Amorphous c-cores – properties and application notes

What is the best soft magnetic material for a choke? The simple answer is that there is no best material in general, but of course there is always a best compromise for a specific application.

Besides ferrites and powder cores there are some more "exotic" offerings. Among them c-cores from amorphous Fe-based strip-material.

If properly designed they allow volume optimized chokes. For the specific applications of course.

If you consider using amorphous c-cores the following remarks or design considerations might be of help. Please note that the use of approximation formulae is what it says – an approximation. They allow a first approach to a good solution, but not more.

In case of questions please feel free to contact us (contact data are on the last slide). Also if you have comments.

Amorphous c-cores feature a high saturation flux density in combination with low cores losses. They are especially suitable for power factor correction or storage chokes in power or frequency converters.

The ampere-turns capability is achieved by appropriate air gaps allowing a high degree of flexibility. Approximations for the saturation behavior of amorphous c-cores allow a straight-forward design approach with only a few iterations.
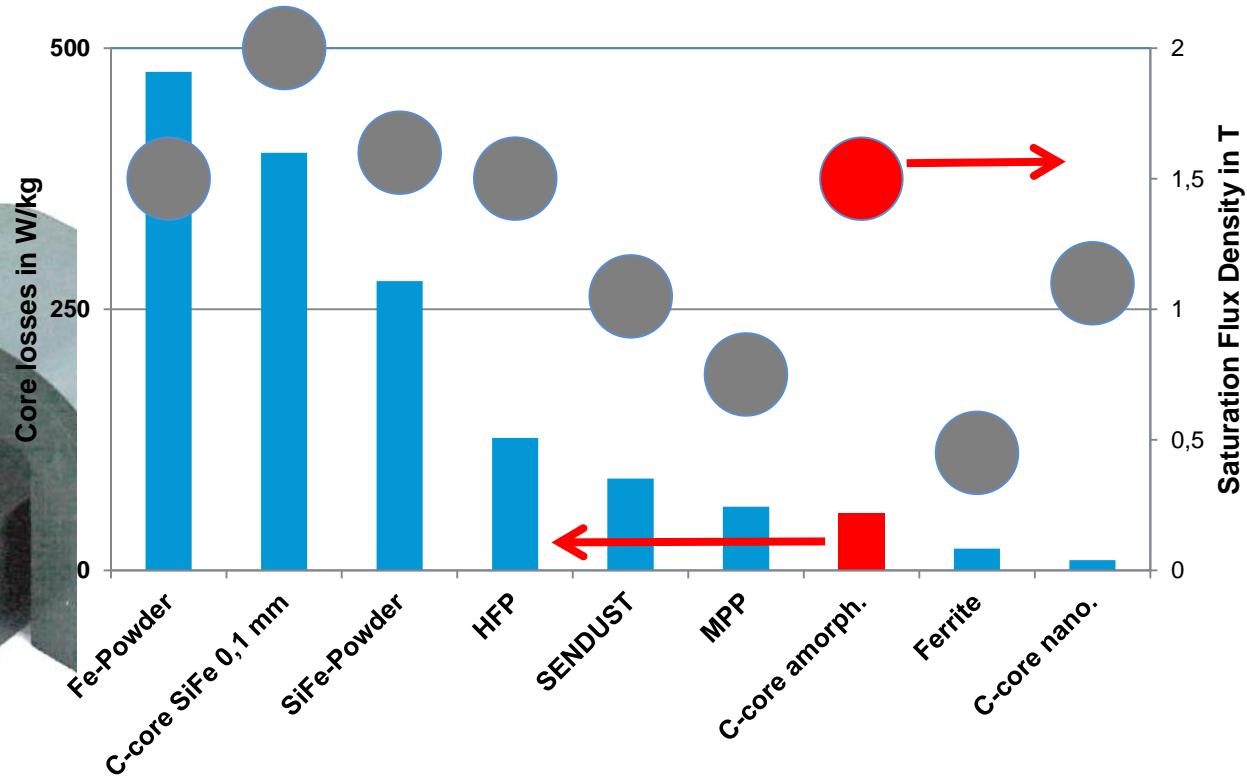
| **High Saturation Flux Density**

