Electrical Energy
Conversion and
Power Systems

Universidad
de Oviedo

Lesson 9: Magnetic Components Design

- Semester 2 – Industrial Electronics in renewable energy generation systems

Lecturer: Jorge García

Contents

Seminar:

Design of Inductors

Introduction

¿Why do we need reactive elements in power electronics?

They store temporarily energy. The are used as energy buffers in a power converter, between the load and the source.P Ideally, the power management of such reactive element is free of losses.

¿Which is the alternative technology?

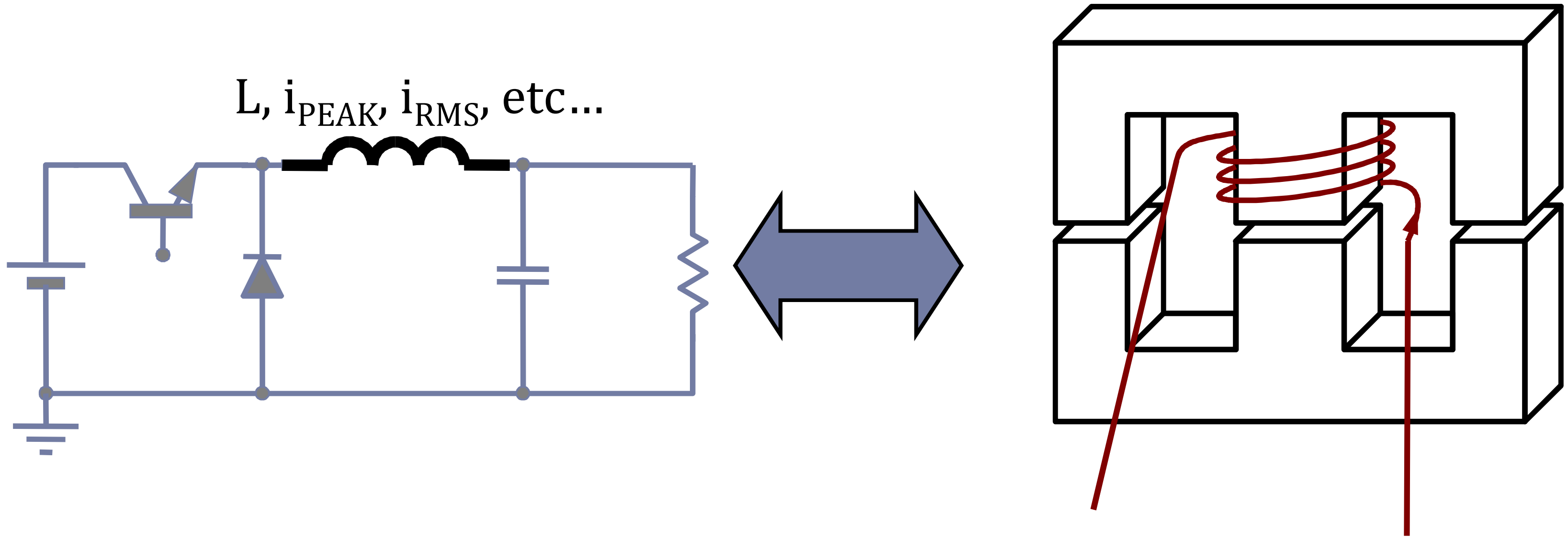
Linear regulators (resistor, zener diodes, transistors in linear operation points). They all imply LOSSES, even considering ideal components.

¿What kind of reactive elements exist?

There are magnetic and capacitive reactive elements. Magnetic elements can be inductors, transformers or coupled inductors.

Introduction

The target of the design is to construct an inductor for a **given circuit**, but minimizing the size and the power losses (optimal design)



These devices are usually custom-made for the application

Number of turns,
∅ wire diameter,
Number of wires per turn,

Core material
Core size
Air gap

Introduction

How to study a magnetic component

Current in a magnetic component → Magnetic field in a given geometry and a given material → Voltage in a magnetic component

$$u_L(t) = L \cdot \frac{di_L(t)}{dt}$$

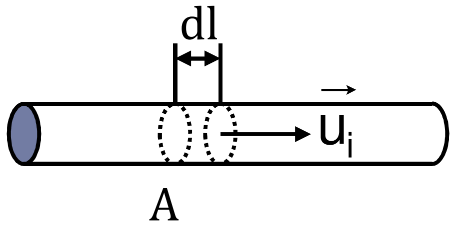
What is the physical background needed to understand this equation?

Physical background

The magnetic field: Biot-Savart Law

Electric current (intensity) is the variation of charge, Q, with time.

$$i = \frac{dQ}{dt}$$



There is magnetism if a charge Q is traveling at a given velocity, u_i (that is to say, if there is current flowing)

$$Q \cdot \vec{v} = \ldots = i \cdot dl \cdot \vec{u_i}$$

Physical background

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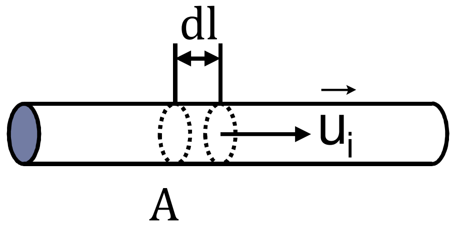

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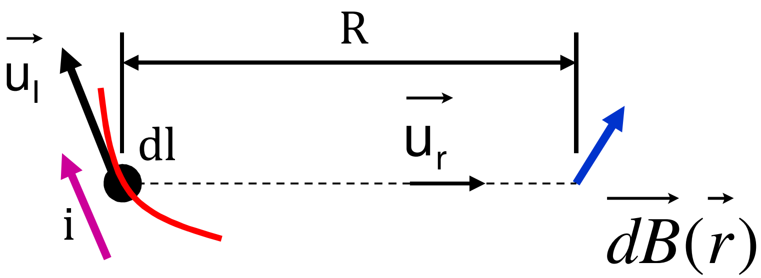
Biot-Savart law states the magnetic density, **B**, generated when a **time-constant** current, **i**, is flowing in a wire differential element (**dl**).



