Transformers ACADEMY

Design of power transformers e-lesson #5: Core

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Education:

- Master of Electrical Engineering

Experience:

- 2014 – 2021: Head of Electrical design at the Končar Power Transformers Ltd., a Joint Venture of Siemens Energy AG and Končar; responsible for offer & order design, design reviews and design tools development
- 2019 – 2020: a lecturer at Postgraduate specialist study Transformers - Transformer Design at the University of Zagreb, faculty of Electrical Engineering and Computing.

Notable projects (more than 200 design verifications):

- 200 MVA autotransformer with phase shift regulation for Croatia
- 560 MVA, 550 kV single phase autotransformer for USA
- 1 000 MVA, 420 kV autotransformer for Norway
- 240 MVA, 275 kV ester filled autotransformer for UK

Content

Design of power transformers – Basic / Introductory level

- Lesson 1 – Design process
- Lesson 2 – Components & Calculations

Design of power transformers – Intermediate level

- Lesson 1 – Core
- Lesson 2 – Windings
- Lesson 3 – Load losses
- Lesson 4 – Short circuit withstand
- Lesson 5 – Insulations design
- Lesson 6 – Temperature rise
- Lesson 6 – Noise

Content

Lesson 1 – Core

Lecture – 45 min

- Core function
- Core material
- Core types
- Core geometry
- Core losses
- Core temperature rise
- Clamping frame and bandaging system
- Core earthing

Guest presenter (ThyssenKrupp) - 15 min

- Recent achievements in material development

Questions & Exam process & Optional practical tasks 30 min

Core function

Core provides a low reluctance path to the magnetic flux

$$B = \frac{10^4}{\sqrt{2} \times \pi \times 50} \times \frac{e_t}{Q_{FE}} \times \frac{50}{f} \; (T)$$

B – induction in wound limb (T)

f – frequency (Hz)

Q_{FE} – effective core cross section – wound limb [cm^2]

e_t - voltage per turn (V) = phase voltage / number of turn

Cold rolled grain oriented electrical steel (CRGO, GOES) types:

- Conventional
- Super oriented (high permeability, HiB)
- Domain refined (also high permeability, HiB)
  - Laser scribing
  - Plasma treatment
  - Etching
  - Scratching

(Other core materials: Amorphous metal, Microcrystalline – not used in power transformers)

Designation acc. IEC 60404-8-7

- M130 30S 5

  1) M - electrical steel

  2) 130 - specific loss of 1,30 W/kg at 1,7 T (one hundred times the specified value of maximum specific total loss)

  3) 30 - nominal thickness of 0,30 mm (one hundred times the nominal thickness)

  4) S - regular materials (P high permeability)

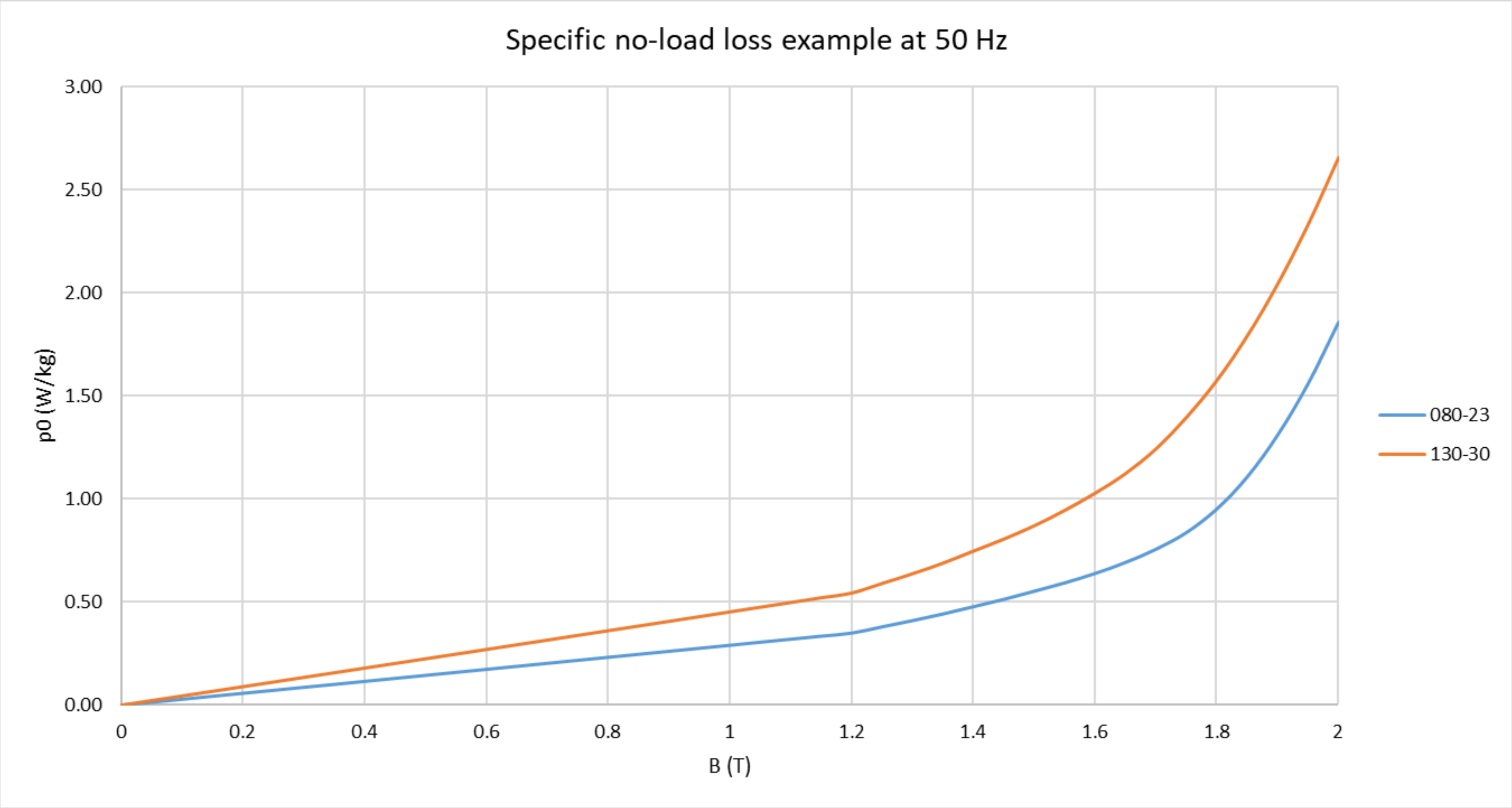
  5) 5 - 50 Hz (one tenth of the frequency)

Different transformer suppliers & electrical steel suppliers designations exist:

- M5/0,30; M4/0,27; M0H/0,27; ZDKH /0,23
- C 130-30; C 120-27; H 105-30; H 080-23
- …

Core material

- Density(IEC 60404-8-7): 7650 kg/m3
- Sheet thickness(IEC 60404-8-7):0,23-0,35 mm
- Burr height(IEC 60404-8-7): 0,025 mm
- Minimum stacking factor (IEC 60404-8-7):
  - 0,23 mm – 0,945
  - 0,27 mm – 0,950
  - 0,30 mm – 0,955
  - 0,35 mm – 0,960
- Saturation flux density:2,03 -2,05T


Specific no-load loss example at 50 Hz
3.00
2.50
2.00
1.50
1.00
0.50
0.00
p0 (W/kg)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
B (T)
080-23
130-30

