Transformer Magnetic Circuit

Transformer Concepts & Applications Seminar

Goldsboro, NC

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Jason joined Prolec GE Waukesha in July 2005 as a design engineer at our Goldsboro, North Carolina, facility. He designs medium power transformers, including LTC and re-connectable types. He also works on updating and maintaining design software for the plant. Jason earned his Bachelor of Science, Electrical Engineering and Computer Engineering Degrees from North Carolina State University.

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Agenda

- Transformer Fundamentals
- Core Loss
- Core Steel
- Core Types
- Core Design & Construction
- Core Related Problems & Solutions

Transformer Fundamentals

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$$\nabla \times E = \frac{-\partial B}{\partial t}$$

$$\nabla \times B = \mu_0 (J + \varepsilon_0 \frac{\partial E}{\partial t})$$

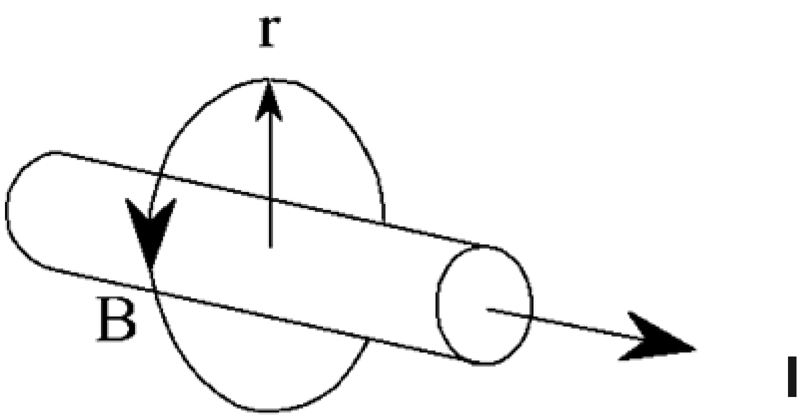
$$\nabla \cdot B = 0$$

$$\nabla \cdot E = \frac{\rho}{\varepsilon_0}$$

Magnetic Terms

- Magnetomotive Force – MMF
  - Symbol ($\mathcal{F}$)
  - ~ EMF that causes current flow
  - Unit: ampere-turn
- Flux
  - Symbol (ϕ)
  - # of magnetic field “lines”
  - Unit: weber
- Magnetic Flux Density
  - Symbol ($\mathbf{B}$)
  - Flux concentration
  - Unit: tesla
- Magnetic Field Intensity
  - Symbol ($\mathbf{H}$)
  - MMF distribution along magnetic path
  - Unit: amp-turns/meter

Currents & Magnetic Fields



B field surrounding conductor carrying current I

Right-Hand Rule

- Thumb in direction of current
- Fingers in direction of magnetic field

Magnetic field intensity (**H**) inversely proportional to distance (r)

Magnetic Induction

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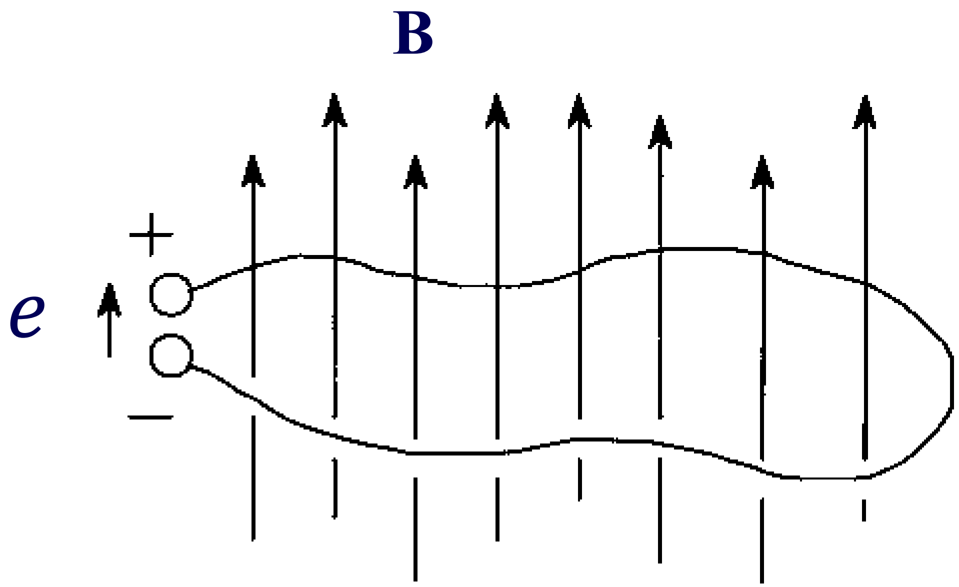
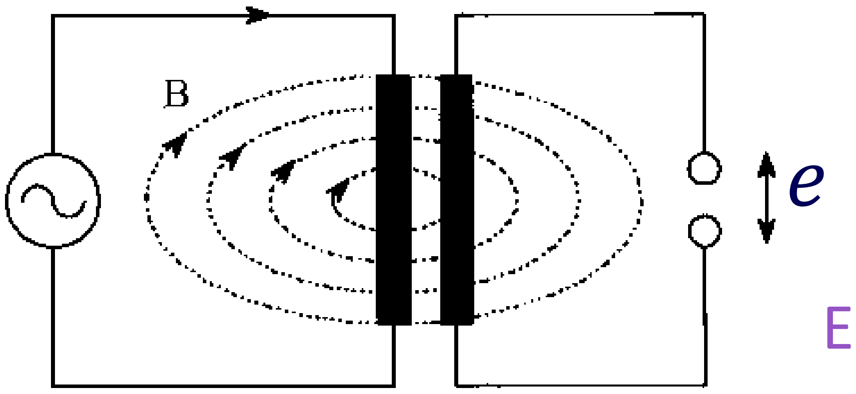


Voltage inducted in a loop surrounding a time-varying **B** *field*

Time-varying flux = induced voltage e
around closed path surrounding ϕ

Faraday’s Law of Induction



Voltage induced in a conductor

EMF is: $= -N \frac{d\Phi_B}{dt}$

Law of induction

- Induced voltage e around path surrounding time-varying flux

Not efficient in air

- Low % age of flux linked to secondary circuit

Ideal Transformer

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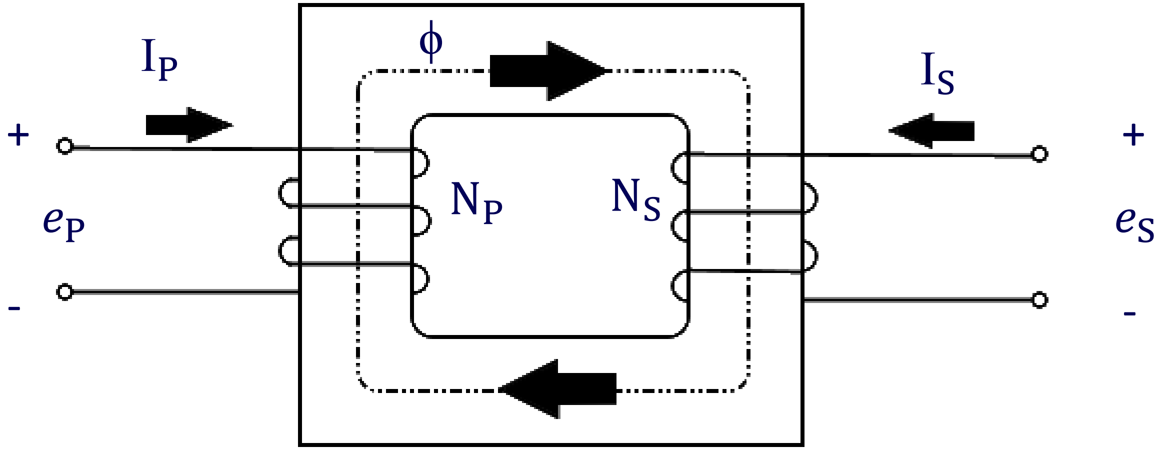


$$\frac{e_P}{e_S} = \frac{I_S}{I_P} = \frac{N_P}{N_S}$$

$$e_P = \sqrt{2}\pi f \phi_m N_P$$

$$\frac{Volts}{Turn} = \sqrt{2}\pi f \phi_m = 4.44 f B_m A$$

Where,

e = voltage (volts – primary or secondary)
I = current (amps – primary or secondary)
A = core cross section area (sq. m)
B = flux density (Tesla)
ϕ = flux (webers)
f = frequency (Hz)

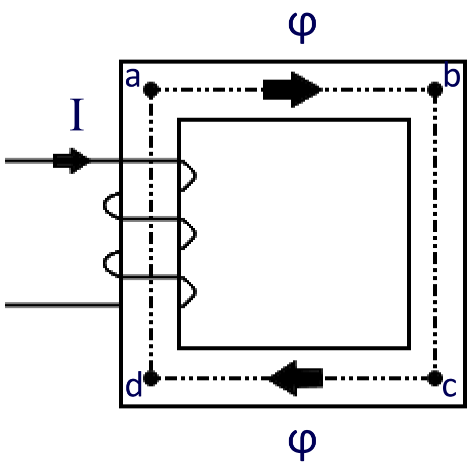
Permeability

- Introduction of core (coupling medium)
  - Magnetic material with affinity for flux
  - Increase in total flux linkage
  - Channeling (linking) coils with high %age of flux
  - Efficiency greatly increased
  - Lower magnetizing current
  - Higher ratio of mutual to leakage flux = reduced stray losses
- Degree of magnetization of material in response to magnetic field

$$\mu = \frac{\mathbf{B}}{\mathbf{H}} = \frac{\text{flux density}}{\text{field intensity}}$$

- Grain-oriented silicon steel conducts flux 1500x vacuum
- For core materials μ varies with flux density and ranges from ~ 200 - 100,000
- For non-magnetic materials $\mu \approx 1 – 10$

Magnetic Circuit



- $\mathcal{R}$ = reluctance of magnetic circuit a-b-c-d-a
- Reluctance: property that resists magnetic flux
- Coil wound around magnetic yoke
- Coil with ***N*** turns carrying current ***I***
- Flow of magnetic flux along path a-b-c-d-a

Magnetic		Electric	
Magnetomotive Force	$\mathcal{F}$	Electromotive Force	e
Magnetic Intensity	$\mathbf{H}$	Electric Intensity	$\mathbf{E}$
Flux Density	$\mathbf{B}$	Current Density	$\mathbf{J}$
Flux	ϕ	Current	I
Reluctance	$\mathcal{R}$	Resistance	R
Permeability	μ	Conductivity	σ

Analogous Magnetic and Electric Quantities

	Magnetic	Electric
Ohm's Law	$\mathcal{F} = \phi\mathcal{R}$	$e = \mathrm{IR}$
KVL (around loop)	$\sum_i \mathcal{F}_i = \sum_i \phi_i\mathcal{R}_i$	$\sum_i e_i = \sum_i \mathrm{I}_i\mathrm{R}_i$
KCL (at a junction)	$\sum_i \phi_i = 0$	$\sum_i \mathrm{I}_i = 0$

