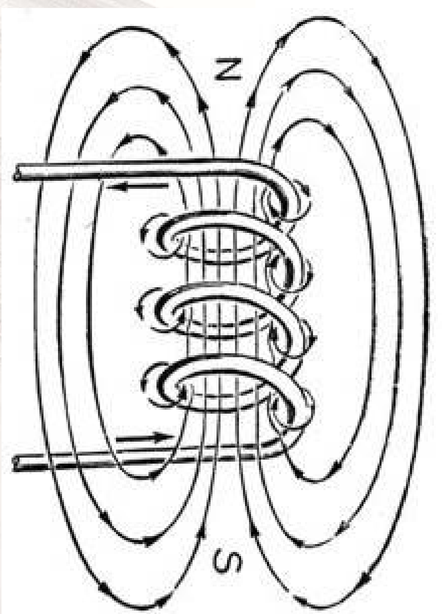
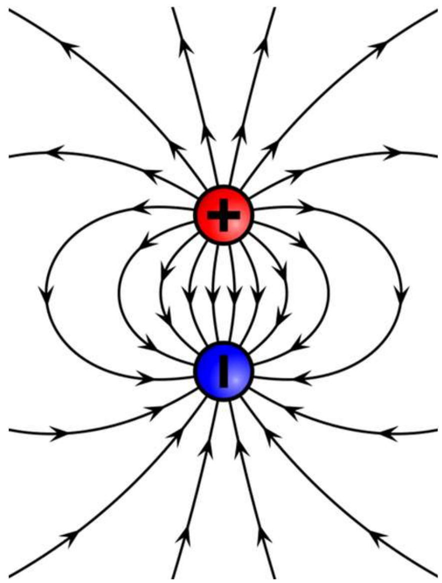
Power Electronics

Passive Components

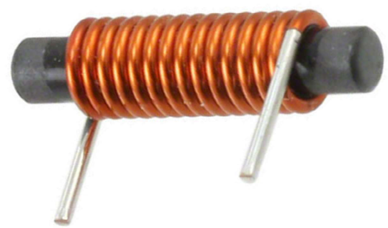
Passive Components

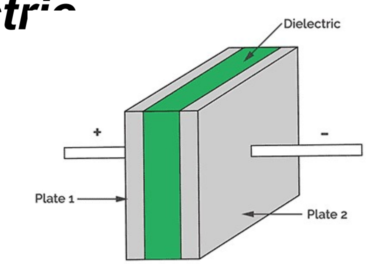


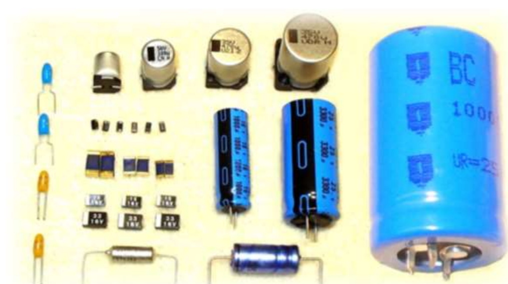


Types of Passive Components


- **Resistive**
  - – ***Heaters, some light sources, ...***
- **Inductive**
  - – ***Stores energy in magnetic fields***
- **Capacitive**
  - – ***Stores energy in electric fields***

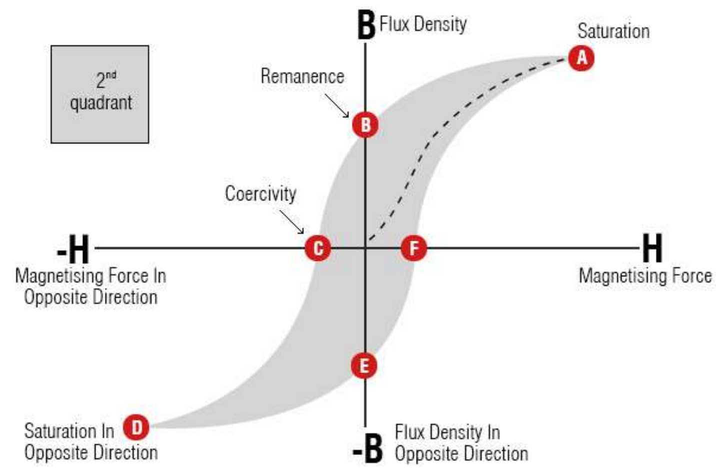






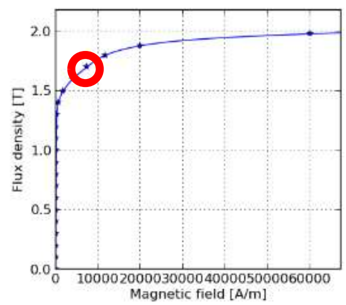
Inductive Elements

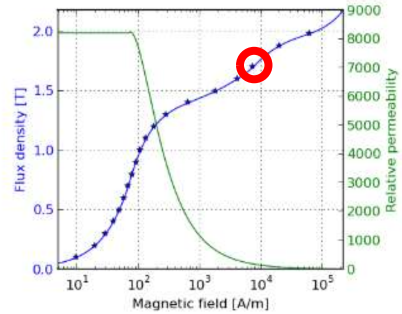
- **Components**
  - *Inductors*
  - *Transformers*
- **Materials**
  - *Laminated alloys (e.g Silicon-steel, high saturation level, low frequency range)*
  - *Iron powder composites (lower magnetic saturation level, low to medium frequency range)*
  - *Ferrites (low saturation level, high frequency range)*