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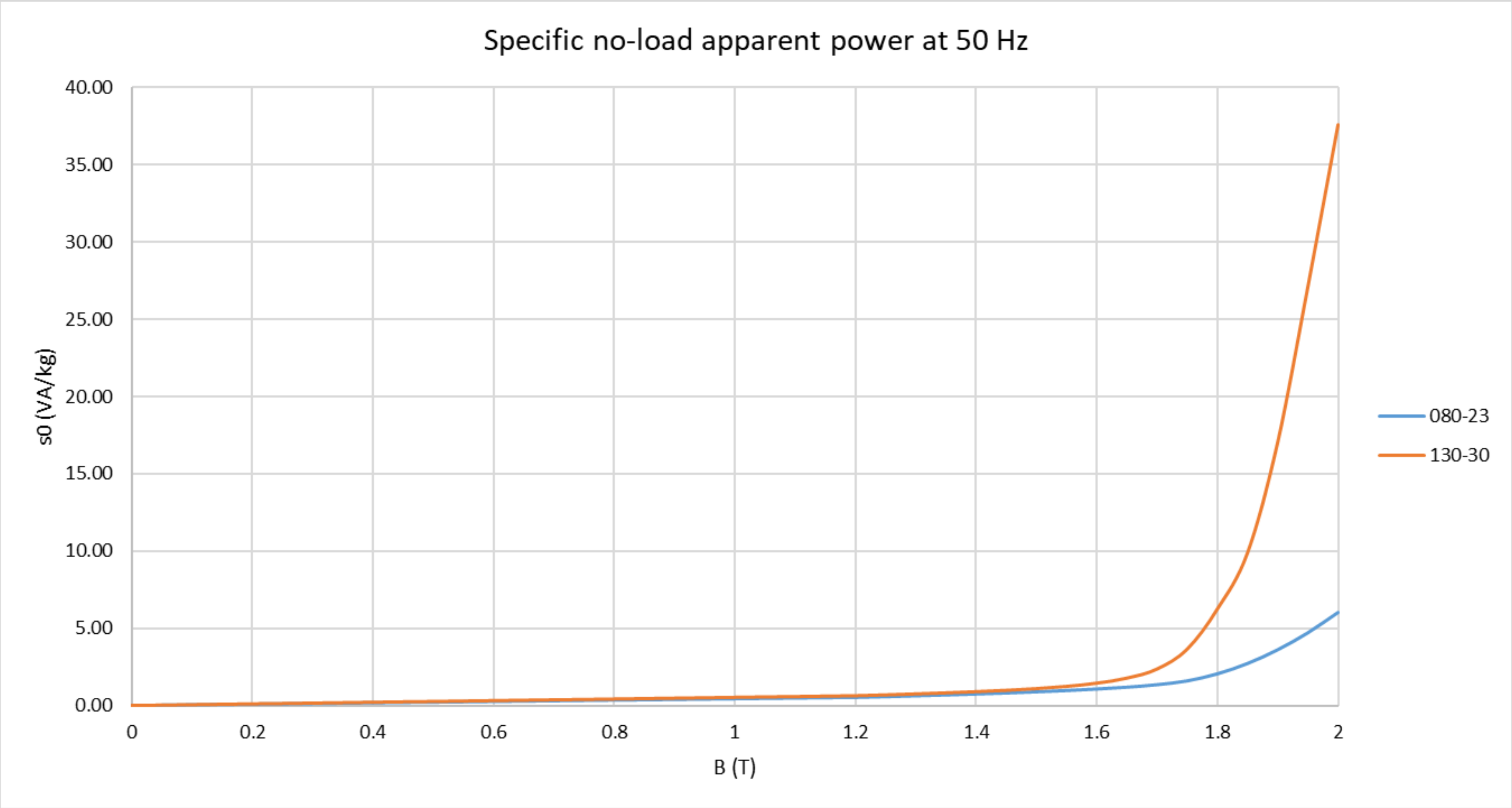
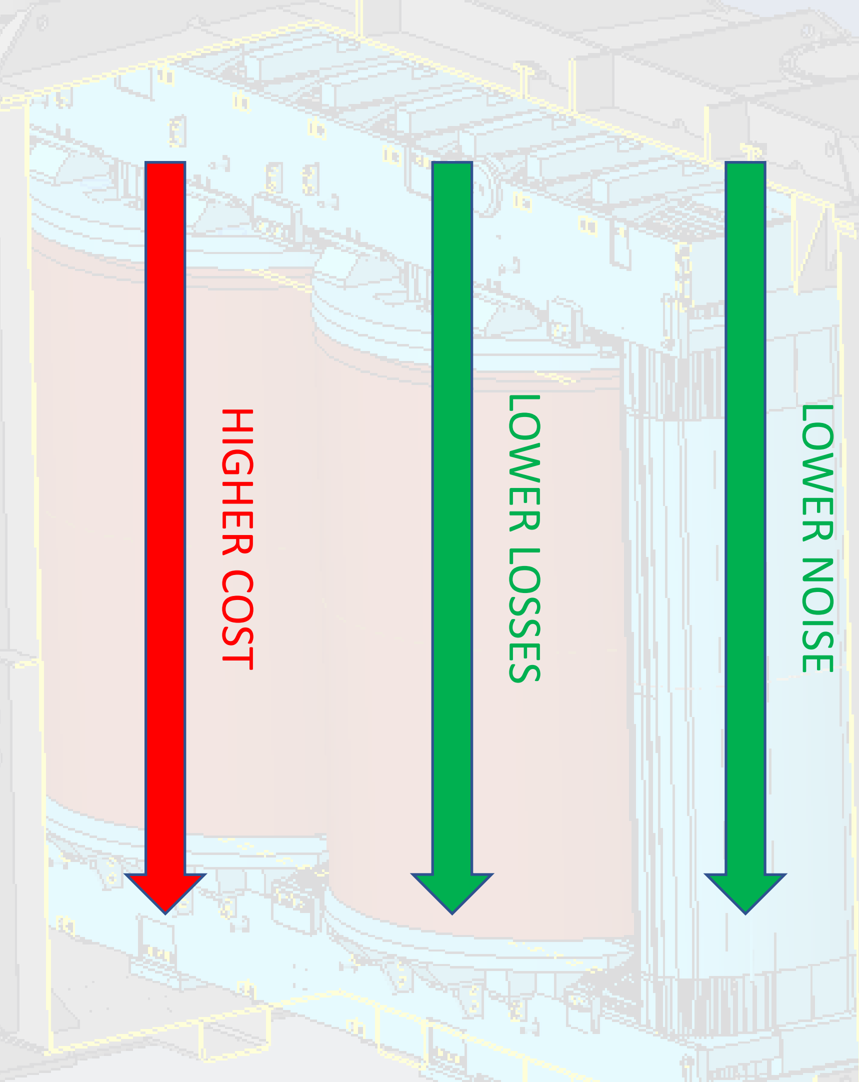
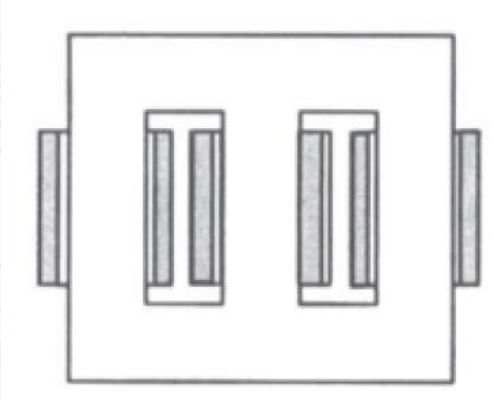


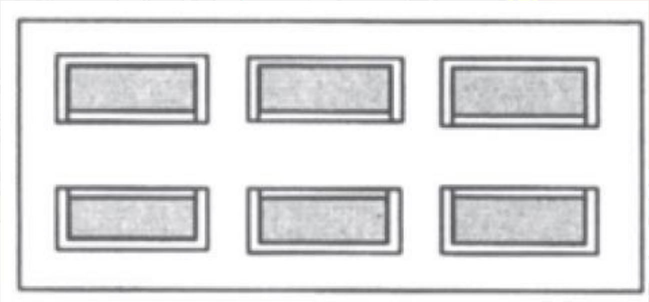
Core material

Core grade
M 130-30S 5
M 120-30S 5
M 105-27P 5
M 095-27P 5
M 080-23P 5
M 070-23P 5



- Core type (windings around the core limb)





- Shell type (core „around” the windings)