Analogous Magnetic and Electric Equations

Core Loss

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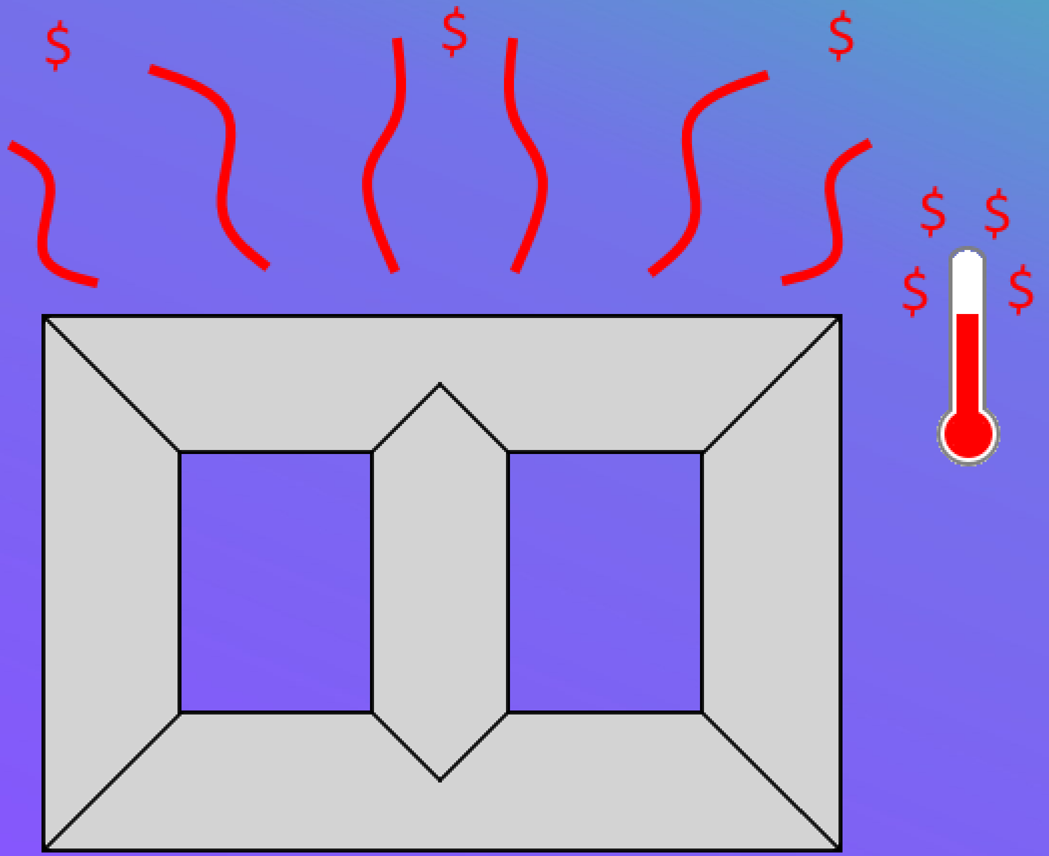


Core Loss

Core Loss means heating of core material

Eddy Loss

- Results from eddy currents circulating
  - Induced by flux flow normal to core width
- Can be reduced by
  - Reduced thickness
  - Application of thin insulating coating

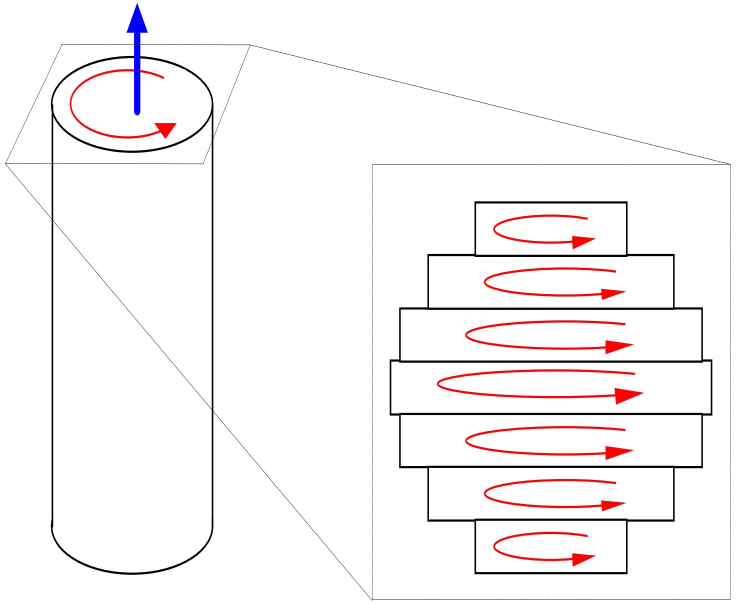
Hysteresis Loss

- Results from cyclical reversal of flux
  - “Friction” during realignment of magnetic domains every half-cycle
- Can be reduced by metallurgical control of steel

Eddy Loss

Proportional to

- Core steel conductivity
- Steel thickness, flux density, and frequency squared



Where,

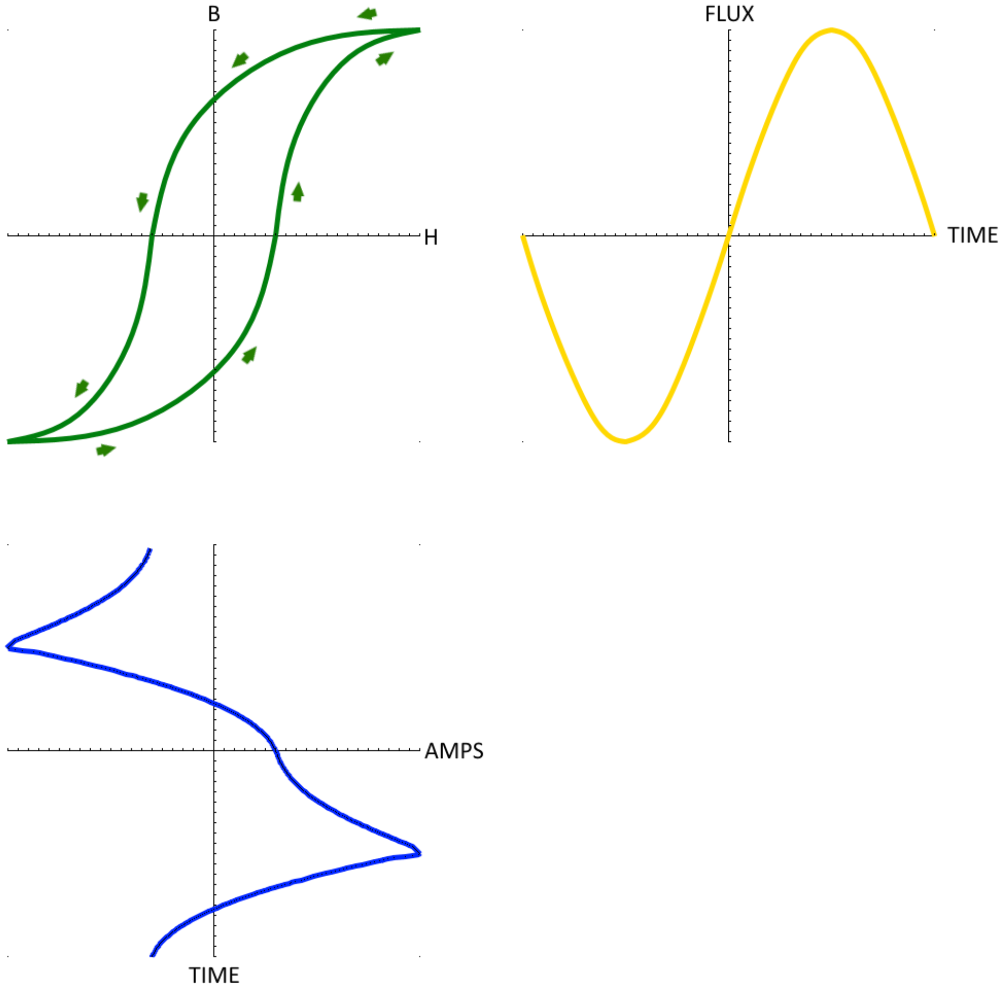
K_e = material constant
f = frequency (Hz)
B = max flux density (Tesla)
τ = lamination thickness (mm)
ν = material volume (cu meters)

$$P_e = K_e f^2 B_m \tau^2 v$$

The B-H Curve

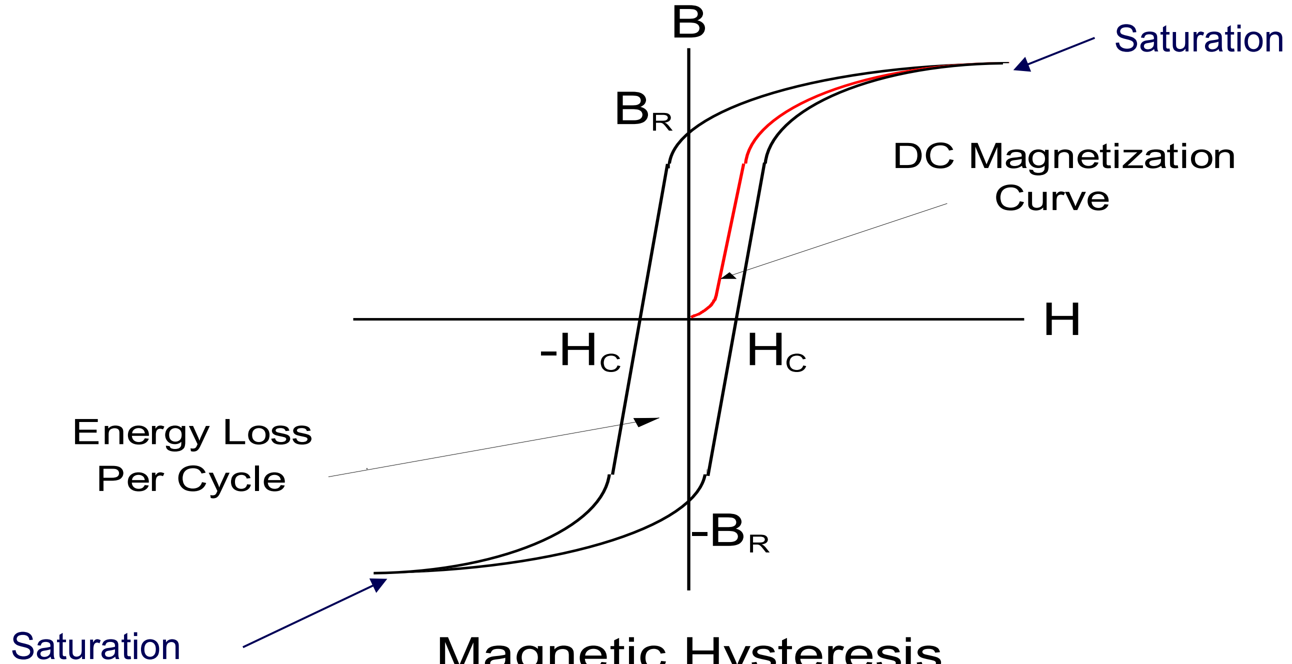
Depends on

- Magnitude of flux density
- Periodic frequency
- When magnetizing current = 0, considerable +ve or –ve residual flux
- Residual flux is from magnetically aligned crystalline structures
- Saturation
  - H ↑ , B ↑ at **smaller** rate
  - μ ↓ ***as* B** ↑
- Occurs at approx. +/- 1.5T
  - Typical for materials used in power transformers



Hysteresis Loss

- Ferromagnetic core material exhibits "*memory*" which causes hysteresis loss in transformers
- Area bounded by the hysteresis loop represents the energy lost during each cycle of magnetization



Magnetic Hysteresis

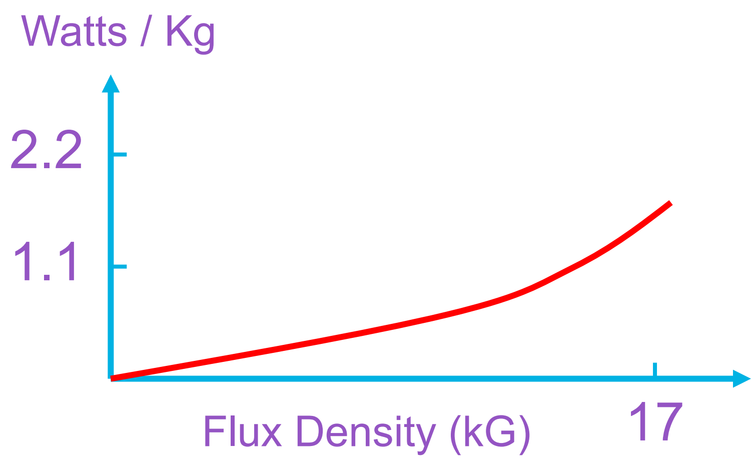
$$P_h = vf\,(K_h B^n)$$

Where,

ν = volume (cu meters)
f = frequency (Hz)
K_h = material constant
B_m = max flux density (Tesla)
n = material constant (1.5 to 2.5)

Core Loss Calculation

- The loss density of a ferromagnetic material increases almost exponentially with flux density (**B**).
- Core loss = Core weight x Watts/kg x Destruction Factor



Typical Curve of Core Loss *vs*. B at 60 Hz

- The loss density of different electrical steels is commonly compared under standard operating conditions.

