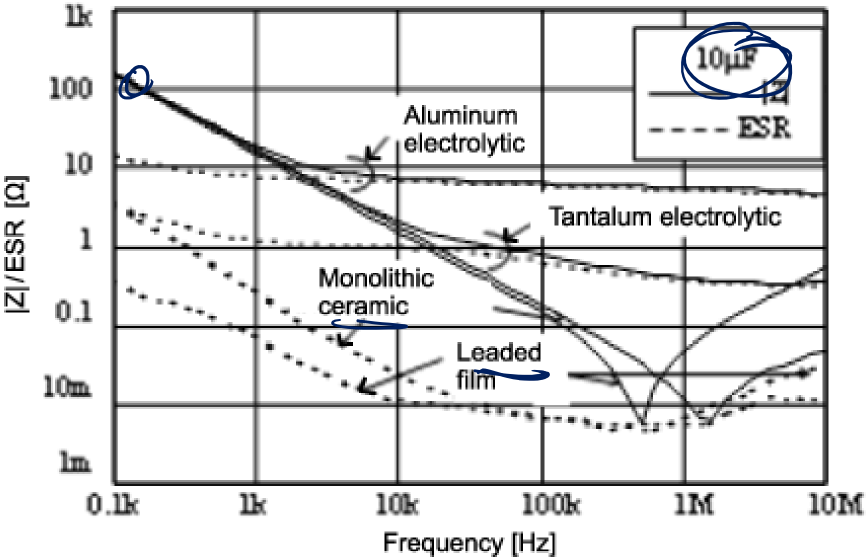
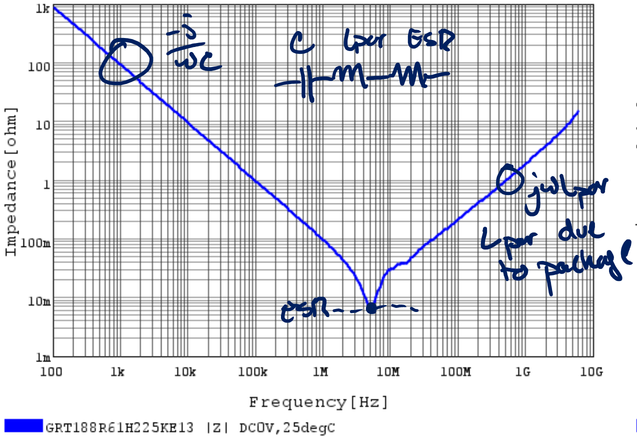
Types of Capacitors

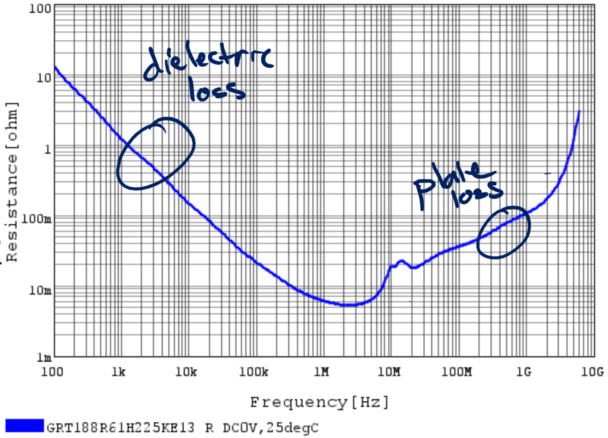
Electrolytic
- High ESR, Large ESL
- High energy / capacitance density
- Limited by current ripple rating

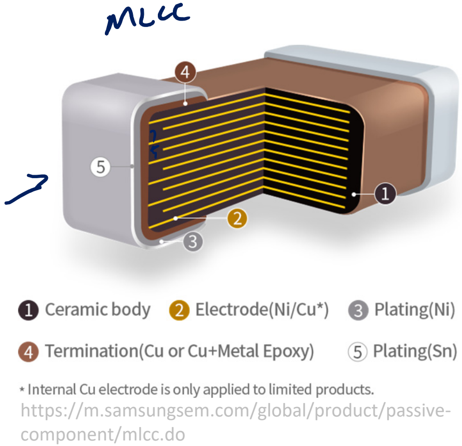
Ceramic / film:
- low ESR, low ESL in SMD packages



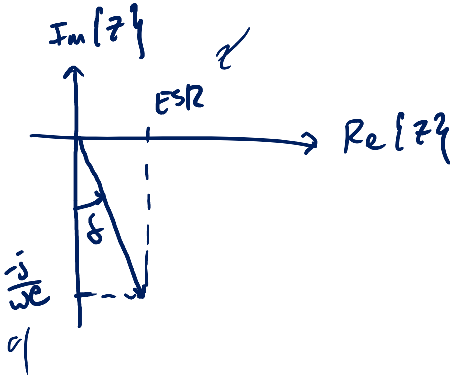
Ceramic Capacitor Impedance and Resistance







$$\tan\delta = DF = \frac{1}{Q}$$



Capacitor data sources

- Murata Simsurfing
- TDK SEAT

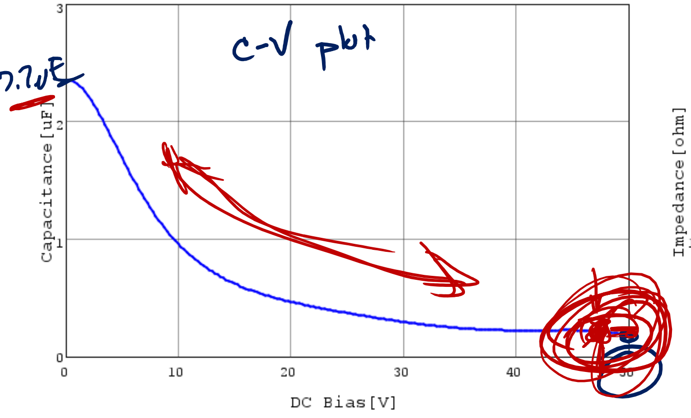
MLCC

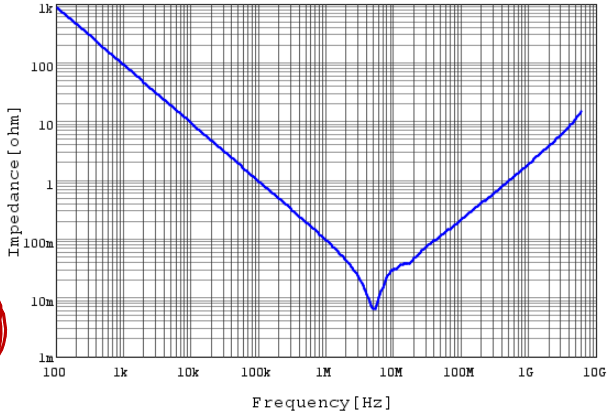
- Capacitor codes, e.g. X7R or C0G standardized to define stability over temperature
  - **Class-II**: Codes begin with X, Y, or Z (e.g. X7R, Y5V)
    - high capacitance
    - poor capacitance linearity / stability