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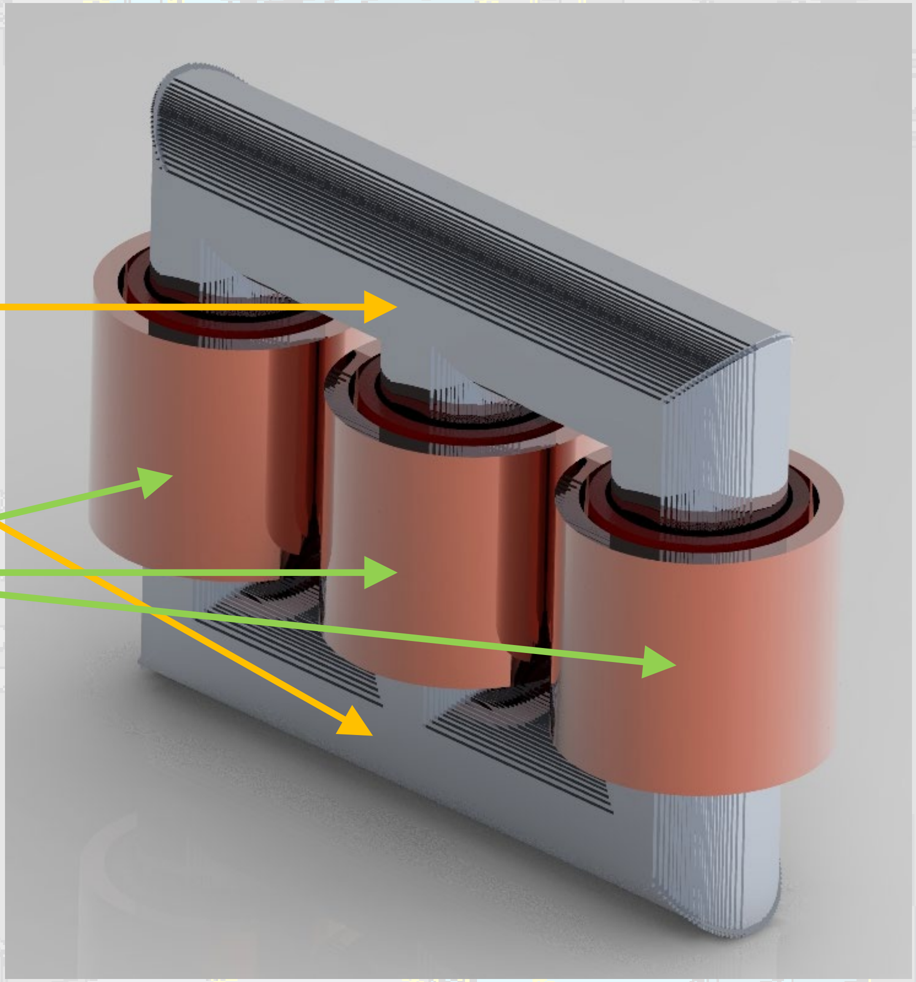
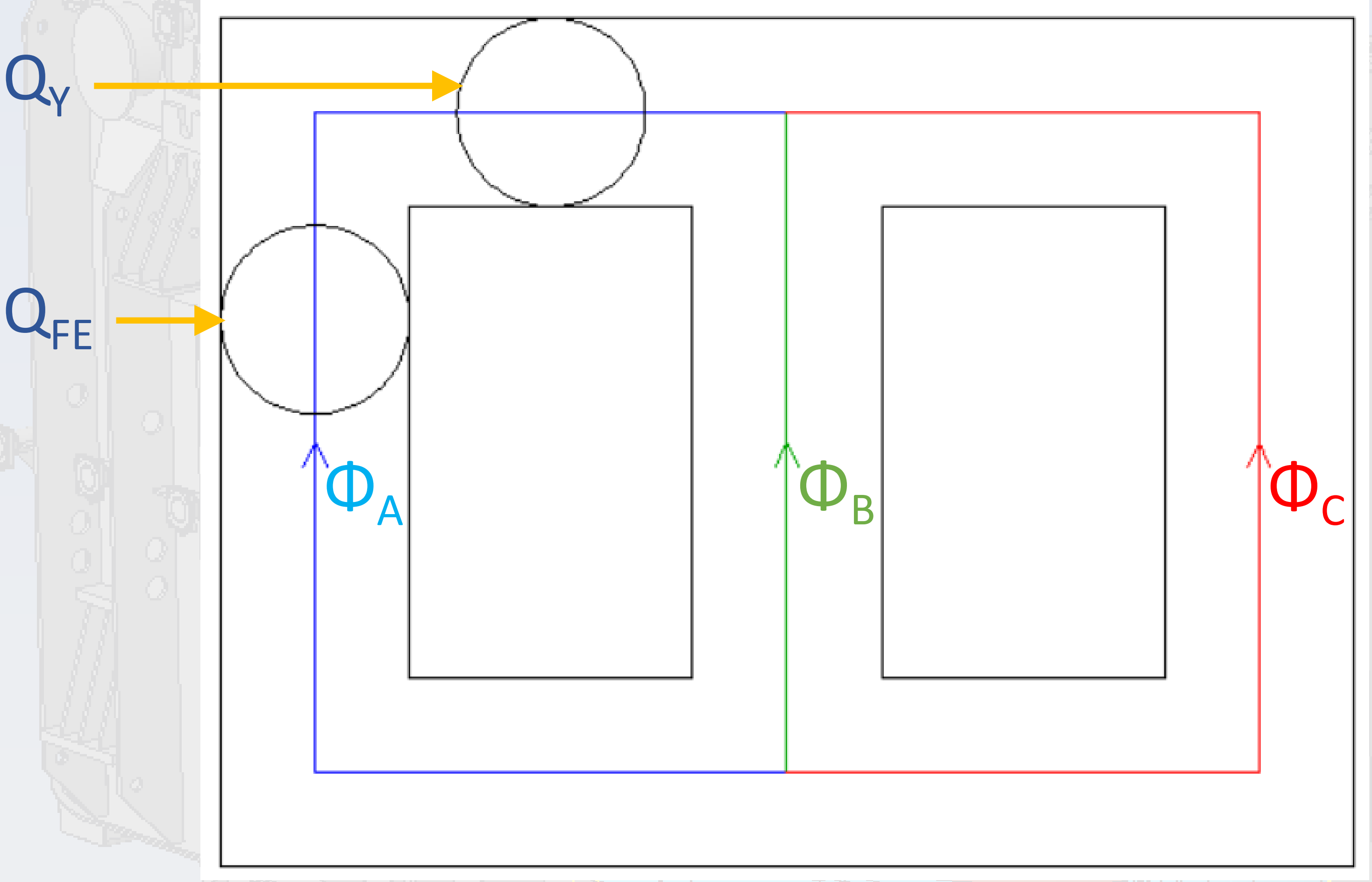
three-phase 3 limb core (3/0)

yokes



wound limbs



$$\Phi_A + \Phi_B + \Phi_C = 0 \quad \Rightarrow \quad Q_Y = Q_{FE}$$

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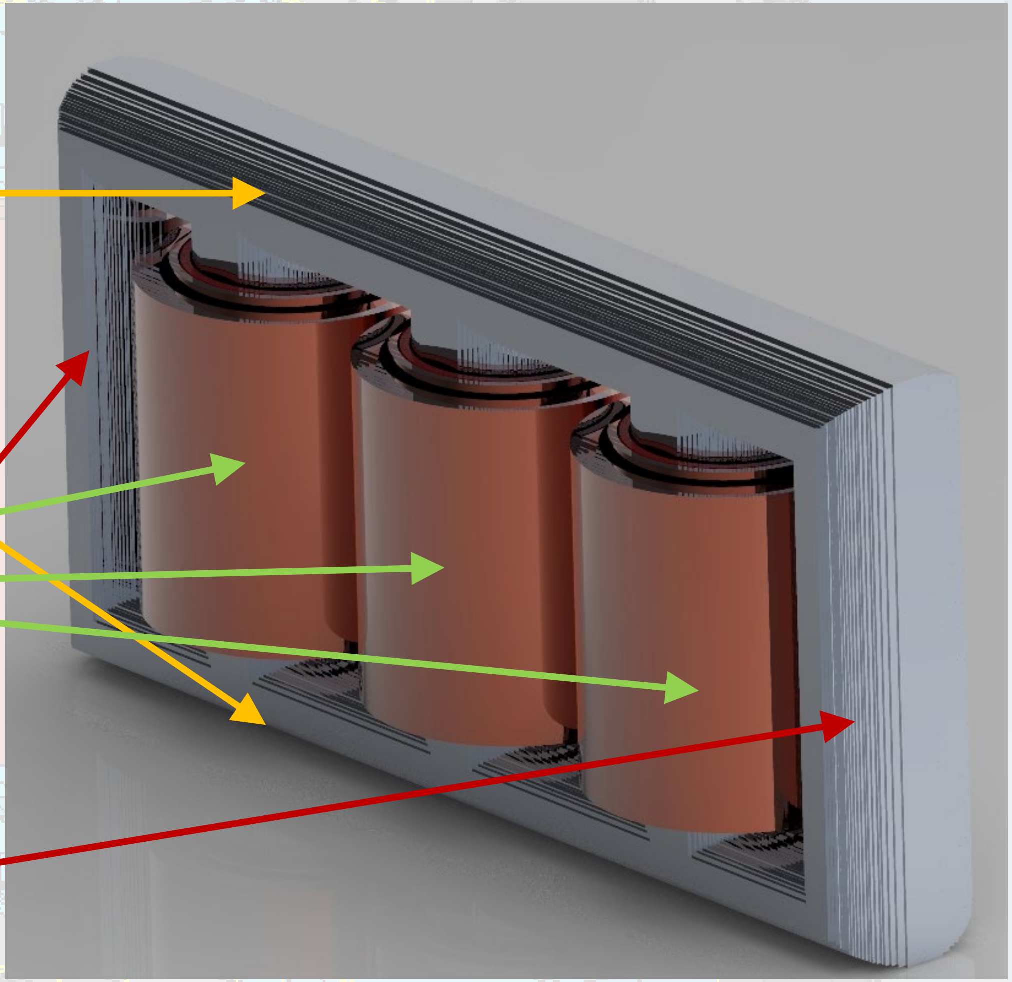
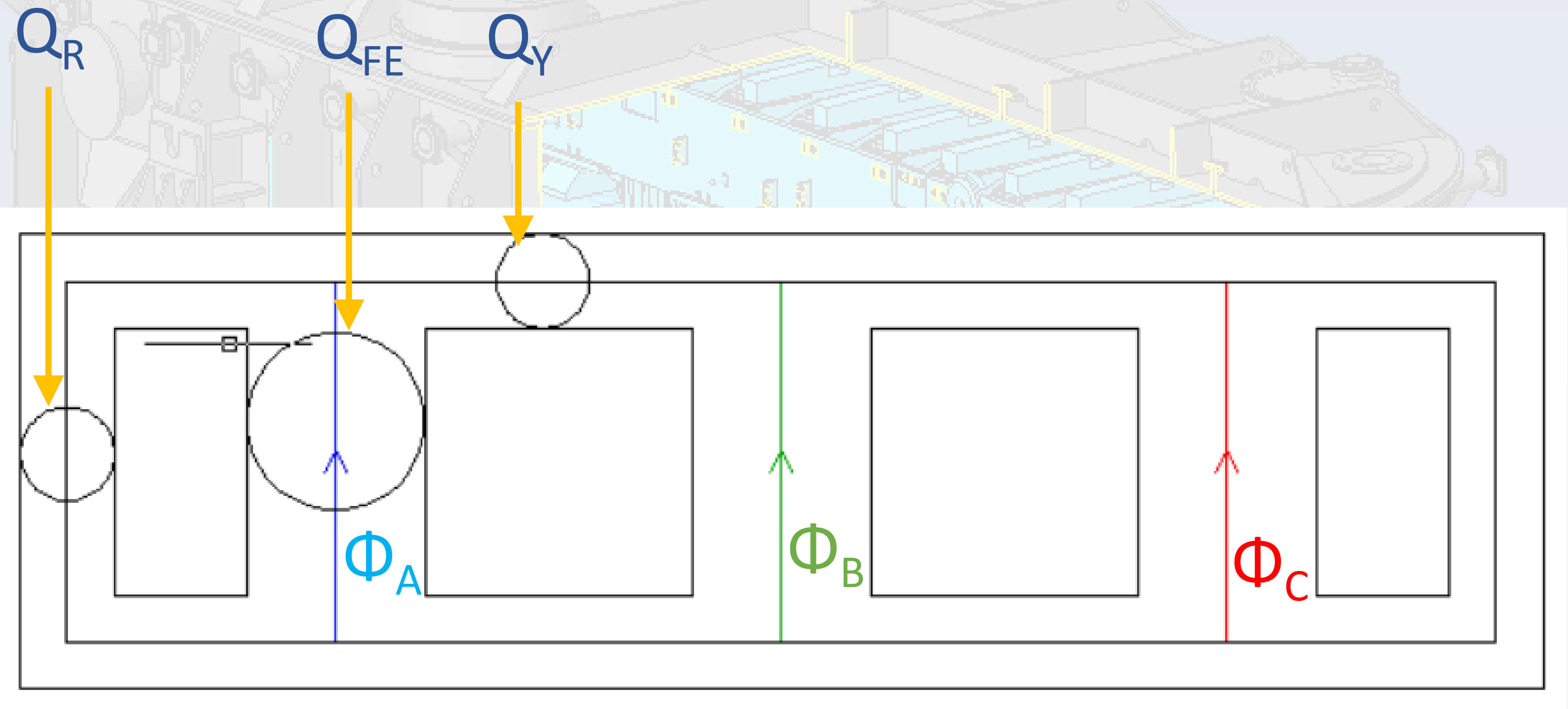
three-phase 5 limb core (3/2)