Core Steel

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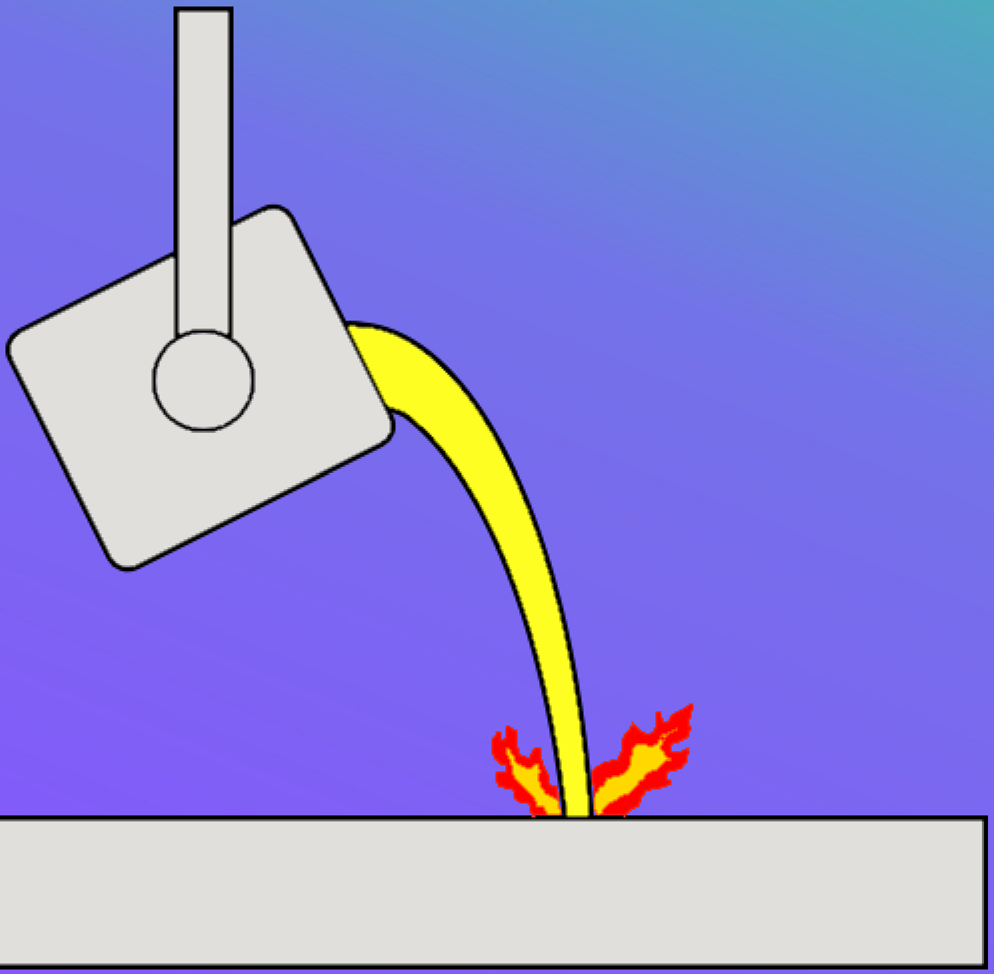


Early Years

Inferior grades of laminated steels

- Higher core losses
- Pronounced aging effects
- Increased hysteresis losses

Silicon alloyed with low carbon content steel

- Low hysteresis losses
- Improved permeability
- Reduced magnetizing current

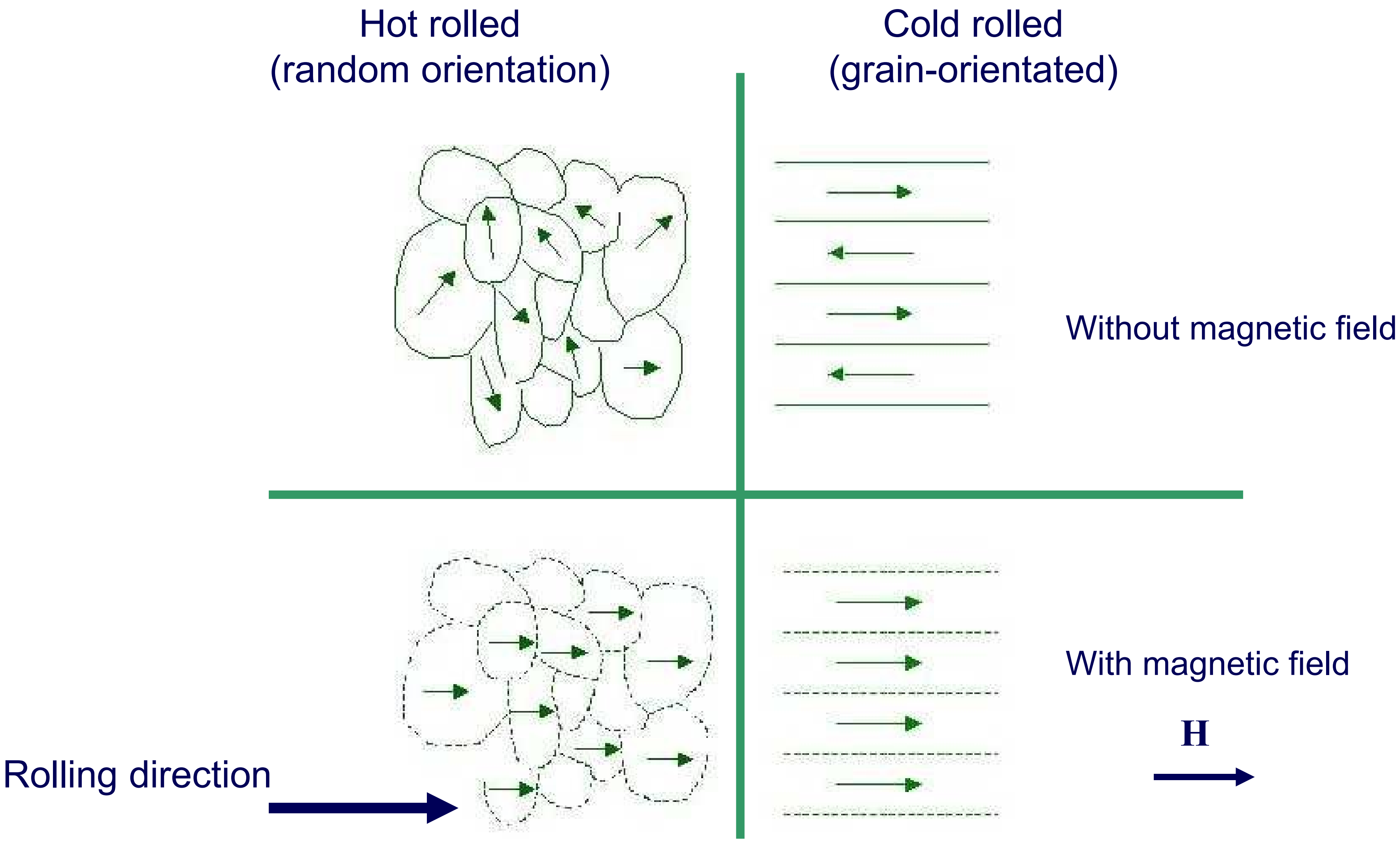
Increased Efficiency

CRGOS (<u>**C**</u>old <u>**R**</u>olled <u>**G**</u>rain-<u>**O**</u>riented <u>**S**</u>ilicon Steel)

Silicon-iron alloy rolled such that permeability is higher and hysteresis losses are lower when flux is in direction of grain

- Pros
  - Magnetic flux flow along grain orientation = min losses
  - Increased power ratings
  - Reduced core losses
- Cons
  - Susceptible to increased losses due to flux flow in other directions, mechanical strain, jointing, bending etc.

Magnetic Domains



Electrical Steels

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Common Grades of Electrical Steels				
Process	Type	Grade		
Hot Rolled	Non Oriented (1900)*	M-47		M-27
		M-45		M-22
		M-43		M-19
		M-36		M-15
Cold Rolled	Grain Oriented (1934)*	M-6		M-3
		M-4		M-2
	Super Grain Oriented (1968)*	H-2	H-1	H-0
	Domain Refined Super Grain Oriented (1984)*			

** approximate date of first commercial product*

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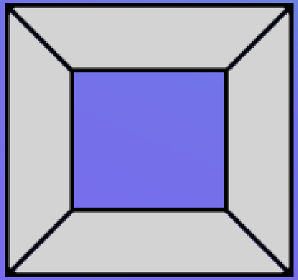
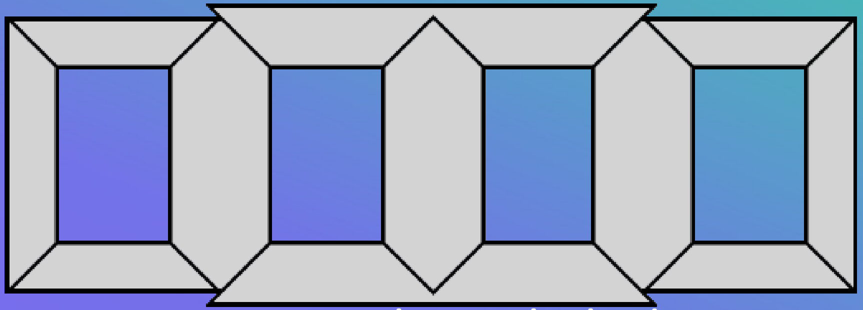
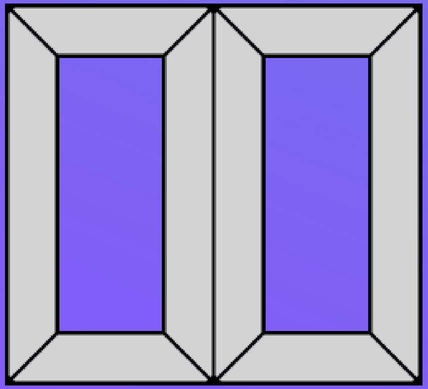
Core Types