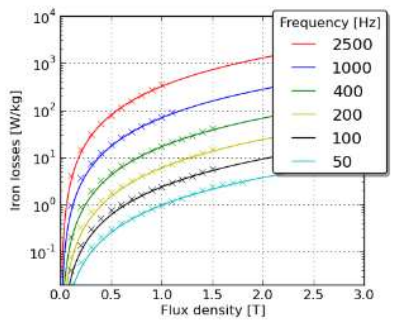
Surahammars M250-35A - laminate

Name:	Sura M250-35A
Manufacturer:	Surahammars Bruk
Density:	7600 kg/m3
Resistivity:	5.5e-07 Ωm
Lamination thickness:	0.35 mm
Stacking factor:	0.95 (rule of thumb)
BH curve:	





Iron losses:



https://www.emetor.com/edit/materials/sura-m1000-100a/?cat=6&co=10

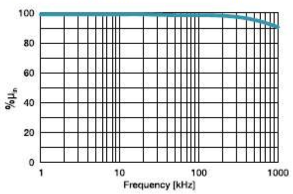
Soft Magnetic iron Powders Cores

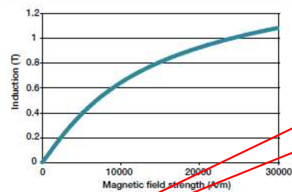
Typical Data C-80

Magnetic properties

Measured on ring geometry OD55ID45H5mm

B_{sat} [T]	H_c [A/m]	μ_{max}	μ_{in}
1.5	160	85	82





Core loss

f [Hz] \ B [T]	0.25	0.5	0.75	1.0
50	3.1	11	24	41
60	3.8	14	29	[illegible]

Core loss [mW/cc]

Low frequency (0-200 Hz) - high induction (0-1 T):
P[mW/cc]=0.55•B[T]^[illegible]•f[Hz]^[illegible]

f [kHz] \ B [T]	0.05	0.1	0.15	0.2
10	26	110	250	460
20	57	240	560	[illegible]

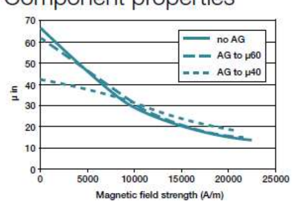
Core loss [mW/cc]

High frequency (2-30 kHz) - low induction (0-0.2 T):
P[mW/cc]=950•B[T]^[illegible]•f[kHz]^[illegible]

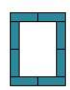
41 mW/cc = 0.041/(6300/10000) = 0.065 W/kg @ 50 Hz

460 mW/cc = 0.46/(6300/10000) = 0.73 W/kg @ 10 kHz

Component properties



Measurment set up
8pcs B60.30.20C-80
arranged as shown



μin = c0+c1*H+c2*H^2+c3*H^3+c4*H^4

	c0	c1	c2	c3	c4	Gap (mm)*
No gap	67.4	-4.99E-03	9.69E-08	3.06E-12	-9.33E-17	0
μ60	61.6	-3.34E-03	-4.79E-08	8.30E-12	-1.61E-16	4x0.2
μ40	40.9	-3.52E-04	-1.13E-07	4.87E-12	-5.73E-17	4x2.5

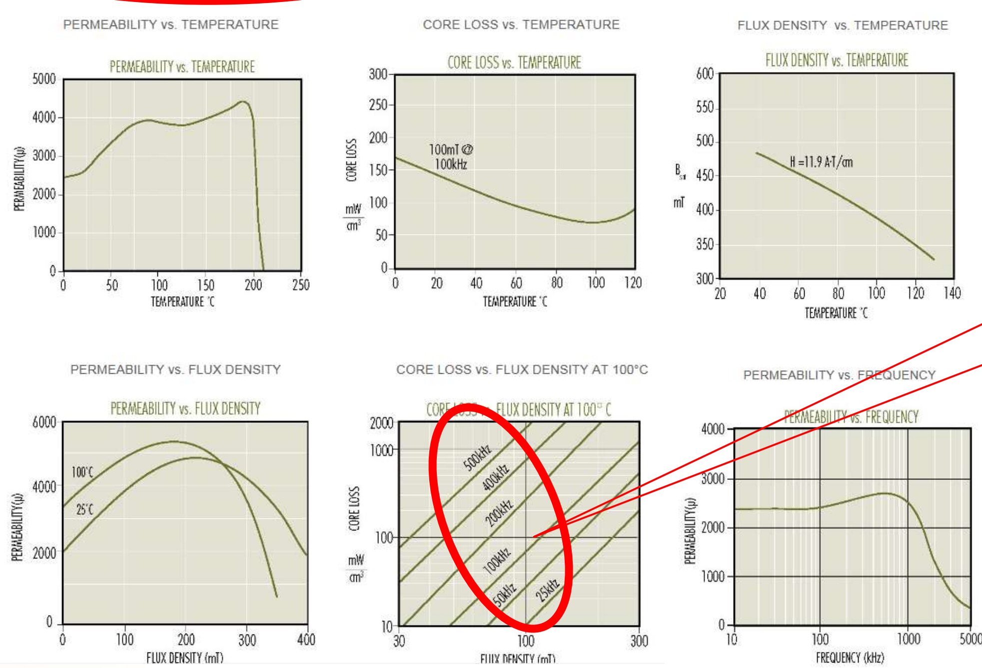
* Gapping required for core structure illustrated.

https://www.hoganas.com/globalassets/media/sharepoint-documents/BrochuresanddatasheetsAllDocuments/Inductit_C80.pdf

Ferrite Core material from Mg-Inc

P material is a low-medium frequency general-purpose power converter material. Engineered for lowest losses at 95°C. Available in almost all core sizes and shapes.