yokes

wound limbs

return limbs





USUALLY $Q_Y = Q_R \approx (1,1 - 1,15) \times 0,5\ Q_{FE}$

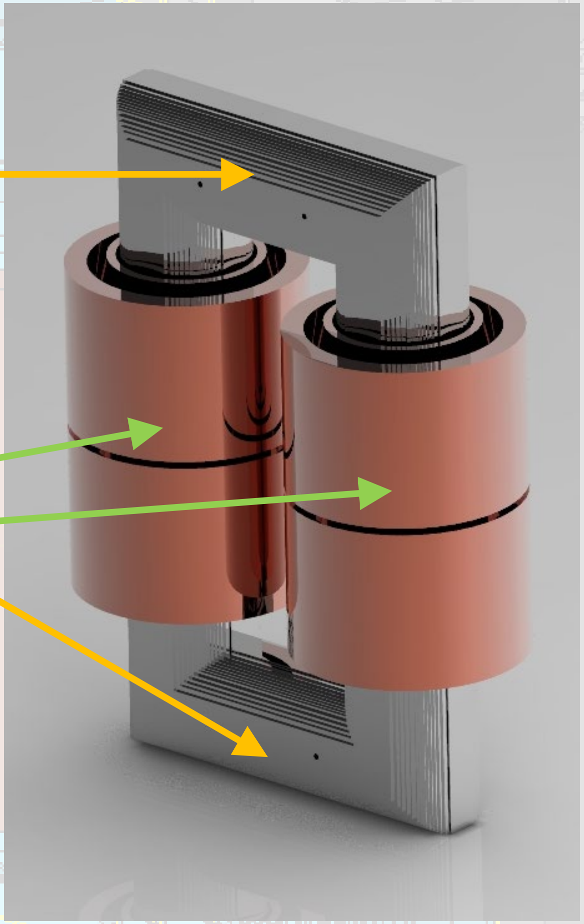
Benefits vs 30 core type:

- lower transport height
- less cross section of the tie bars (better filling factor)
- more simple clamping frame plate (smaller thickness thickens)
- better space usability (less distance from window top / bottom)

Core types

single-phase 2 limb core (2/0)

yokes



wound limbs

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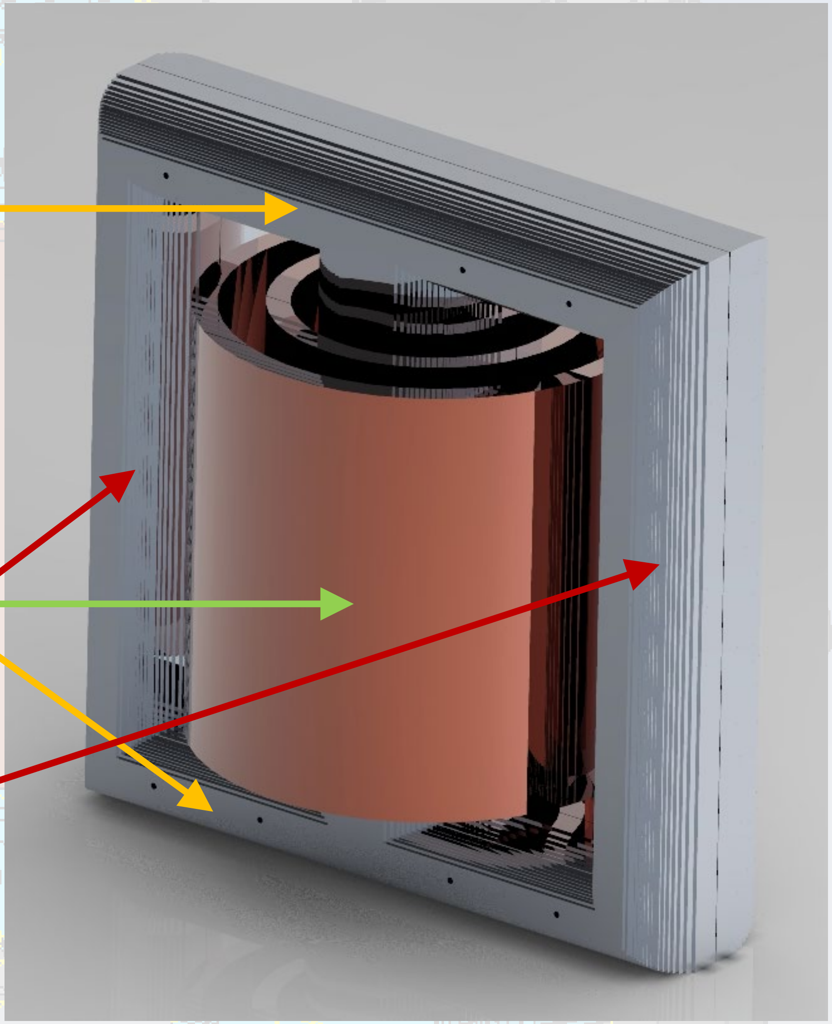
single-phase 3 limb core (1/2)

yokes

wound limb

return limbs



Core types

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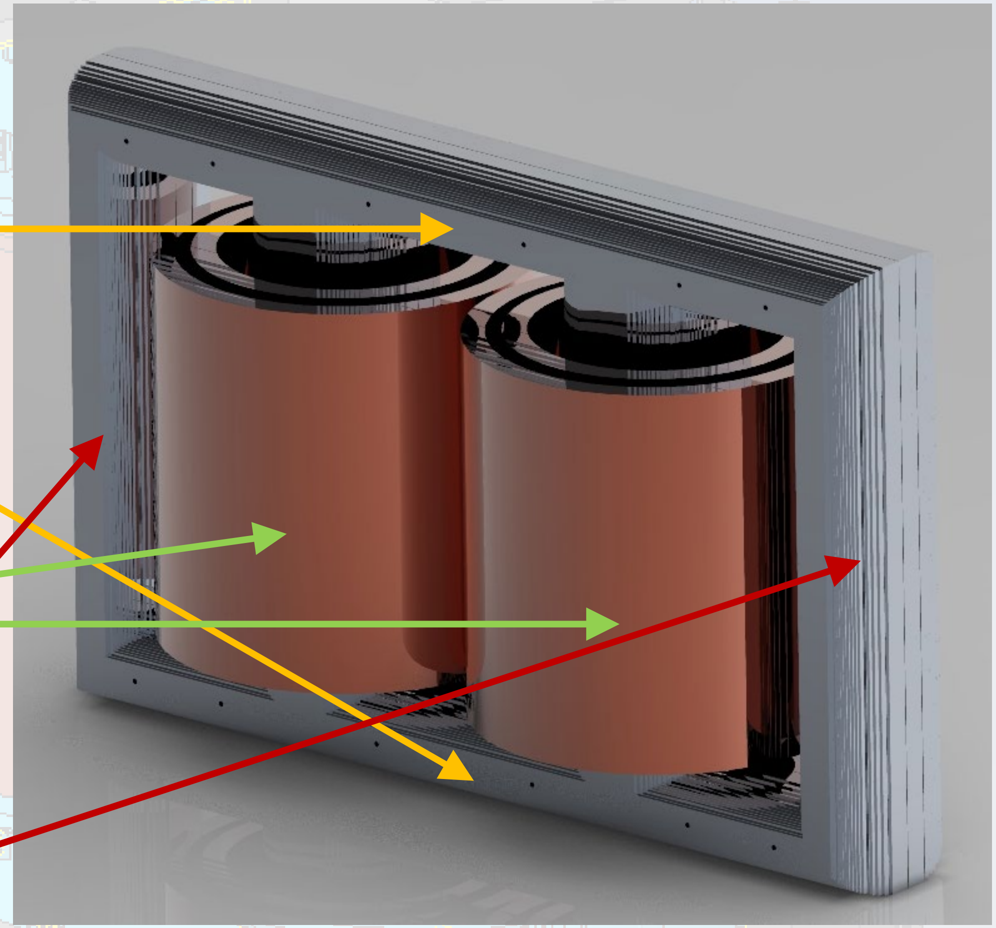
single-phase 4 limb core (2/2)