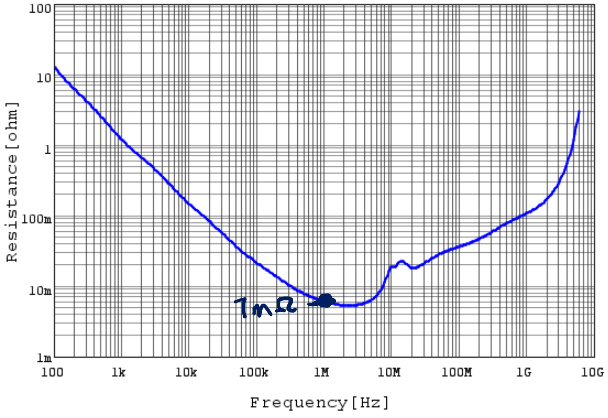
    50V, 0603
    X5R, 47uF
    -55°C - 85°C
  - **Class-I**: Codes begin with [CBLAMPRSTVU] (e.g. C0G, NPO)
    - low capacitance
    - good capacitance stability

    50V, 0603
    C0G, 18nF
    -55 - 125°C

2.2µF, 50V X7R (Class-II) 0603 footprint

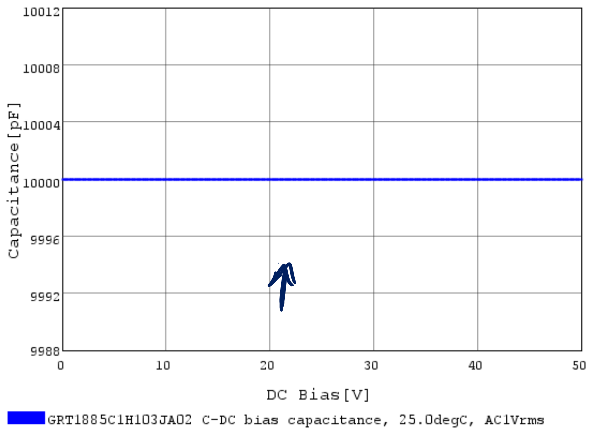


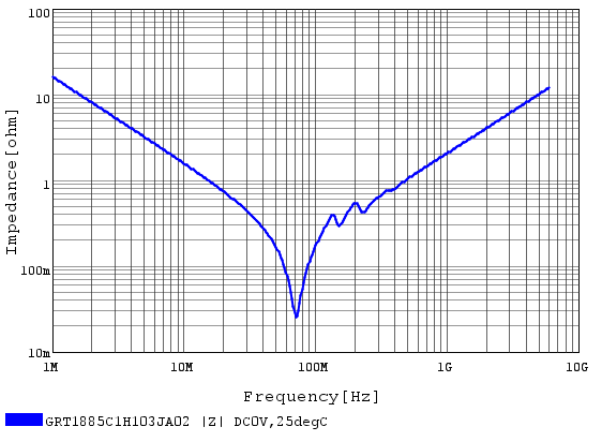


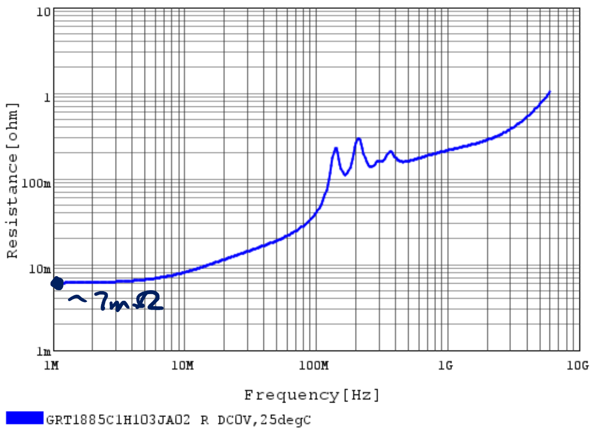


Remaining: 7.2% at full voltage

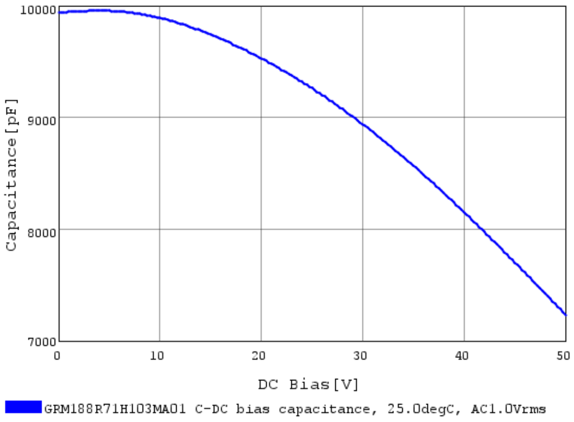
10nF, 50V C0G (Class-I) 0603 footprint

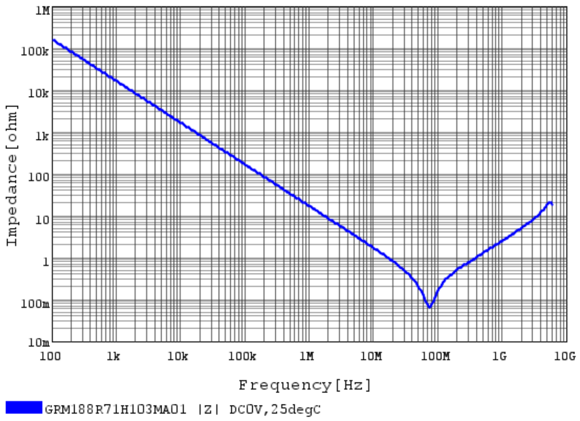


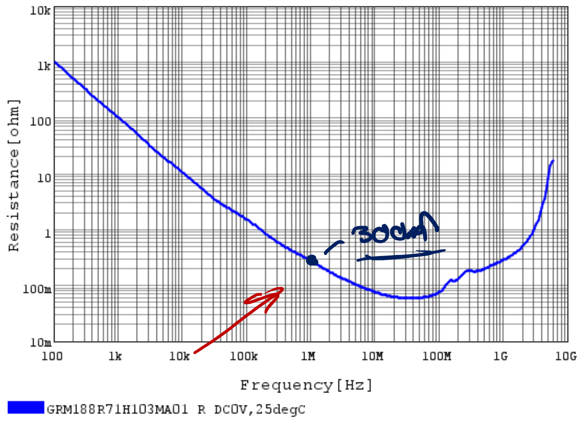




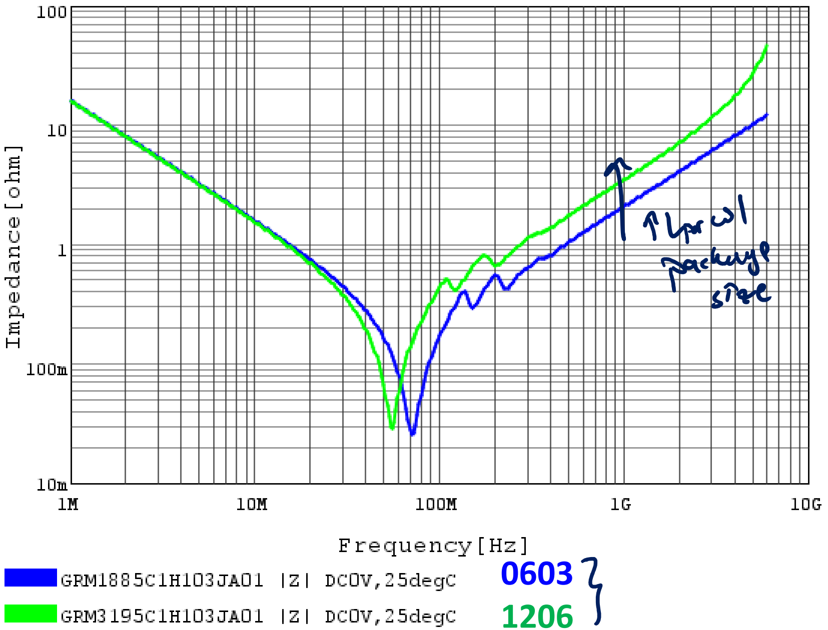
10nF, 50V X7R (Class-II) 0603 footprint







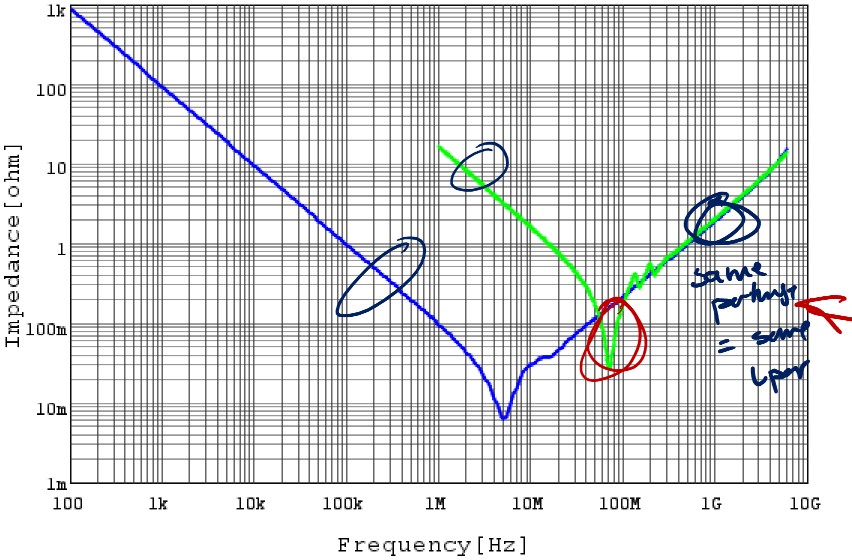
10nF, 50V C0G (Class-I) varied footprint



0603

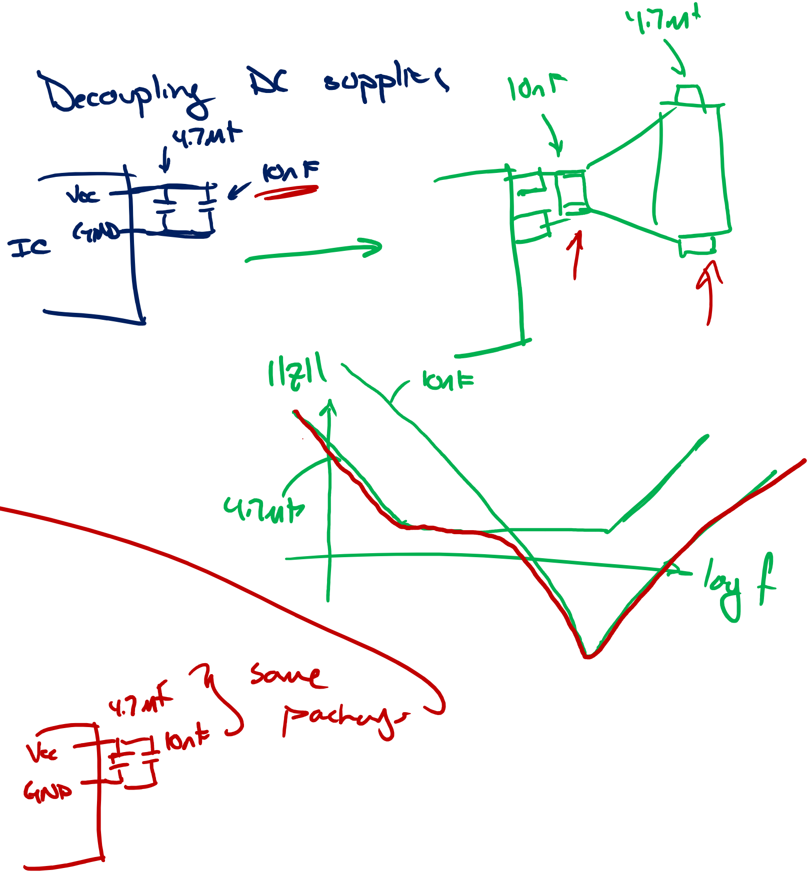
1206

Same 0603 Footprint