Initial Perm (10 kHz)	2,500 ± 25%
Saturation Flux Density (4,700 G at 15 Oe,25°C)	470 mT, 11.9 A•T/cm
Curie Temperature	210°C
Maximum Usable Frequency (50% roll-off)	≤1.8 MHz
Remanence (1,600 G, 25°C)	160 mT
Resistivity	5 Ω-m
Density	4.8 g/cm^3



100 mW/cc = 0.1/(4800/10000) = 0.21 W/kg @ 100 kHz and 100 mT

http://www.mag-inc.com/products/ferrite-cores/p-material

Inductive Elements - Core Losses

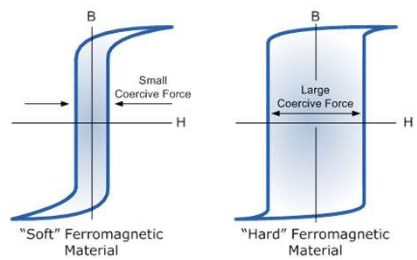
- **Core losses depend both on frequency and peak flux density**
  - ***Usually specified in loss curves (one curve for certain frequencies)***
  - ***Also analytical expressions like Steinmetz's formula:***

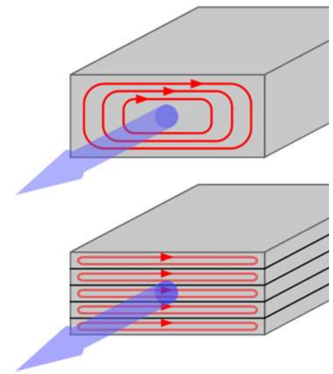
Hysteresis losses

Eddy current losses

$$p_{Fe} = k_h f^{a_1} \hat{B}_{ac}^{a_2} + k_{ec} f^2 \hat{B}_{ac}^2$$

  - ***One loop per period*** $\rightarrow a_1 \approx 1$
  - ***Loop roughly quadratic*** $\rightarrow a_2 \approx 2$
- **Steinmetz's formula includes two loss terms**
  - ***Hysteresis loss***
  - ***Eddy current loss***
- **Empirical expressions are provided by some core manufacturers**





$$p_{Fe} = \frac{f}{\frac{a}{\hat{B}_{ac}^3} + \frac{b}{\hat{B}_{ac}^{2.3}} + \frac{c}{\hat{B}_{ac}^{1.65}}} + \left(d f^2 \hat{B}_{ac}^2\right)$$

Inductor Design

Inductance

$$L = \frac{d\psi}{di}$$

$$N \cdot i = H_{Fe} \cdot l_{Fe} + H_\delta \cdot l_\delta$$

$$\begin{cases} B_{Fe} = \mu_0 \mu_{Fe} H_{Fe} \\ B_\delta = \mu_0 H_\delta \end{cases}$$

$$N \cdot i = \frac{B_{Fe}}{\mu_0 \mu_{Fe}} \cdot l_{Fe} + \frac{B_\delta}{\mu_0} \cdot l_\delta$$

$$\Phi = \frac{\psi}{N} = B_{Fe} A_{Fe} = B_\delta A_\delta$$

$$N \cdot i = \frac{\psi}{\mu_0 N} \cdot \left(\frac{l_{Fe}}{\mu_{Fe} A_{Fe}} + \frac{l_\delta}{A_\delta} \right)$$

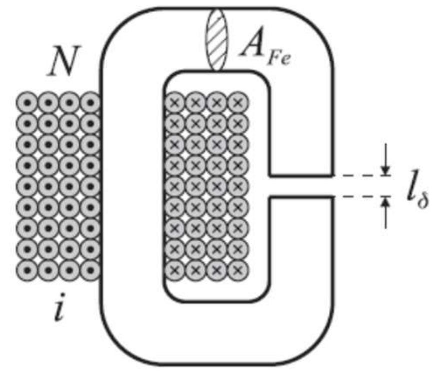
$$B_\delta = B_{Fe} = B \Leftrightarrow A_\delta = A_{Fe}$$

$$N \cdot i = \frac{\psi}{\mu_0 \cdot A \cdot N} \cdot \left(\frac{l_{fe}}{\mu_{fe}} + l_\delta \right)$$

$$L = \frac{\psi}{i} = \frac{\mu_0 \cdot A \cdot N^2}{\left(\frac{l_{fe}}{\mu_{fe}} + l_\delta \right)}$$

$$l_\delta \gg \frac{l_{fe}}{\mu_{fe}}$$

$$L = \frac{\psi}{i} = \frac{\mu_0 \cdot A \cdot N^2}{l_\delta}$$



Given a certain total design space, and…

- ***A desired inductance, L***
- ***An intended current level → A certain minimum conductor area for resistive losses***

… then the number of turns (*N*) and the core area (A_{fe}) are in conflict. If one is to big, there will be no room for the other…

Need for optimization!!!

Where is the Energy in a magnetic circuit?

- **First, derive the total energy**

$$W = \frac{1}{2} \cdot L \cdot i^2 = \frac{1}{2} \cdot L \cdot \left(\frac{\psi}{L}\right)^2 = \frac{1}{2} \cdot \frac{\psi^2}{L} = \left\{ \begin{matrix} A_{core} \approx A_{gap} = A \\ B_{fe} \approx B_\delta = B \\ \psi = N \cdot B \cdot A \end{matrix} \right\} = \frac{1}{2} \cdot \frac{N^2 \cdot B^2 \cdot A^2}{\frac{\mu_0 \cdot A \cdot N^2}{\left(\frac{l_{fe}}{\mu_{fe}} + l_\delta\right)}} = \frac{1}{2} \cdot \frac{B^2 \cdot A}{\mu_0} \cdot \left(\frac{l_{fe}}{\mu_{fe}} + l_\delta\right)$$