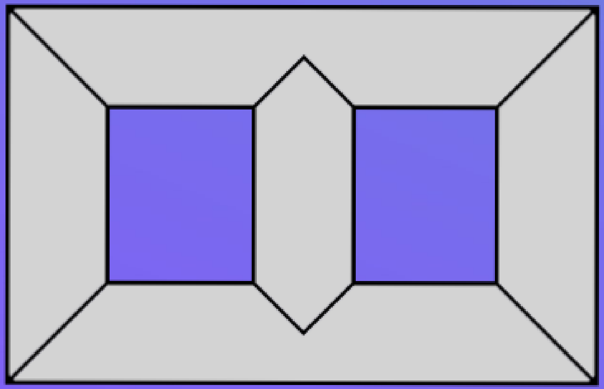
Single phase 2-limbed core



3 phase 5-limbed core



Single phase 3-limbed core



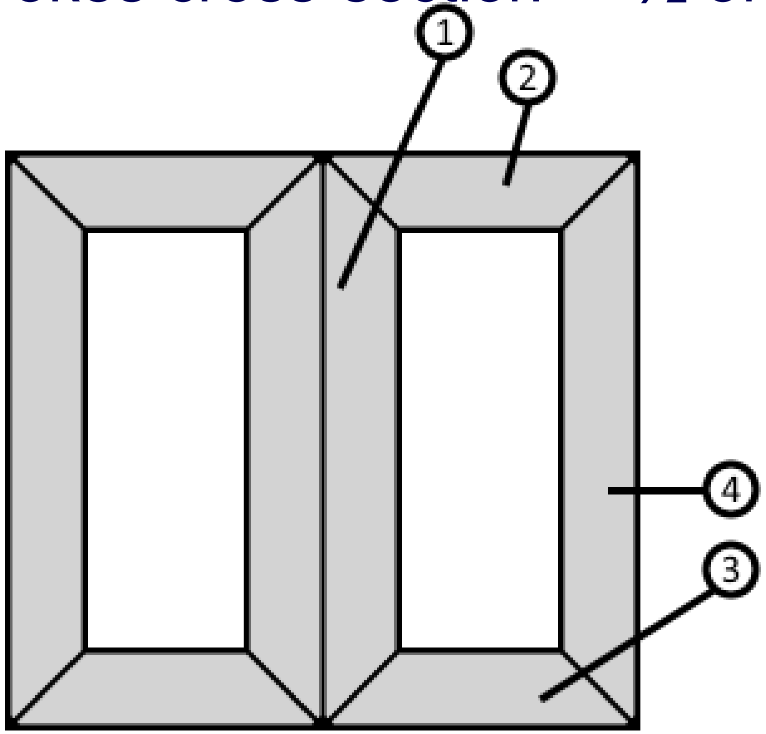
3 phase 3-limbed core

Core Types

- Single phase 2-limbed core
- Single phase 3-limbed core
- 3 phase 3–limbed core
- 3 phase 5–limbed core

Single-Phase 3-Limbed Core

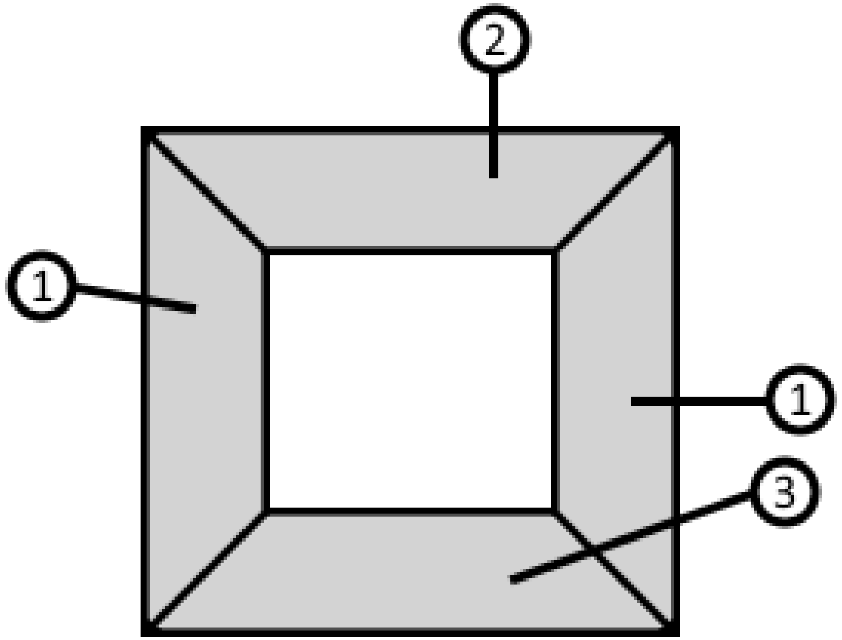
- Main magnetic flux divided into 2 parallel return paths
- Aux limbs, yokes cross-section = ½ of main limb



Single-phase three-limbed core:
(1) main limb, (2) top yoke,
(3) bottom yoke, (4) aux limb.

Single-Phase 2-Limbed Core

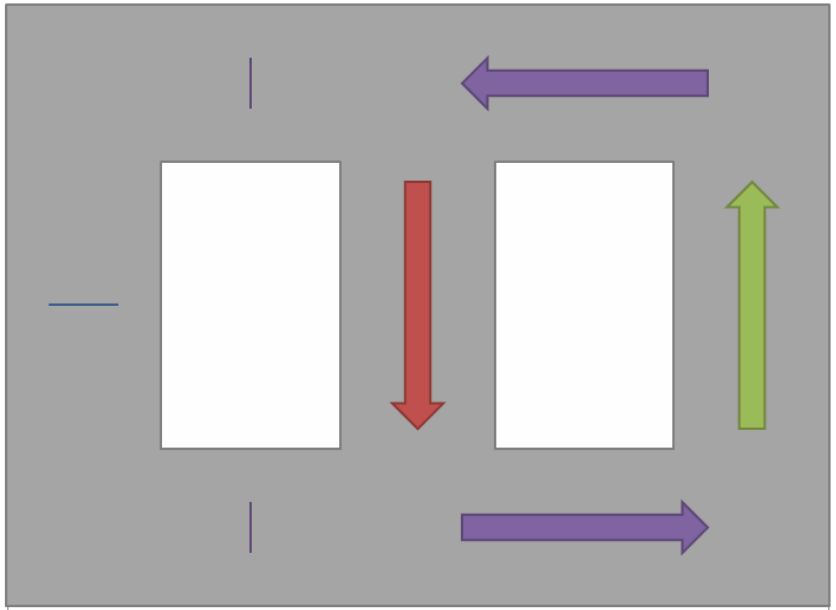
- Cross-sectional area of legs & yokes same
- Windings split into 2 → higher % age leakage reactance

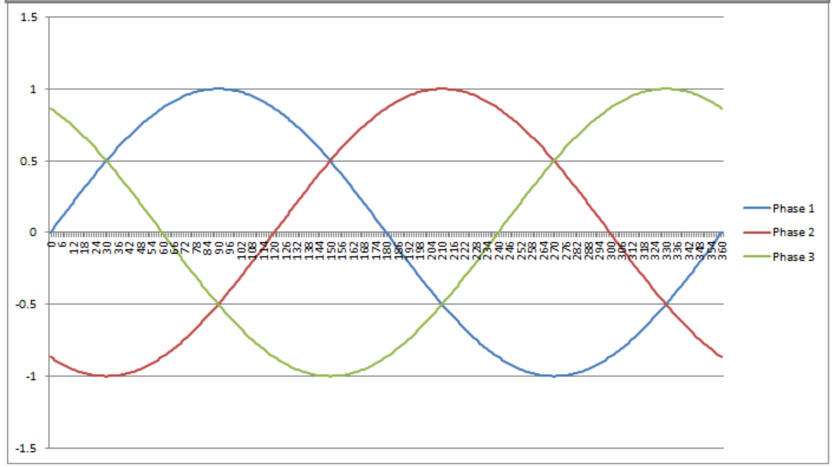


Single-phase two-limbed core:
(1) main limb, (2) top yoke,
(3) bottom yoke

3-Phase 3-Limbed Core

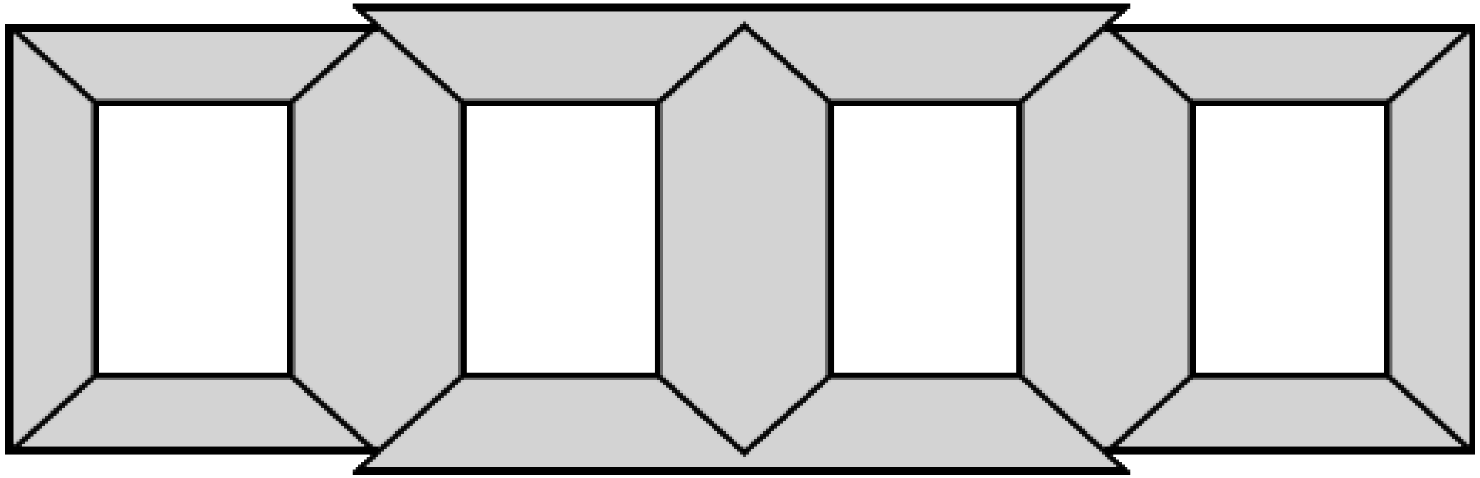
- 1 leg per phase
- Yokes & 2 limbs provide return path to flux of 1 limb
- At any instant of time, phase fluxes
- $\Phi_A + \Phi_B + \Phi_C = 0$
- Legs & yokes have identical cross-section
- More economical vs. bank of three 1-phase transformers
- Restricts 3rd harmonic flux and allows for a distortion-free secondary voltage wave shape



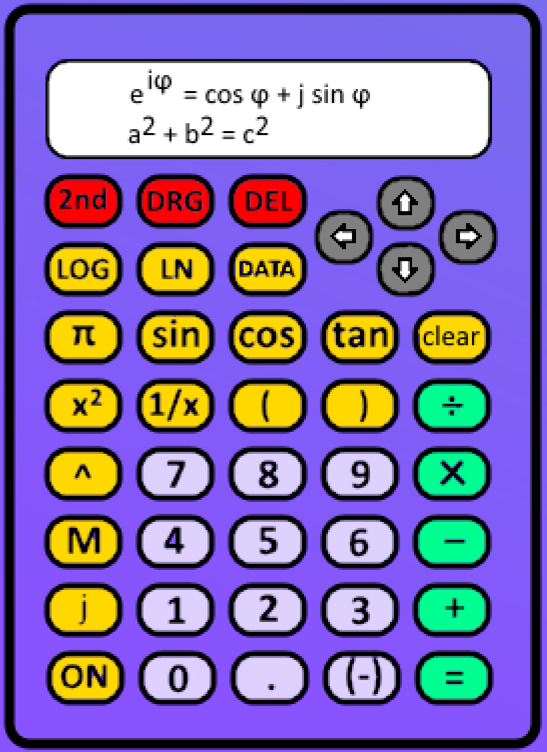


3-Phase 5-Limbed Core

- Large power rated XFMRs → Large diam cores →
- Increased core height → transportation problems
- Yoke cross section reduced ~40%
- Aux yokes & limbs provide return path to flux
- Cross section & height of aux yokes & limbs < main yokes



Core Design & Construction



Design of Magnetic Circuit

- MVA rating of transformer
- Performance parameters
  - Impedance
  - BIL
  - kV class
- Operational conditions
- Sound level requirements
- No-Load loss evaluation $/kW
- Transport limitations

- Magnetic flux density saturation of CRGOS
  - Core saturation dependent on input voltage and frequency
  - Suitable value to avoid saturation
- Increased magnetic flux density
  - ↓ Core weight
  - ↑ Core losses

Core Design & Construction

Air gaps = Reluctance

- Reduce inductance of coil, increase magnetizing currents
- Eliminate all air gaps?

