Yields an accurate means to find loss density of a core material as a function of flux density at VHF**

Find the Measurement Frequency

- Challenge: the precise resonant frequency f_s is unknown because of the parasitics and components' errors
- To address this issue, we pre-calculate the capacitor value to achieve the approximate resonant frequency, then adjust the frequency around the calculated resonant frequency to find the frequency point $f_s^{'}$ where $\frac{V_{out-pk}}{V_{in-pk}}$ has the maximum value
- $f_s^{'} = f_s\sqrt{1-\frac{1}{2Q_L^2}}$ As $Q_L >> 1$ for all cases of interest, $f_s^{'}$ is approximately equal to f_s

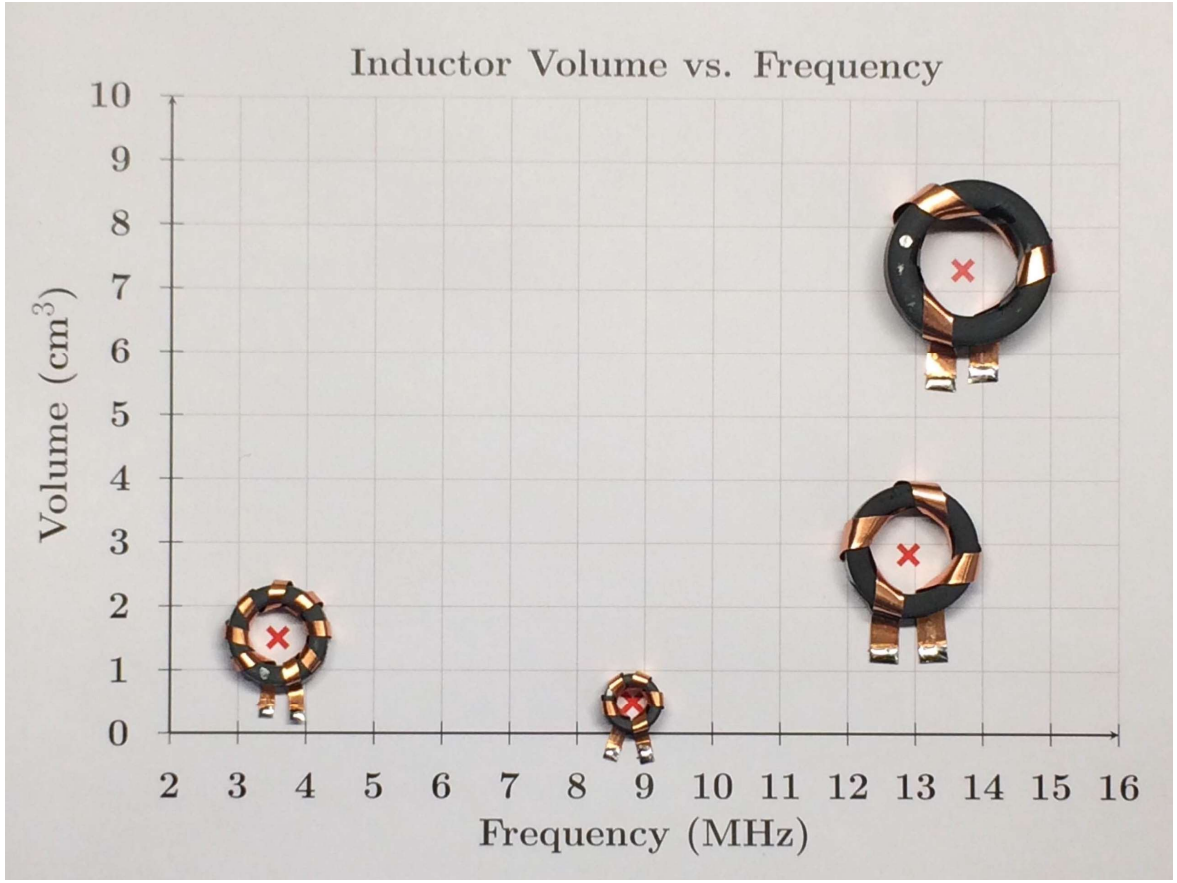
Achievable Power Density (crude example)

- Ungapped cores with identical *Z*, *Q*, and current *I* (not optimal; for illustration only)

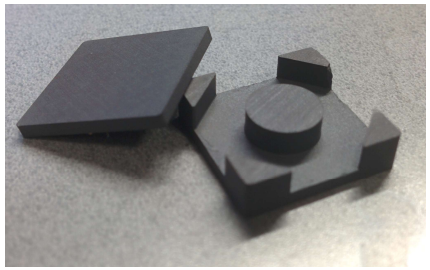
Fair-Rite 67

$\mu_r = 40$

$I_{pk} = 1.6\ A$



Frequency MHz	Impedance Ω	Large-Signal Q	Volume cm^3
3.58	36.5	212	1.50
8.83	33.7	193	0.49
12.90	33.4	220	2.83
13.70	39.9	202	7.33



(Can be made in planar shapes!)