GRT188R61H225KE13 |Z| DC0V,25degC → **2.2µF X5R**

GCM1885C1H103GA16 |Z| DC0V,25degC **10nF C0G**



Class-II Capacitor Hysteresis Loss

TABLE II
EMPLOYED COMPONENTS

Component	Dielectric	Manufacturer	Part Number	V_n	C_n	N(parallel)	C_{tot}	DF
C_{cal}	C0G	TDK	CAA572C0G2J204J640LH	650 V	200 nF	2	400 nF	< 0.02 %
C_{ref}	C0G	TDK	C5750C0G2A154J230KE	100 V	150 nF	32	4.8 µF	< 0.03 %
C_{DUT}	X7R	Knowles Syfer	2220Y1K00474KETWS2	1 kV	470 nF	1	470 nF	> 0.71 %

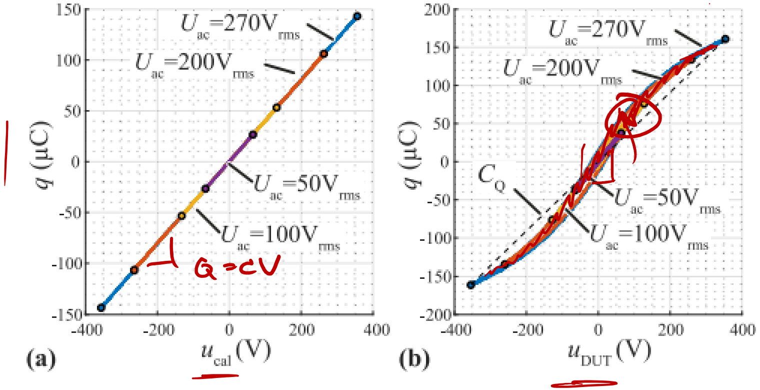


Fig. 6. $U - Q$ hysteresis recorded at 50 Hz for a range of excitation voltages for (a) the calibration capacitor, which shows no hysteresis and has a constant $C_Q = C_d$ at all voltages, and (b) the DUT, which exhibits increasing hysteresis and losses with increasing excitation voltage. C_Q highlighted for U_{ac} =270 V_{rms}. Measured $U - Q$ curves are identical at 50 Hz and 100 Hz.