| **Low Losses**

| **Small Package Volume**

| **Flexible via Individual Air Gaps**

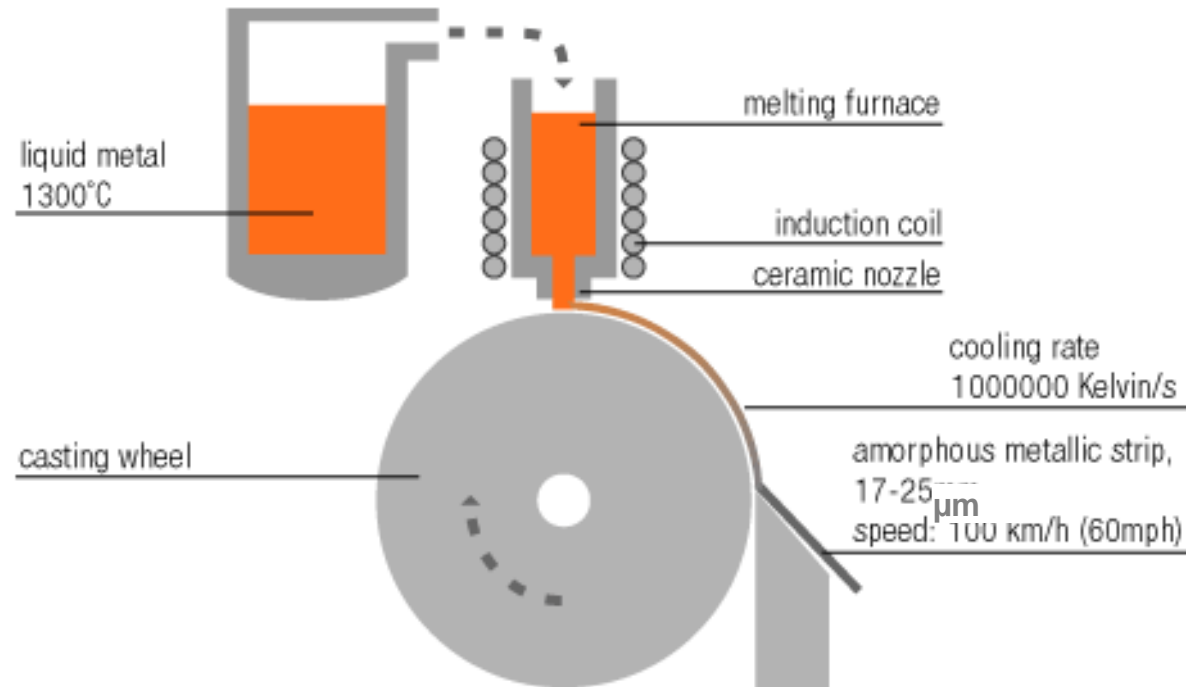# Amorphous c-cores – comparison with alternative choke materials

Typical core losses in W/kg (f = 25 kHz, Bp = 0,2 T, left) and saturation flux density (right) of choke materials

✓ Significantly lower losses compared with SiFe
✓ Lower losses compared with Fe and SiFe powder
✓ Higher flux density compared with Ferrite

Amorphous c-cores - strip production

liquid metal 1300°C

melting furnace

induction coil

ceramic nozzle

cooling rate 1000000 Kelvin/s

amorphous metallic strip, 17-25 μm
speed: 100 κm/h (60mph)

casting wheel

Amorphous metals are produced in only one step from a hot melt (of about 1500 °C) to a thin metallic foil of about 25 μm thickness, with widths up to more than 200 mm. Cooling rates of about 1.000.000 K per second are necessary to avoid crystallization and to achieve the (meta-stable) amorphous condition.

Amorphous c-cores - material properties

Amorphous metals are characterized by the lack of the usual crystalline structure with grains and grain boundaries. This is of advantage for soft magnetic behavior as disturbances like crystal anisotropies or domain wall pinning at grain boundaries are simply eliminated.
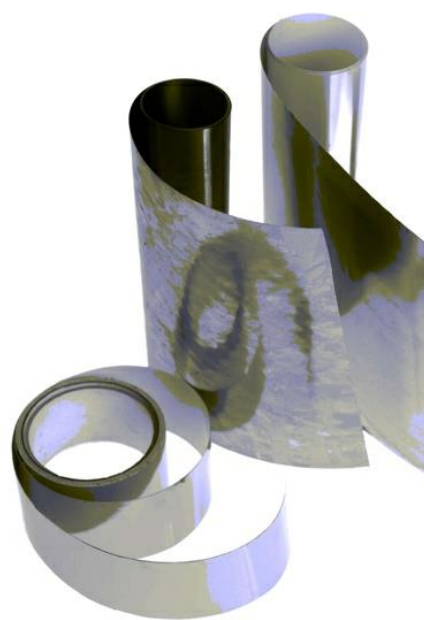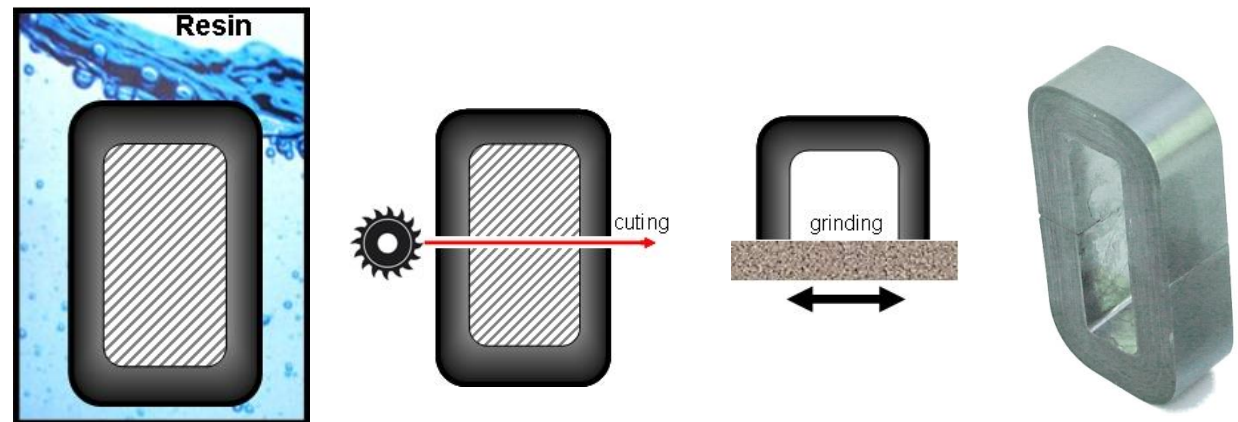
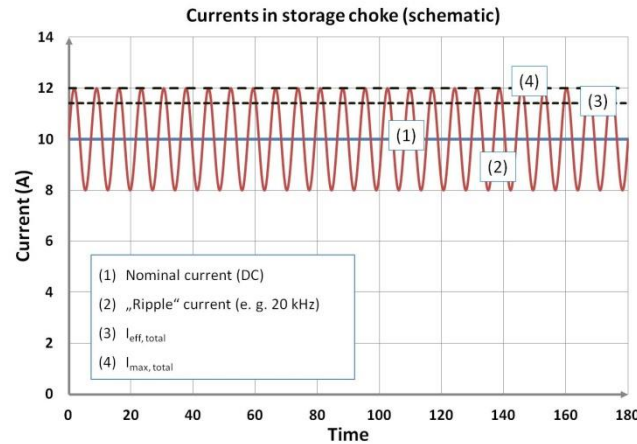|				
Saturation Flux Density	B_s	RT	[T]	1.56
Curie Temperature	T_c		[°C]	399
Cristallisation Temperature			[°C]	508
Upper Application Temperature			[°C]	abt. 130
Magnetostriction	λ_s		ppm	27
Spez. Electrical Resistivity	P_{el}	RT	[μΩm]	1.3
Density	P		[g/cm³]	7.18
Typ. Stacking Factor	FF		[%]	82
Core Losses	P_{Fe}	(0.1T, 25 kHz)	[W/kg]	abt. 15
Core Losses	P_{Fe}	(0.3T, 50 kHz)	[W/kg]	abt. 300