Materials Overview (1)

- **Many high permeability and low frequency (<10 MHz) magnetic materials:**
  - **Exhibit unacceptable high losses at frequencies above a few megahertz (e.g., 3F4 from Ferroxcube shown in Fig. 1)**

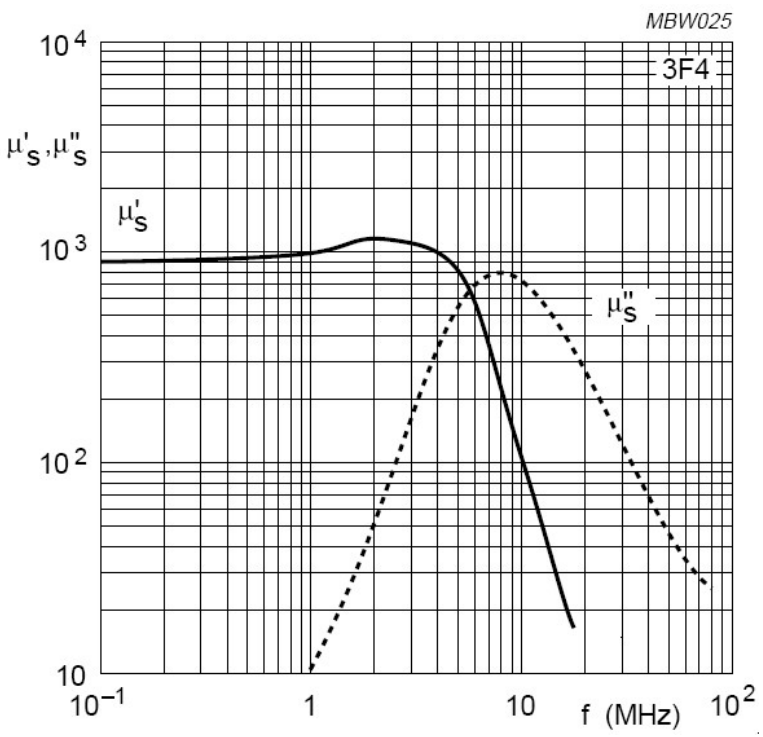


Fig. 1. 3F4 (NiZn, μ_r=900) Complex permeability as a function of frequency (Adapted from Ferrocube 3F4 Material Specification Data Sheet).

$$Q_{L\,\max} = \frac{\mu_s'}{\mu_s''} \quad \text{(Core loss only)}$$

Materials Overview (2)

- **Some low permeability and high frequency (>3 MHz) magnetic materials are available:**
  - **Low loss characteristics under large AC flux swings make these materials potentially suitable for HF/VHF applications (e.g. M3 from National Magnetics Group, Inc. shown in Fig.2)**
  - **ONLY characterized for small-signal drive condition, and NOT under the high flux-density conditions desired for VHF power conversion**

