Design Considerations for High Frequency Magnetic Materials

PRESENTED BY JOHN LYNCH
DIRECTOR OF ENGINEERING
FAIR-RITE PRODUCTS CORP

Agenda

- Market Motivation
- Measurement of high frequency power loss.
- Leveraging Existing Materials in Emerging Application
- New Material Development
- The advantages of ferrite materials in power supply designs
- Important parameters of ferrite materials and their impact on performance, such as:
  - Permeability
  - Performance factor
  - Power Loss characteristics
- Guidelines to selecting the appropriate ferrite material
  - Operating conditions
  - Environmental factors
- Optimizing core configuration based on design limitations
  - Effects of size and geometry
  - Effects of DC and air gaps

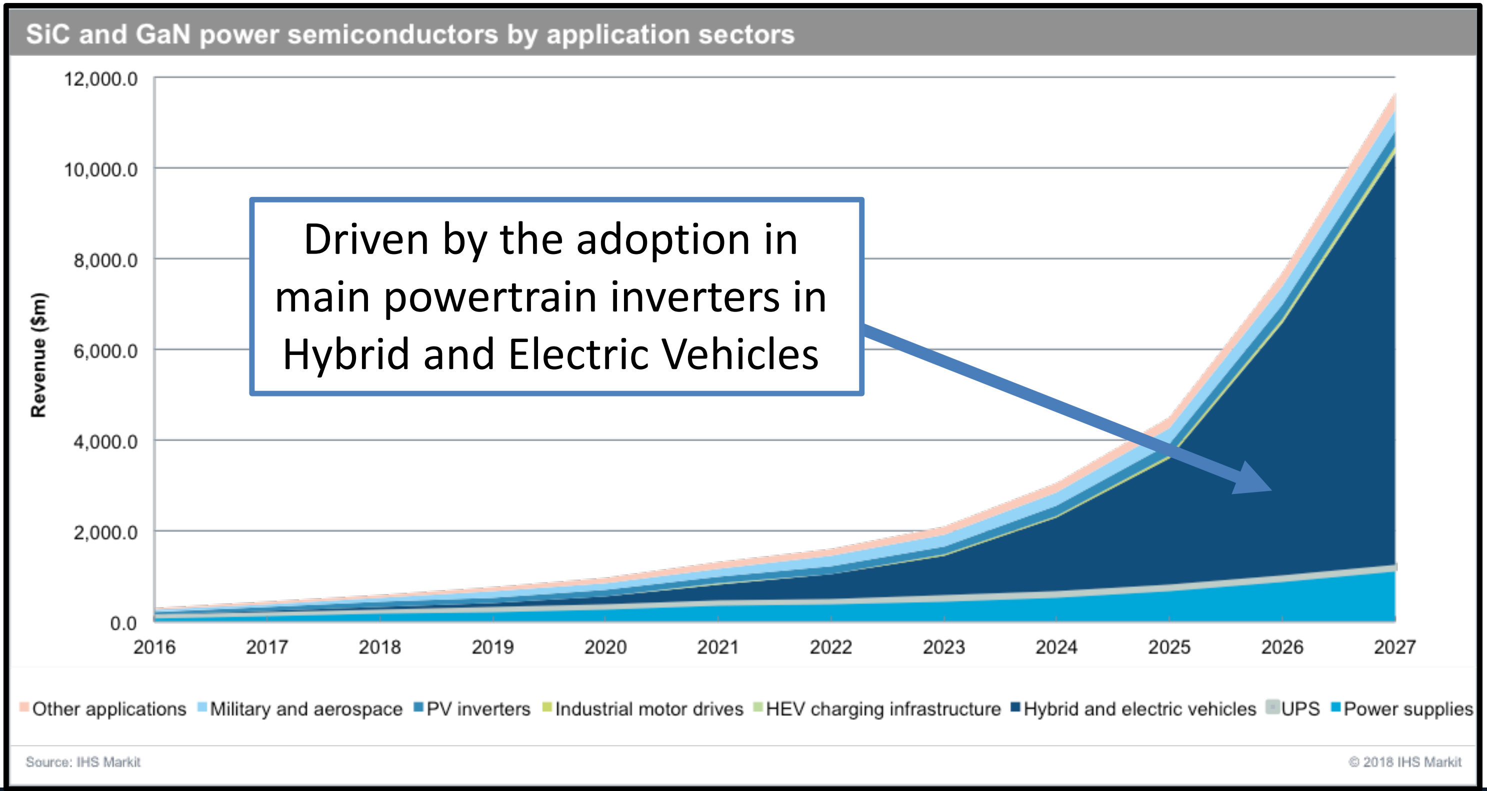
Market Motivation

- Miniaturization is a driving force in electronics design.
  - Magnetics are typically the largest component in power supplies.

  - In order to minimize power supply footprints, operating frequency has been increasing.
    - Power loss of magnetic components incorporated into these designs can cause issues with efficiency and heat management
- Increased efficiency
  - GaN has no reverse recovery charge which enables topologies such as the totem-pole PFC to improve efficiency

Markets for GaN and SiC

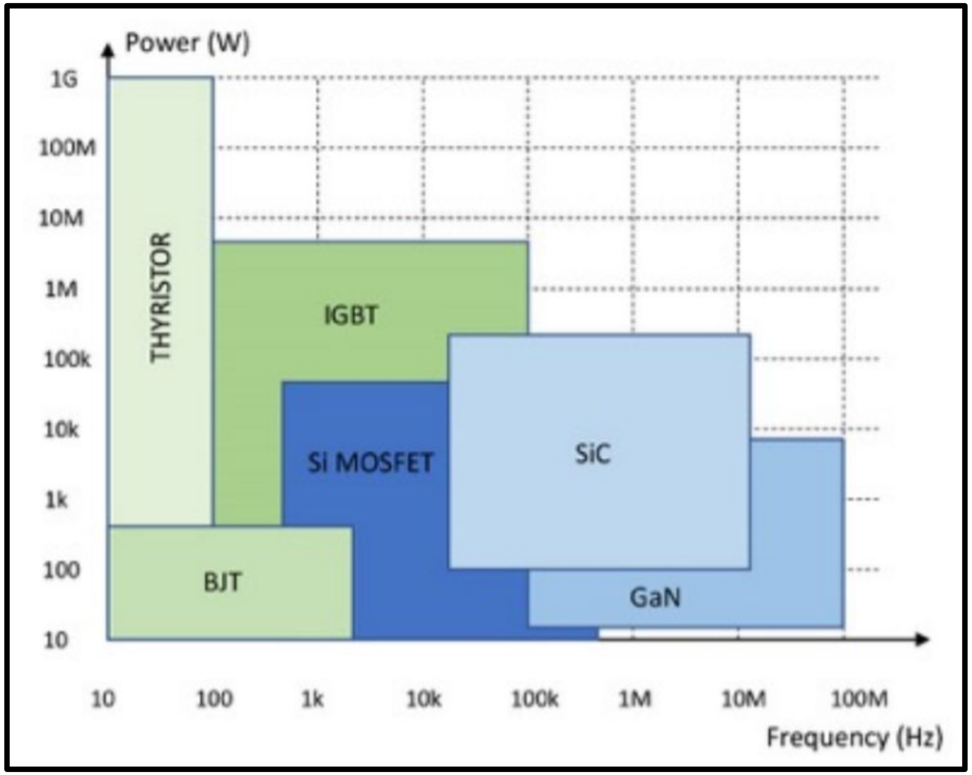
- GaN + SiC likely to reach ~$10B by 2027[1]
  - GaN is expected to achieve price parity with Si MOSFETS and IGBTs by 2020, leading to a CAGR = 21.5% from 2017 to 2025[2]



IHS Markit | Technology[1]

Increasing Operating Frequencies

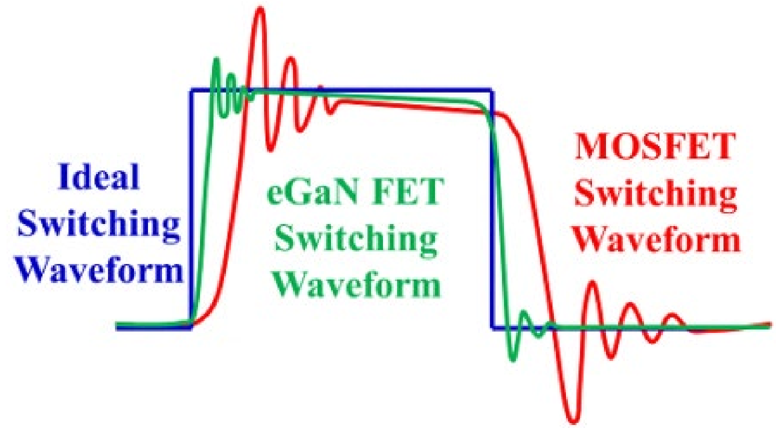
- EPC: "Cutting new ground for power transistors, these devices have switching transition speeds in the sub nano-second range, making them capable of hard switching applications <u>**above 10 MHz**</u>."[1]
- GaN Systems: "We have many customers using our devices from **hundreds of kHz, to 13.56MHz, and even some above 50MHz**."[2]
- Cree: "Each gate drive circuit … can comfortably switch the SiC MOSFETs at **up to 3MHz.**"[3]