Amorphous c-cores – core production
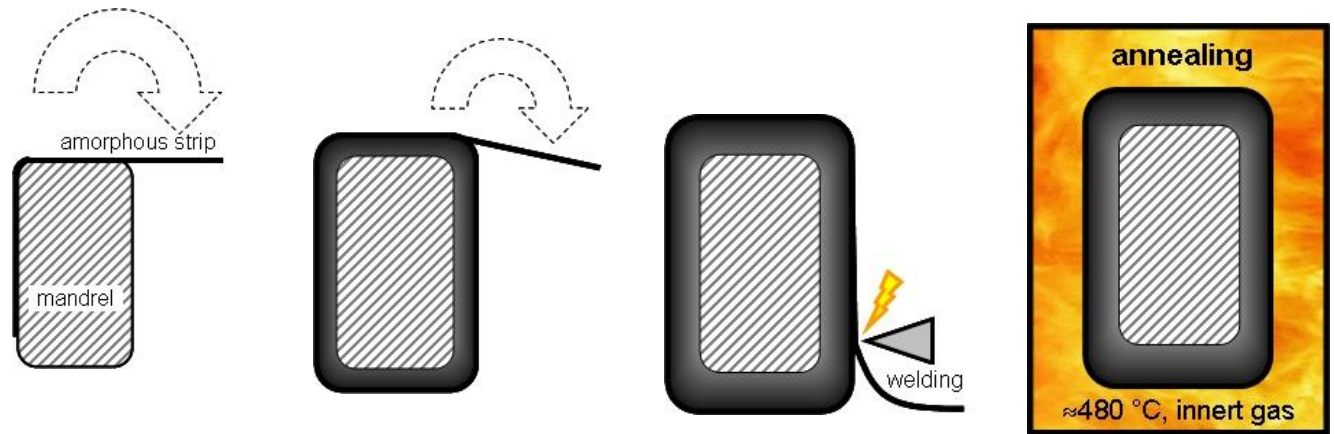
The amorphous strip is wound on a mandrel, fixed by welding, magnetically annealed and impregnated with resin. After cutting the cross-section is grinded and lapped.
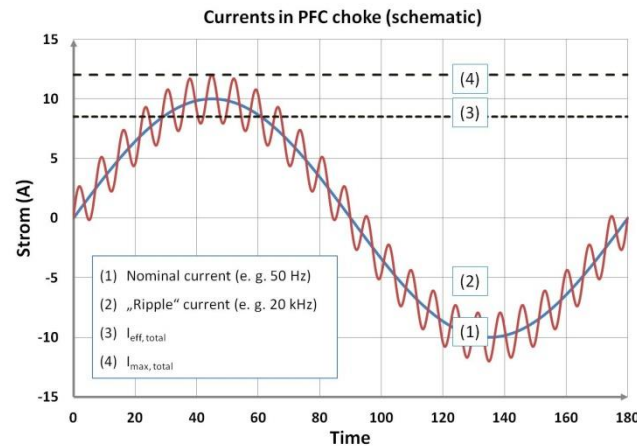
Amorphous c-cores – currents in storage and pfc chokes

Currents in storage choke (schematic)

(4)
(3)
(1)
(2)

(1) Nominal current (DC)
(2) „Ripple" current (e. g. 20 kHz)
(3) $I_{eff, total}$
(4) $I_{max, total}$

$$\hat{I}_{max} = I_{N,DC} + \frac{I_{R,ss}}{2}$$

$$I_{eff,ges} = \sqrt{(I_{N,DC})^2 + \left(\frac{1/2 * I_{R,ss}}{\sqrt{2}}\right)^2}$$

Currents in PFC choke (schematic)

(4)
(3)
(2)
(1)