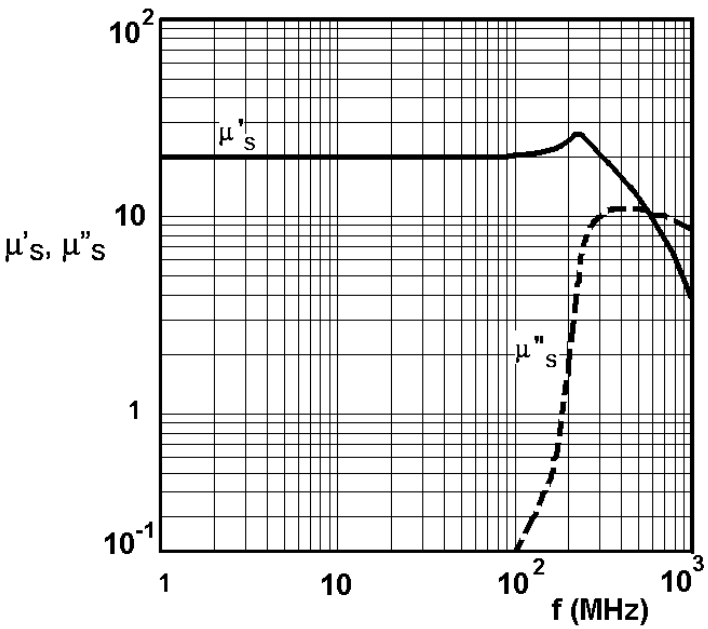
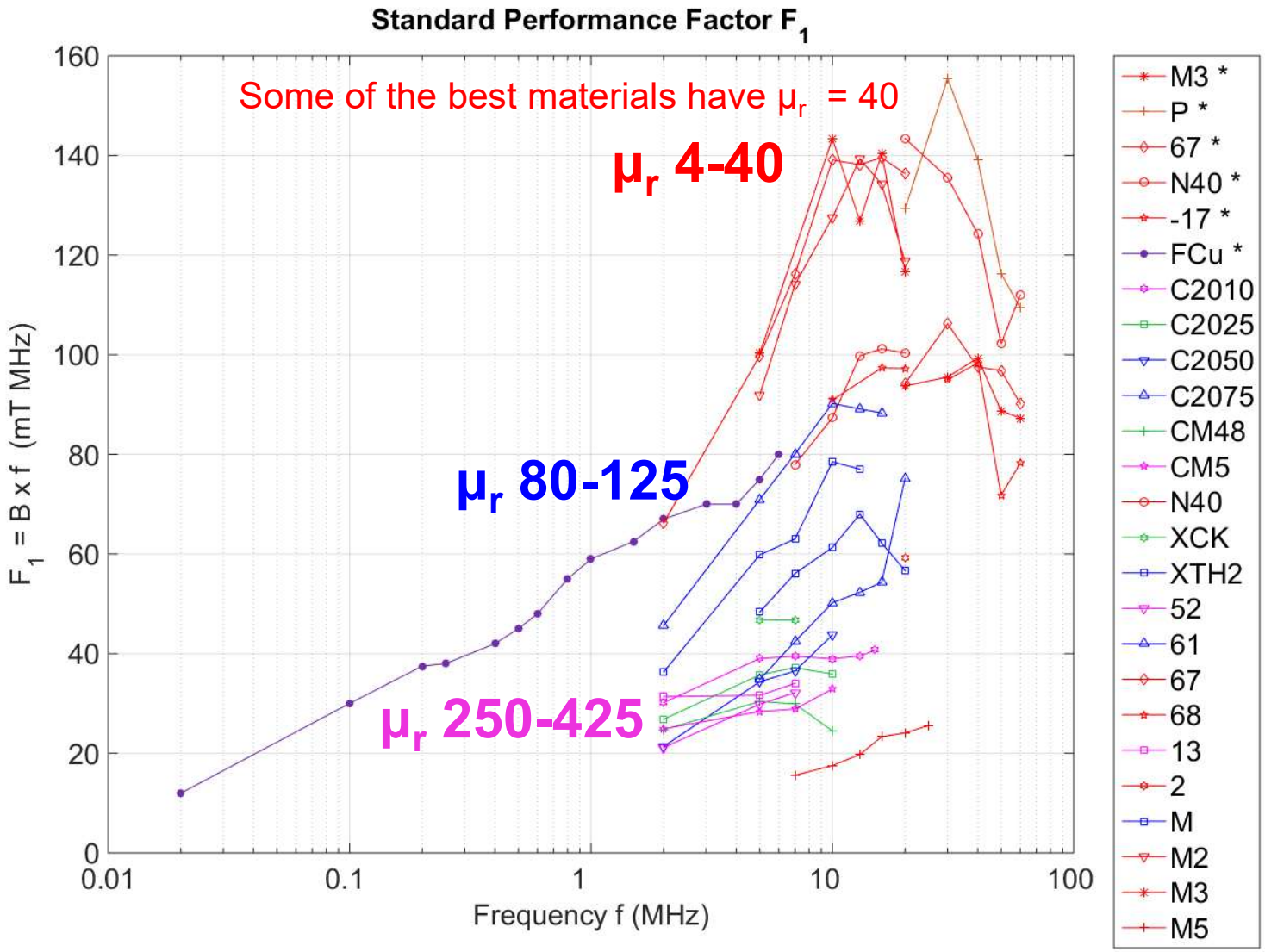


Fig. 2. M3 (NiZn, μ_r=20) Complex permeability as a function of frequency (Adapted from National Magnetics Group M3 Material Specification Data Sheet).