- ***Example*:**
  - $l_{fe} = 200\ mm, l_\delta = 1\ mm$
  - $\mu_{fe} = 10000$
  - $\frac{l_{fe}}{\mu_{fe}} = 0.02\ or\ {}^{1}/_{50^{th}}$ of l_δ

- **Conclusion: Almost all energy is bound in the air gap!**

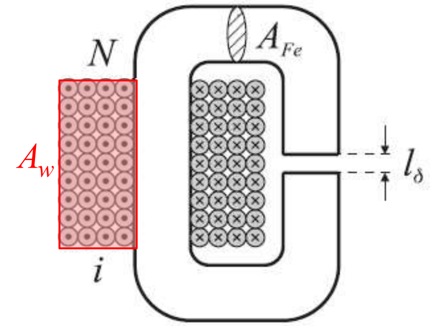
Inductor Core Size Selection

$$\widehat{W}_{magn} = \frac{1}{2} \cdot L \cdot \hat{\imath}_m^2 = \frac{1}{2} \cdot L \cdot \hat{\imath}_m \cdot \hat{\imath}_m =$$
$$= \frac{1}{2} \cdot \frac{\mu_0 \cdot A_{fe} \cdot N^2}{l_\delta} \cdot \hat{\imath}_m \cdot \hat{\imath}_m =$$
$$= \frac{1}{2} \cdot N \cdot A_{fe} \cdot \frac{\mu_0 \cdot \hat{\imath}_m \cdot N}{l_\delta} \cdot \hat{\imath}_m =$$
$$= \frac{1}{2} \cdot N \cdot A_{fe} \cdot \hat{B}_m \cdot \hat{\imath}_m =$$
$$= \frac{1}{2} \cdot N \cdot A_{fe} \cdot \hat{B}_m \cdot J_{cu} \cdot A_w \cdot k_{cu} =$$
$$= \frac{1}{2} \cdot N \cdot \hat{B}_m \cdot J_{cu} \cdot k_{cu} \cdot A_w \cdot A_{fe}$$
$$= \frac{1}{2} \cdot L \cdot \hat{\imath}_m \cdot N \cdot I_{cu}$$

$$\Rightarrow AP = A_w \cdot A_{fe} = \frac{L \cdot \hat{\imath}_m \cdot I_{cu}}{\hat{B}_m \cdot J_{cu} \cdot k_{cu}}$$

The more inductance or current, the bigger inductor

The higher the flux density, current density or fill factor, the smaller inductor



For an inductor with a single winding

$$i_m(t) = i_{Cu}(t)$$

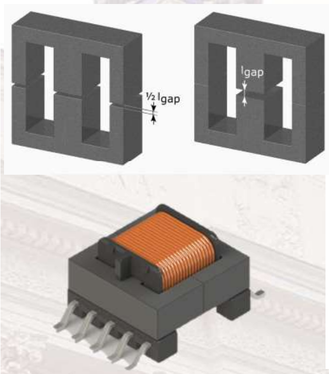
$$AP = \frac{L \hat{i}_{Cu} I_{Cu}}{k_{Cu} \hat{B} J_{Cu}}$$

For an inductor with several windings

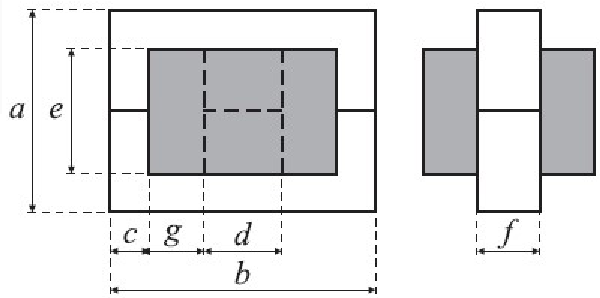
$$A_{w1} = \frac{A_w}{N_w} = \frac{N}{N_w} \frac{A_{Cu}}{k_{Cu}}$$