Possible future scenario presented by UnitedSiC

Semiconductor Development

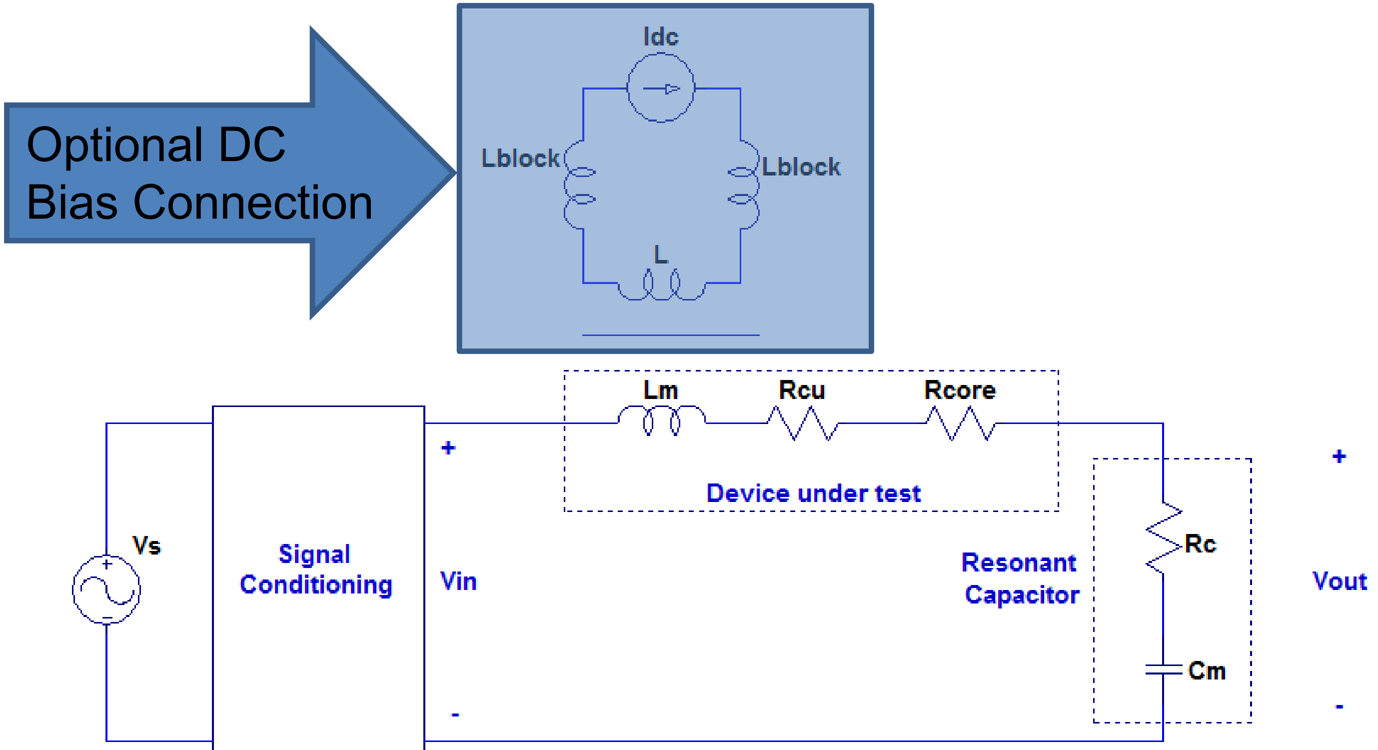
- "The rapid progress in GaN and SiC power semiconductors will lead to a further miniaturization of power electronic assemblies and subsystem…
  - **The drastically increased frequency requires improved ferrite materials with lowest losses."**



Jungwirth,, H., Schmidhuber, M., Baumann, M., Schmeller, M.
"A new high frequency ferrite material for GaN applications", PCIM Europe 2016.
Lidow, Alex. "How to GaN: eGaN® FETS in High Performance Class-D Audio Amplifiers." EE Web. February 19. 2014.

Measurement Setup for Power Loss

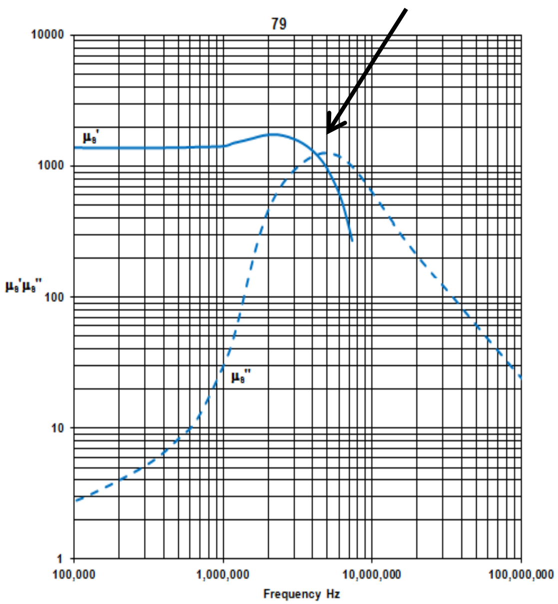
- Fair-Rite utilizes the "resonant Q" method developed by MIT to conduct measurements.
  - This system has been replicated at Fair-Rite with MIT's assistance.
- This method removes the reliance on phase angle as part of the measurement.



(1) Han, Y; Cheung, G; Li, A; Sullivan, C.R.; Perreault, D.J.; "Evaluation of Magnetic Materials for Very High Frequency Power Applications" in Power Electronics, IEEE Transactions on , vol. 27, no.1, pp.425-435

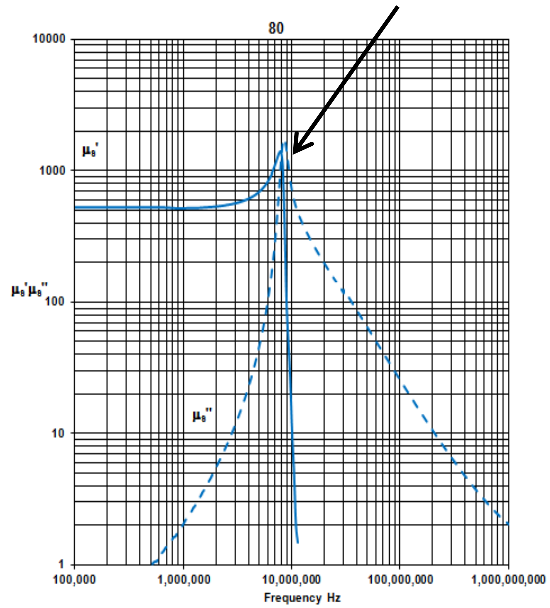
79 material

cut-off frequency 4MHz



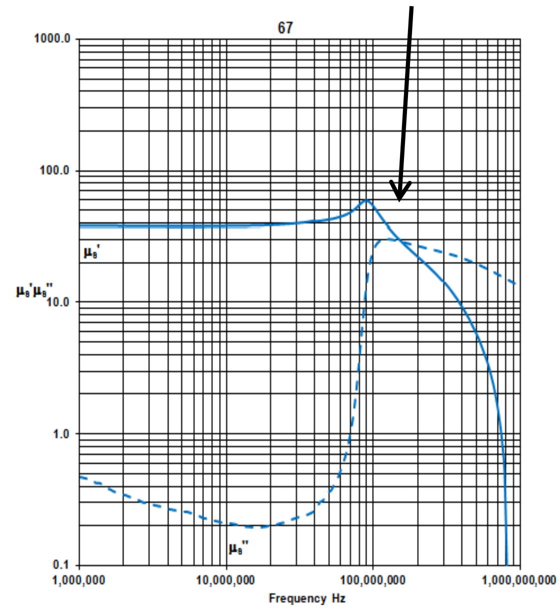
80 material

cut-off frequency 8MHz



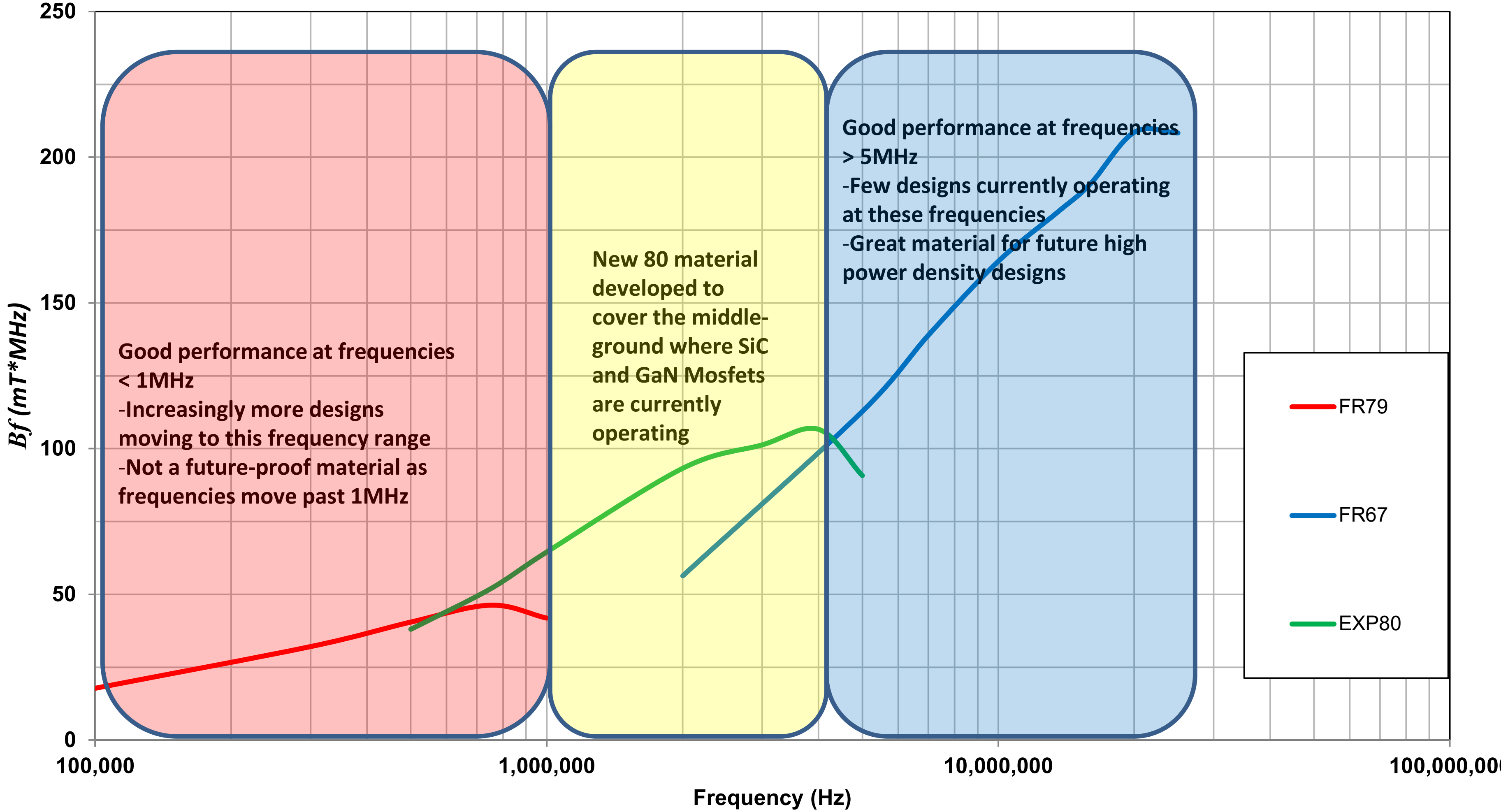
67 material

cut-off frequency 150MHz



- Loss factor is the principal loss parameter at low flux density (u''/u'^2)
- Typically lowest loss factor will have lowest core loss
- Higher cut-off frequency typically means lower core loss to higher frequencies