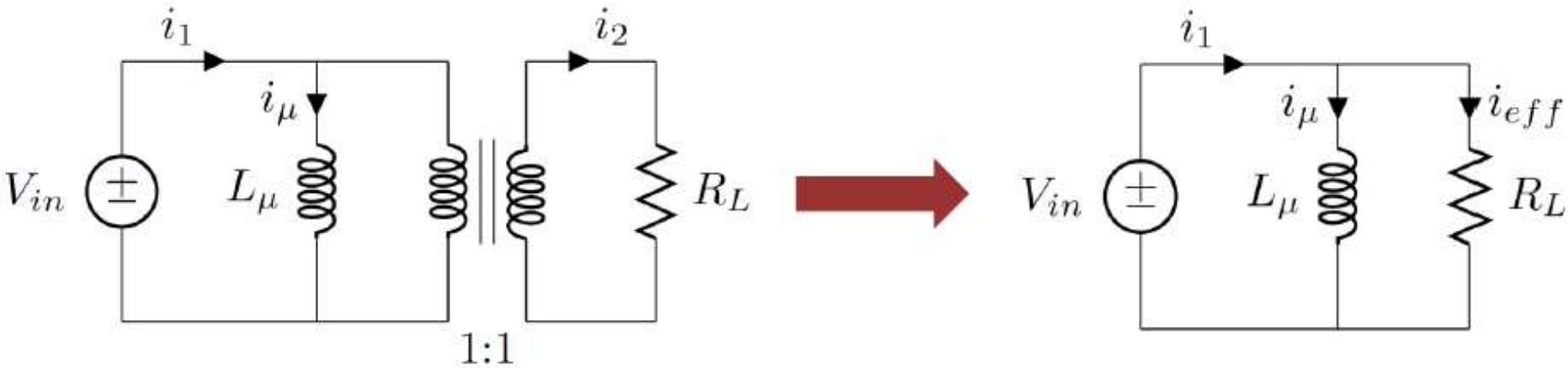
What about Permeability?

- **Many low-frequency materials have μ_r > 500, but the HF/VHF materials have μ_r in the range of 4 - 425**



Consideration of Permeability

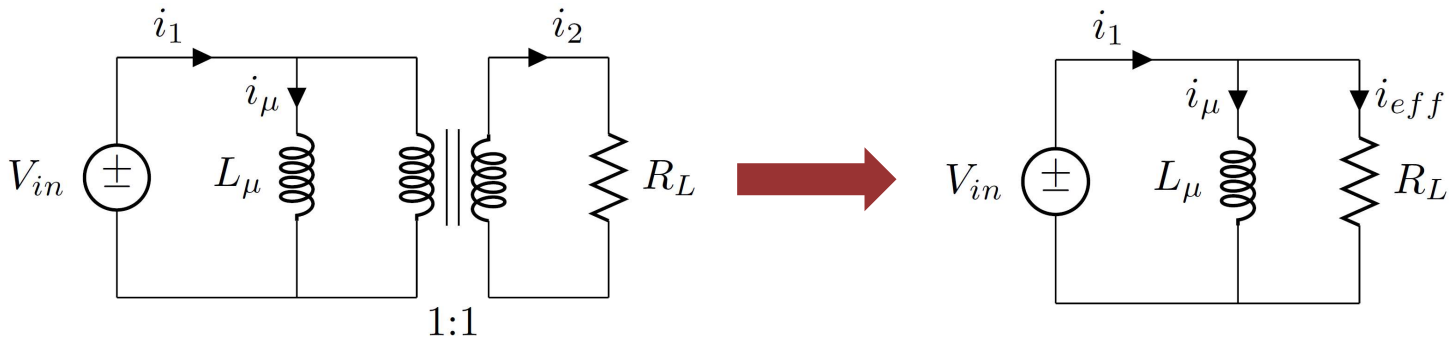
- **Reduced permeability increases the magnetizing current one must drive to magnetize the core**
  - **e.g., in a transformer**
  - **Causes added conduction loss (but current orthogonal to load)**



- **Define acceptable loss levels at:** $B = \hat{B}$

$$NI = K = \hat{K} l_c$$

Permeability Extension



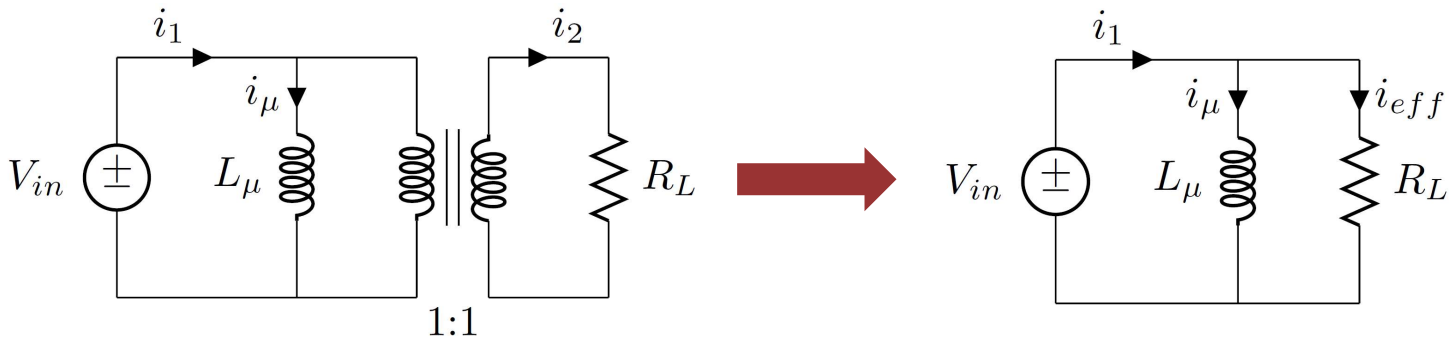
$$P_{DEL} = V_{in} I_{eff} = \frac{1}{2} 2\pi f \cdot N A_C \hat{B} \cdot \sqrt{\left(\frac{\hat{k} l_C}{N}\right)^2 - \left(\frac{l_C}{N^2 \mu_C A_C * 2\pi f}\right)^2}$$