Approach 1: Core from solid block

- Impractical
  - Coils wound through core window
- Large circulating currents
  - Oppose changing flux
  - Effectively “short out” transformer

Core Design & Construction (cont.)

Approach 2: Thin laminated steel sheets stacked together

- Excellent magnetic properties
- Relatively inexpensive
- 0.010” – 0.020” thick
- Formed from steel ribbon
    - Cut into sections by Georg
    - Various sizes and shapes

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Core Steel Laminations

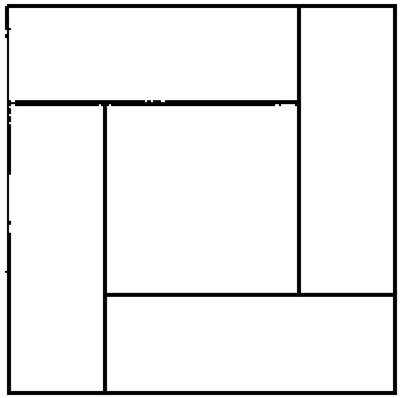
- Carlite – Oxide coating for insulation
- Stacking factor
  - ↑ with thicker laminations = ↑ eddy current (proportional to square of thickness)
  - ↓ with thinner laminations = ↓ eddy current (preferred)
  - Deburring
    - Improves stacking factor
    - Minimizes eddy losses

Core Stacking Methods

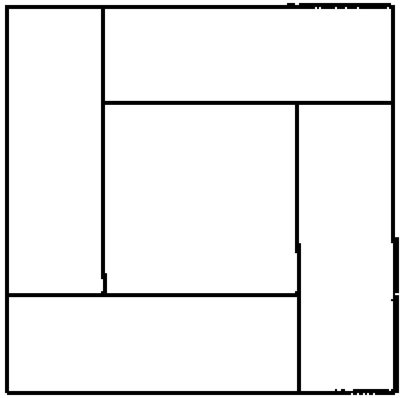
Butt Lap Method

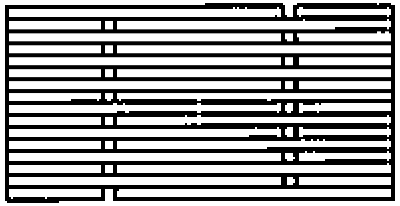
- Edges butted
  - Alternating layers assure continuous
  - path across surfaces
- Simple in terms of manufacturing
- Higher losses
- Works best with non grain-oriented steel
- Small rating transformers

Even Layer



Odd Layer





Core Stacking Methods (cont.)

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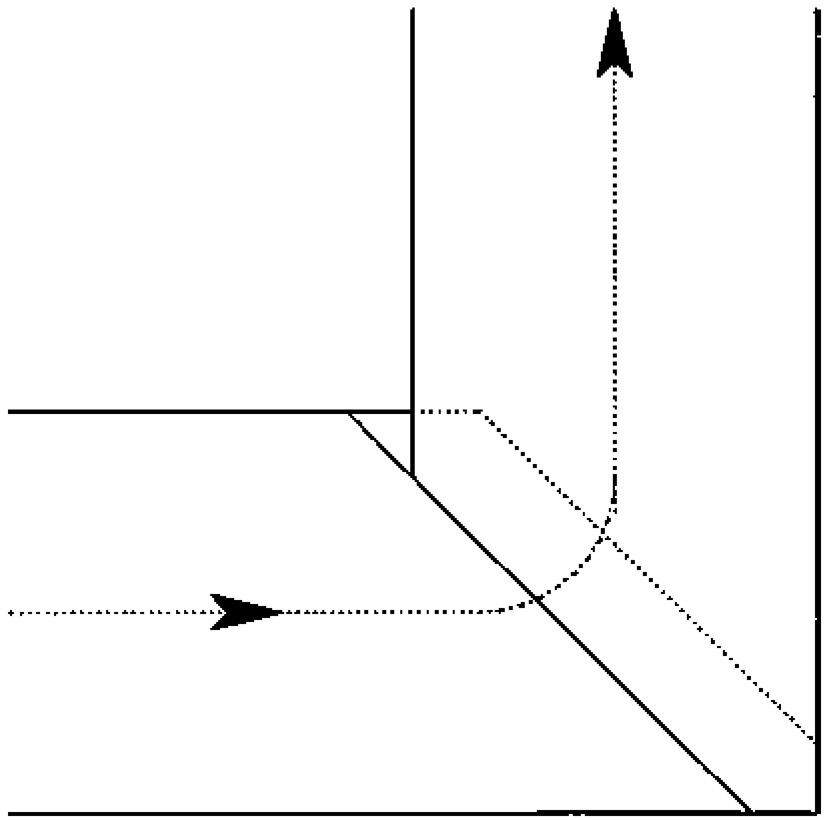
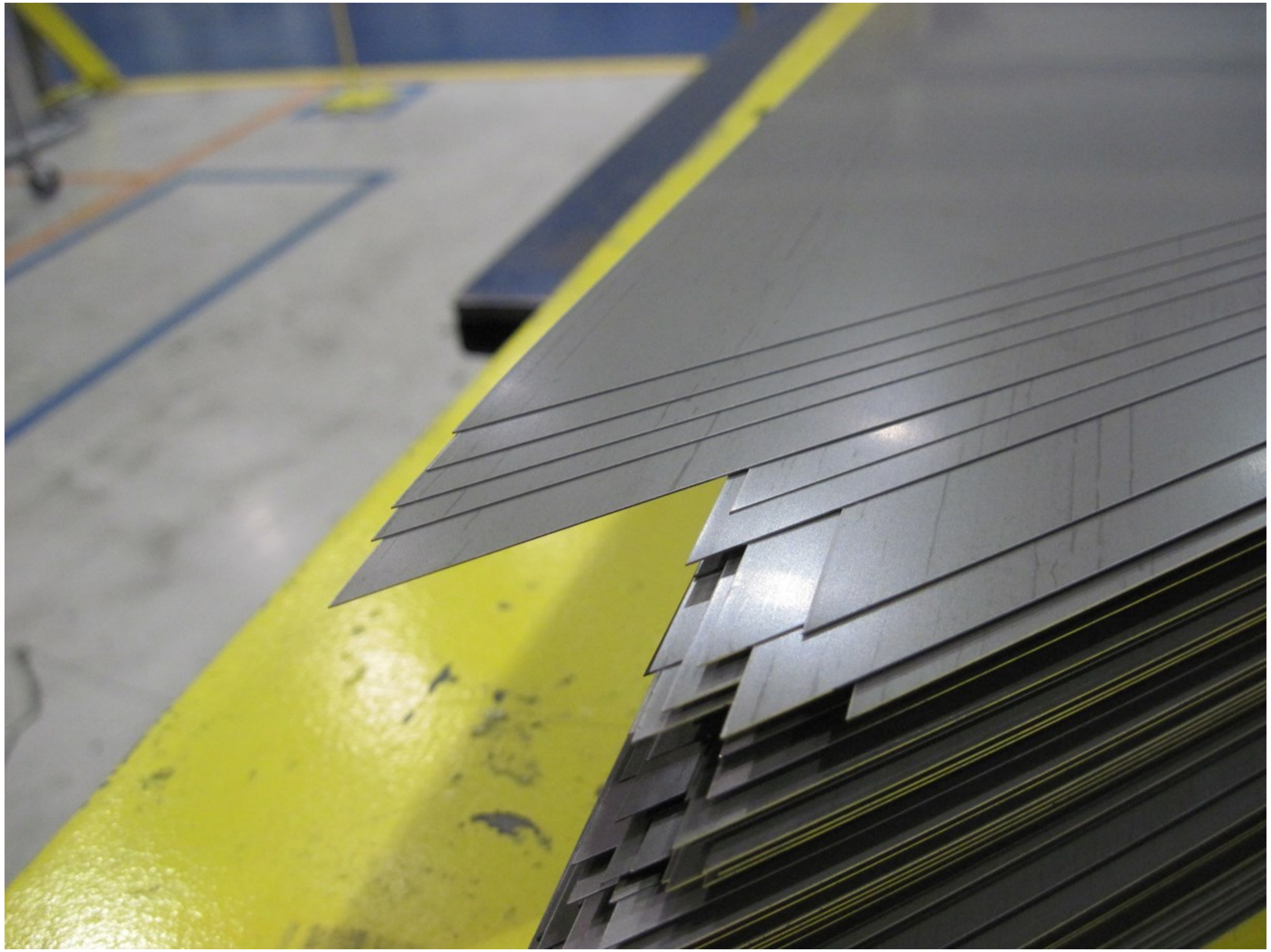
Mitered Joints

- Corners cut at 45˚
- Alternate layers
  - Cut into slightly different lengths
  - Have slightly different shapes
- Smooth path of flow for magnetic flux
- Grain oriented along lengths
  in horizontal and vertical directions
- Losses minimum
- Extra manufacturing cost