(1) Nominal current (e. g. 50 Hz)
(2) „Ripple" current (e. g. 20 kHz)
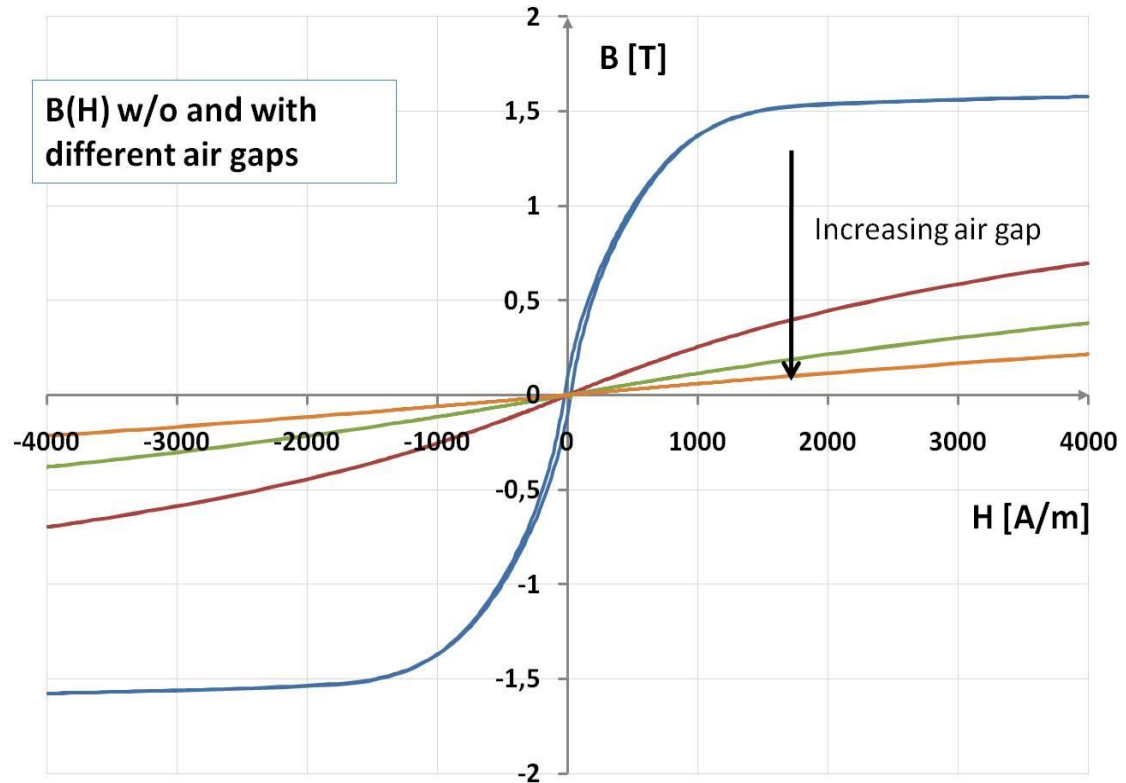(3) $I_{eff, total}$
(4) $I_{max, total}$

$$\hat{I}_{max} = I_{N,eff} * \sqrt{2} + \frac{I_{R,ss}}{2}$$

$$I_{eff,ges} = \sqrt{(I_{N,eff})^2 + \left(\frac{1/2 * I_{R,ss}}{\sqrt{2}}\right)^2}$$
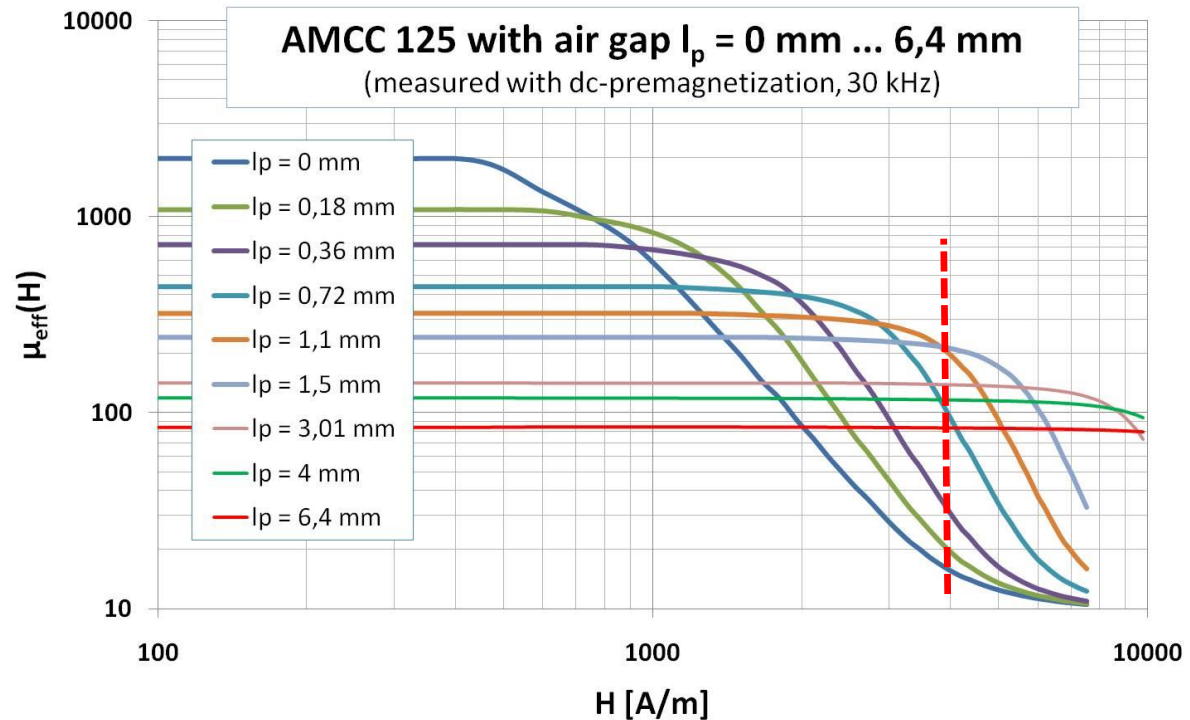
Amorphous c-cores - influence of air gap