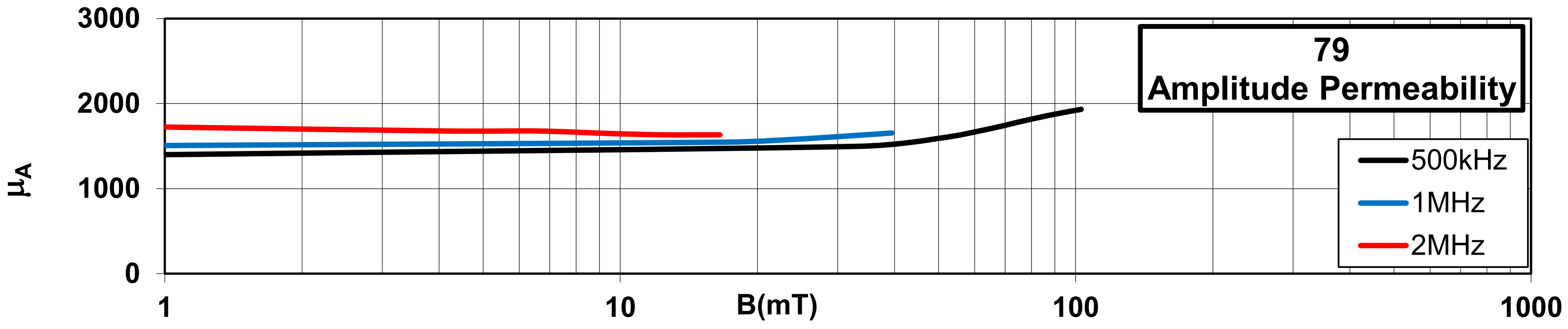
Performance Factor(500mW/cc) for Fair-Rite's Materials

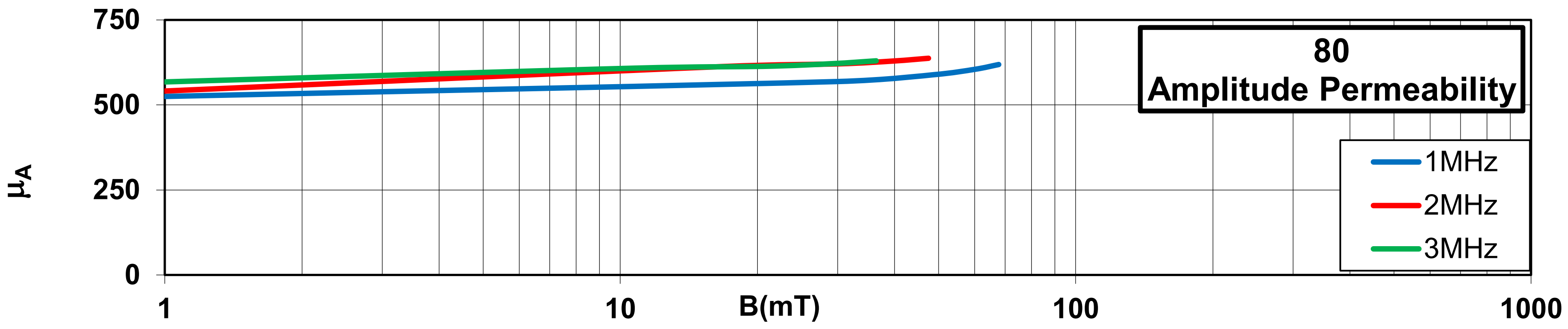


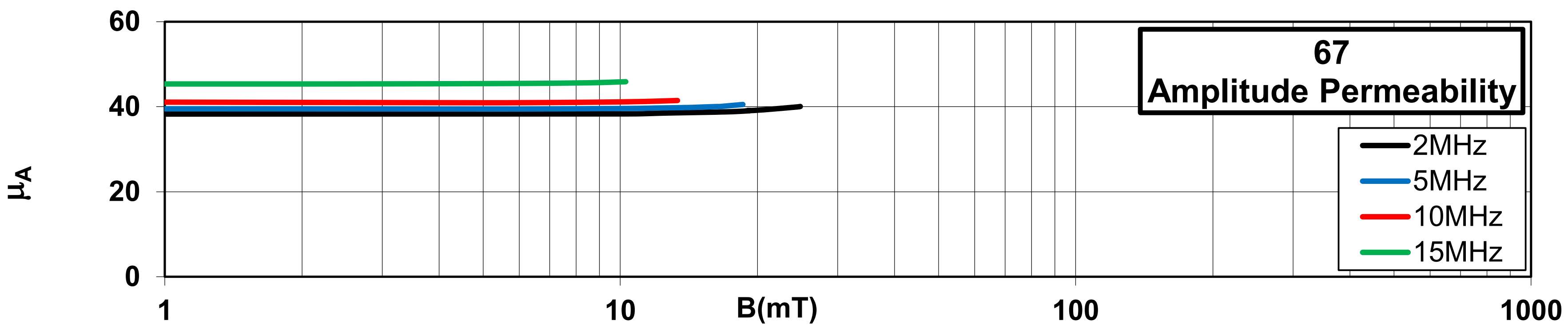
Considerations for selecting appropriate material and core configuration

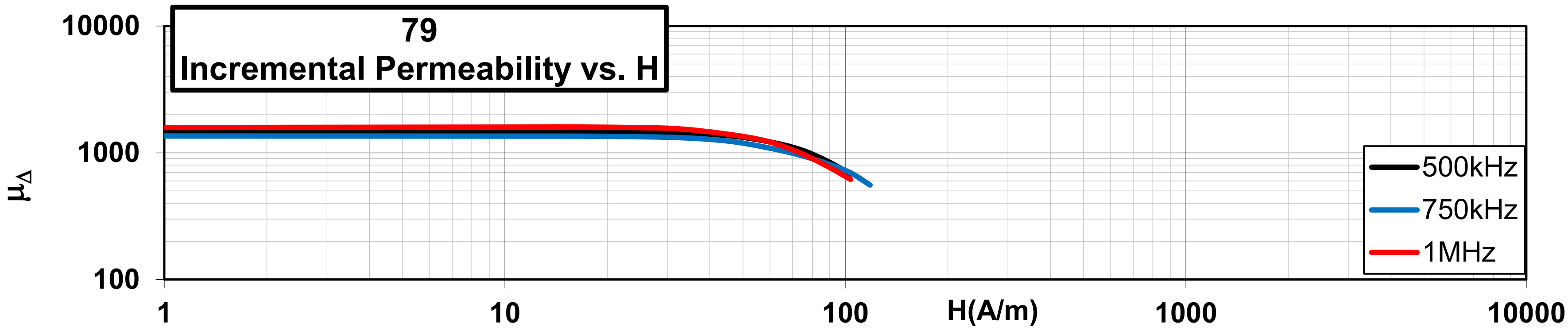
- Permeability with:
  - Elevated flux densities
  - DC bias over frequency
- Power loss density
  - At operating frequency
  - Over temperature
- Optimal core size considering operating frequency.
- Geometry selection based on design requirements.
- Effects of DC bias on performance.
- Impacts of adding an air gap.

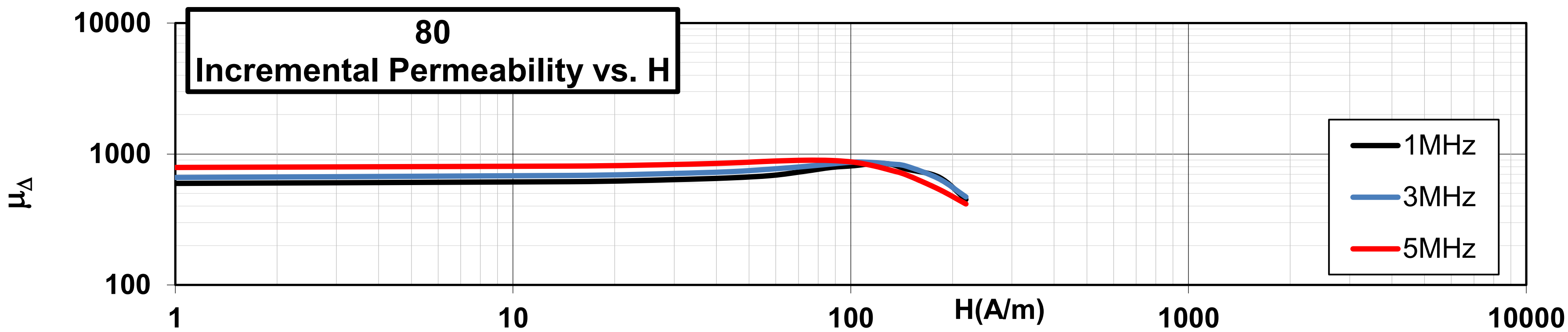
It looks like you're trying to select a magnetic core. Do you want my help?