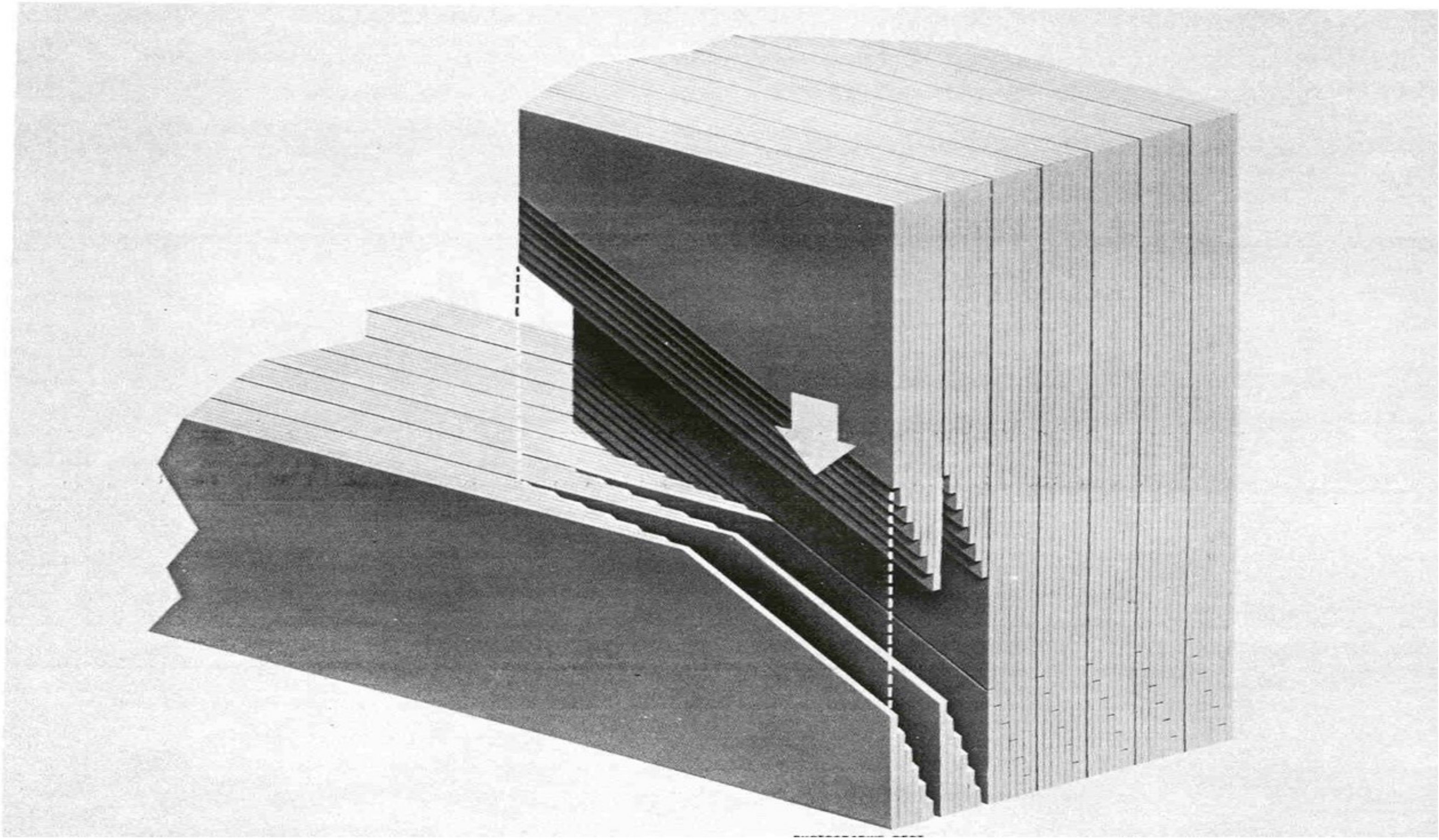


Flux transition at the corner of a mitered core

5 Step Lap

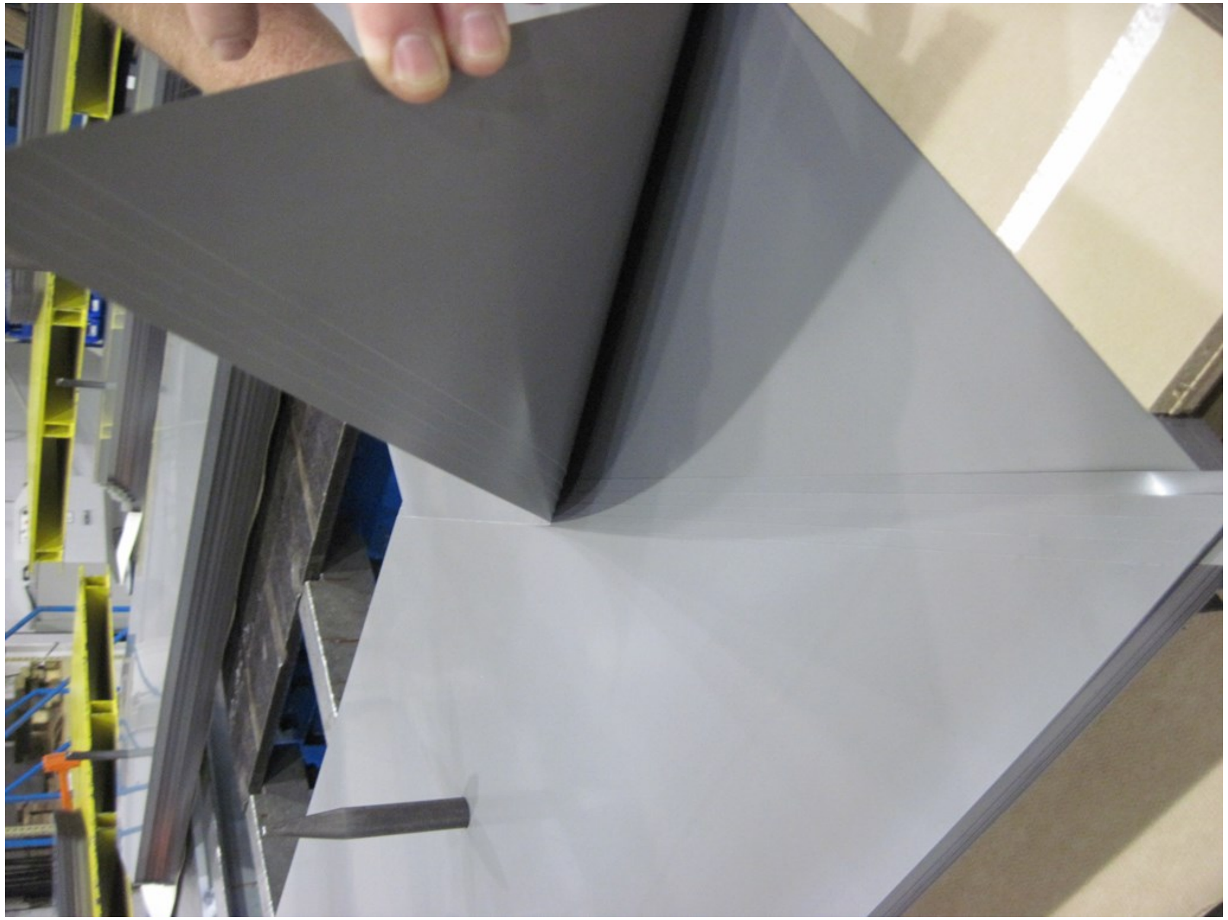


Step Lap Joint



Corner Joints: Step Lap Detail (7-step lap shown)

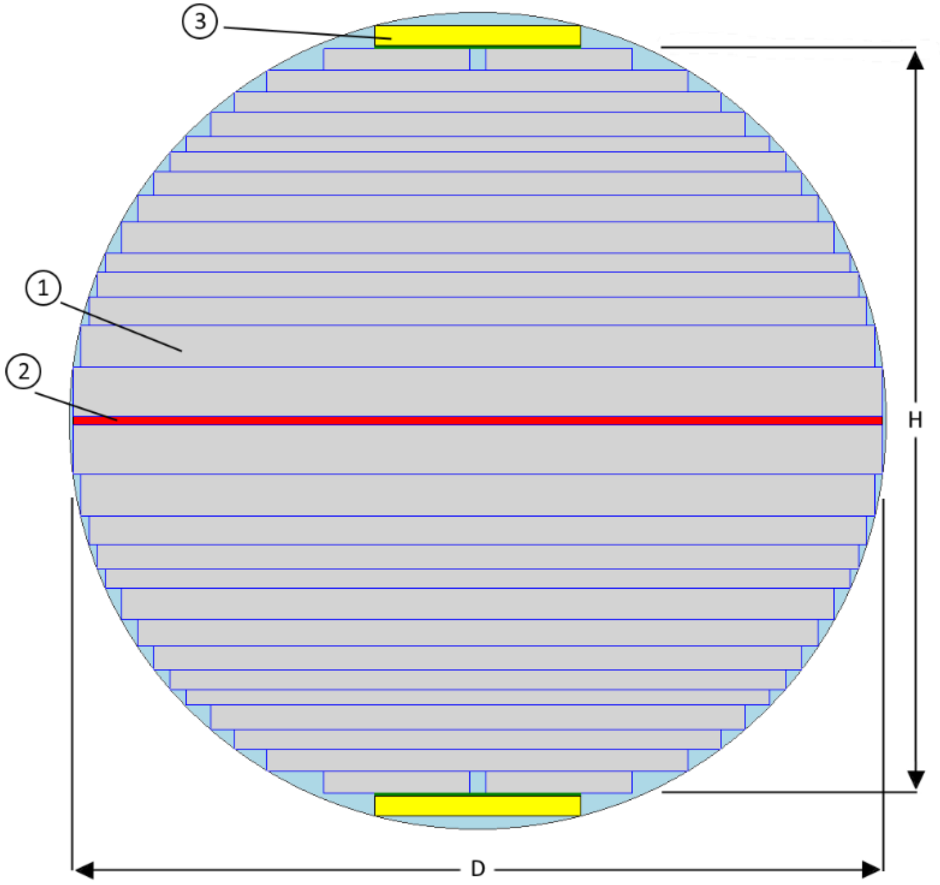
Step Lap Joint (cont.)



Corner Joints: 5-step lap shown

Optimum Design of Core

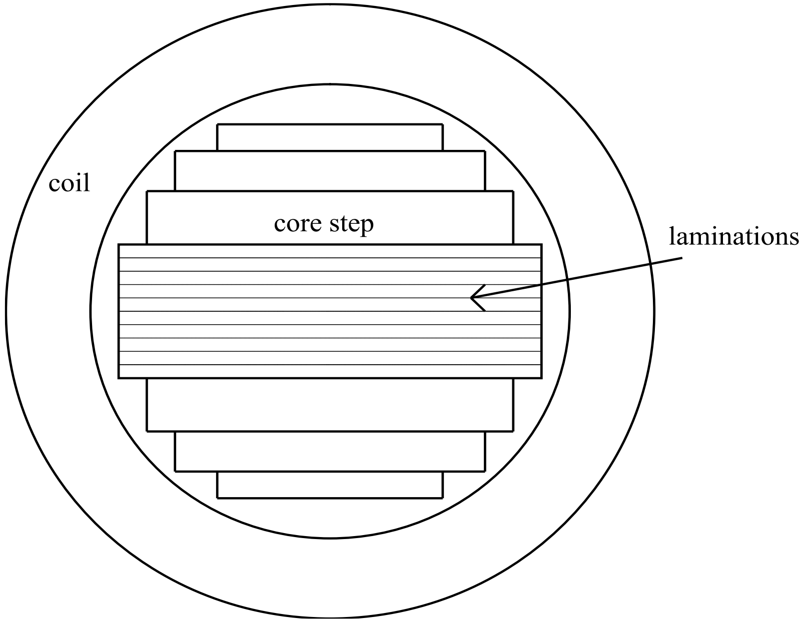
- Ideal shape: Circle
  - No wasted space besides insulation space
  - Possible but uneconomical
- Varying widths & packet heights approximate a circle
- Within core circle
  - Steel sheet laminations
  - Oil duct
  - Clamp plates
- Stacking factor: space lost between laminations
  - Burrs lower stacking factor