B(H) w/o and with different air gaps

Increasing air gap

B(H) characteristic of a typical amorphous c-core, w/o air gap and with increasing air gaps to demonstrate the influence. An optimized air gap corresponds to a size optimized design

Amorphous c-cores - effective permeability

AMCC 125 with air gap l_p = 0 mm ... 6,4 mm
(measured with dc-premagnetization, 30 kHz)

Legend:
- lp = 0 mm
- lp = 0,18 mm
- lp = 0,36 mm
- lp = 0,72 mm
- lp = 1,1 mm
- lp = 1,5 mm
- lp = 3,01 mm
- lp = 4 mm
- lp = 6,4 mm

y-axis: $\mu_{eff}(H)$

x-axis: H [A/m]

$$L \approx N^2 * \mu_0 * \mu_{eff} * \frac{A_{Fe}}{l_{Fe}}$$

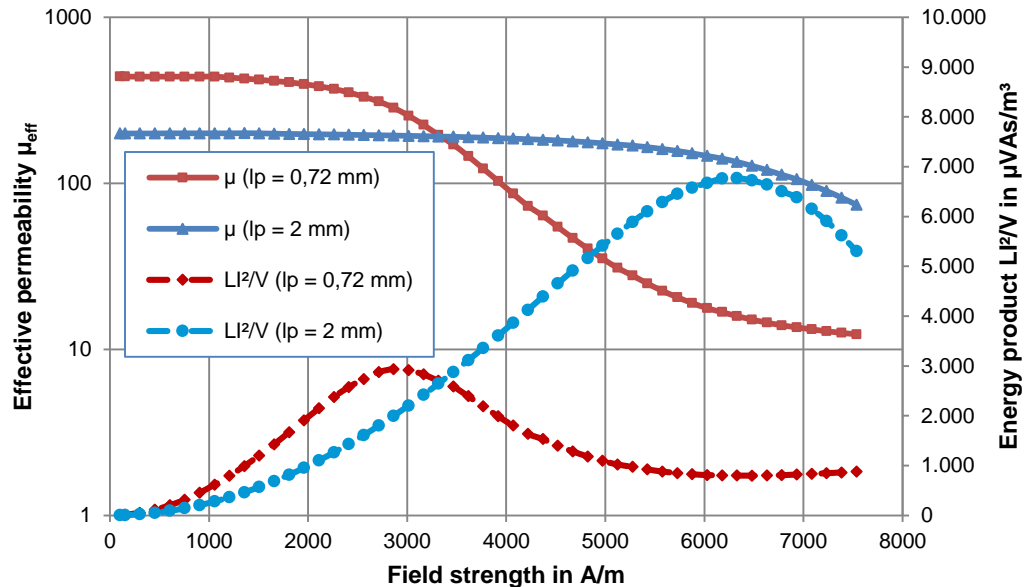$$H_{max} = \frac{\hat{I}_{max} * N}{l_{Fe}}$$

Choke designs are based on the fact that the inductivity L is proportional to the square of the number of turns N, whereas the field strength in the core increases only linear with N
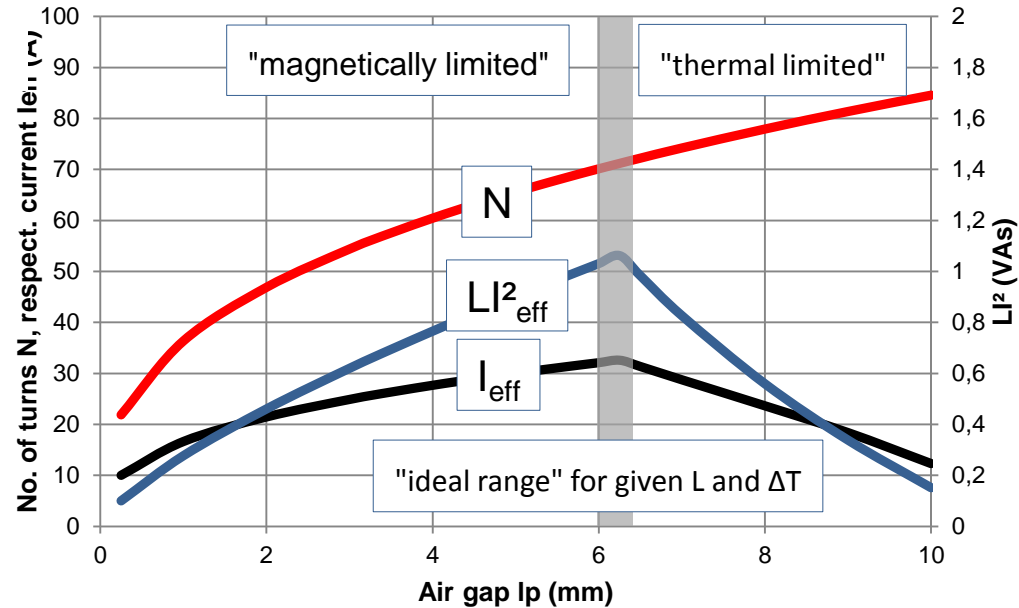
Amorphous c-cores - energy product