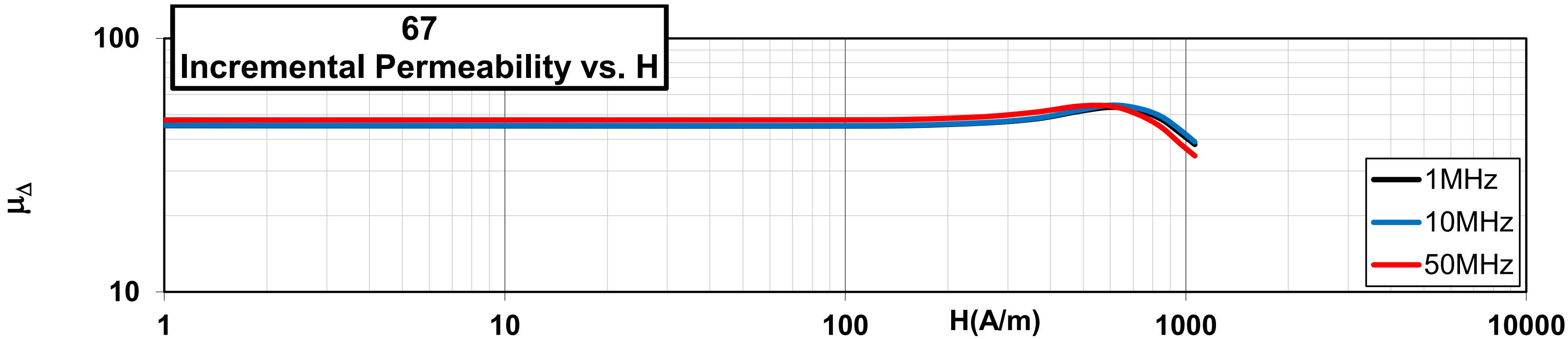

79
Amplitude Permeability
3000
2000
1000
0
μA
1
10
B(mT)
100
1000
500kHz
1MHz
2MHz


80
Amplitude Permeability
750
500
250
0
μA
1
10
B(mT)
100
1000
1MHz
2MHz
3MHz

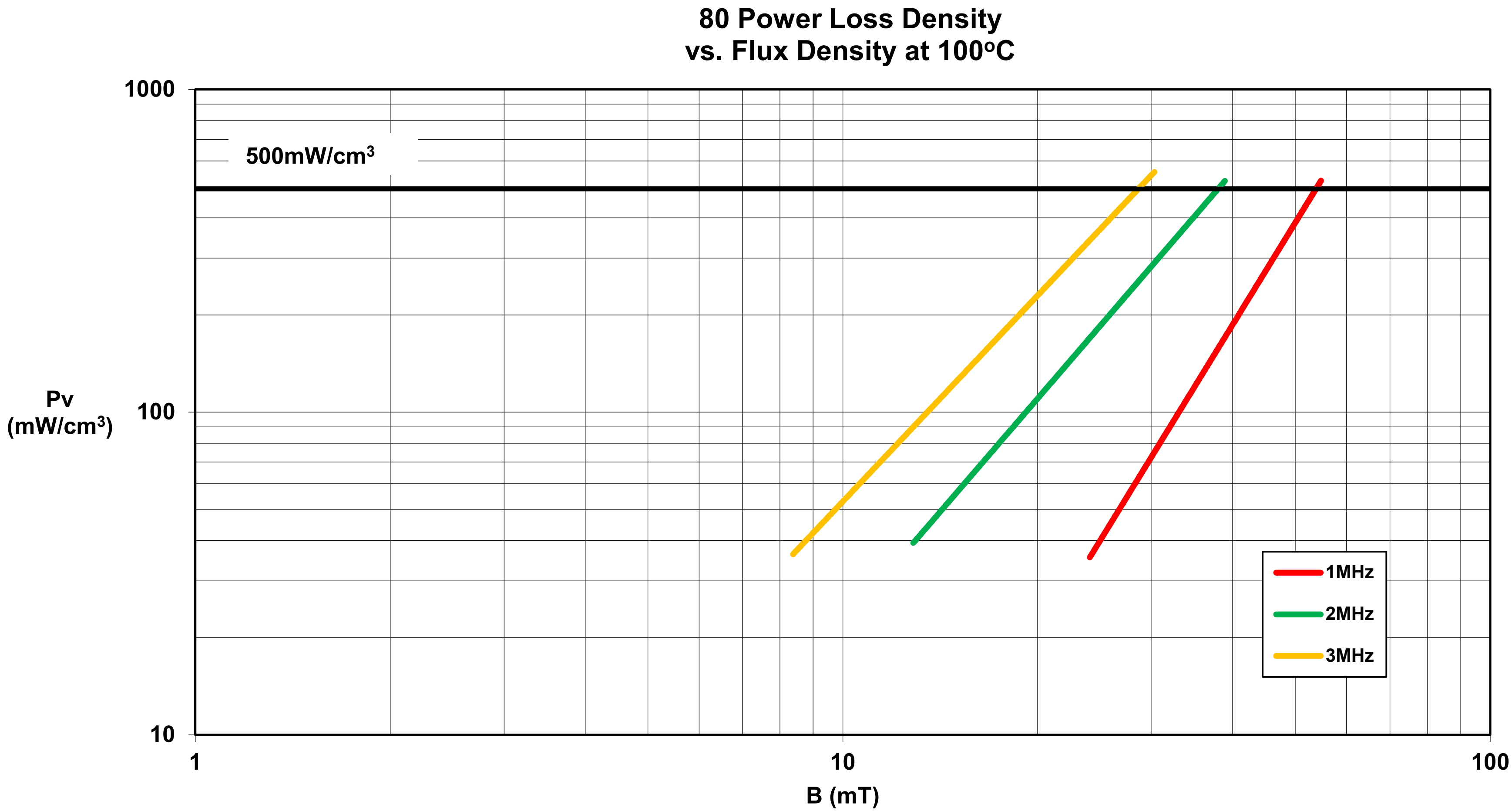

67
Amplitude Permeability
60
40
20
0
μA
1
10
B(mT)
100
1000
2MHz
5MHz
10MHz
15MHz


79
Incremental Permeability vs. H
10000
1000
100
μ∆
1
10
100
H(A/m)
1000
10000
500kHz
750kHz
1MHz


80
Incremental Permeability vs. H
10000
1000
100
μ∆
1
10
100
H(A/m)
1000
10000
1MHz
3MHz
5MHz

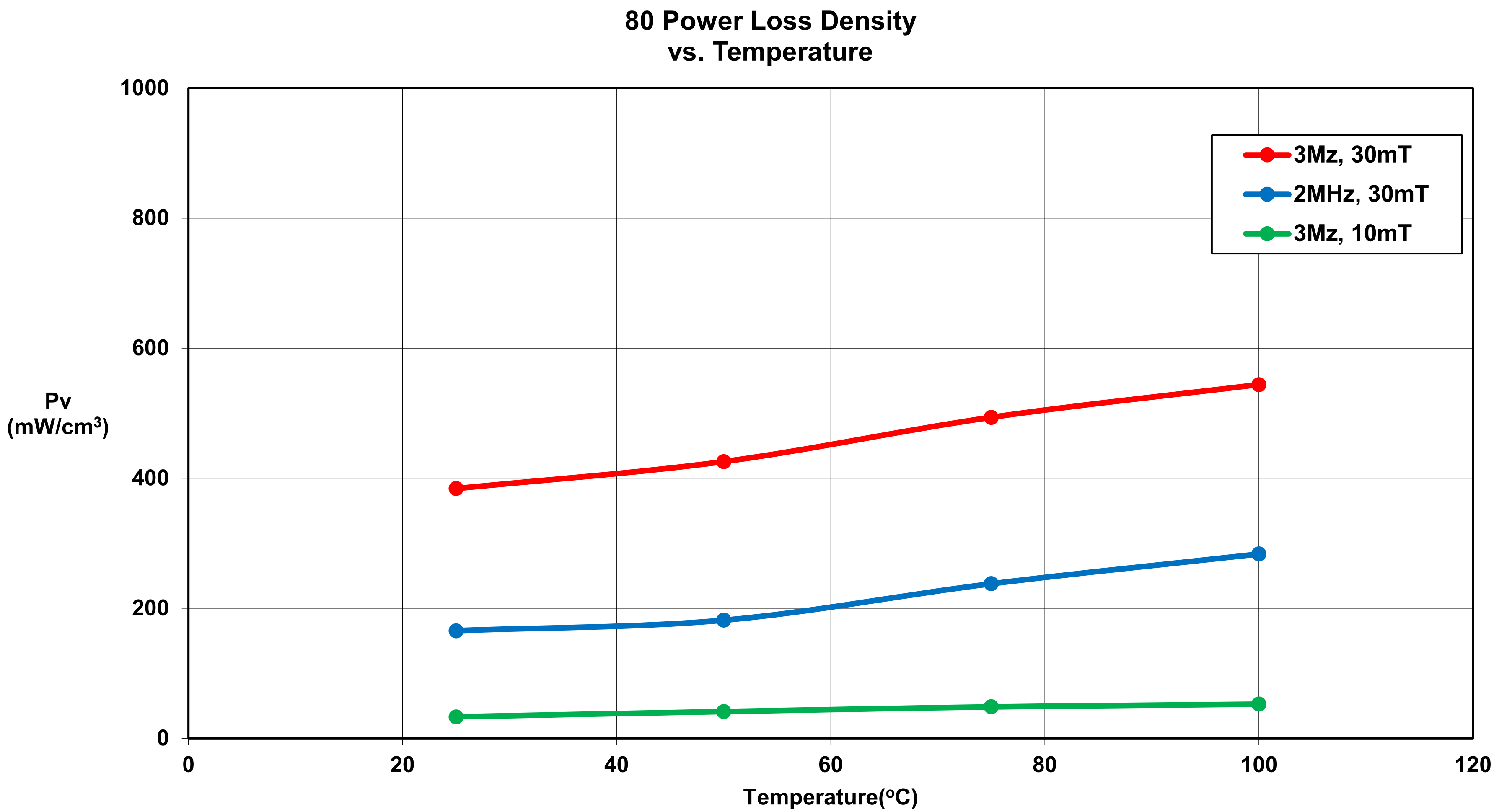

67
Incremental Permeability vs. H
100
10
μ∆
1
10
100
H(A/m)
1000
10000
1MHz
10MHz
50MHz

HF Power Loss Curves @ 100°C

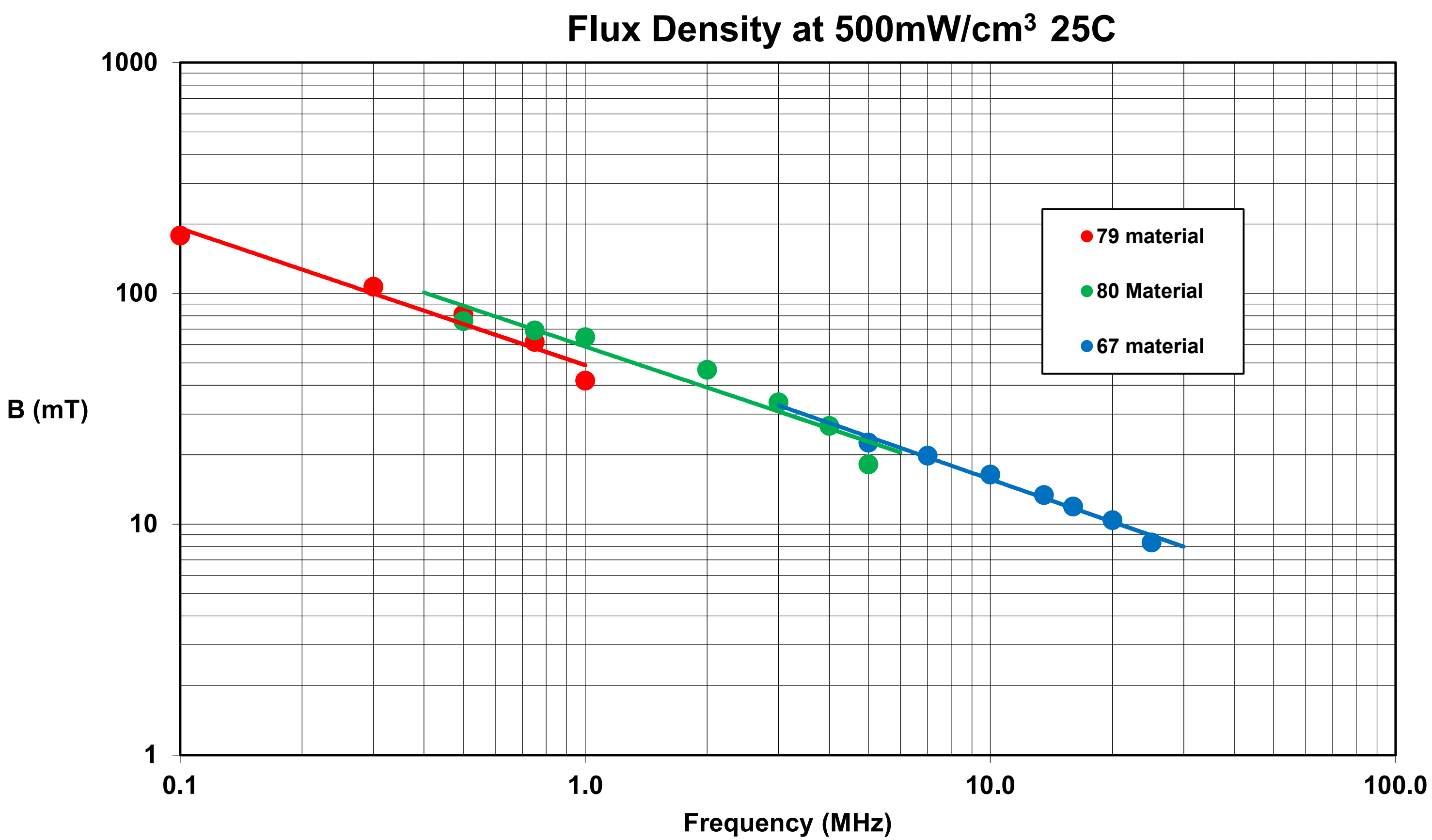


Measured on a 22.1mm/13.7mm/6.35mm toroid at100° C.