yokes

wound limb

return limbs

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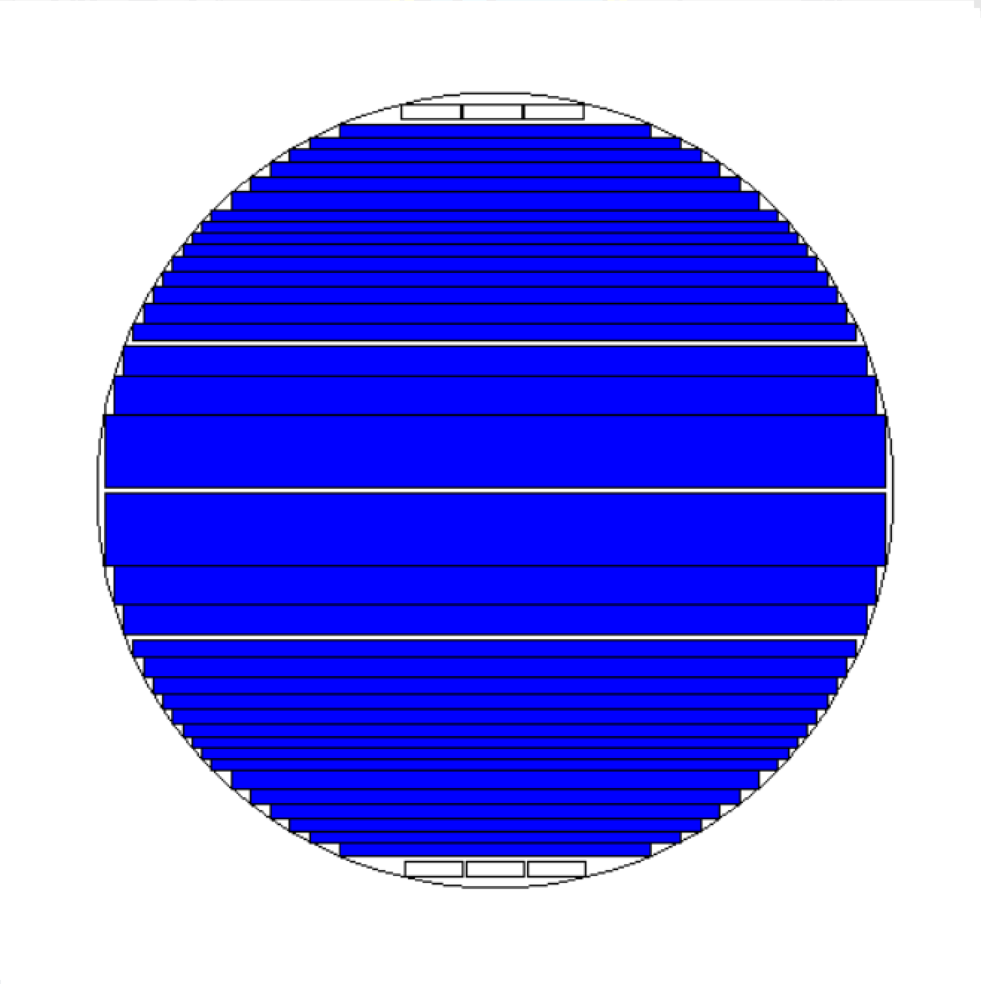
Core cross section



Core filling factor:

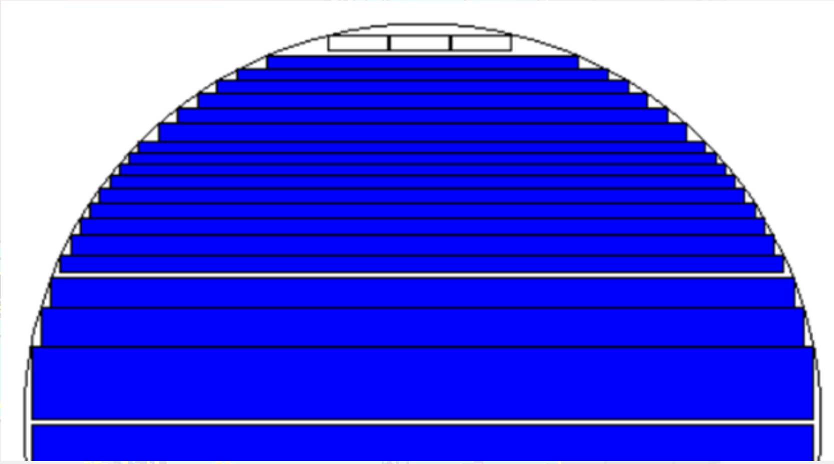
$$FF = \frac{effective\ core\ cross\ section}{geometrical\ core\ circuit\ cross\ section}$$

typical value 0,90 – 0,93

Effective core cross section (Q_{FE}) = ∑[(area of cores steps) x (stacking factor)]

Influence factors:

- number of cooling ducts
- thickness of core sheets
- number of core steps
- dimensions of tie bars
- core diameter



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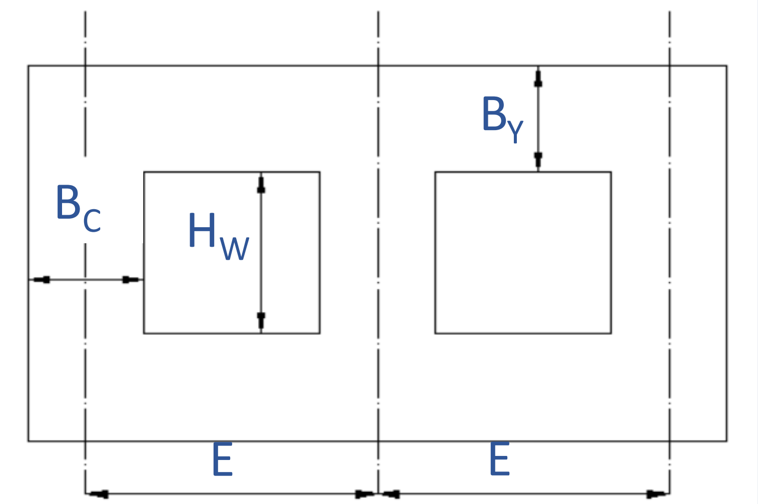
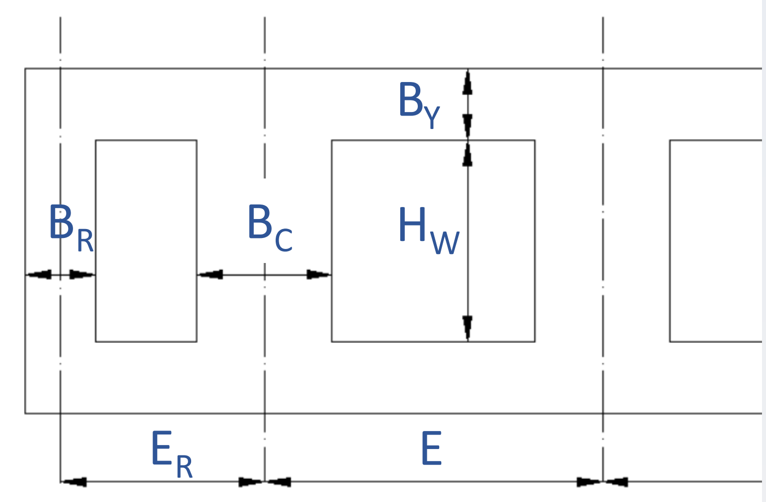
B_Y (mm) widest lamination width of the yoke
B_R (mm) widest lamination width of the return limb
B_C (mm) widest lamination width of the wound limb
D_{FE} (mm) diameter of the wound limb (core circle)
E (mm) middle distance of the wound limb
E_R (mm) middle distance of the wound limbs to the return limb
H_W (mm) window height
N_C (1) number of wound limbs
N_U (1) number of (unwound) return limbs
Q_Y (cm^2) effective cross section of the yoke
Q_R (cm^2) effective cross section of the return limb
Q_{FE} (cm^2) effective cross section of the wound limb