Eff. permeability μ_{eff} and energy product LI^2/V vs field strength H

The energy product increases with decreasing permeability

The maximum energy product is reached when the effective permeability has dropped about 20 % – 30 %

Amorphous c-cores – optimization of the energy product

Curves calculated with constant inductivity L and constant heat raise ΔT

The increase of the energy product with decreasing permeability (and increasing air gap) is limited by copper losses

$$N_{mag} \approx \frac{\hat{B}_{max} * l_{Fe}}{\mu_0 * \mu_{eff} * \hat{I}_{max}}$$

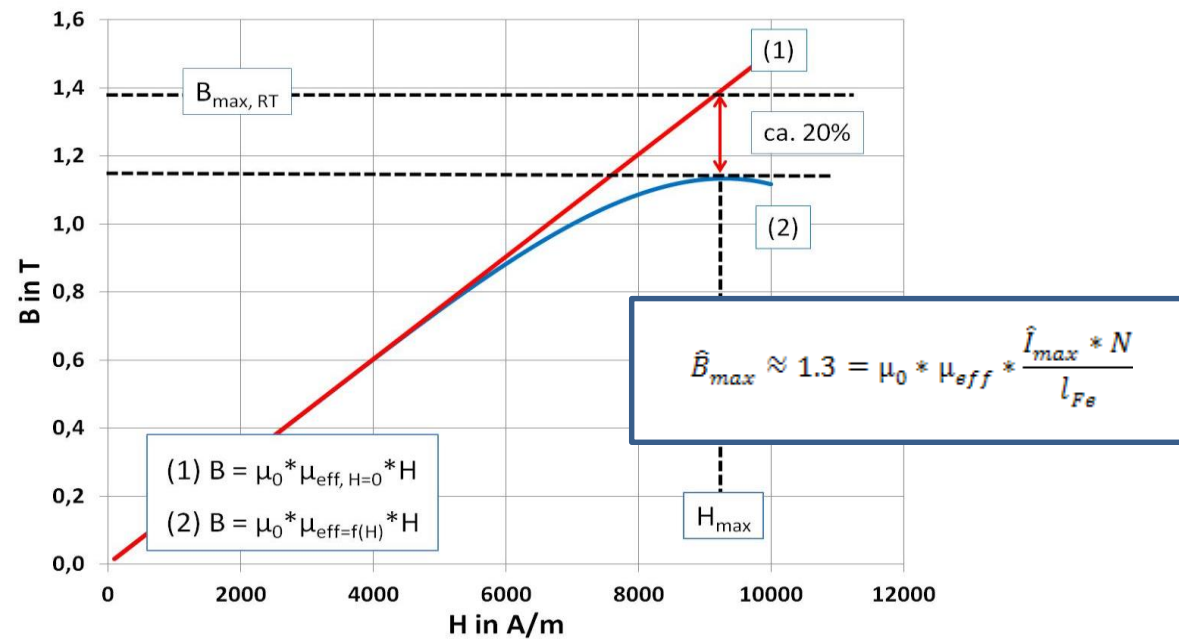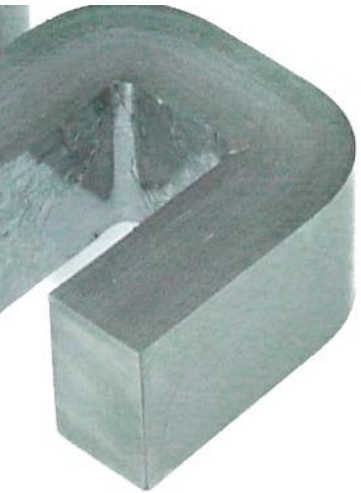$$N_{therm} \approx S * \frac{A_{Cu}}{I_{eff,therm}}$$

N_{mag} for a given current is limited by the saturation approach of the core and proportional to $1/\mu_{eff}$

N_{therm} for a given current is limited by possible current density S_{eff}

The maximum energy product is reached when the magnetically allowed and thermal possible no. of turns are in a balance