D. Menzi, D. Bortis, G. Zulauf, M. Heller and J. W. Kolar, "Novel iGSE-C Loss Modeling of X7R Ceramic Capacitors," TPEL 2020

C_{oss} Hysteresis

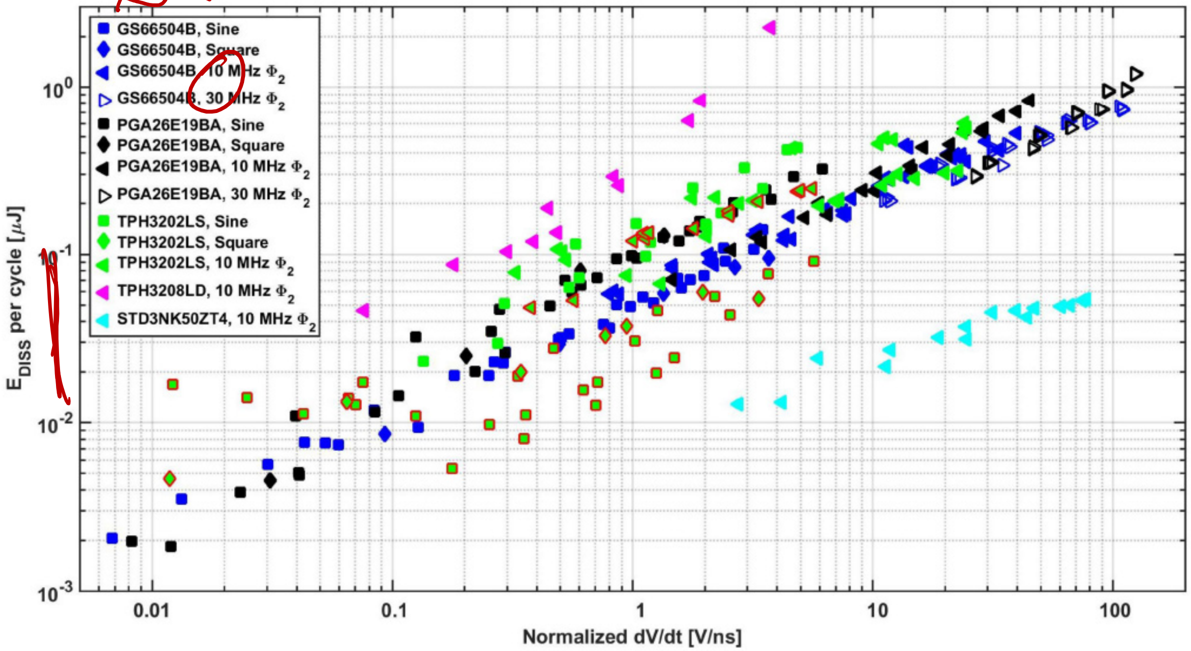


Fig. 15. Losses per cycle versus normalized, by (8), $\mathbf{dV/dt}$ for the three studied devices and two additional "extreme performance" devices. The red outline around the TPH3202LS results indicates applied voltages under 300 V and $\beta = 1.46$ in (8). All recorded measurements are included here. There are no measurements for the TPH3202LS 30 MHz Φ_2, as the Φ_2 wave generator could not be tuned to maintain ZVS with the TPH3202LS device and C_{REF} in parallel.

Transistor Structure and Material

SiC

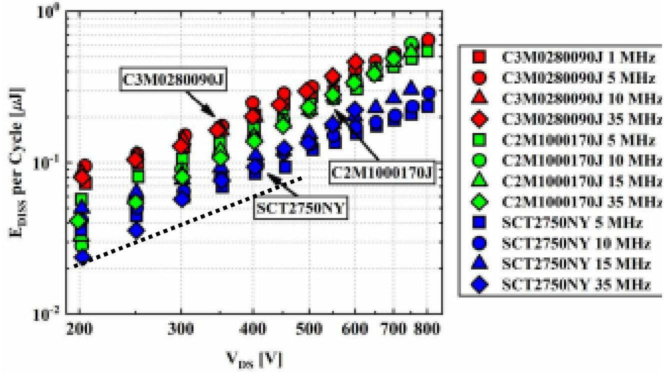
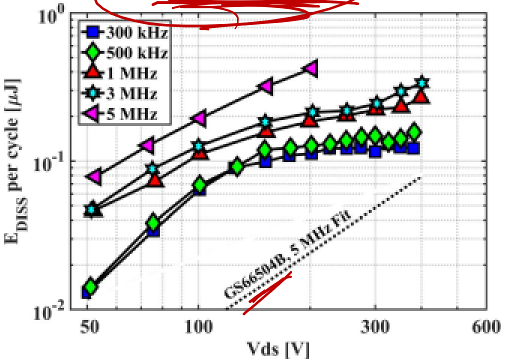


Fig. 4: C_{OSS} losses for three devices from 1-35 MHz.

Si Superjunction



(b) High-frequency C_{OSS} losses for the R6011KNTJL device.

Fig. 6: Silicon superjunction C_{OSS} loss data.

Si

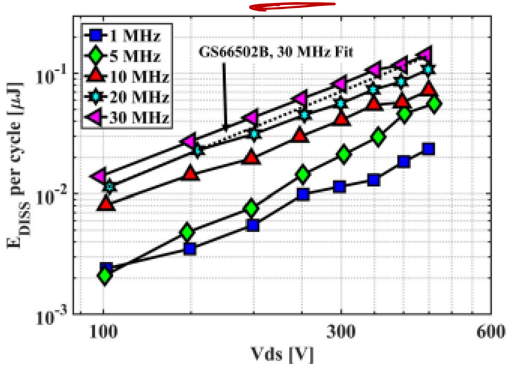


Fig. 7: C_{OSS} losses for STD3NK50ZT4.

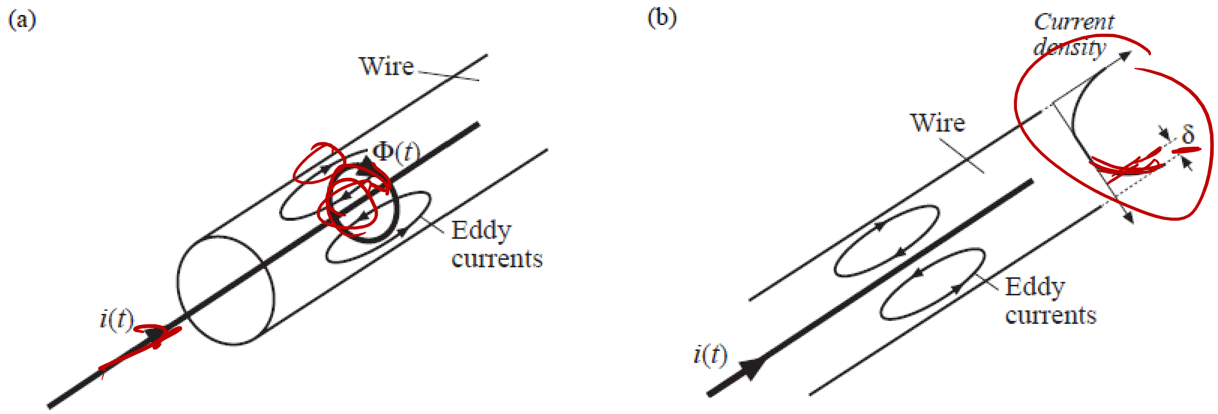
G. Zulauf, Z. Tong and J. Rivas-Davila, "Considerations for Active Power Device Selection in High- and Very-High-Frequency Power Converters," COMPEL *2018*

INDUCTOR AC LOSSES

Tiny Box Comments

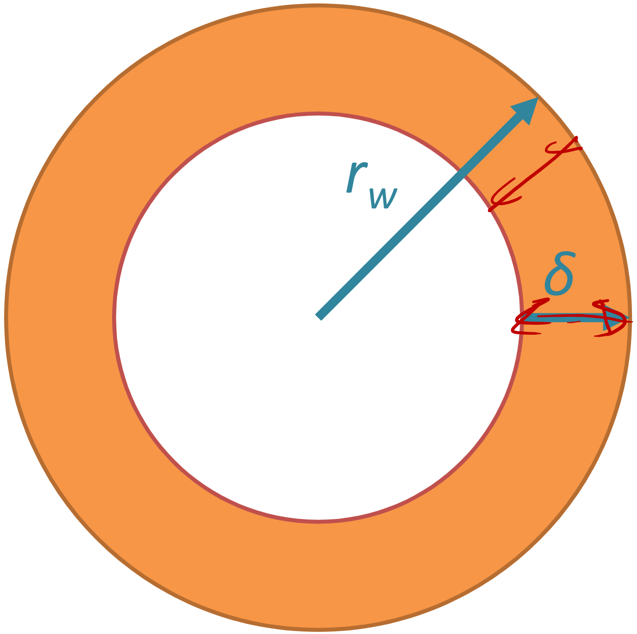
- Many nonlinear and complex loss phenomena in magnetics
- Online tools from manufacturers are usually poor predictors of performance with large, high-frequency ripple