$$AP = N_w \frac{L_k \hat{i}_{m,k} I_{Cu,k}}{k_{Cu} \hat{B}_m J_{Cu}}$$

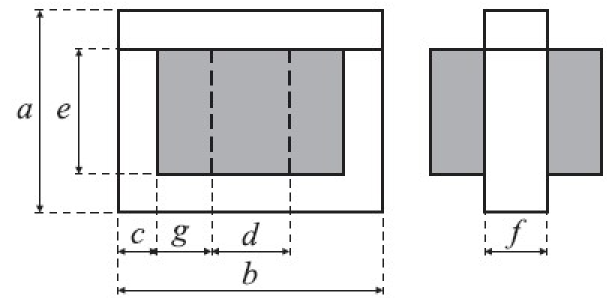
Core Configurations – Main variants

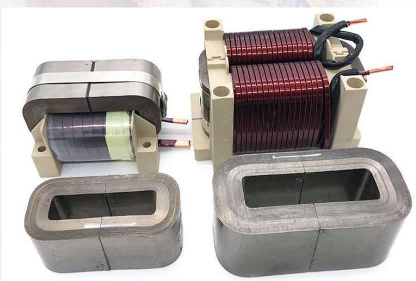


EE

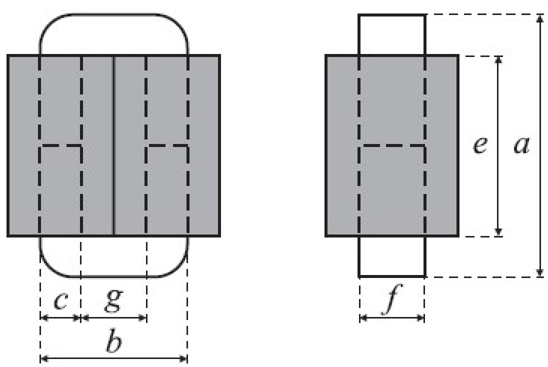


EI

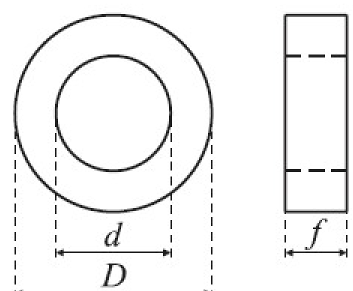


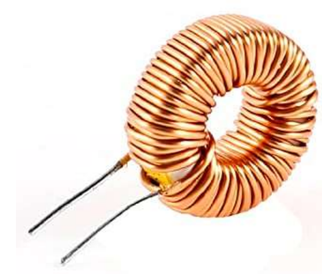


C



Toroidal





Inductor Design Example (I)

Inductor specification

Table 5.4: Inductor specification.

L	0.3 mH
I_{RMS} @ 1 kHz	120 A
I_{PEAK} @ 5 kHz	10 A
I_{PEAK} @ 10 kHz	5 A

Area product

$$AP = \frac{L \cdot \hat{\imath}_m \cdot I_{cu}}{\hat{B}_m \cdot J_{cu} \cdot k_{cu}}$$

$I_{Cu} \approx 120$ A

$\hat{i}_{Cu} = 120\sqrt{2} + 10 + 5$ A $= 185$ A

$\hat{B} = 0.35$ T ← Guess!

$$AP = \frac{L\hat{i}_{Cu} I_{Cu}}{k_{Cu}\hat{B}J_{Cu}} = 2379 \text{ cm}^4$$

0.4

2

The C-core TELMAG Su 150b (Figure 5.5), have geometrical properties according Table 5.5.

Table 5.5: Geometry of the core Su 150b.

a	255.6 mm
b	150.2 mm
c	49.4 mm
d	76.2 mm
e	154.0 mm
g	50.0 mm

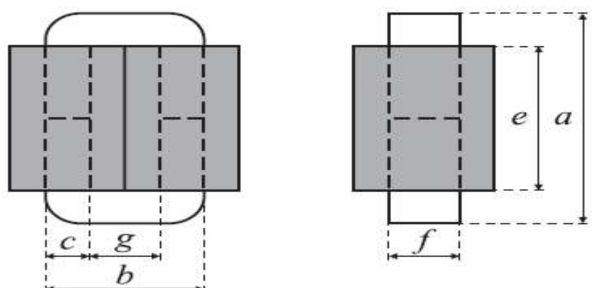
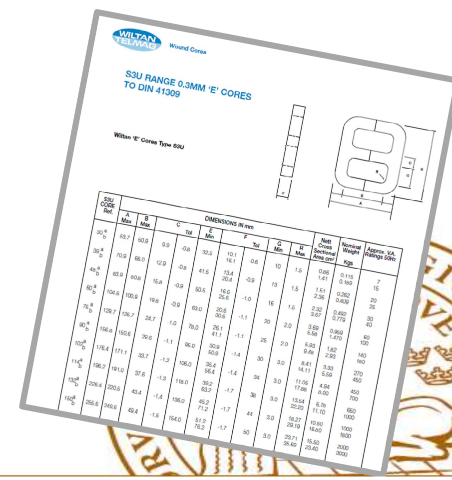


Figure 5.5: Inductor based on a C-core. The winding (grey) is split into two parallel connected windings.



IEA

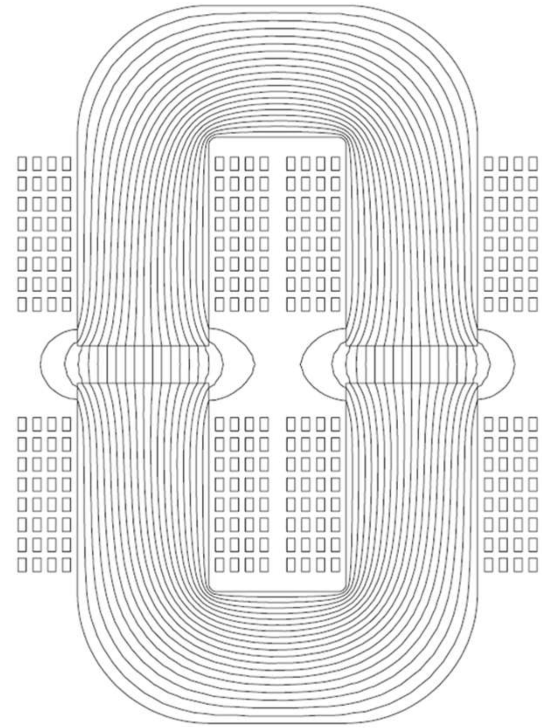
Flux Fringing factor

- ”Fringing” leads to:
  – *Larger air gap area = lower reluctance = higher flux density in the core*

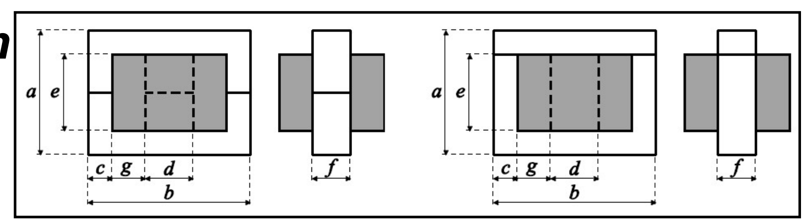
$$k_{FF} = 1 + \frac{l_\delta}{\sqrt{A_{Fe}}} \cdot \ln\left(\frac{2 \cdot e}{l_\delta}\right) \qquad N = \sqrt{\frac{l_\delta \cdot L}{\mu_0 \cdot A_{Fe} \cdot k_{FF}}}$$

air gap region

$$P_{Gap,i} = 1550 \cdot d \cdot l_\delta \cdot f_i \cdot \hat{B}_i^2$$



E- and I-cores



Lamination Stacking Factor

- **With thinner laminates, a larger part of the iron core is isolation material**