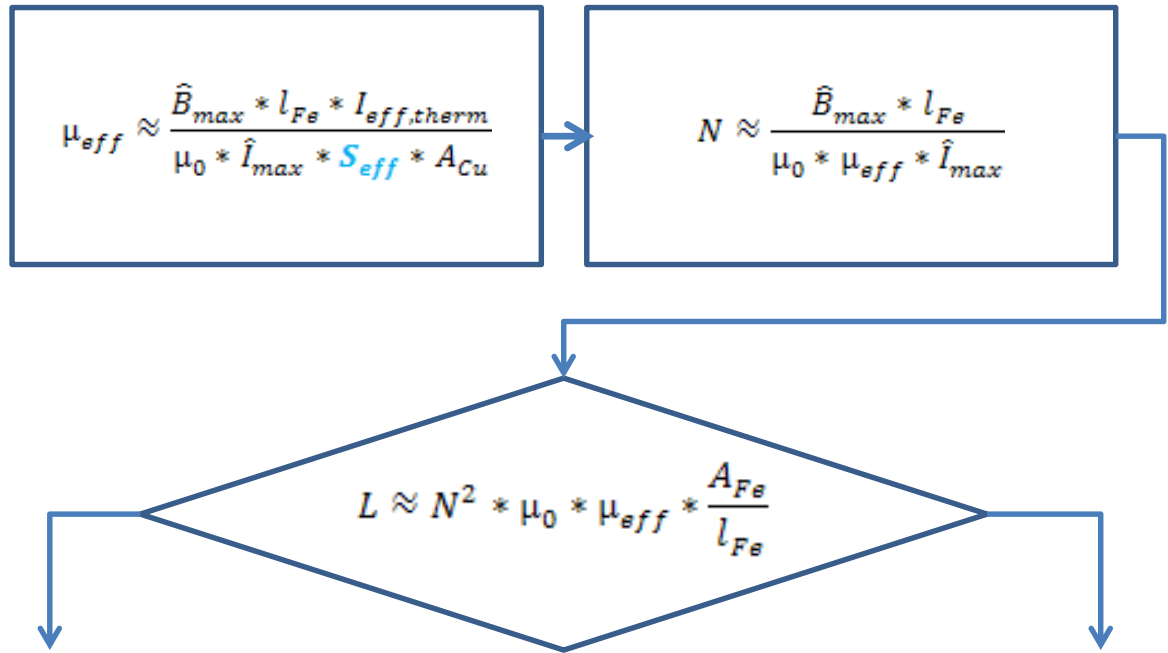The balance is a function of mainly the current density S and the maximum induction B

Amorphous c-cores – approximation for „optimal" induction

The graph shows B in T (y-axis, 0,0 to 1,6) versus H in A/m (x-axis, 0 to 12000) with:
- Line (1): $B = \mu_0 * \mu_{eff,\,H=0} * H$
- Curve (2): $B = \mu_0 * \mu_{eff=f(H)} * H$
- $B_{max,\,RT}$ dashed line at ~1,38
- ca. 20% difference marked
- H_{max} marked

$$\hat{B}_{max} \approx 1.3 = \mu_0 * \mu_{eff} * \frac{\hat{I}_{max} * N}{l_{Fe}}$$

In a first approximation the maximum energy product corresponds with a induction of 1,3 Tesla assuming a linear permeability

This leaves the current density S the "only" variant for a design approach

$$\mu_{eff} \approx \frac{\hat{B}_{max} * l_{Fe} * I_{eff,therm}}{\mu_0 * \hat{I}_{max} * S_{eff} * A_{Cu}}$$

$$N \approx \frac{\hat{B}_{max} * l_{Fe}}{\mu_0 * \mu_{eff} * \hat{I}_{max}}$$

$$L \approx N^2 * \mu_0 * \mu_{eff} * \frac{A_{Fe}}{l_{Fe}}$$

The optimum permeability μ_{eff} for the peak and effektive currents can be calculated using e. g. Bmax = 1,3 T and typical values for the current density S_{eff}

Consequently the no. of turns and the L-value can be determined. If the required L is not reached a bigger core is required

Amorphous c-cores – approximation of temperature raise
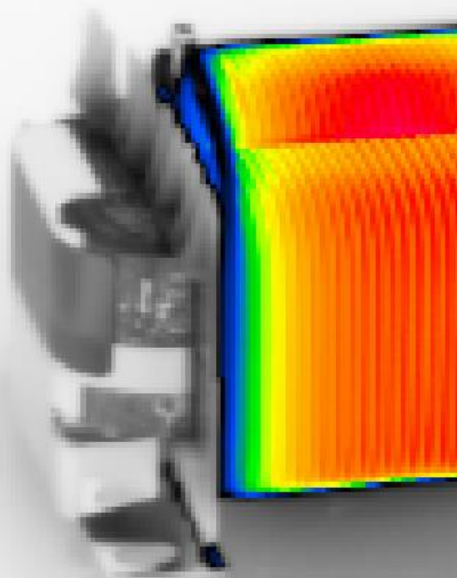
$$P_{Cu} \approx \left(\frac{\rho_{el} * l_{Cu} * N^2 * I^2_{eff}}{A_{Cu}} \right) * K_{Prox}$$

$$P_K \approx m_{Fe} * 6{,}5 * f^{1{,}51} * \hat{B}_{ripple}^{1{,}74}$$

$$\hat{B}_{Ripple} = \frac{\mu_0 * \mu_{eff} * 0{,}5 * N * I_{R,ss}}{l_{Fe}}$$

$$P_{Gesamt} \approx (P_K + P_{Cu}) * K_L$$

$$K_L \approx 100 * (\mu_{eff})^{-0{,}8}$$

$$\Delta T[K] \approx \left(\frac{1000 * P_{Gesamt}}{O} \right)^{0{,}85}$$

The formula delivers a rough estimation for the temperature raise. K_{prox} considers additional copper losses due to the proximity effect, K_L considers additional copper and core losses due to the stray field of the air gap.