Skin Effect in Copper Wire



- Current profile at high frequency is exponential function of distance from center with characteristic length δ

AC Resistance



$$A_{w,eff} = \pi {r_w}^2 - \pi(r_w - \delta)^2$$

$$R_{ac} = \rho \frac{l_b}{A_{w,eff}}$$

Skin Depth

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}}$$

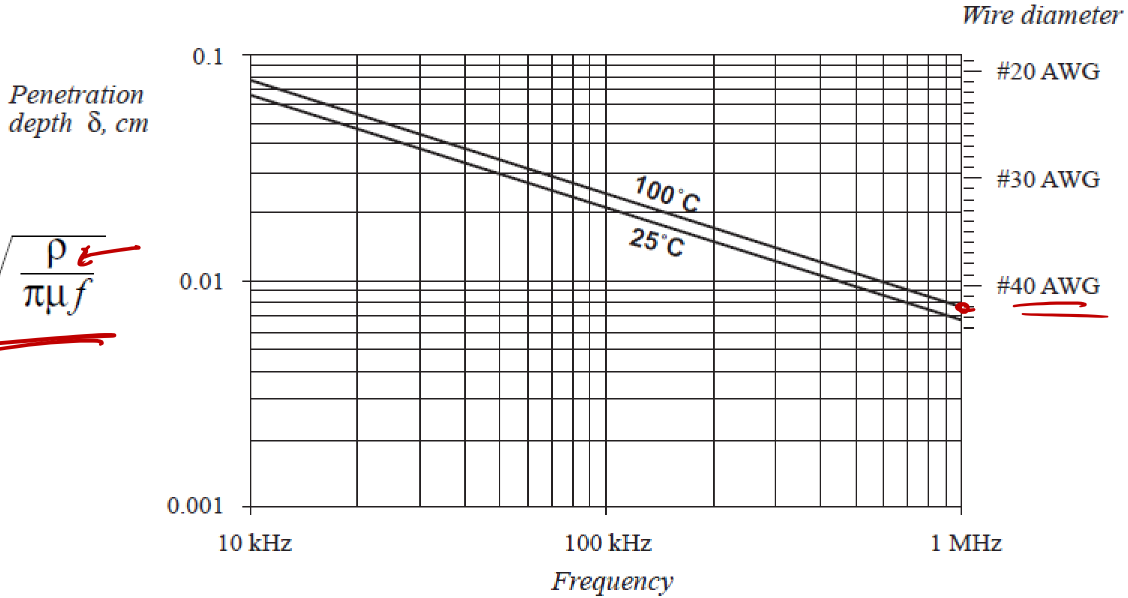
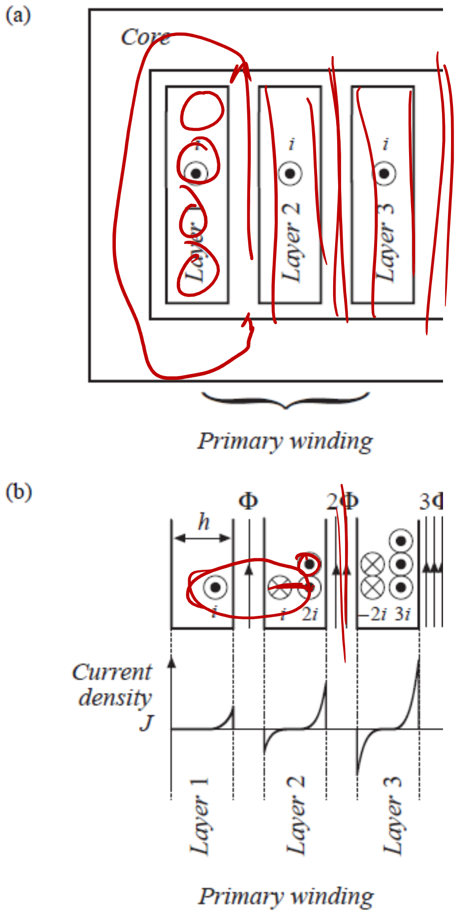


Fig. 13.23 Penetration depth δ, as a function of frequency *f*, for copper wire.



Proximity Effect

- In *foil* conductor closely spaced with $h >> \delta$, flux between layers generates additional current according to Lentz's law.

$$P_1 = {I_{L,rms}}^2 R_{ac}$$

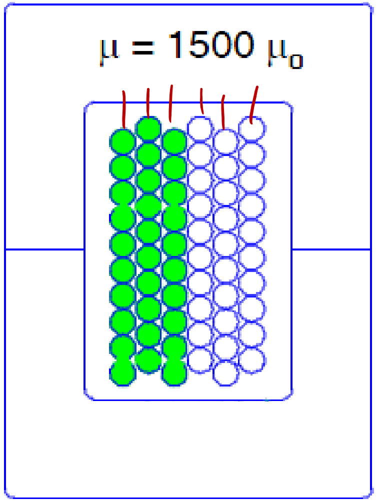
- Power loss in layer 2:

$$P_2 = {I_{L,rms}}^2 R_{ac} + \left(2I_{L,rms}\right)^2 R_{ac}$$

$$P_2 = 5P_1$$

- Needs modification for non-foil conductors

Simulation Example



- AWG#30 copper wire
  - Diameter $d = 0.294$ mm
  - $d = \delta$ at around 50 kHz
- 1:1 transformer
  - Primary and secondary are the same, 30 turns in 3 layers
- Sinusoidal currents, $I_{1rms} = I_{2rms} = 1$ A

Numerical field and current density solutions using FEMM (Finite Element Method Magnetics), a free 2D solver, http://www.femm.info/wiki/HomePage

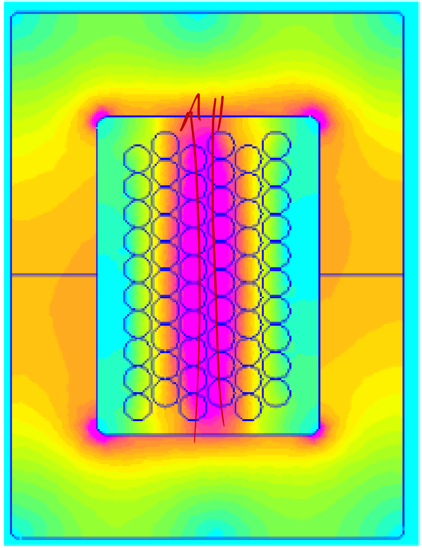
Flux density magnitude

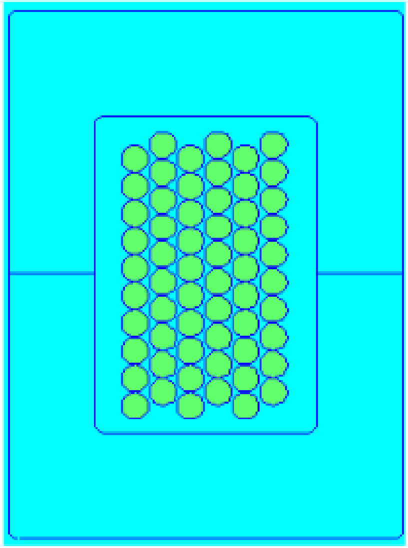
Density Plot: |B|, Tesla
9.500e-003 : >1.000e-002
9.000e-003 : 9.500e-003
8.500e-003 : 9.000e-003
8.000e-003 : 8.500e-003
7.500e-003 : 8.000e-003
7.000e-003 : 7.500e-003
6.500e-003 : 7.000e-003
6.000e-003 : 6.500e-003
5.500e-003 : 6.000e-003
5.001e-003 : 5.500e-003
4.501e-003 : 5.001e-003
4.001e-003 : 4.501e-003
3.501e-003 : 4.001e-003
3.001e-003 : 3.501e-003
2.501e-003 : 3.001e-003
2.001e-003 : 2.501e-003
1.501e-003 : 2.001e-003
1.001e-003 : 1.501e-003
5.010e-004 : 1.001e-003
<1.000e-006 : 5.010e-004