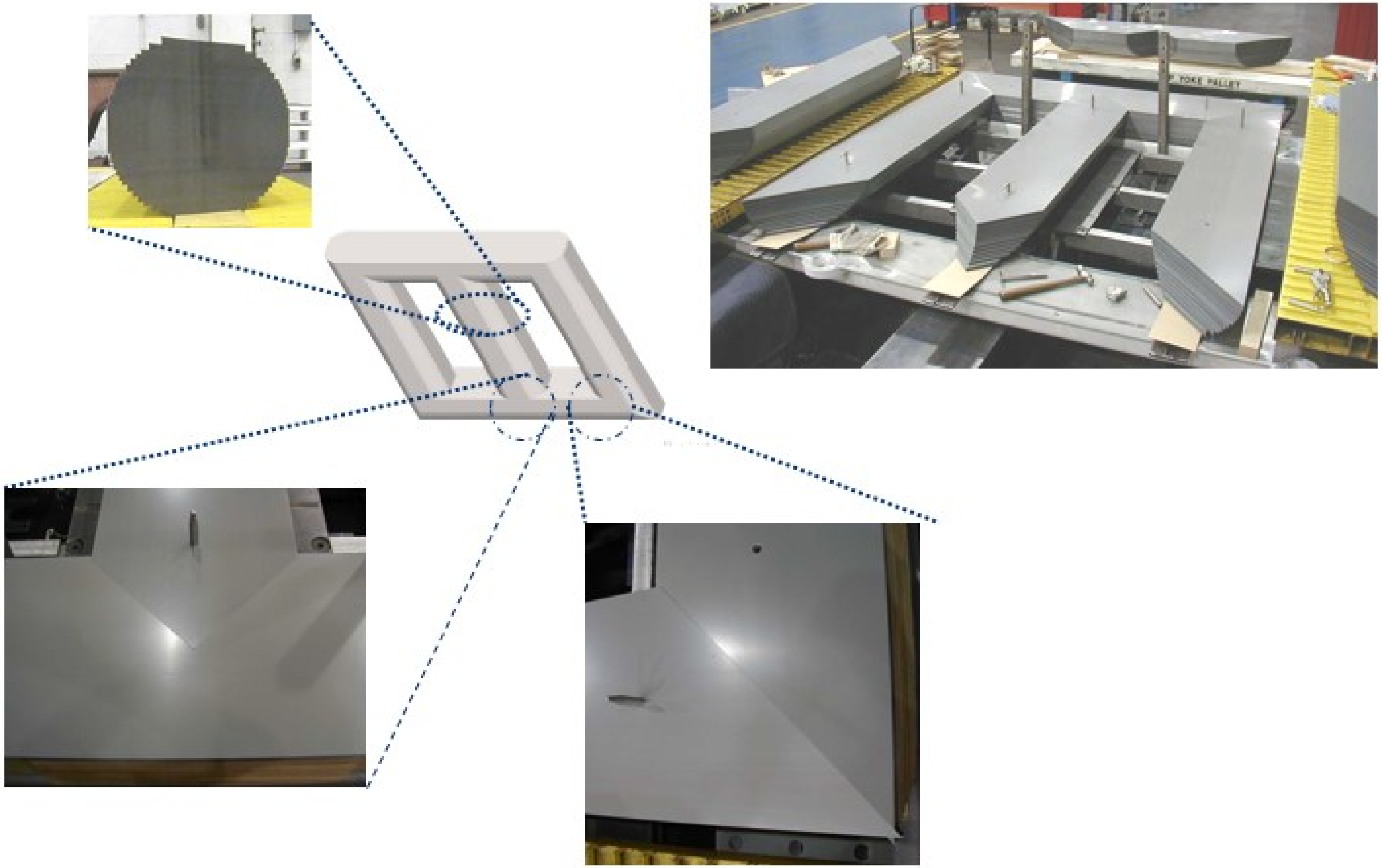
Circular core cross section: D - diameter of core, H - total lamination stack height (1) laminations, (2) oil duct, (3) steel clamp plates.

Optimum Design of Core (cont.)

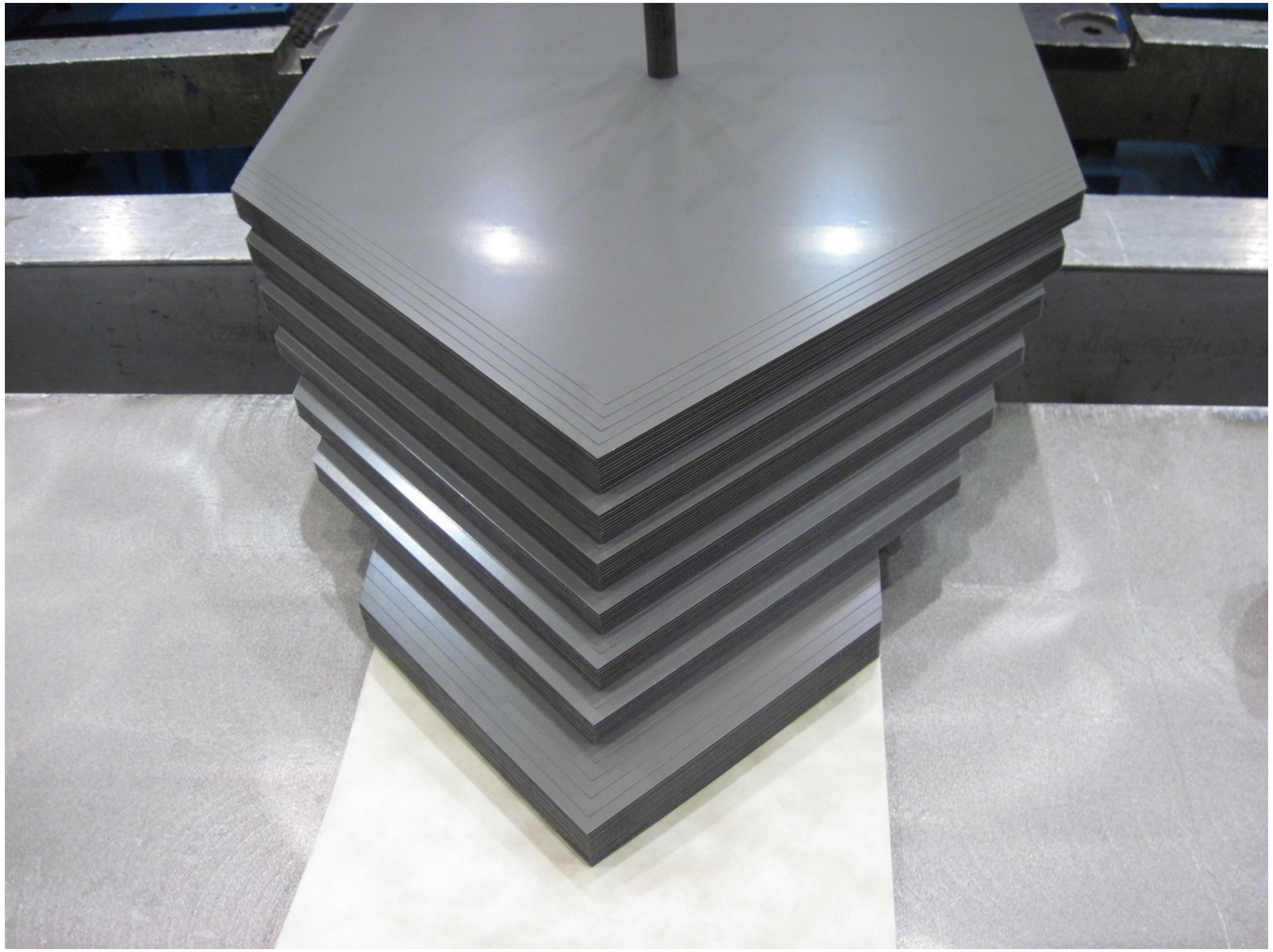
- Utilization factor (UF): Ratio of net cross-sectional area & gross area of core circle
  - ↑ # of core steps → ↑ UF → ↑ manufacturing cost
- Core with 6–15 core steps is cost-effective
- Optimizing core stacking step patterns → maximize core flux carrying area → more economical design