$$= \pi A_C l_C \cdot \hat{B} f \cdot \sqrt{\hat{K}^2 - \left(\frac{\hat{B}}{\mu_C}\right)^2}$$

$$= \left(\boldsymbol{\pi \hat{K}}\right) \cdot \left(\boldsymbol{A_C l_C}\right) \cdot \left(\boldsymbol{\hat{B} f}\right) \sqrt{\mathbf{1} - \left(\frac{\boldsymbol{\hat{B}}}{\boldsymbol{\hat{K} \mu_C}}\right)^2}$$

$$= (scale) \cdot (volume) \cdot (\mathcal{F}_1) \cdot (\mu\, factor)$$

Permeability Extension



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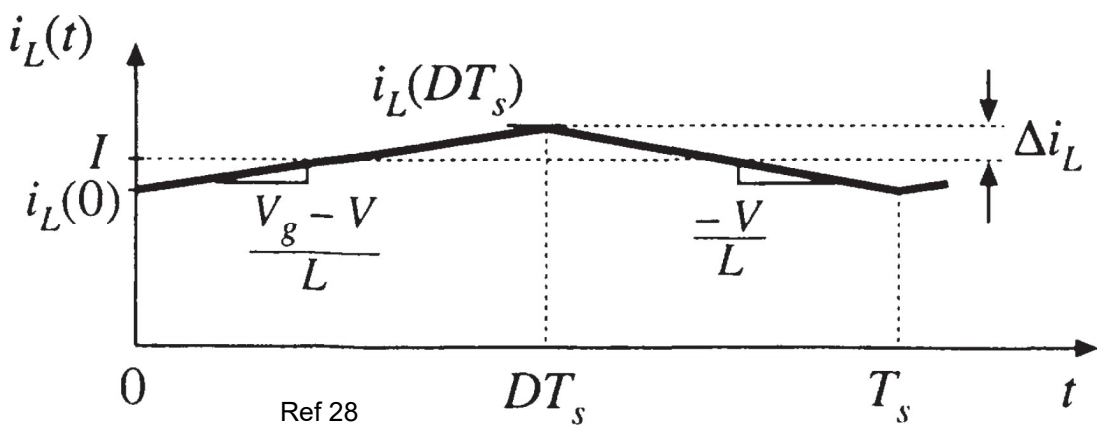
  - **One *needs* less permeability at HF, VHF**

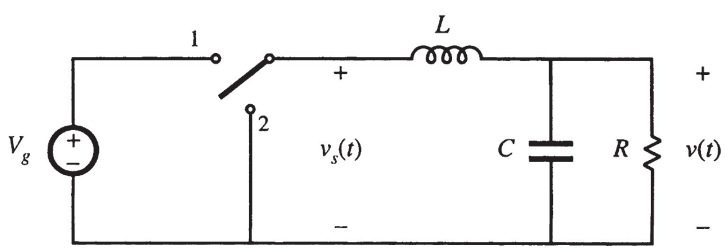
$$P_{DEL} = (\pi\hat{K}) \cdot (A_C l_C) \cdot (\hat{B} f) \sqrt{1 - \left(\frac{\hat{B}}{\hat{K}\mu_C}\right)^2}$$

When magnetic field isn't AC

- Many popular DC/DC converters have a DC component to inductor current (and hence to magnetic field)
  - Buck, Boost, Buck-Boost, Ćuk
  - Forward
  - Flyback
  - Etc.
- Most textbooks (including Kassakian [26] and Erikson [27]) ignore the DC component and take the AC component only
- While the effects of AC harmonics have been extensively studied[21-24], the *fact that the loss curves change with bias* has not as much