General condition for approximate calculation:
$B_R = B_Y$; $Q_R = Q_Y$
General <u>approximate</u> formula for cores with circular section of transformers:

$$G_{FE} = 7{,}65 \,\{N_C \cdot Q_{FE} \cdot H_W + Q_Y \cdot [(2 - N_U)\, D_{FE} + 2\,(N_C - 1)\, E + N_U\,(2E_R + H_W + B_Y)]\} \cdot 10^4 \ \text{(kg)}$$

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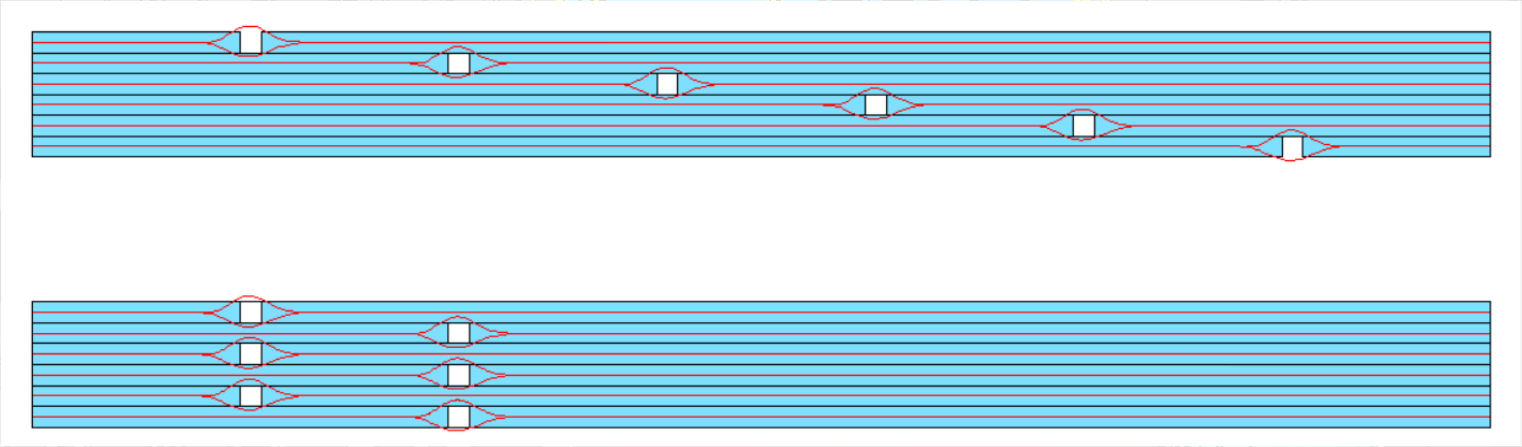
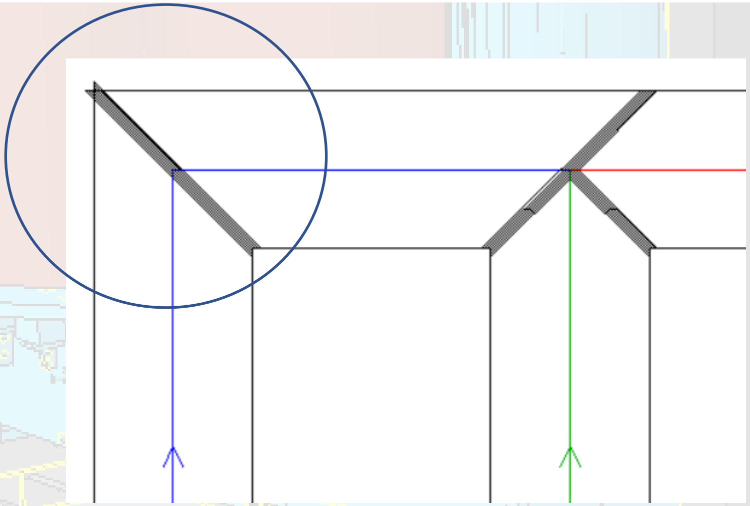
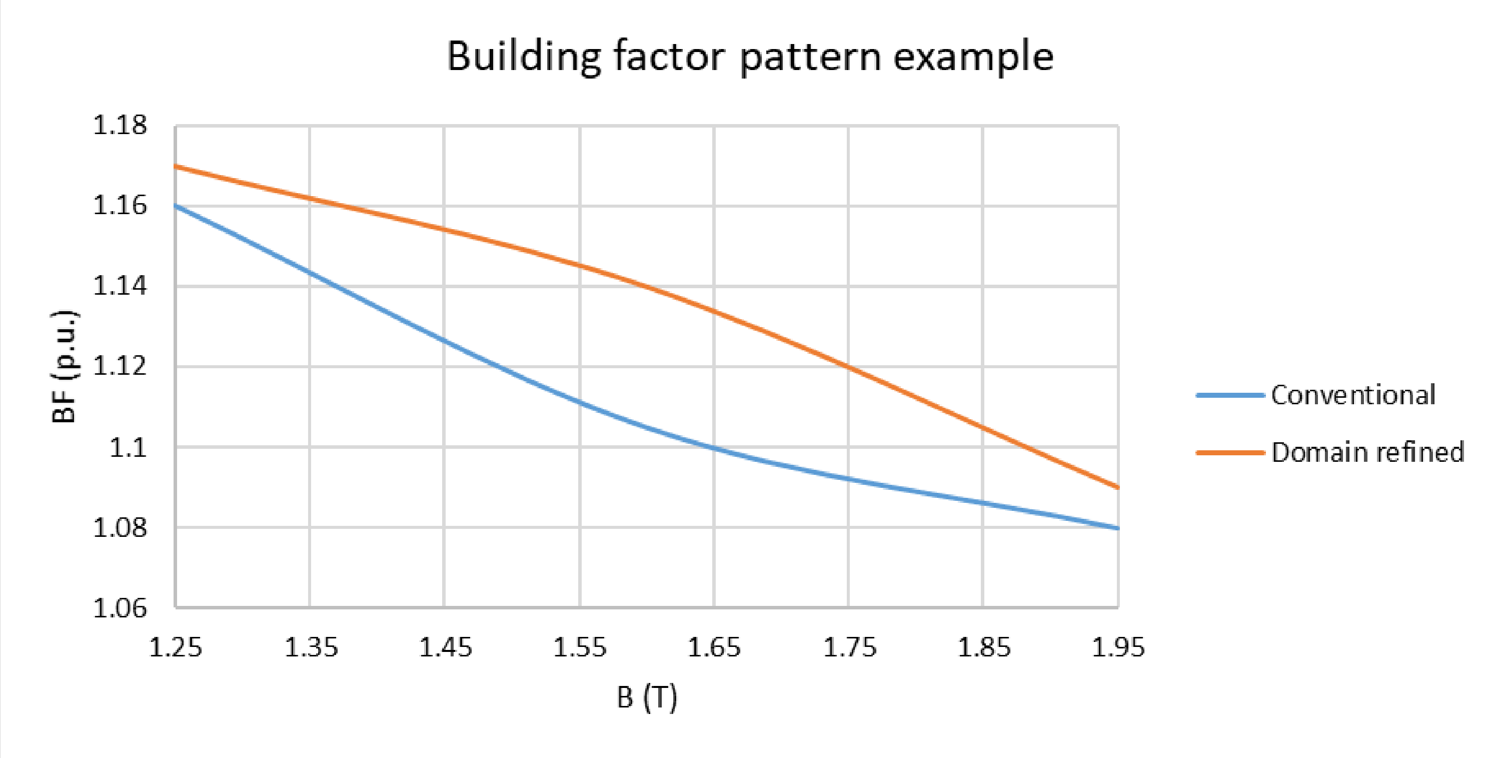
Classical vs Step lap core joint





Core losses

$$\boldsymbol{Building\ factor} = \frac{\boldsymbol{Built\ transformer\ core\ losses\ (watts/kg)\ (core\ losses\ /\ core\ weight)}}{\boldsymbol{Material\ Epstein\ losses\ (watts/kg)}}$$



<u>At the corner joints the flux is not along the grain orientation:</u>

- As electrical steel is better oriented, higher is building factor („better" core grade „worse" building factor)
- The higher the proportion of corner weight in the total core weight, the higher are the losses.

Core losses (no load losses)

$$P_{0\_Calc} = G_{FE} \cdot p0 \cdot K_B \quad (W)$$

G_{FE} (kg) - core weight

p0 (W/kg) - specific no load losses (Epstein core loss, function of frequency and peak induction)

K_B - building factor (function of core dimensions ratio (<u>weight of the corners</u>) and core type)

Other influence factors for K_B:

- step lap (5-7 standard)
- number of layers in step lap (1-2 standard)
- gap in step lap joints area

Other approach to calculate no load loss is <u>lumped circuit model</u>.