Power Loss vs. Temperature



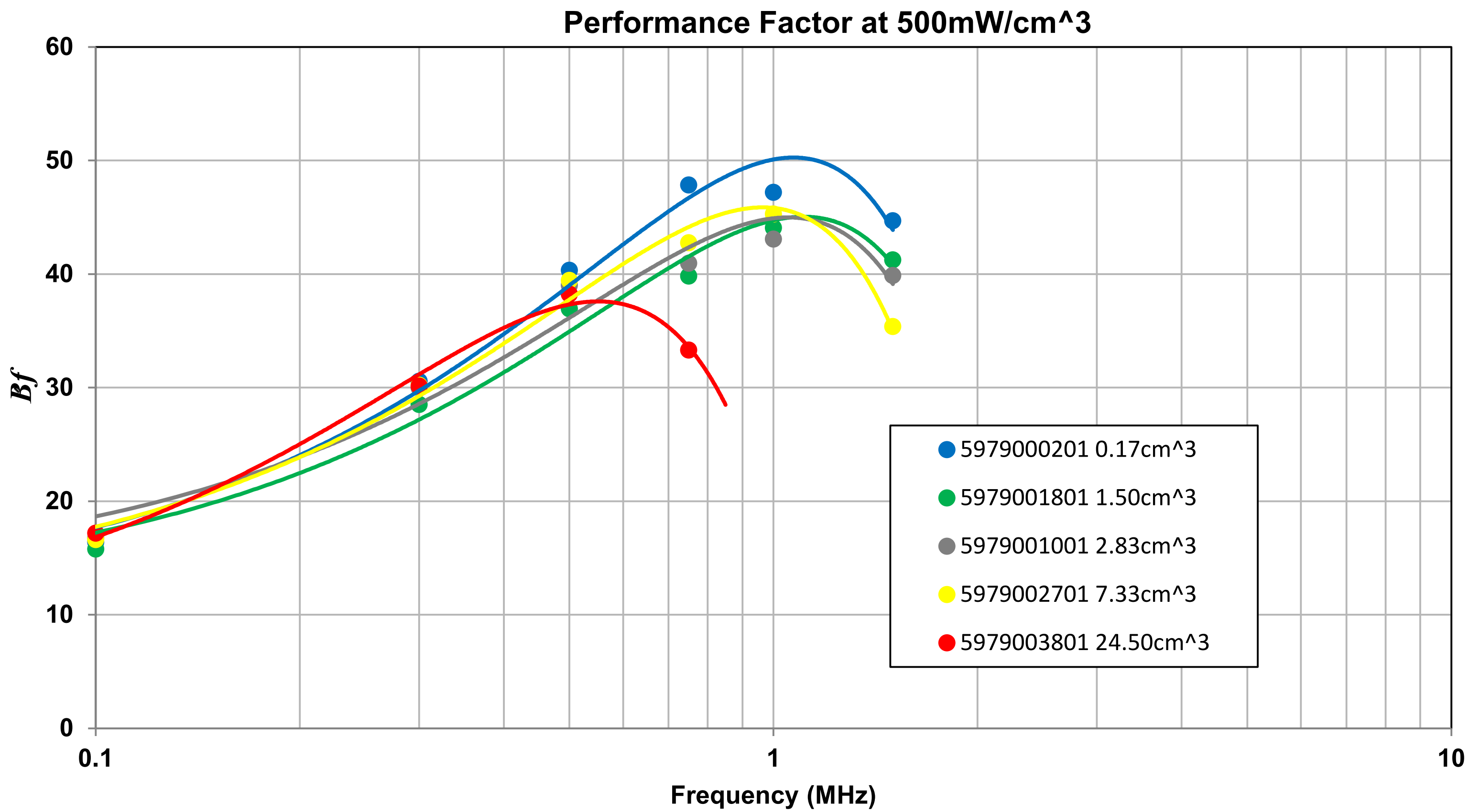
Measured on a 22.1mm/13.7mm/6.35mm toroid .



Measured on a 12.7mm/7.9mm/6.35mm toroid at 25° C.

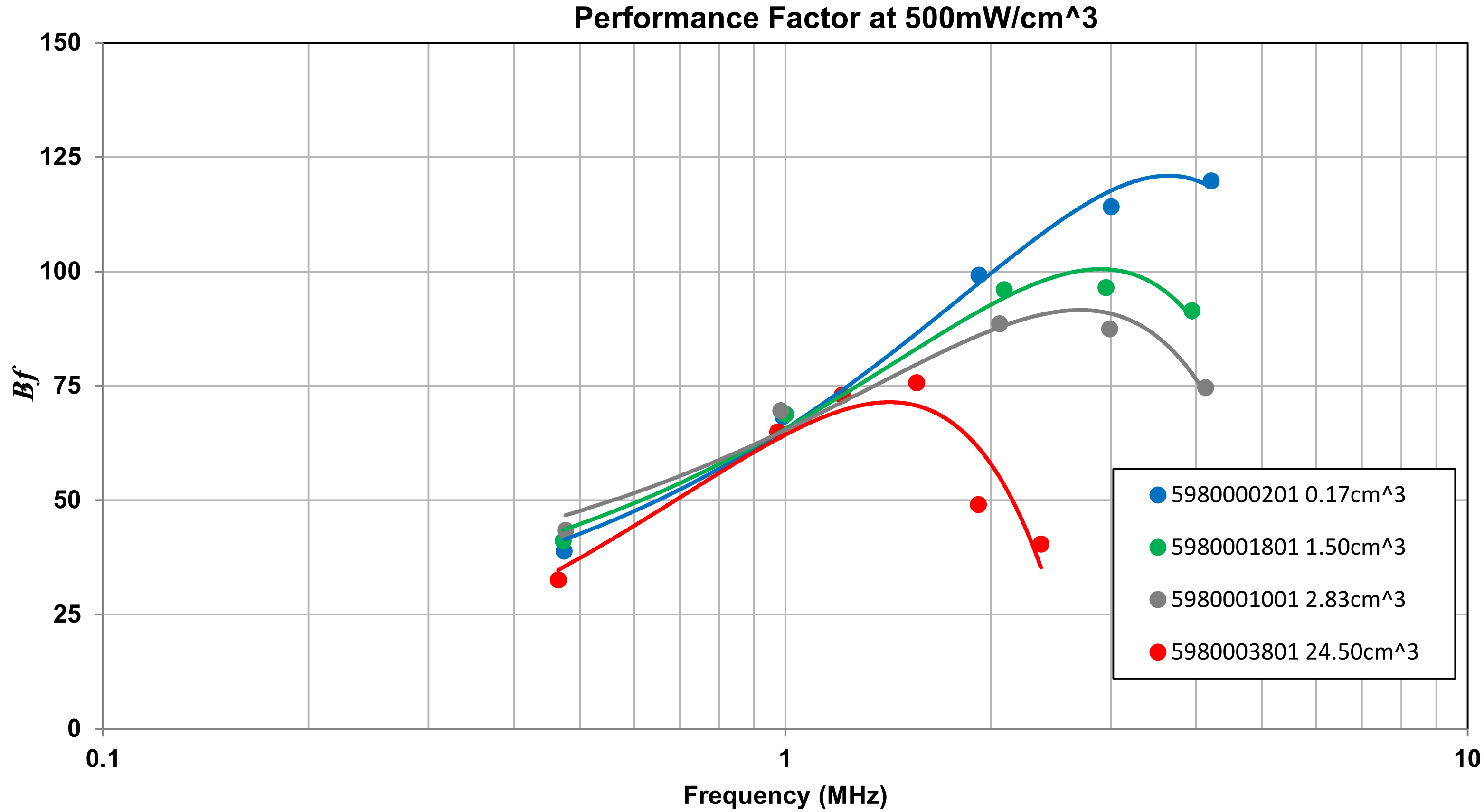
- For Power Conversion purposes operation should be limited to 500 mW/cc.
- For more conservative limiting of heat rise: 300 mW/cc is a better design constraint.
- At higher frequencies: operation is "loss limited" as opposed to flux density limited at low frequency.

Performance Factor Curves for different size 79 material toroids



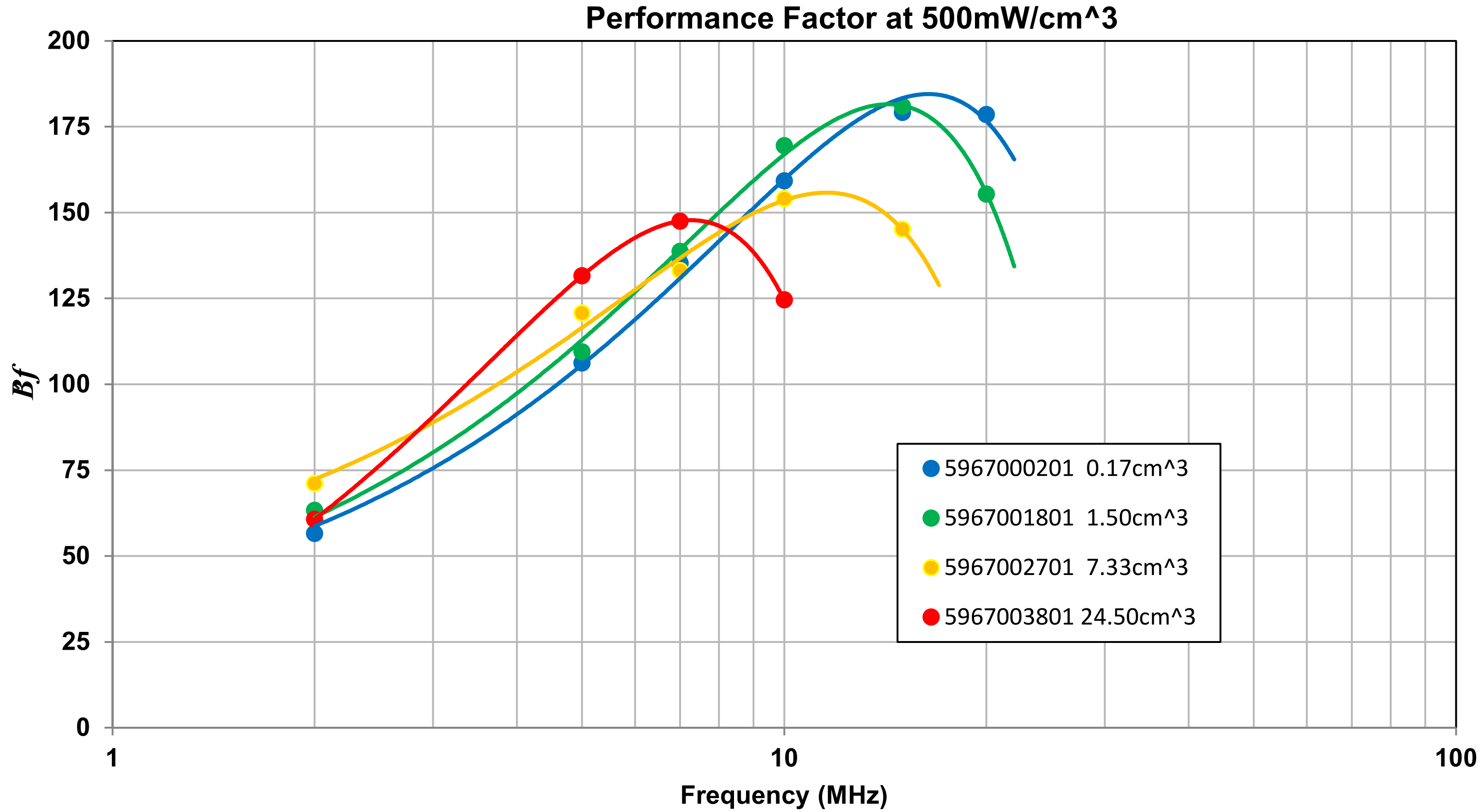
- Optimal operating frequency decreases as core size increases