Current density magnitude

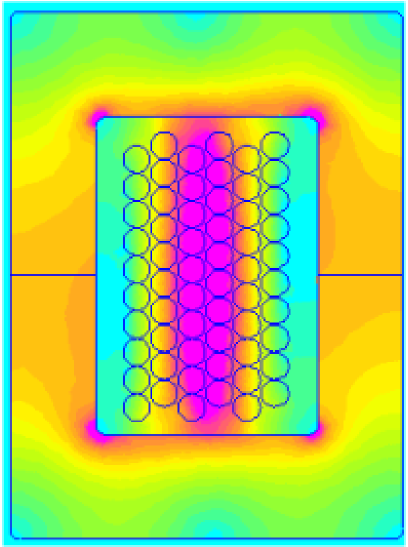
Density Plot: |J|, MA/m^2
9.500e+001 : >1.000e+002
9.000e+001 : 9.500e+001
8.500e+001 : 9.000e+001
8.000e+001 : 8.500e+001
7.500e+001 : 8.000e+001
7.000e+001 : 7.500e+001
6.500e+001 : 7.000e+001
6.000e+001 : 6.500e+001
5.500e+001 : 6.000e+001
5.000e+001 : 5.500e+001
4.500e+001 : 5.000e+001
4.000e+001 : 4.500e+001
3.500e+001 : 4.000e+001
3.000e+001 : 3.500e+001
2.500e+001 : 3.000e+001
2.000e+001 : 2.500e+001
1.500e+001 : 2.000e+001
1.000e+001 : 1.500e+001
5.000e+000 : 1.000e+001
<0.000e+000 : 5.000e+000

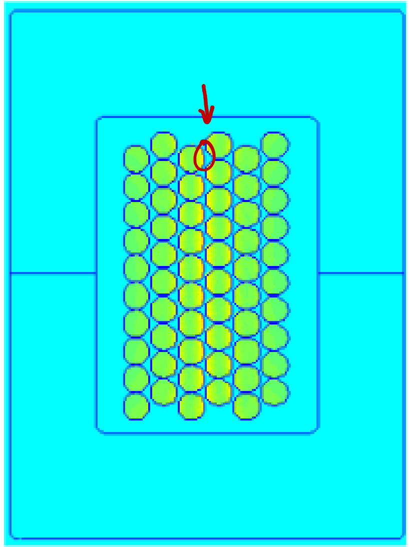
Frequency: 1 kHz





Frequency: 100 kHz

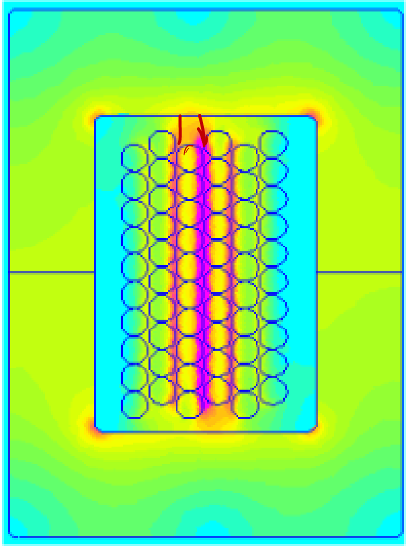




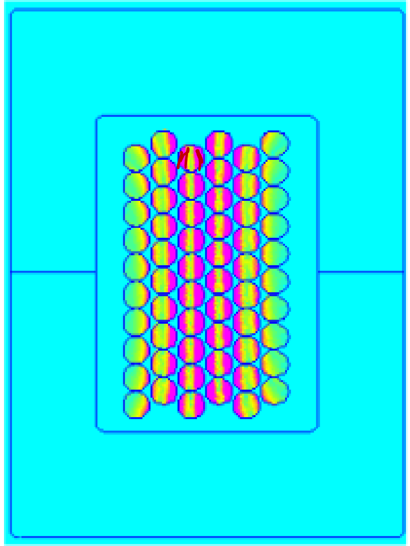
Total copper losses 1.8 larger than at 1 kHz