Technical tolerances acc. IEC 60076 -1:

- $P_{0\_Guaranteed}$ + 15 %

Technical tolerances acc. IEEE C57.12.00:

- $P_{0\_Guaranteed}$ + 10 %

Customer often require:

- $P_{0\_Guaranteed}$ + 0 %

  option A: transformer rejection if measured higher value

  option B: penalties within tolerances

P_{0_Calc} + calculation tolerance ? (what we expect to be measured ?)

Case study: 1 kW no load losses 5 k€ capitalized value, 100 trafo pieces per year of average 70kW and if we reduce 1% tolerance on calculation vs measured value, we gain 350 k€ per year savings.

Core losses

Apparent power:

$S_0 = G_{FE} \cdot s0 \cdot K_{BS0}$ (VA)

G_{FE} (kg) - core weight

s0 (VA/kg) - specific no load exciting power (function of frequency and peak induction)

K_{BS0} – building factor

No load current:

$$i_0 = 100 \times \frac{S_0}{S_r} \times \frac{U_r}{U} \ (\%)$$

S_r – transformer rated power

U_r – transformer rated voltage

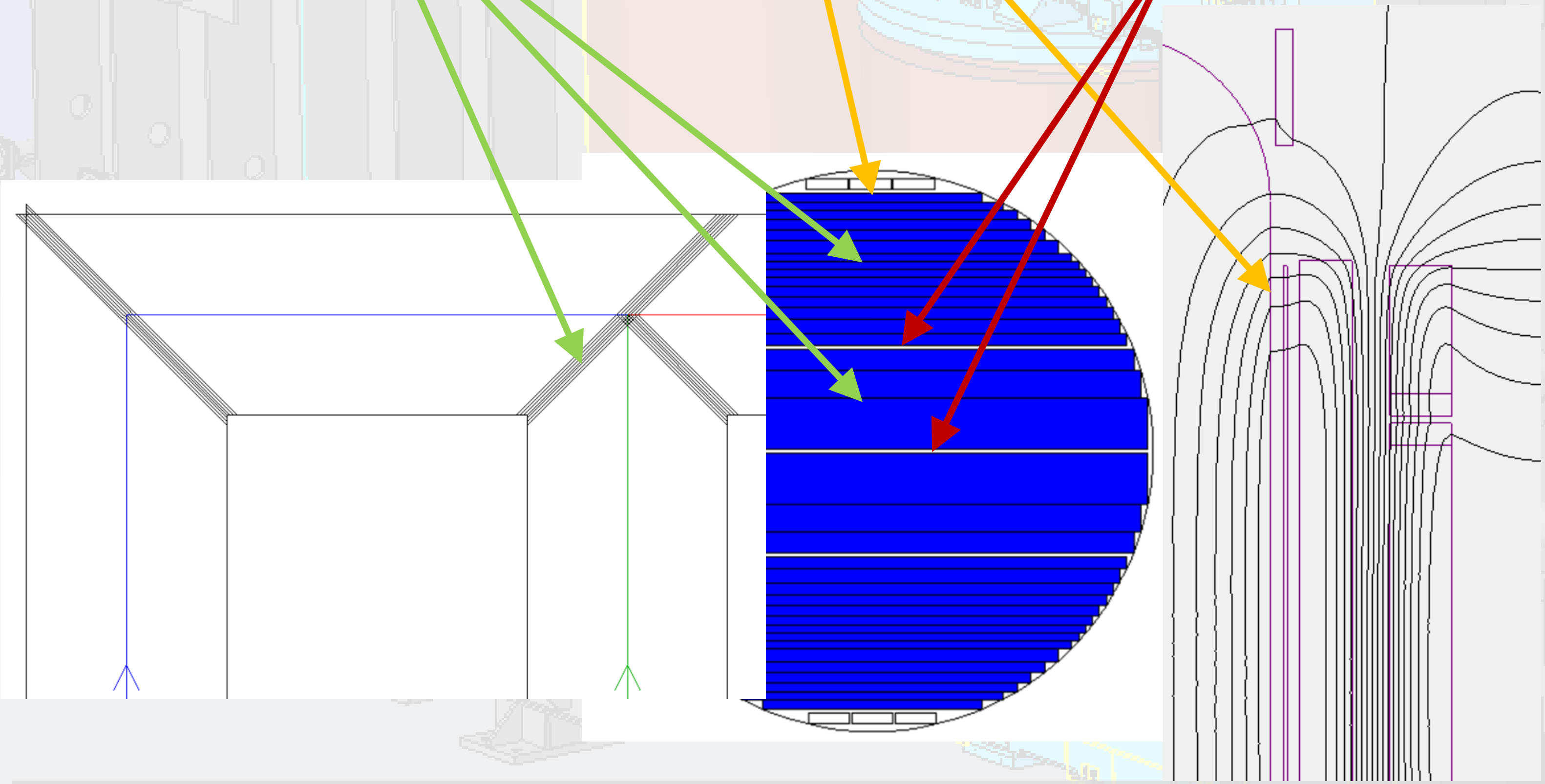
U – any voltage

Core losses

Target induction [T]	1.67			
Assumed core filling factor	0.915			
Voltage per turn [V/turn]	262.50			
SFE [mm^2]	707583.93			
DFE[mm]	992.28			
DFE[mm]	992			
Hw	2010			
Ww	1154			
GFE	89845.26			
	B[T]	Po[kW]	S0[kW]	i0
1.00Ur	1.67	118.3	185.9	0.06%
1.05Ur	1.75	143.1	408.7	0.14%
1.10Ur	1.84	174.3	956.0	0.32%

Target induction [T]	1.77			
Assumed core filling factor	0.915			
Voltage per turn [V/turn]	262.50			
SFE [mm^2]	667607.44			
DFE[mm]	963.84			
DFE[mm]	964			
Hw	2010			
Ww	1154			
GFE	83911.25			
	B[T]	Po[kW]	S0[kW]	i0
1.00Ur	1.77	138.9	453.2	0.15%
1.05Ur	1.86	171.3	1096.0	0.37%
1.10Ur	1.95	212.0	2359.9	0.79%

- last core step (last core package) due to winding leakage flux
- inner temperature rise (IEC 130°C for ambient temperature 40°C / IEEE 130°C for ambient temperature 30°C)
- core surface temperature rise (IEC 120°C for cellulose material, 140°C for high temperature material)



Core clamping system & core bandage

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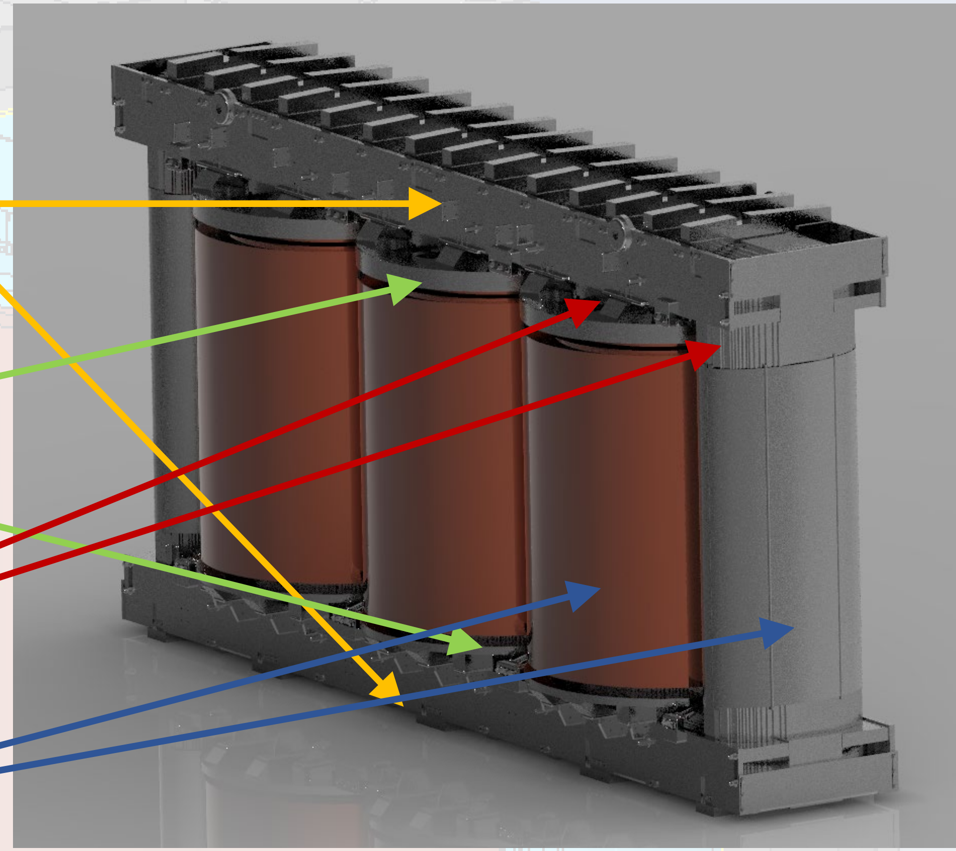
clamping plates