Performance Factor Curves for different size 80 material toroids



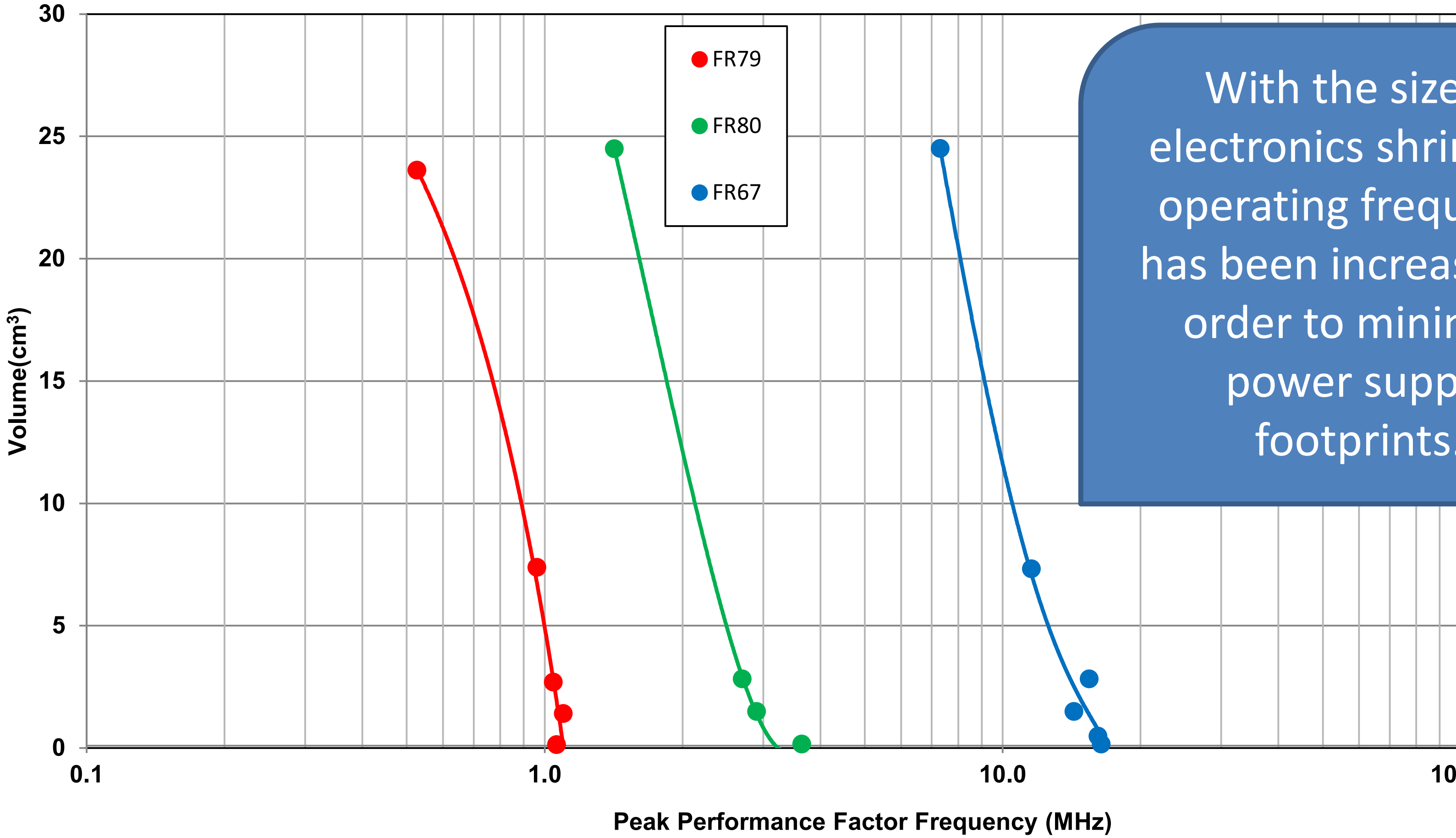
- Optimal operating frequency decreases as core size increases

Performance Factor Curves for different size 67 material toroids



- Optimal operating frequency decreases as core size increases

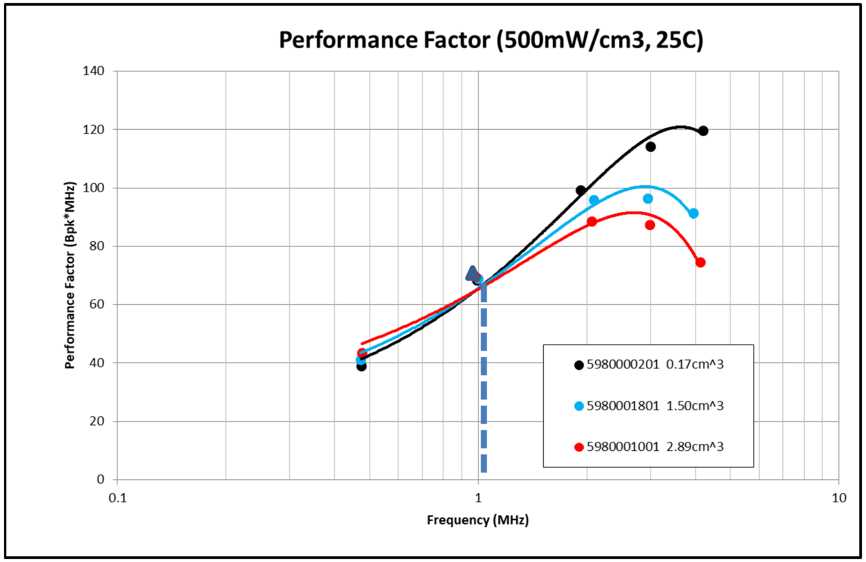
Peak Performance Factor Frequency for Toroids



With the size of electronics shrinking, operating frequency has been increasing in order to minimize power supply footprints.

- Want to operate where performance factor is highest, but smaller cores cannot handle as high a power level.

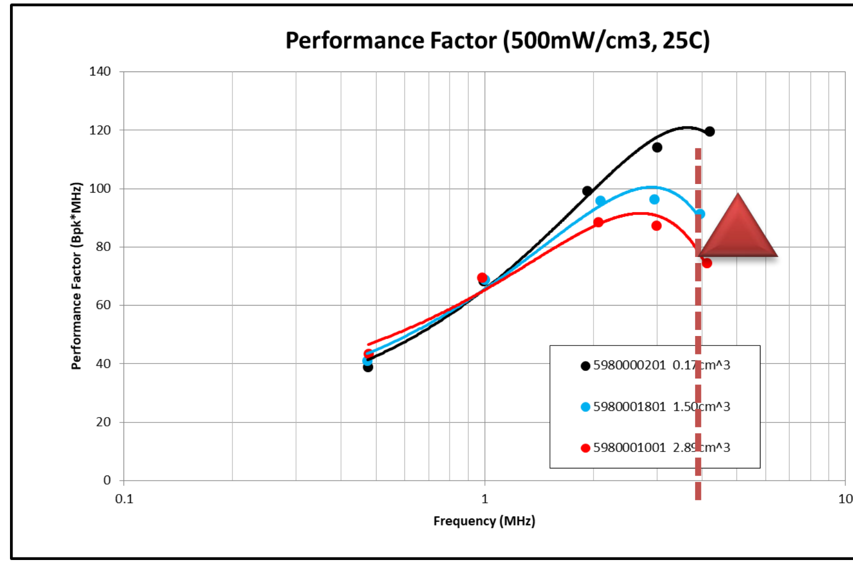
Comparison #1



Max Temperature	
46.3°C	53.3°C

Maximum Temperature Difference = 7°C.

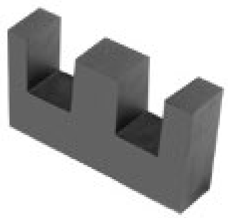
Comparison #2

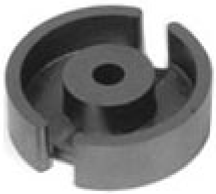


Max Temperature	
50.3°C	77.1°C

Maximum Temperature Difference = 26.8°C.