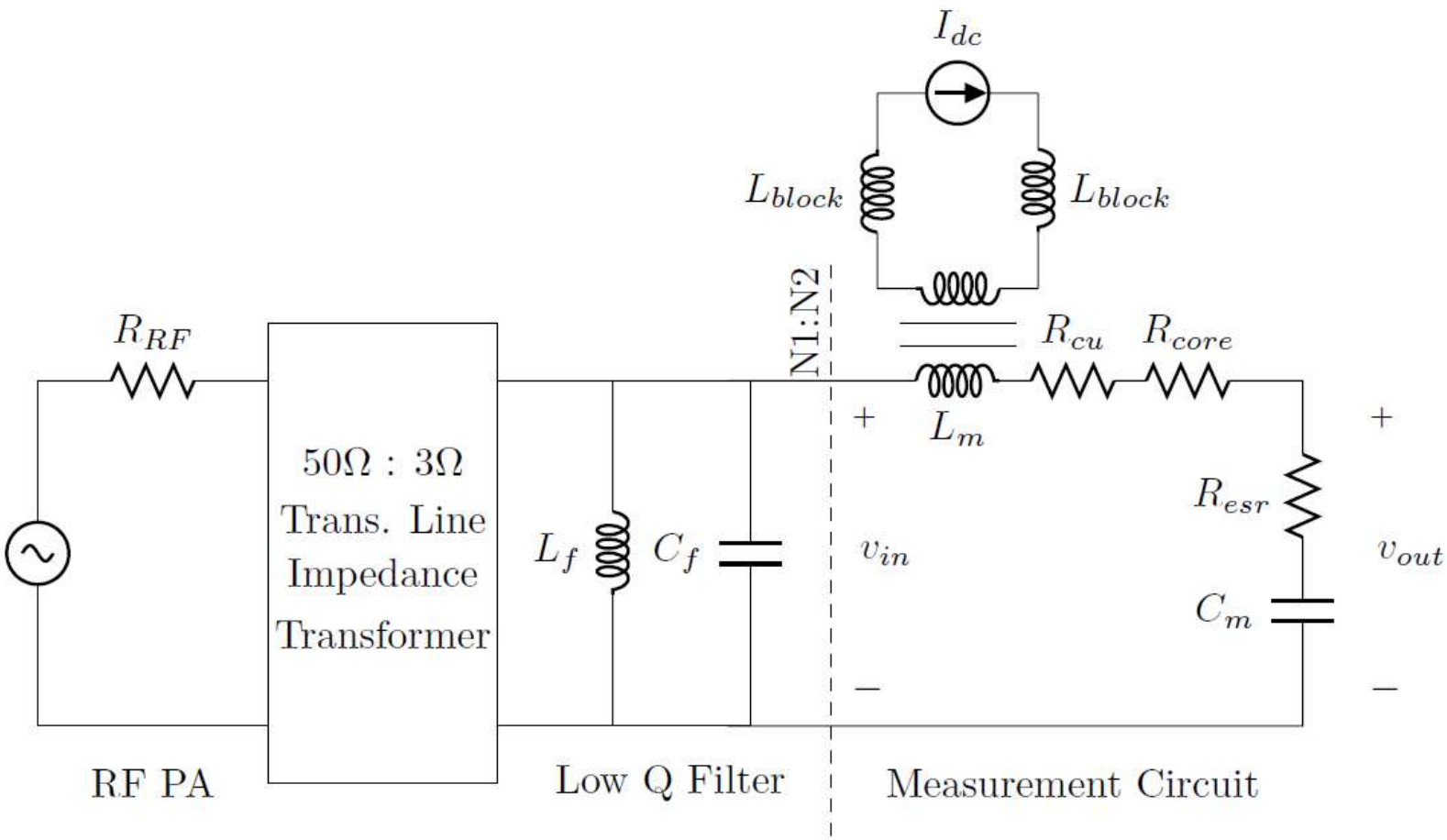


Ref 28



Ref 29

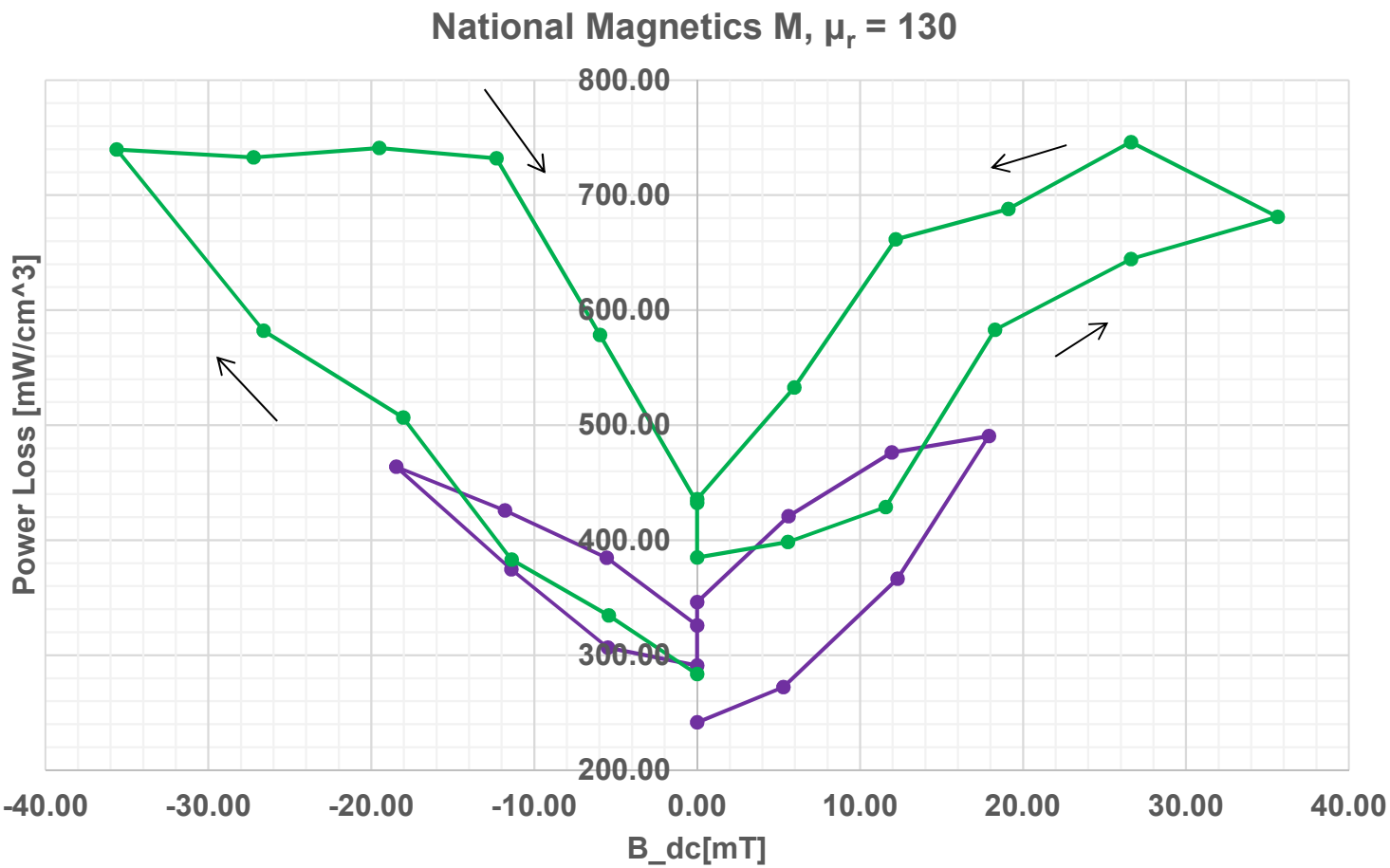
Longitudinal Bias: Experimental Setup



Longitudinal Bias: Effect on Loss

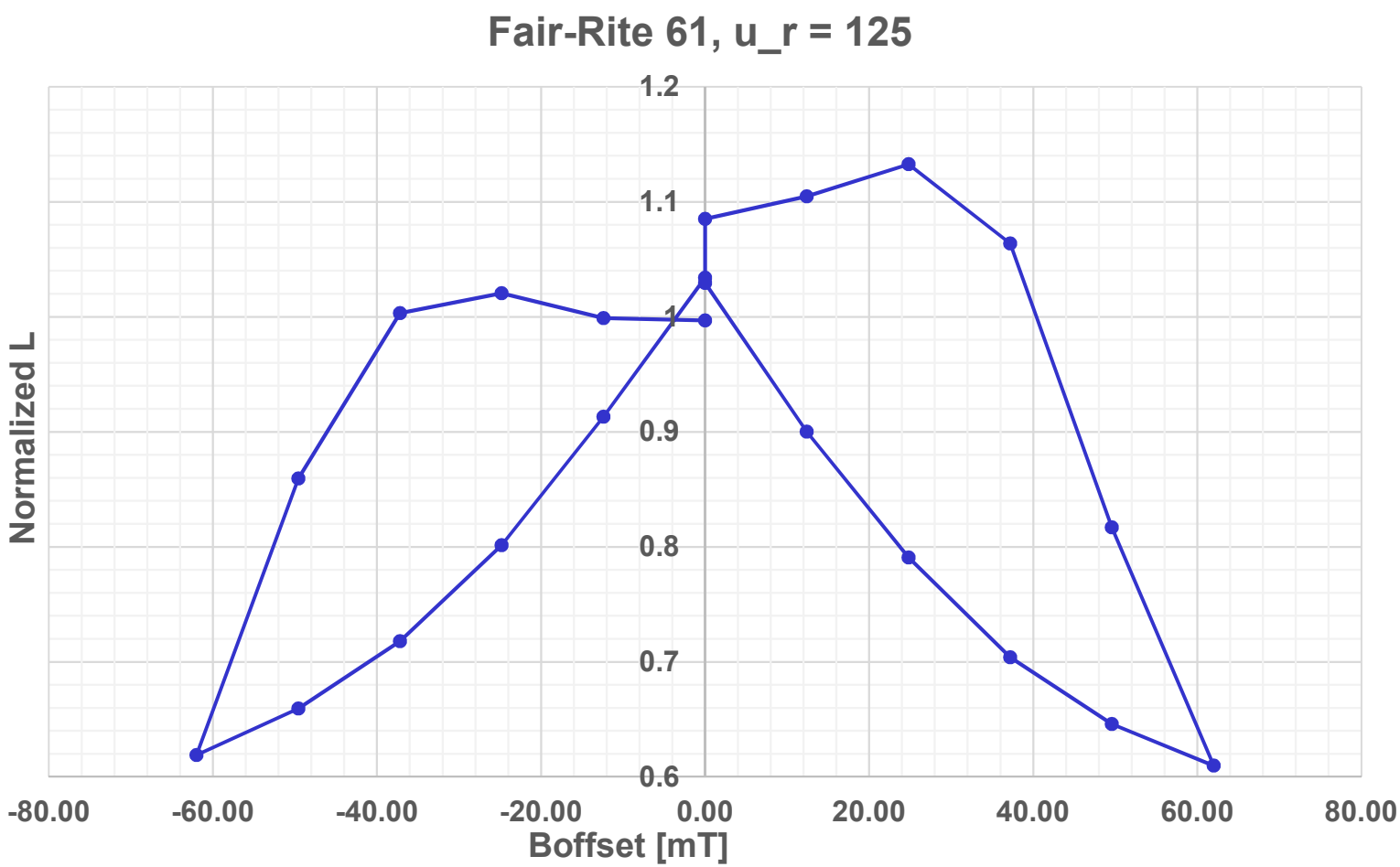
- Bpk = 6.5 mT
- Frequency = 10 MHz