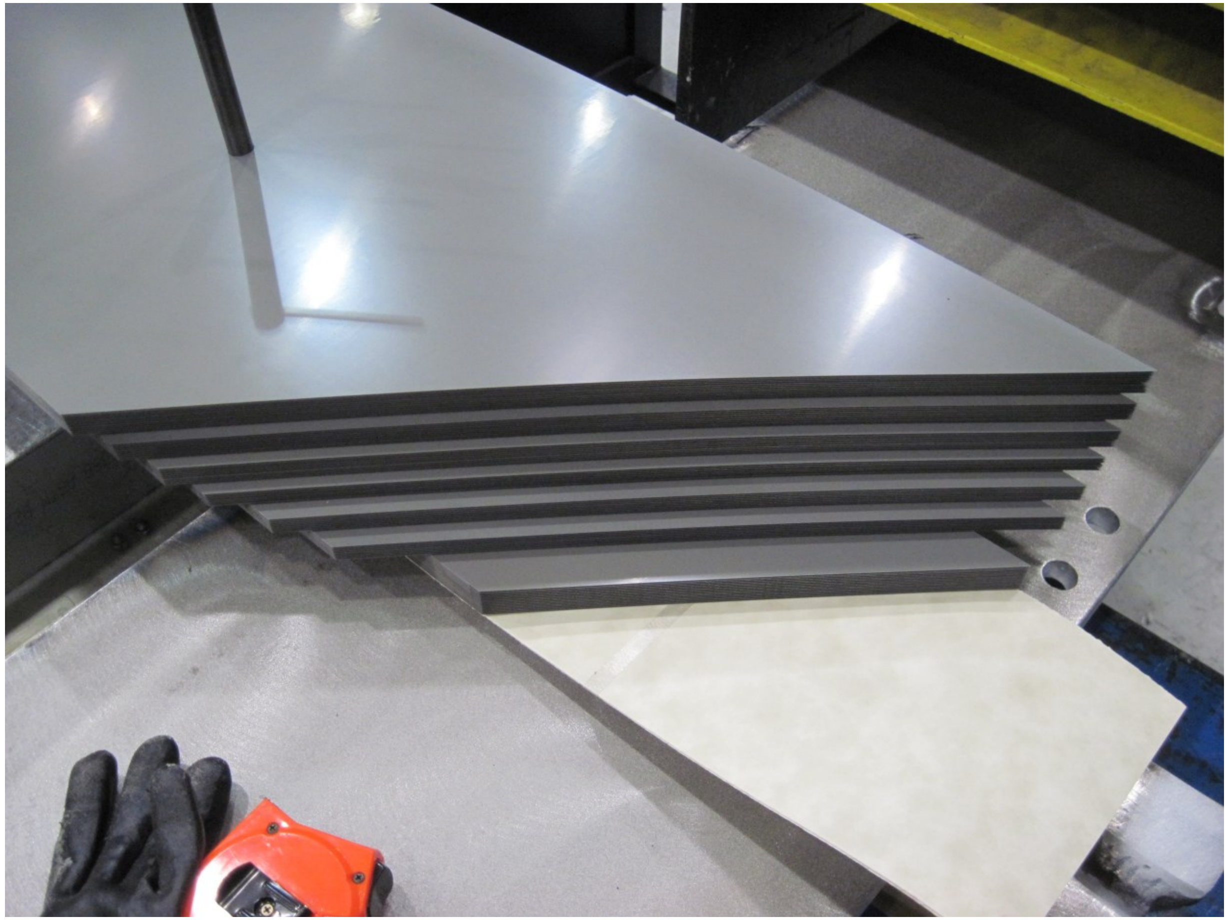
Core Construction



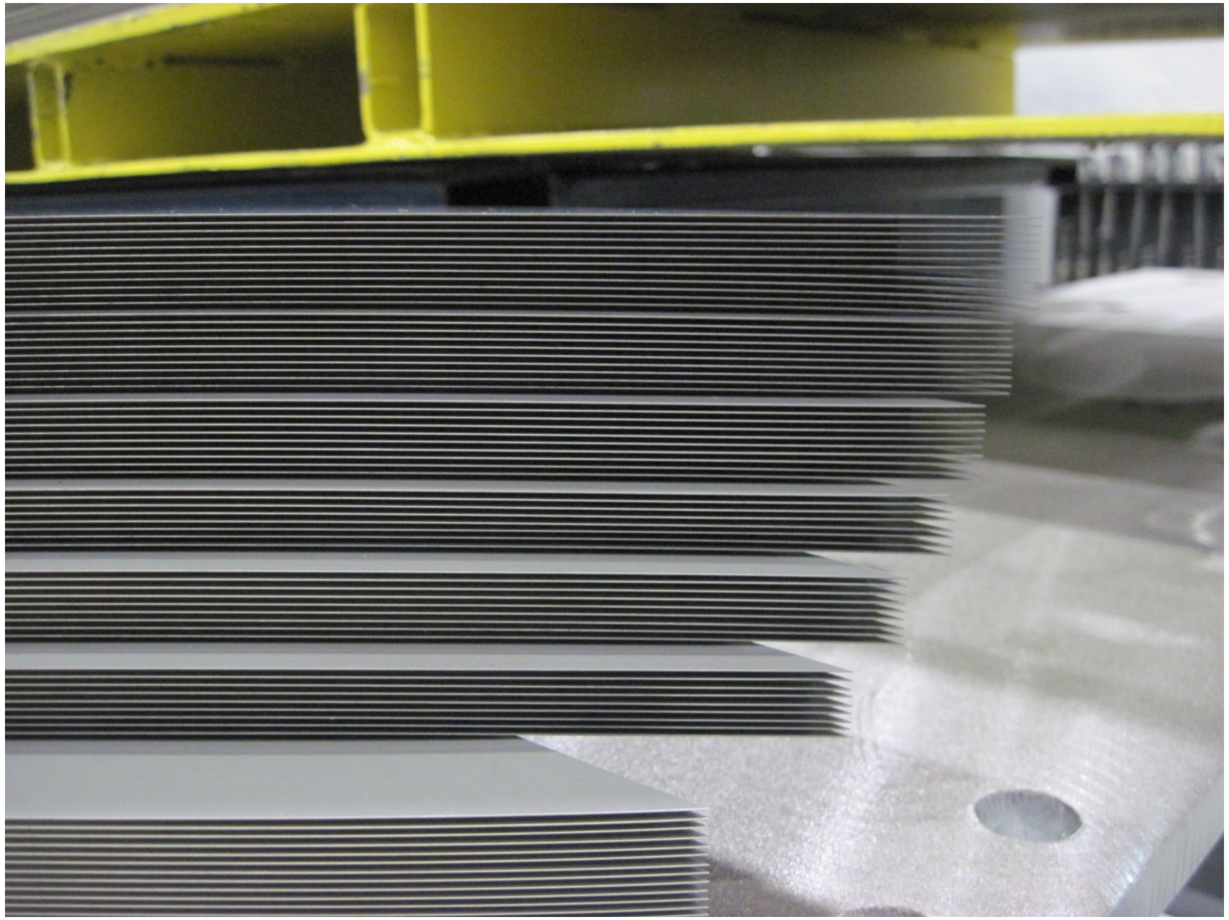
Core Leg



Core Leg (cont.)



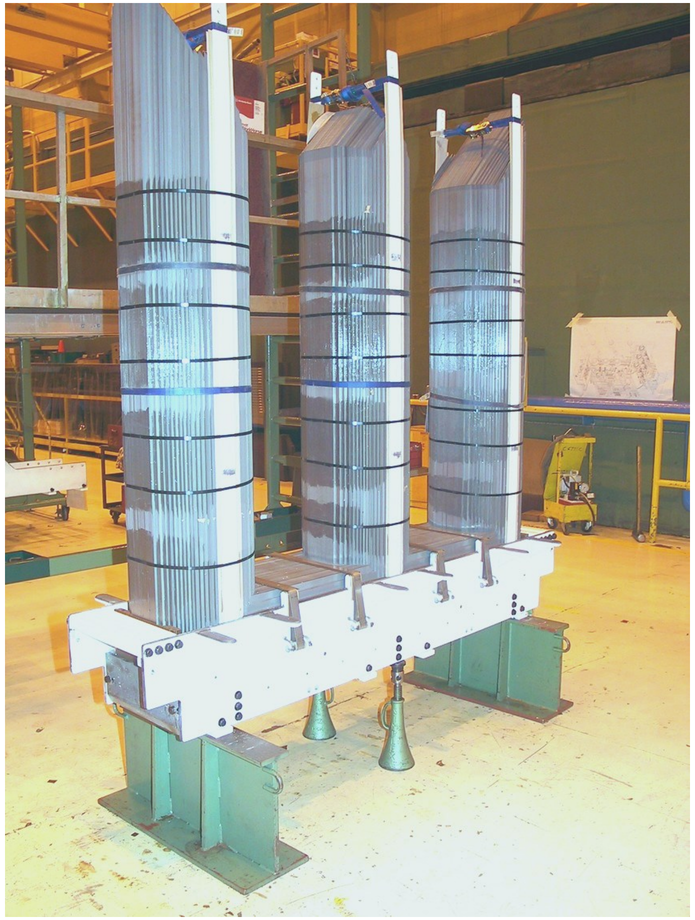
Core Leg (cont.)



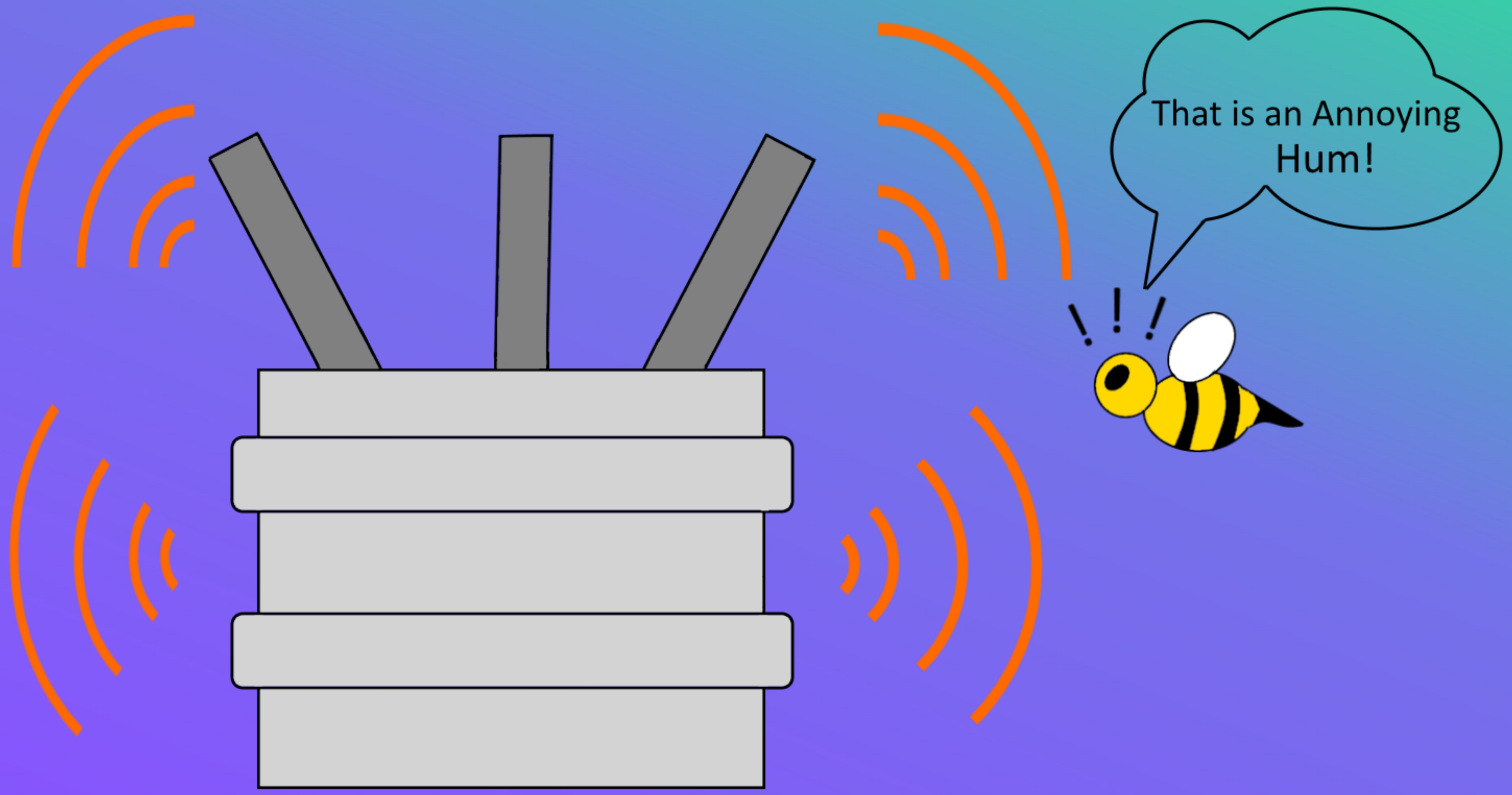
Bottom Yoke

Core Assembly

Core “E” Assembly



Core Related Problems & Solutions



Core Sound

Annoying Magnetostriction

- Contraction of steel when magnetized
- Occurs 120x / sec in 60Hz unit
- Not linear to flux density
  - Harmonics ➡ Amplified noise

Control of Sound

- Use of lower flux density
- Reduced air gaps at joints
- Step lap core construction
- Core banding

Core Hot Spot Temperature

- Use of core ducts
- Lower flux density
- Use of Hi-B laser scribed material
- Reduction in corner losses – step lap core
- Splitting initial few steps of core leg

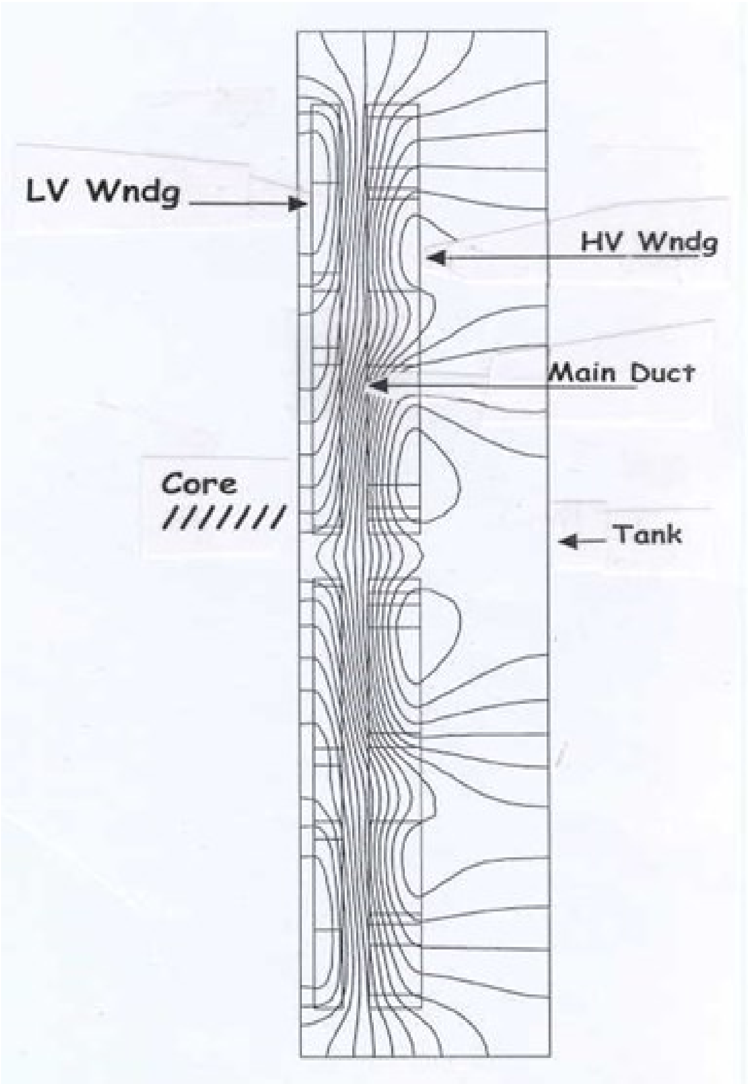
Stray Losses

Stray Flux

- Attract to and concentrate in:
  - Core clamps
  - Verticals (tie plates)
  - Tank Walls
- Excessive temperature rise

Flux Shunts

- Attract and re-direct stray flux
- Provide low reluctance path



Contact

THANK YOU!

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