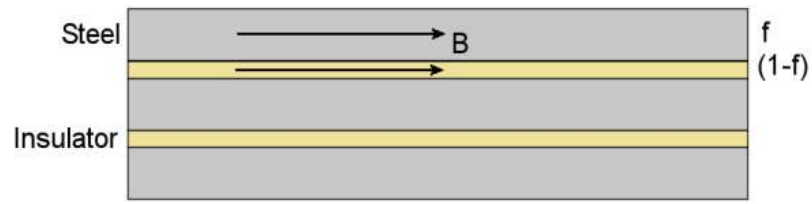


Table 5.3 Typical stacking factor *kFe* for tape wound C cores as a function of the steel tape thickness [15].

Lamination thickness [mm]	k_{Fe}
0.025	0.83
0.05	0.89
0.1	0.90
0.18	0.92
0.22 - 0.3	0.95

Inductor Design Example (II)

TELMAG Su 150b

$$A_{Fe} = 0.968 \cdot 33.9\ \text{cm}^2 = 32.8\ \text{cm}^2$$

$$A_w \approx 15.4 \cdot 5.0\ \text{cm}^2 = 77.0\ \text{cm}^2$$

$$AP = A_w A_{Fe} = 2527\ \text{cm}^4$$

$$N = \frac{L\hat{i}_{Cu}}{A_{Fe}\hat{B}} = 48\ \text{turns}$$

$$L = \frac{\mu_0 A_{Fe} N^2}{l_\delta}$$

$$l_\delta = \frac{\mu_0 A_{Fe} N^2}{L} = 3.2\ \text{mm} = 2 \cdot 1.6\ \text{mm}$$

$$k_{FF} = 1 + \frac{l_\delta}{\sqrt{A_{Fe}}} \cdot \ln\left(\frac{2e}{l_\delta}\right) = 2.265$$

$$N = \sqrt{\frac{l_\delta L}{\mu_0 A_{Fe} k_{FF}}} = 32\ \text{turns}$$

$$L = \frac{\mu_0 A_{Fe} N^2}{l_\delta}$$

$$\frac{L \cdot \hat{i}}{N \cdot A_{FE}}$$

$$Spec\ Loss \cdot Volume$$

$$\hat{B} = \frac{L\hat{i}_{Cu}}{A_{Fe}N} = 0.53\ \text{T}$$

L	0.3 mH
I_{RMS} @ 1 kHz	120 A
I_{PEAK} @ 5 kHz	10 A
I_{PEAK} @ 10 kHz	5 A

$$\begin{cases} \hat{B}_{1\,\text{kHz}} = 0.486\ \text{T} \\ \hat{B}_{5\,\text{kHz}} = 0.029\ \text{T} \\ \hat{B}_{10\,\text{kHz}} = 0.014\ \text{T} \end{cases} \Rightarrow \begin{cases} P_{Fe,1\,\text{kHz}} = 141\ \text{W} \\ P_{Fe,5\,\text{kHz}} = 10\ \text{W} \\ P_{Fe,10\,\text{kHz}} = 6\ \text{W} \end{cases}$$

$$P_{Fe} = \sum_i P_{Fe,i} = 157\ \text{W}$$

$$P_{\delta,i} = 388 d l_\delta f_i \hat{B}_i^2$$

OBS! Different than from E & I-cores

$$\begin{cases} P_{\delta,1\,\text{kHz}} = 212\ \text{W} \\ P_{\delta,5\,\text{kHz}} = 4\ \text{W} \\ P_{\delta,10\,\text{kHz}} = 2\ \text{W} \end{cases}$$

$$P_\delta = \sum_i P_{\delta,i} = 218\ \text{W}$$

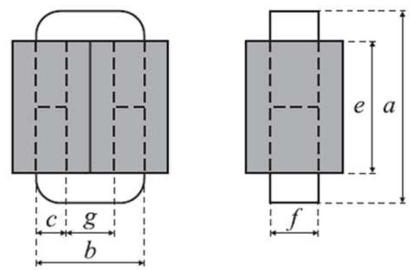
IEA

Inductor Design Example (III)

TELMAG Su 150b

$$MLT = 2c + 2f - 2g = 351 \text{ mm}$$

"Mean length per turn"



$$R_{Cu} = \rho_{Cu} \frac{N \cdot MLT}{A_{Cu}} = 4.04 \text{ m}\Omega$$

$$P_{Cu} = R_{Cu} I_{Cu}^2 = 58 \text{ W}$$

$$A_{T,Cu} = 4e(c+g) + 2e(d+g) + 4g(c+g) + 2dg = 0.1276 \text{ m}^2$$

$$A_{T,Fe} = 4bc + 2bd + 4cf = 0.0676 \text{ m}^2$$

$$\Psi_{T,Cu} = \frac{1}{A_{T,Cu}} \left(\frac{e}{b+e} P_{Fe} + P_{\delta} + P_{Cu} \right) = 2782 \text{ W/m}^2$$

Thermal flux densities

$$\Psi_{T,Fe} = \frac{1}{A_{T,Cu}} \left(\frac{b}{b+e} P_{Fe} \right) = 1154 \text{ W/m}^2$$