(I – type (flat), C – type option)

clamping rings

tie bars

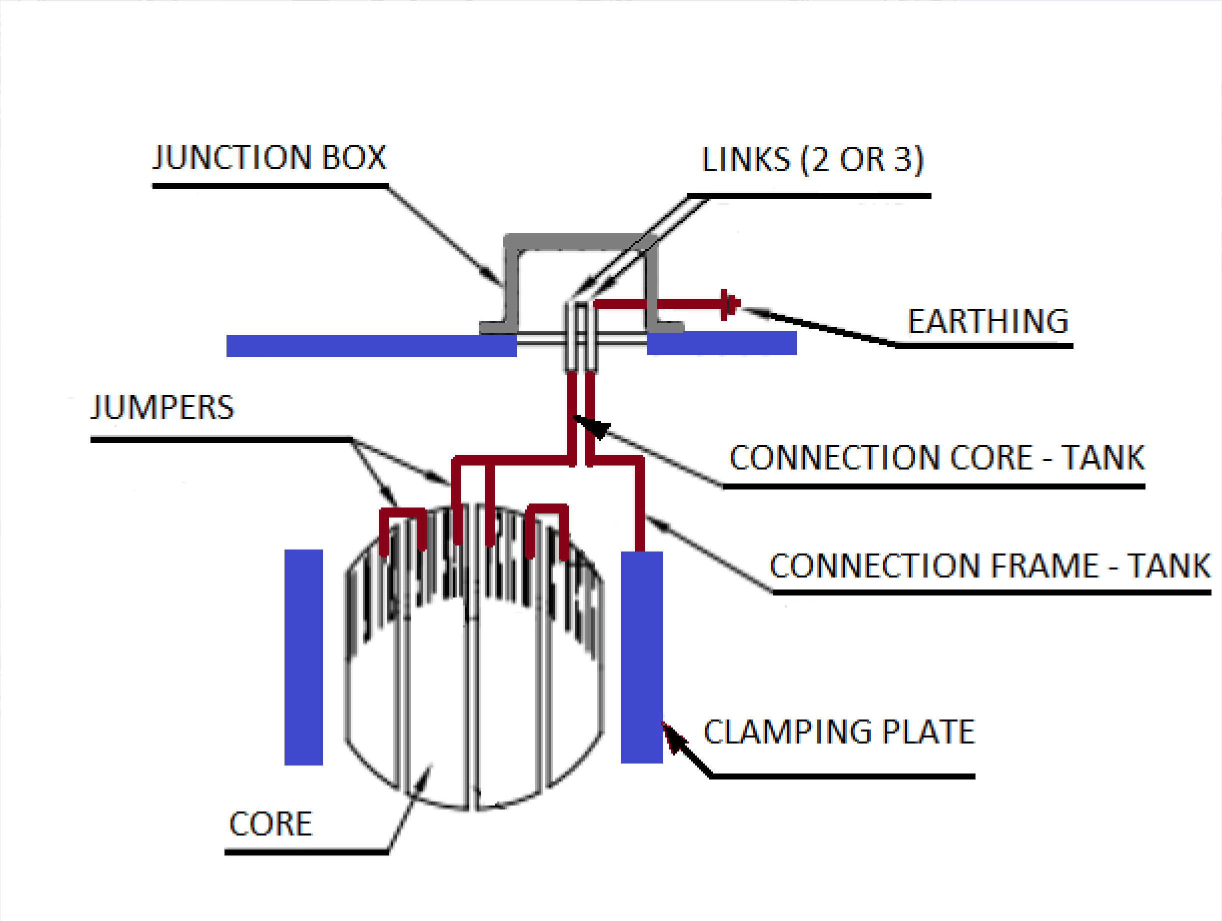
polyglass bandage



Clamping system must ensure appropriate pressure on core sheets as well as withstand active part lifting and short circuit forces.

Different manufacturing practice regarding insulating LV from HV side, top from bottom. Material can be magnetic or nonmagnetic steel (in special cases, it can be wooden)

Core grounding



Insulating core from clamping system we assure that there is no circulating currents between them. Circulating currents and weak contact can generate local hot spots and gassing.

- voltage per turn is main optimization factor for core weight and losses
- temperature rises (caused by main flux (inside the core) and windings stray field (last core package)) should be considered in design
- over excitations (especially continuous) should be considered in design
- different optimization methods to improve BF and losses (e.g. number of core packages, core sheet grade, mixing of grades, cross section of yoke and return limb optimization, cross section of tie bars...) although with less impact still important as every mm of core diameter and kW influence on transformer cost
- production tolerances have influence on overall design and reliability
- calculation tolerances should be continuously monitored and improved
- penalties and rejection criteria should be clarified in offer stage (benefit for customer and supplier)

[1] IEC 60404-8-7 MAGNETIC MATERIALS

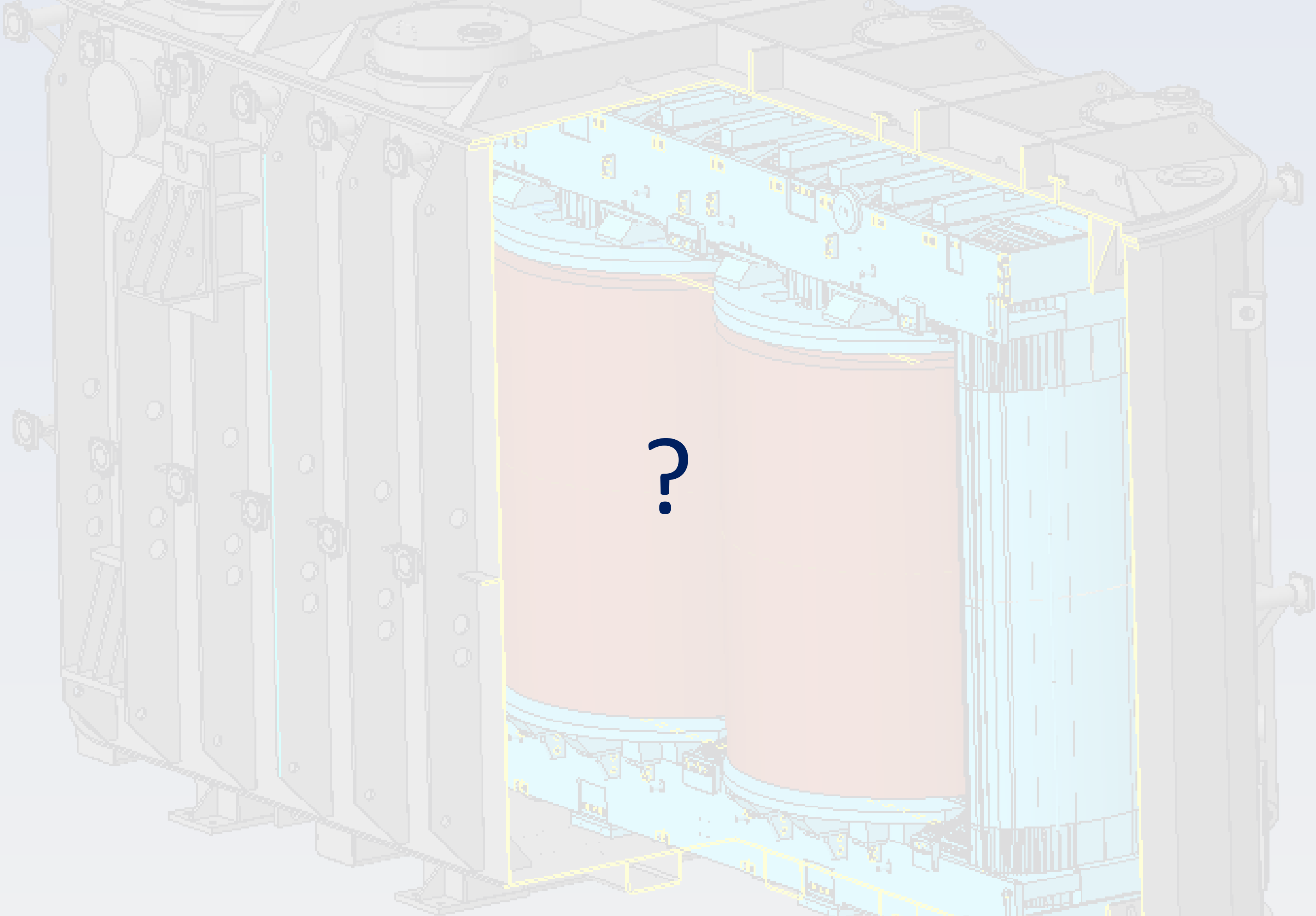
[2] Transformer Engineering Design and Practice; S. Kulkarni, S.Khaparde

[3] IEC 60076 - 7 Loading guide for mineral oil immersed power transformers

[4] IEC 60076 - 1 Power transformers Part 1: General

[5] IEEE C57.12.00 Standard for general requirements for liquid-immersed distribution, power and regulating transformers

Questions



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Thank you!

Aleksandar Lojpur, Power Transformer Consultant