Considerations for Core Geometry Selection





- Power handling limited by temperature rise due to:
  - Copper losses of the windings
  - Power loss of the core
- Core size limited by available space on board
  - Low profile vs. large volume
- Magnetic shielding to limit EMI
- Cost and manufacturability

Desired Geometry Characteristics

Feature	Relation	Desired Ratio
inductance / length of wire	Lo/MTL	High
power-to-volume density	AeAw/FPtotal	High
uniform cross section	Amin/Ae	High
magnetic shielding	Exposed Winding Area/Footprint	Low
heat dissipation	Exposed Winding Area/Footprint	High

Case study

- *Geometries with largest physical dimension [A] in range of 20-30 mm and throughput power of 30-60 watts in traditional designs @ 100 kHz, < 200 mT*

Comparison of the Different Geometries

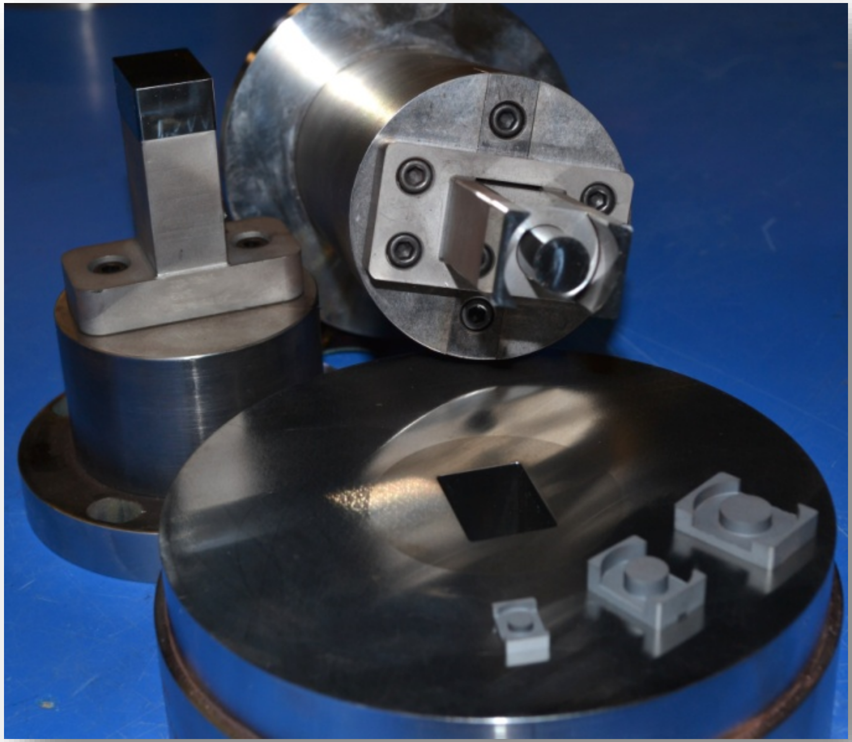
feature	T	std UU	std EE	P	EP	EFD	PQ	RM	ETD/ EER	pEE	pE I	pEER/ pEEQ	pERI/ pEQI
inductance/wire length	2	1	1	3	4	1	2	2	1	4	5	3	4
power to volume density	5	5	5	2	2	3	3	3	4	3	2	3	2
off board height	3	1	2	3	1	4	2	2	2	4	5	3	5
round center post	5	1	1	5	5	1	5	5	5	1	1	5	5
uniform cross section	5	5	5	3	3	5	5	4	5	5	5	4	4
magnetic shielding	4	1	1	5	5	1	3	4	1	2	2	3	3
heat dissipation	4	5	5	1	1	4	4	2	5	4	3	4	3
core standardization	no	no	IEC	IEC	IEC	IEC	IEC	IEC	IEC	IEC	IEC	de facto	de facto
totals :	28	19	20	22	21	19	24	22	23	23	23	25	26
rating :	0.80	0.54	0.57	0.63	0.60	0.54	0.69	0.63	0.66	0.66	0.66	0.71	0.74

Rating: 1 to 5, where 1 is least and 5 is best.
Note: Small ‘p’ indicated planar shape.

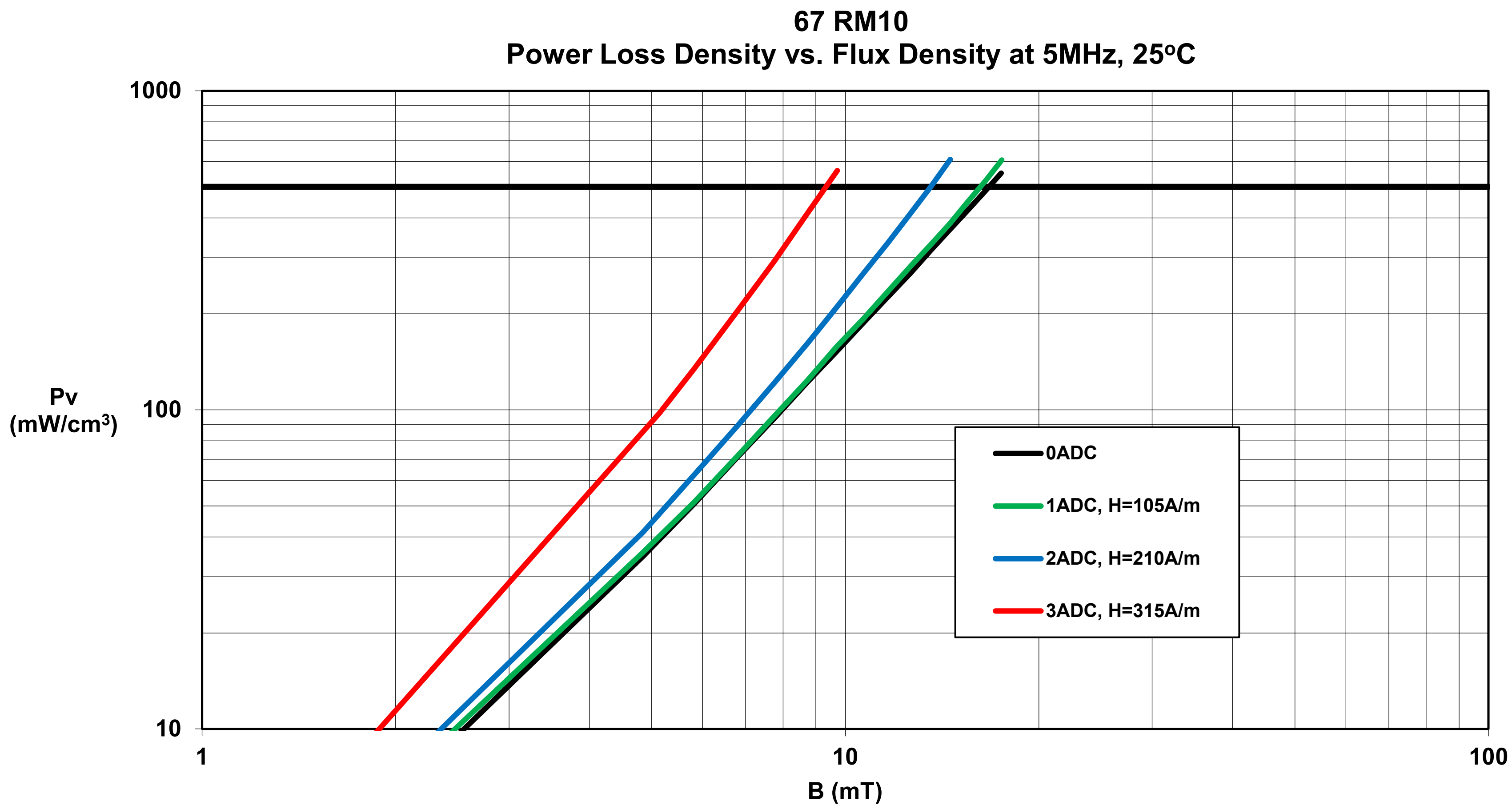
Geometry Conclusion

- Tradeoff of heat dissipation versus magnetic self shielding
- Center posts set back from the outer edge is most desirable for self shielding
- Maximum Lo/MTL is most desirable for lowest AC and DC copper losses
- Low Aw to Ae ratio pushes ratio of overall losses toward the ferrite instead of the winding
- Higher frequency operation requires less winding area because less inductance required

Toroids, Planar ER and EQ designs achieve best tradeoff for high frequency geometries