Emmissivity

$$\Psi_{T,rad} = 5.70 \cdot 10^{-8} \varepsilon \left(T_s^4 - T_a^4 \right)$$

$$\Psi_{T,conv} = 2.17 F (T_s - T_a)^{\eta} \sqrt{p}$$

Shape dependent

$$\Psi_T = \Psi_{T,rad} + \Psi_{T,conv}$$

$$T_s = T_a + \frac{\Psi_T}{\alpha_0 + k_\alpha T_a}$$

$$T_{s,Cu} - T_a = 174 \text{ °C}$$

$$T_{s,Fe} - T_a = 72 \text{ °C}$$

Inductor Design Example (IV)

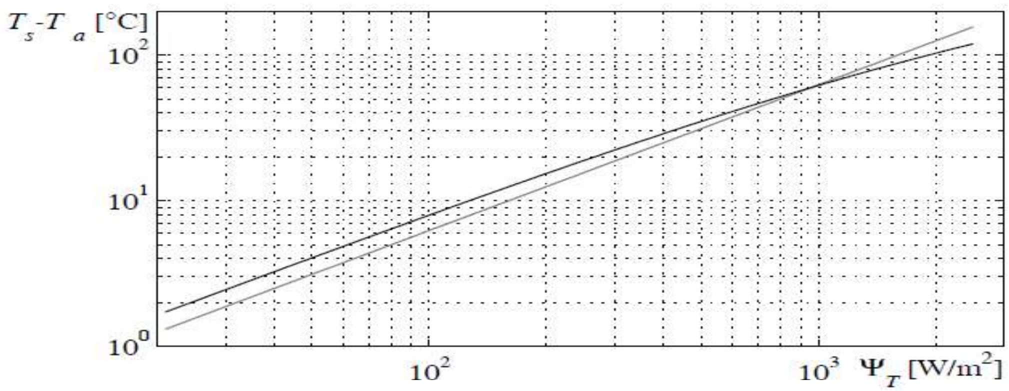


Figure 5.6: Calculated temperature rise at an ambient temperature of 40 °C, based on radiated heat (black) and an approximate method (grey).

Air-gap losses not included ⇒

$$\Psi_{T,Cu} = \frac{1}{A_{T,Cu}} \left(\frac{e}{b+e} P_{Fe} + P_{Cu} \right) = 1074 \text{ W/m}^2$$

$$T_{s,Cu} - T_a = 67 \ ^\circ\text{C}$$

Inductor Design Example (V)

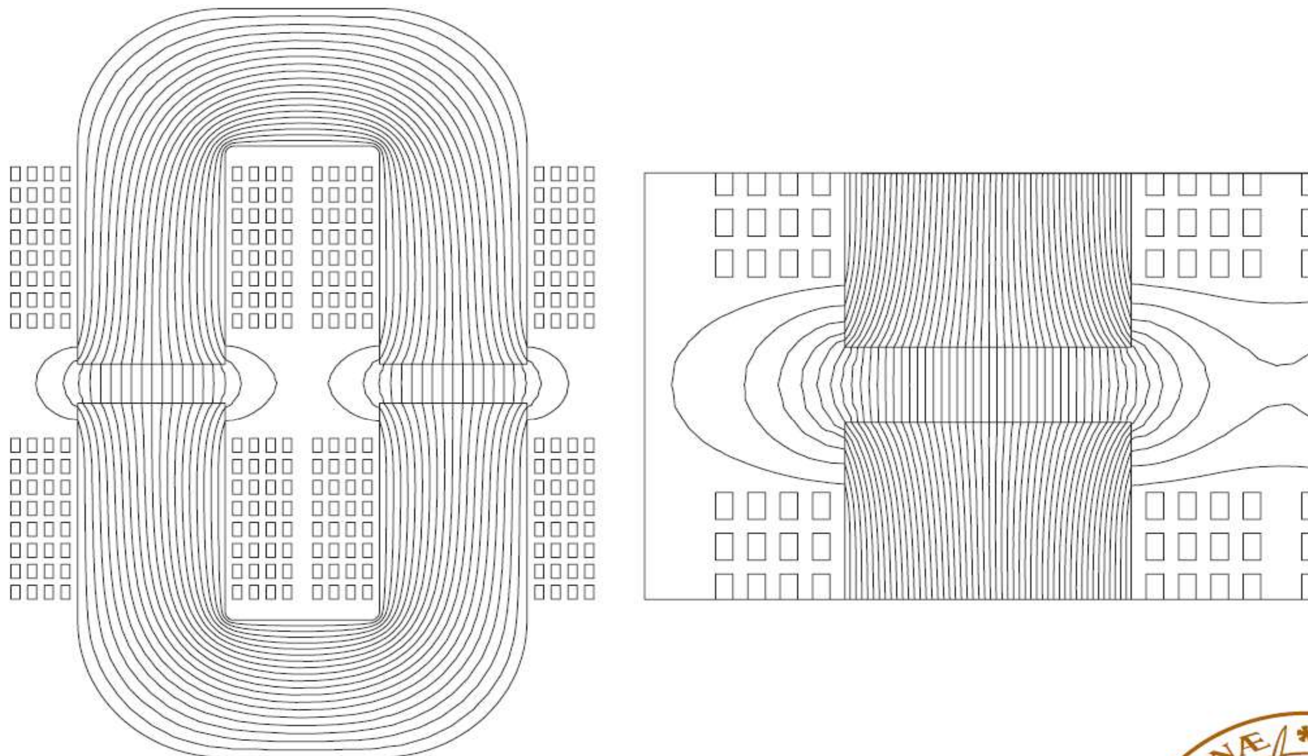
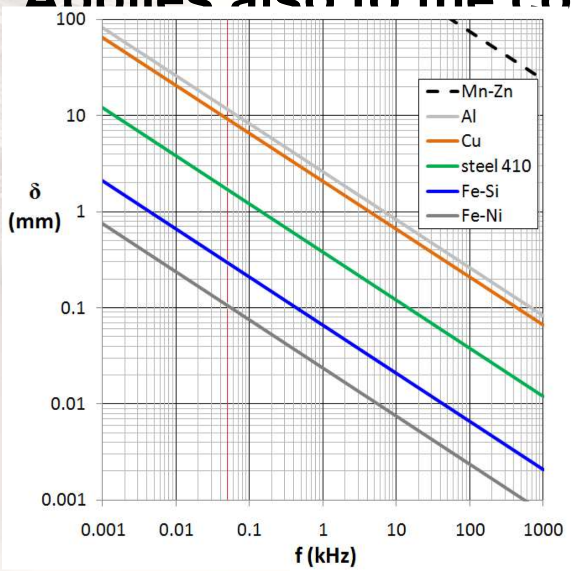
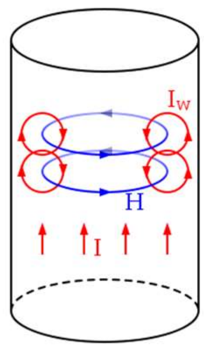