Frequency: 1 MHz

Flux density

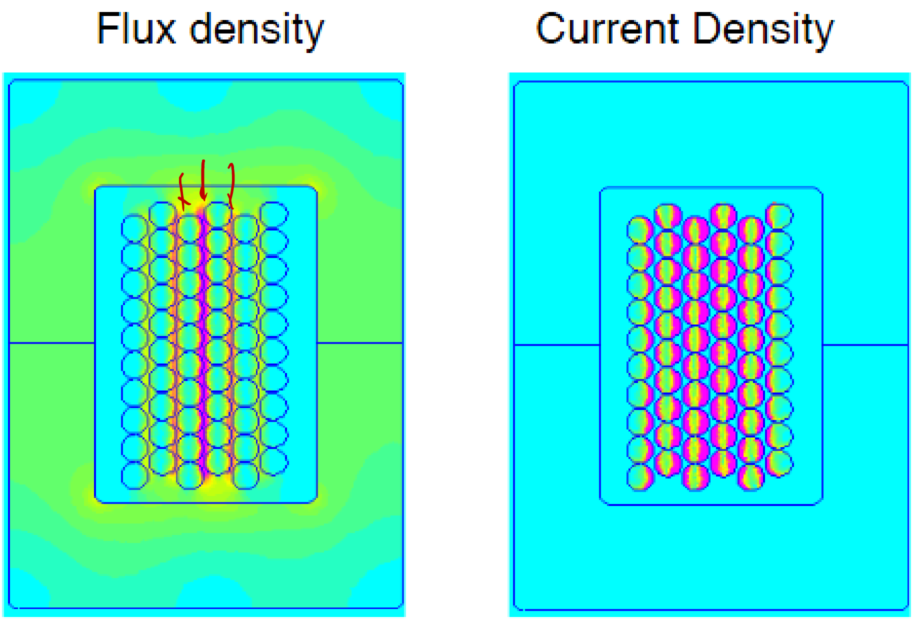


Current Density



Total copper losses 20 times larger than at 1 kHz

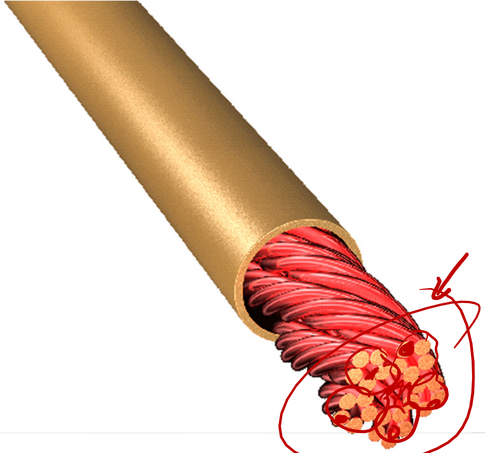
Frequency: 10 MHz

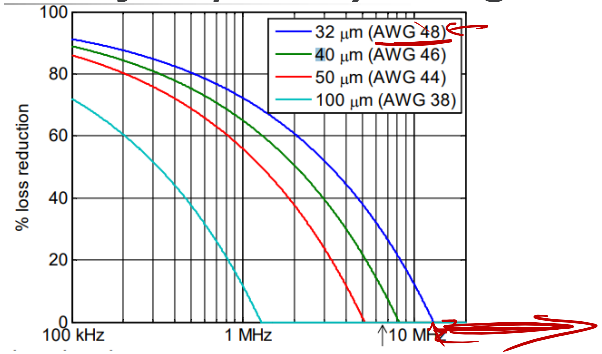


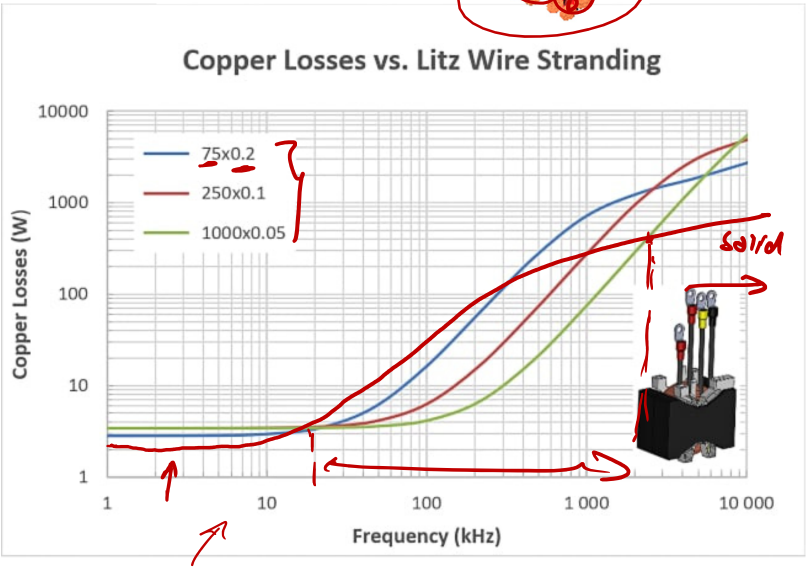
Very significant proximity effect
Total copper losses = 65 times larger than at 1 KHz

Litz Wire

- Braided, insulated strands with *d<<δ*
- Now has strand/bundle/wire level ac resistance effects
- Significantly lower resistance *in a bounded frequency range*



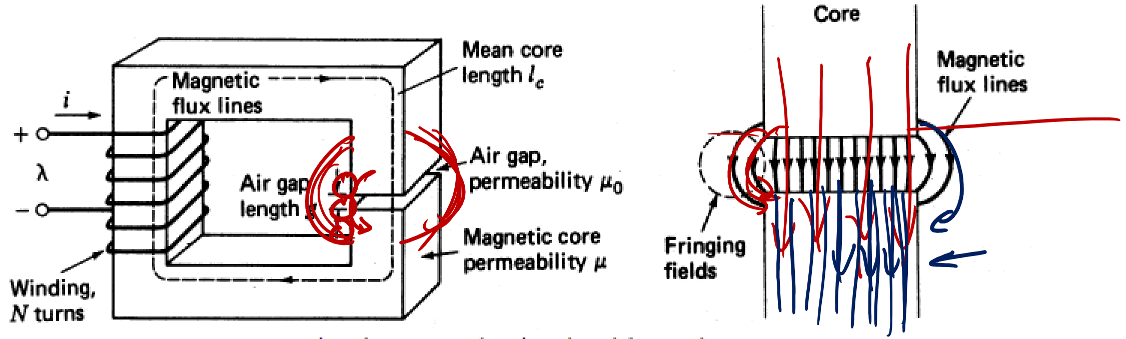




Patrick Fouassier, "Practical Guidelines for Litz Wire Selection and AC Copper Losses Estimation“
C. Sullivan, “High-Frequency Magnetics Design: Overview and Winding Loss”

THE UNIVERSITY OF TENNESSEE KNOXVILLE

Fringing

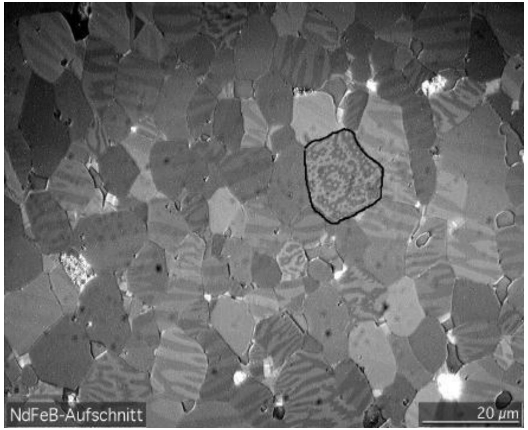


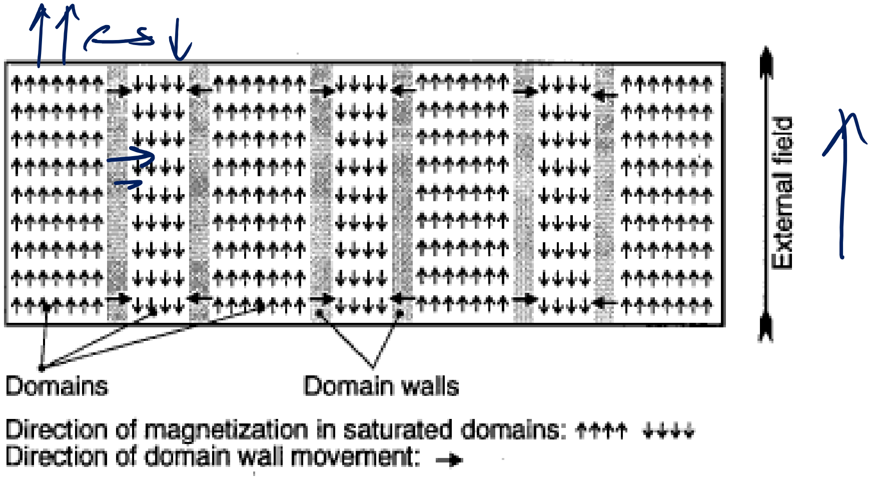
A simple magnetic circuit with an air gap

- Near air gap, flux may bow out significantly, causing additional eddy current losses in nearby conductors

Physical Origin of Core Loss

- Magnetic material is divided into “domains” of saturated material
- Both Hysteresis and Eddy Current losses occur from domain wall shifting





Reinert, J.; Brockmeyer, A.; De Doncker, R.W.; , "Calculation of losses in ferro- and ferrimagnetic materials based on the modified Steinmetz equation,"