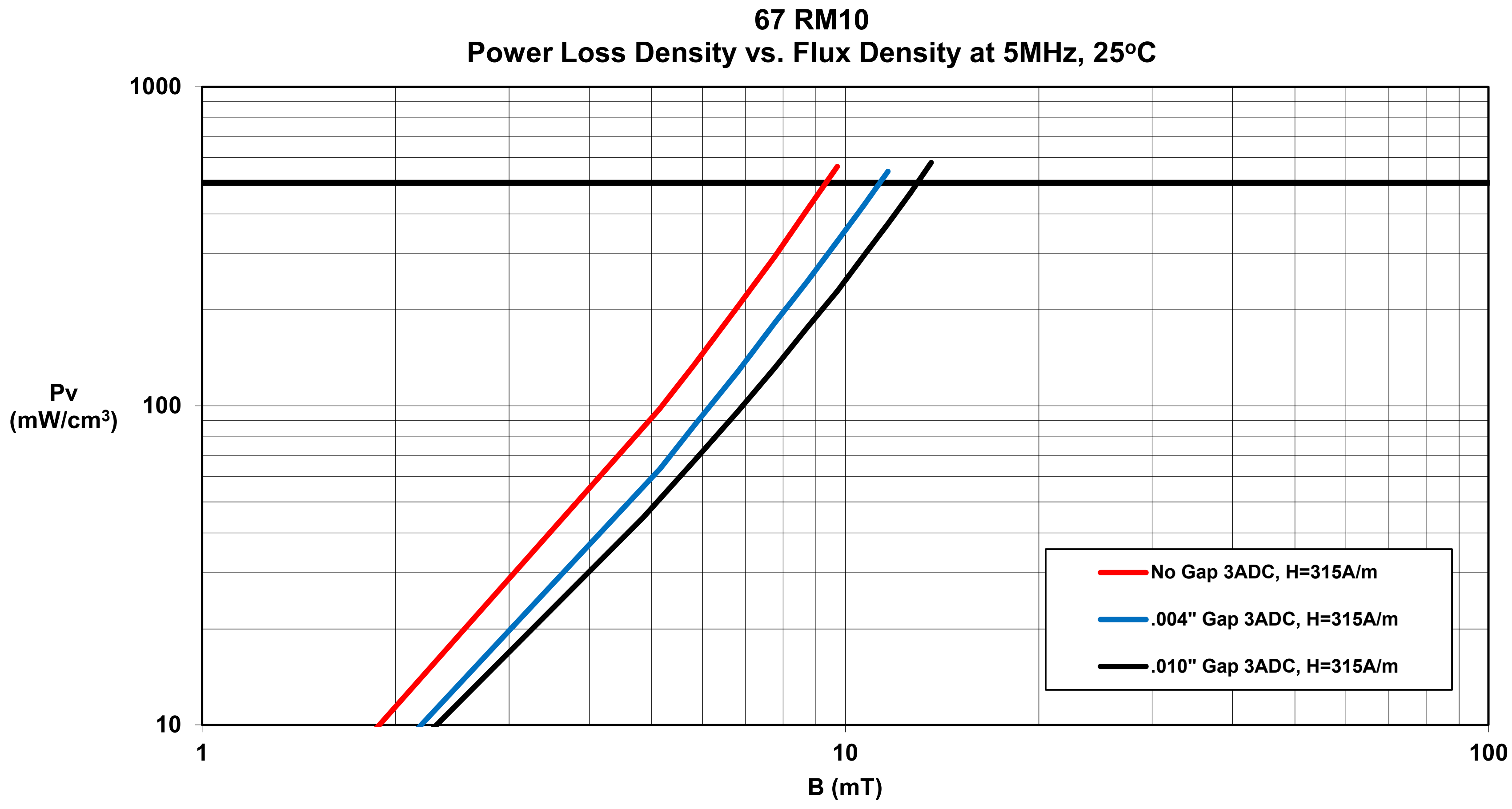


Effects of DC Bias



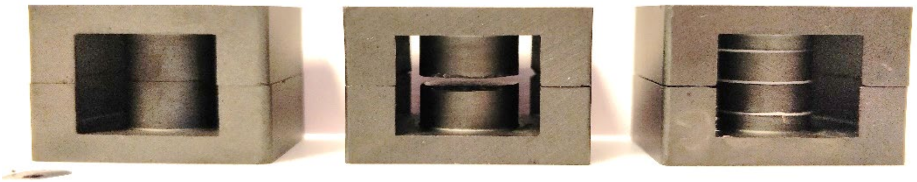
N=5

Effects of DC Bias with a Gap

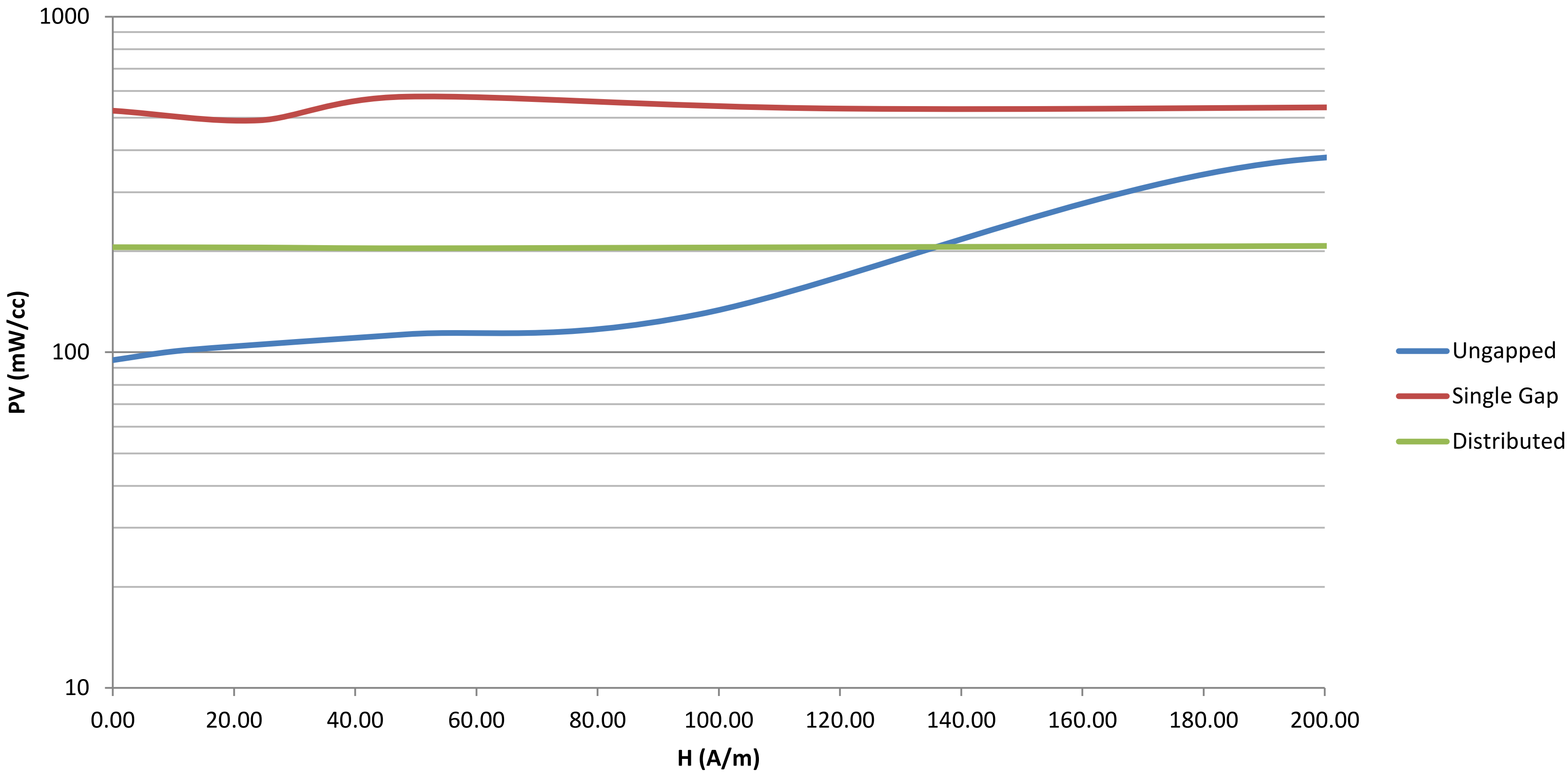


N=5

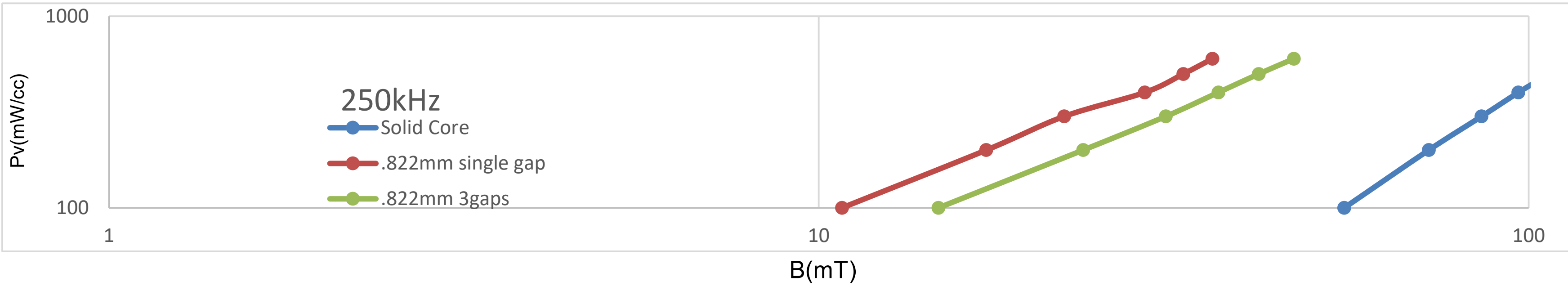
Effect of Bias

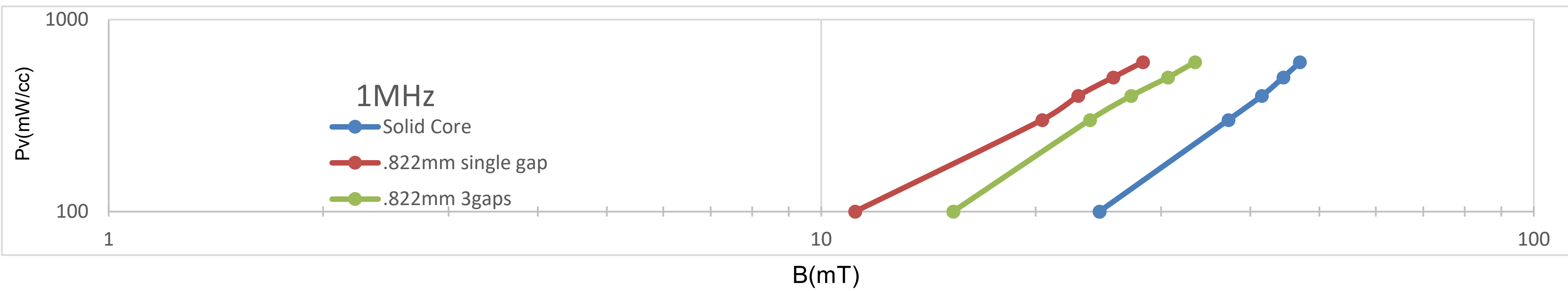


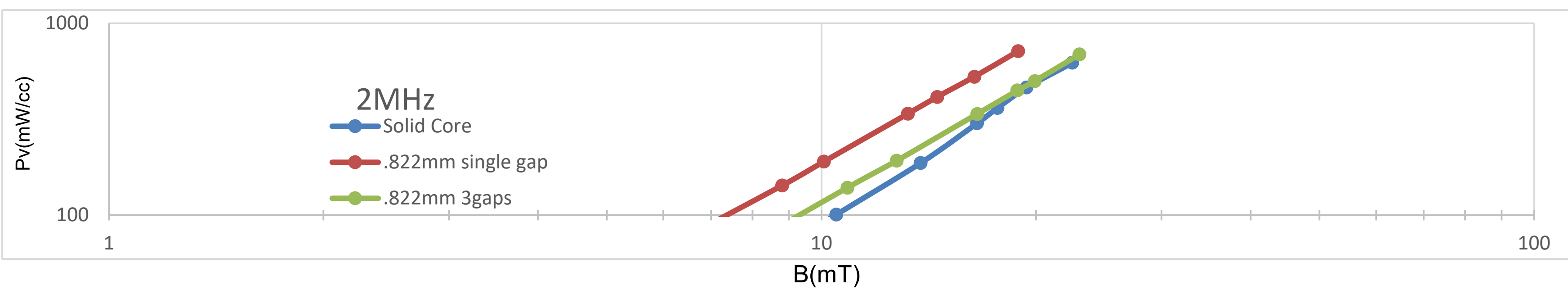
79 Material EQ25 1MHz 24mT



Power Loss 79 EQ25 Gapped vs Ungapped



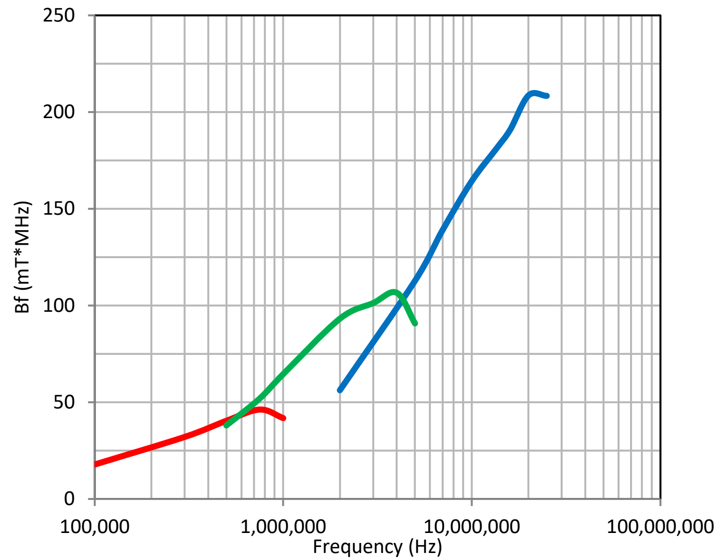




As frequency increases, power loss due to gap becomes less significant

Summary

- Market moving toward higher frequency with smaller core sizes.
- Materials developed to cover the higher frequencies:
  - 79 material (f<1MHz)
  - 80 material (1-5MHz), newly developed
  - 67 material (f>5MHz), optimized
- 79, 80, and 67 offer:
  - Stable permeability with increased flux densities and DC currents over frequency.
  - Low power loss density at higher frequencies covering a range from 500kHz to over 10MHz.
  - Stable power loss densities over temperature.
- Fair-Rite currently offers toroids and EQ cores and continues to add new parts.
- Custom parts and evaluation kits available upon request.



Thank you!

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