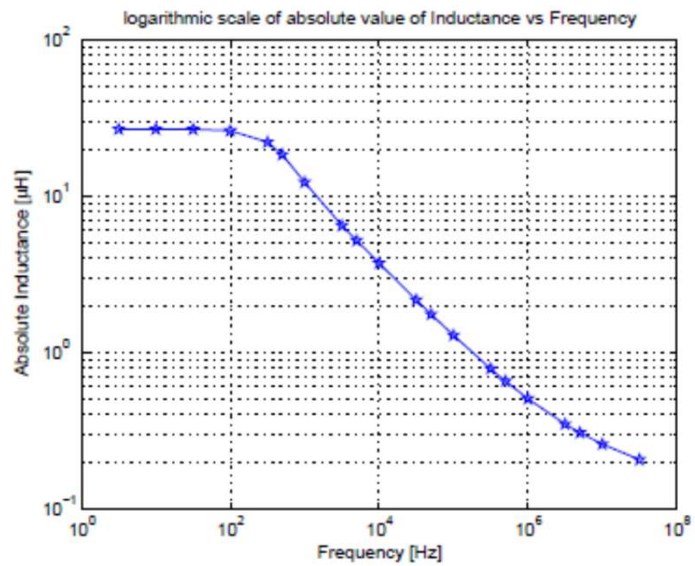
Figure 5.7: Magnetic flux lines (left) of the entire inductor, and (right) of the region around one of the air gaps. Note the component of the fringing flux that is perpendicular to the surface of the steel tape.

Skin Depth – different metals

- **Current induction in the core materials forces the flux outside the core**
- **Applies also to the conductor**

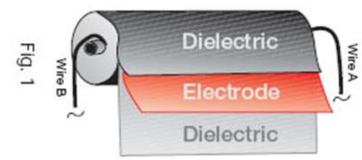


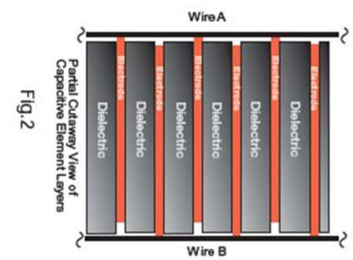


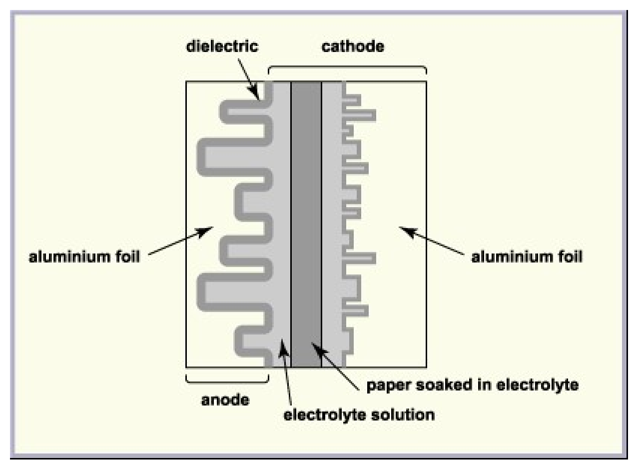


Capacitors - Design

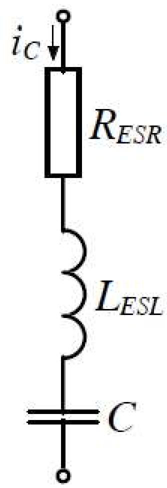
- **Metallized film polypropylene capacitors**
  - *thin plastic film to support the metal layer of the electrodes.*
  - *the dielectric consists of a polypropylene film.*
  - *to avoid air pockets resulting in a locally high electric field strength, the polypropylene film should be somewhat porous to be able to absorb oil.*
- **Wet aluminium electrolytic capacitors**
  - *contain a fluid, the electrolyte, between the aluminium electrodes.*
  - *the aluminium electrodes are electrically close together, only separated by the dielectric of the capacitor.*
  - *The dielectric constitutes of a thin aluminum oxide layer on the positive electrode.*







Capacitors – equivalent circuit



$$R_{ESR}(f) = R_s + \frac{\tan\delta_0}{2\pi f C}$$

$$P_{ESR}(f) = R_{ESR}(f) \cdot I_C^2(f)$$

$$R_{ESR} = \frac{P_{ESR}}{I_C^2}$$

That’s all folks...