Inductor Core Loss

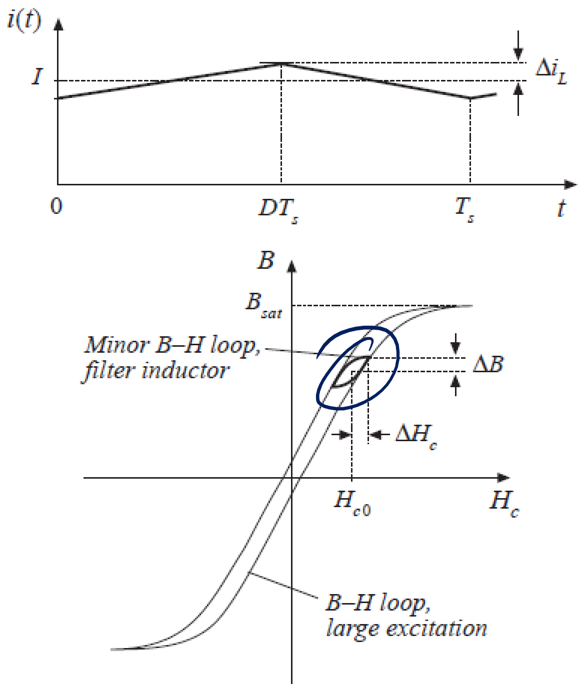
- Governed by Steinmetz Equation:

$$P_v = K_{fe} f_s^{\alpha} (\Delta B)^{\beta} \text{ [mW/cm}^3\text{]}$$

- Parameters K_{fe}, α, and β extracted from manufacturer data

$$P_{fe} = P_v A_c l_m \text{ [mW]}$$

- $\Delta B \propto \Delta i_L \rightarrow$ small losses with small ripple



Steinmetz Parameter Extraction

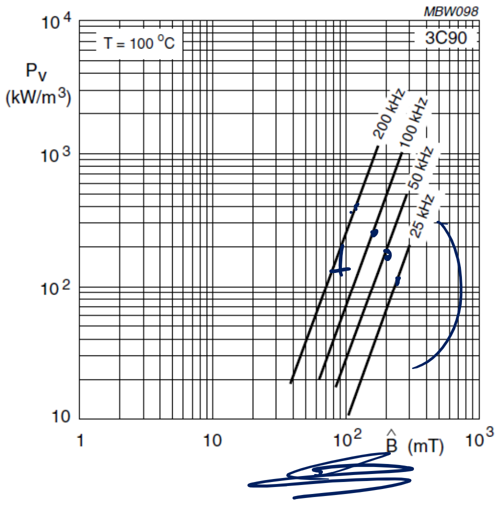


Fig.6 Specific power loss as a function of peak flux density with frequency as a parameter.

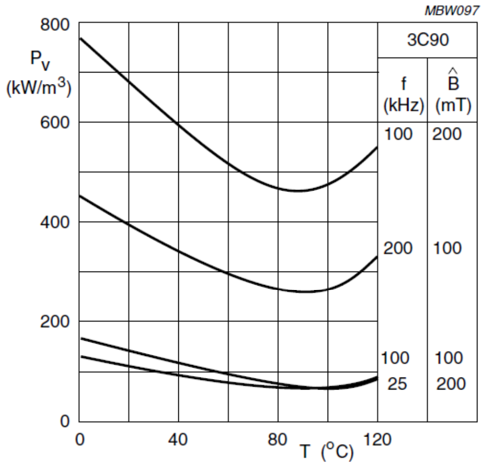


Fig.7 Specific power loss for several frequency/flux density combinations as a function of temperature.

Ferroxcube Curve Fit Parameters

Power losses in our ferrites have been measured as a function of frequency (f in Hz), peak flux density (B in T) and temperature (T in °C). Core loss density can be approximated (2) by the following formula :

$$P_{core} = C_m \cdot f^x \cdot B_{peak}^y (ct_0 - ct_1 T + ct_2 T^2) \quad [3]$$

$$= C_m \cdot C_T \cdot f^x \cdot B_{peak}^y \quad [mW/cm^3]$$

ferrite	f (kHz)	Cm	x	y	ct_2	ct_1	ct_0
3C30	20-100	$7.13.10^{-3}$	1.42	3.02	$3.65.10^{-4}$	$6.65.10^{-2}$	4
	100-200	$7.13.10^{-3}$	1.42	3.02	4.10^{-4}	$6.8 .10^{-2}$	3.8
3C90	20-200	$3.2.10^{-3}$	1.46	2.75	$1.65.10^{-4}$	$3.1.10^{-2}$	2.45
3C94	20-200	$2.37.10^{-3}$	1.46	2.75	$1.65.10^{-4}$	$3.1.10^{-2}$	2.45
	200-400	2.10^{-9}	2.6	2.75	$1.65.10^{-4}$	$3.1.10^{-2}$	2.45
3F3	100-300	$0.25.10^{-3}$	1.63	2.45	$0.79.10^{-4}$	$1.05.10^{-2}$	1.26
	300-500	2.10^{-5}	1.8	2.5	$0.77.10^{-4}$	$1.05.10^{-2}$	1.28
	500-1000	$3.6.10^{-9}$	2.4	2.25	$0.67.10^{-4}$	$0.81.10^{-2}$	1.14
3F4	500-1000	12.10^{-4}	1.75	2.9	$0.95.10^{-4}$	$1.1.10^{-2}$	1.15
	1000-3000	$1.1.10^{-11}$	2.8	2.4	$0.34.10^{-4}$	$0.01.10^{-2}$	0.67

Table 1: Fit parameters to calculate the power loss density

NSE/iGSE

$$P_{NSE} = \left(\frac{\Delta B}{2}\right)^{\beta-\alpha} \frac{k_N}{T} \int_0^T \left|\frac{dB}{dt}\right|^{\alpha} dt$$

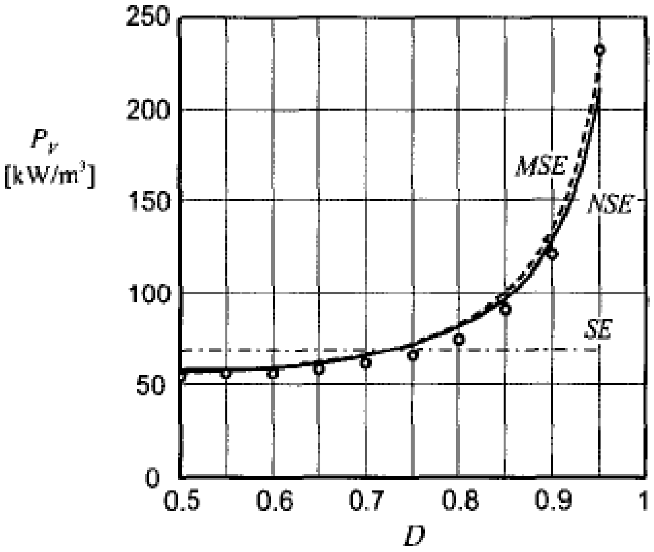
$$k_N = \frac{k}{(2\pi)^{\alpha-1} \int_0^{2\pi} |\cos\theta|^{\alpha} d\vartheta}$$

Simple Formula for Square-wave voltages:

$$P_{NSE} = k_N \, (2f)^{\alpha} (\Delta B)^{\beta} \left(D^{1-\alpha} + (1-D)^{1-\alpha}\right) \qquad (10)$$

where f is the operating frequency;
$\Delta B / 2$ is the peak induction;
D is the duty ratio of the square wave voltage.

Note: The second and third harmonics are dominant at moderate values of duty ratio D. For extreme values of D (95%), a higher value of α could give better matching to the actual losses.



Van den Bossche, A.; Valchev, V.C.; Georgiev, G.B.; , "Measurement and loss model of ferrites with non-sinusoidal waveforms,"
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