- Loss: 241 → 746 mW/cm^3
  - **<u>3x increase</u>**
- Zero bias loss level increases



Longitudinal Bias: Effect on Inductance

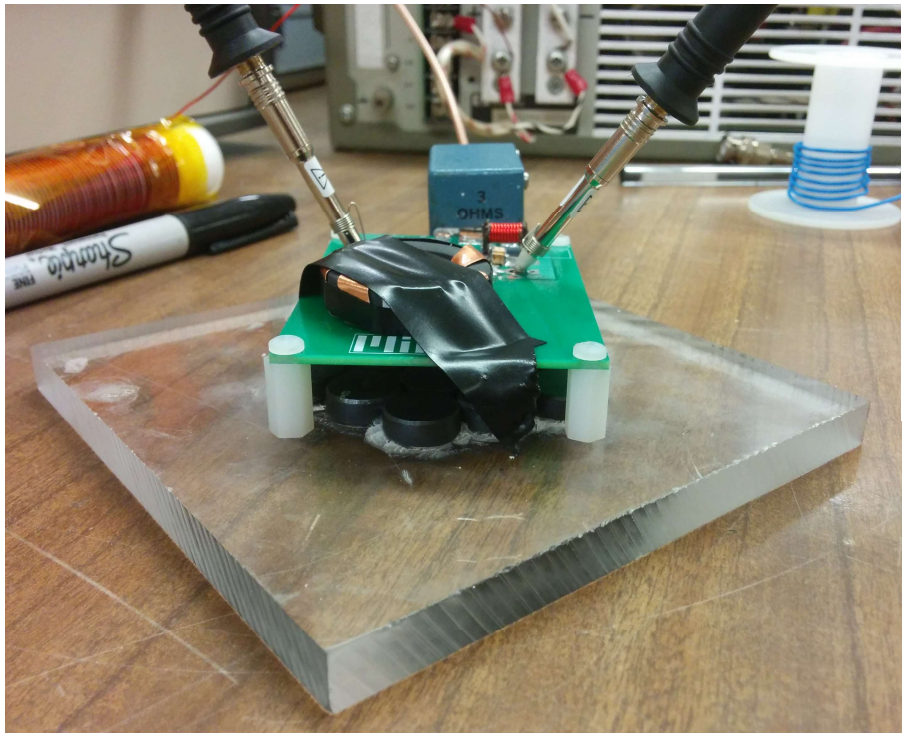
- Bpk = 2.8 mT
- Resonant frequency varies from 9 to 12 MHz



Transverse Bias

- Material: Fair-Rite 67 ($\mu_r = 40$)
- Nominal B_{trans} = 80 mT
- B_{pk} = 5.6 mT
- **<u>4.5x loss increase</u>**

# Plates	P_v	μ_r	f_r
	mW/cm^3		MHz
0	**92.63**	**40.19**	**9.592**
1	**311.98**	**46.47**	**8.92**
2	**418.39**	**58.95**	**7.92**



Experimental Setup (1 plate)