Amorphous c-cores – approximation for different current densities

No. of turns and inductivity vs air gap

S = 1,25 A/mm²	S = 1,5 A/mm²	S = 1,75 A/mm²
$\Delta T \approx 50$ K	$\Delta T \approx 60$ K	$\Delta T \approx 75$ K
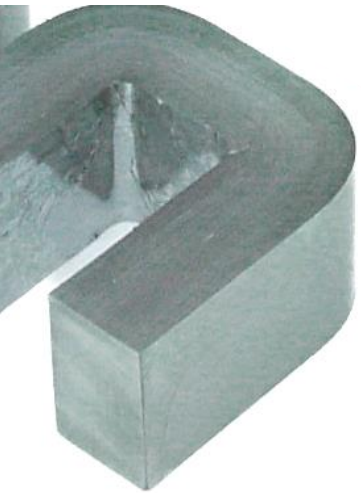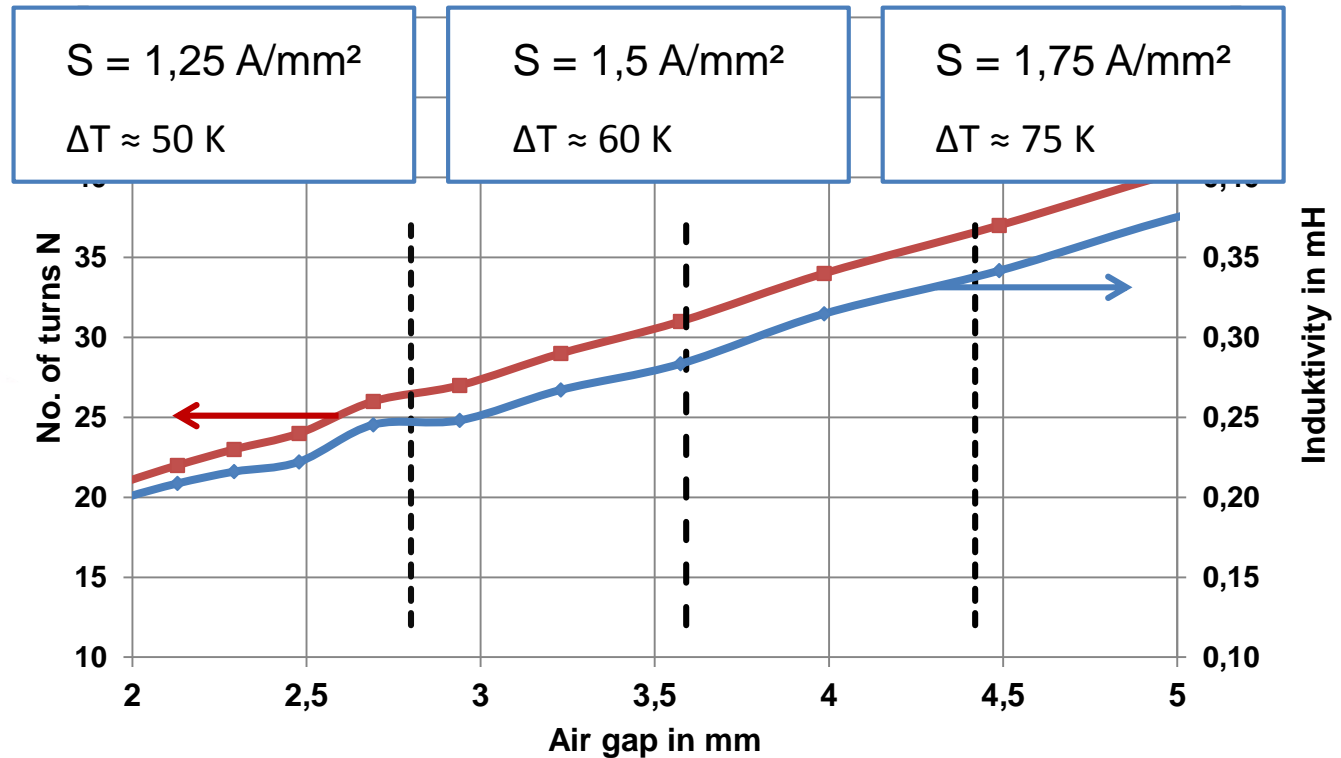
Using the formulae for AMCC 125, $I_{eff} = 50$ A, $I_{pp} = 14,14$ A, $f = 20$ kHz, $B_{max} = 1,3$ T, $K_{prox} = 2$.

Amorphous C-Cores – starting points for choke designs

Guide values for B_{max} = 1,3 T, L = 0,5 mH						
Typ	LI^2_{eff} [VAs]	$I_{N,eff}$ [A]	N (appr.)	μ_{eff} (appr.)	l_p [mm]	S [A/mm²]
AMCC 20	0,20	20	44	133	2,0	2,7
AMCC 32	0,29	24	44	127	2,5	2,5
AMCC 50	0,43	29	53	108	3,75	2,2
AMCC 80	0,59	34	39	127	3,0	1,9
AMCC 100	0,65	35	37	130	3,0	1,85
AMCC 125	0,81	40	44	115	4,25	1,7
SU 75b	1,0	45	33	142	3,25	1,5

$$LI^2_{eff} \approx S * A_{Cu} * A_{Fe} * \frac{B_{max}}{\sqrt{2}}$$

The values have been calculated using the approximation formula of this presentation. Frequency 20 kHz, 10% ripple, free convection.

Amorphous c-cores – more information

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