But, what is magnetic density?

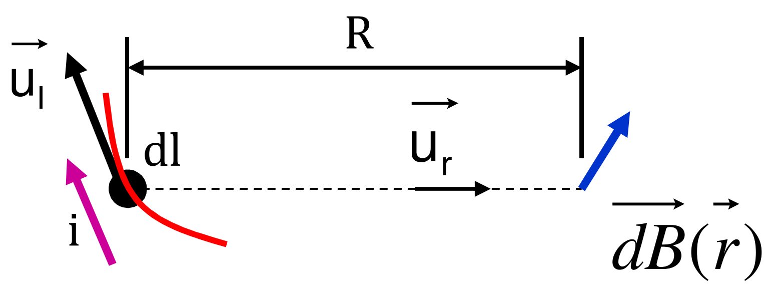
$$d\vec{B}(\vec{r}) = \frac{\mu}{4 \cdot \pi} \cdot \frac{i}{R^2} \cdot dl \cdot \vec{u_l} \wedge \vec{u_r}$$

Physical background

Biot-Savart law and Magnetic Density (B)

Magnetic Density, **B**, is a space-field that makes a force to appear in a field-sensitive element. In this case, the field-sensitive element is a "magnetic dipole" (a charge with a certain velociy, an elemental current).

Thus, the magnetic density can be defined as the magnitude of that magnetic **force** per unit of field-sensitive element (current).



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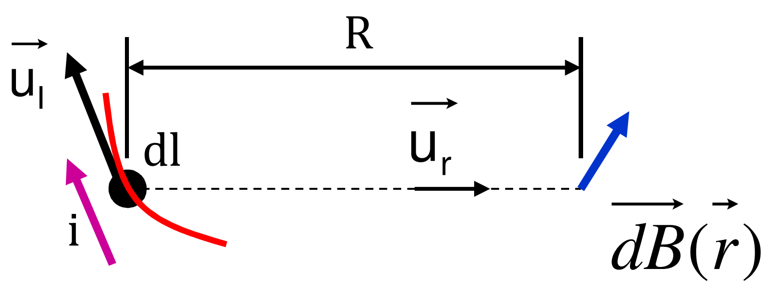
The amplitude of the magnetic density generated by a current depends on the current level itself, but also on the distance to the wire, and on the **magnetic characteristics of the material**. This characteristic is given by the magnetic permeability, **μ**.



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Physical background

Biot-Savart law, Magnetic Density (B) and Magnetic Field (H)

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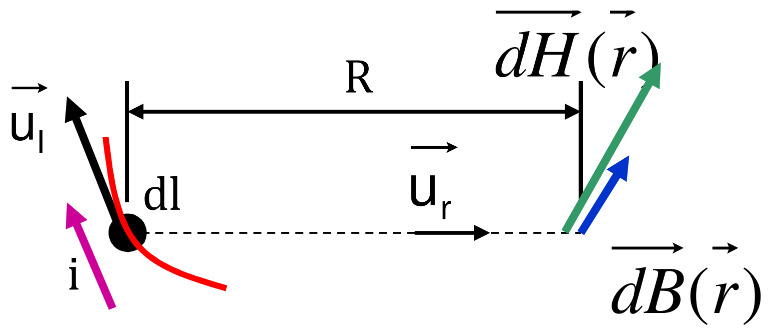
The amplitude of the magnetic density generated by a current depends on the current level itself, but also on the distance to the wire, and on the **magnetic characteristics of the material**. This characteristic is given by the magnetic permeability, **μ**.

The magnitude can be made independent of the material characteristics by defining the **magnetic field**, **H** (instead of magnetic density, B)



$$d\vec{B}(\vec{r}) = \frac{\mu}{4\cdot\pi}\cdot\frac{i}{R^2}\cdot dl\cdot\vec{u_l}\wedge\vec{u_r}$$

$$d\vec{H}(\vec{r}) = \frac{1}{4\cdot\pi}\cdot\frac{i}{R^2}\cdot dl\cdot\vec{u_l}\wedge\vec{u_r}$$

$$\vec{H} = \frac{\vec{B}}{\mu}$$

Physical background

Biot-Savart law and Magnetic Density (B)

The magnetic force (related to the magnetic density, B) must take into account the material magnetic behaviour.

Material Types (Magnetic Behaviour)

Non-magnetic Elements	$\mu = \mu_0 = 4 \cdot \pi \cdot 10^{-7} \, H/m ; \mu_r = 1$	Vacum	
Diamagnetic Materials	$\mu_r < 1$	Cu, Hg, Na, …	
Paramagnetic Materials	$\mu_r \approx 1; \mu_r > 1;$	O, Al, Pt, Mg, …	$\mu_r = \dfrac{\mu}{\mu_0}$
Ferromagnetic Materials	$\mu_r >> 1$	Fe, Co, Ni, …	

Soft Ferromagnetic Materials: μ_r is practically constant for different current levels. Only magnetized if current flows (non-permanent magnets: **ferrites**)

Hard Ferromagnetic Elements: μ_r is complicated. There is field without current (permanent magnets)

Physical background

Relationship between B and H.

Thus, **H is a space magnetic field**, independent of the material, that appears whenever there is a curret flowing nearby.

The **magnetic density, B**, appears when there is a magnetic field in a material , given by its **permeability μ**, and takes into account the force that the sensitive element to this field (another current) will experiment.

Physical background

Relationship between B and H. Energy

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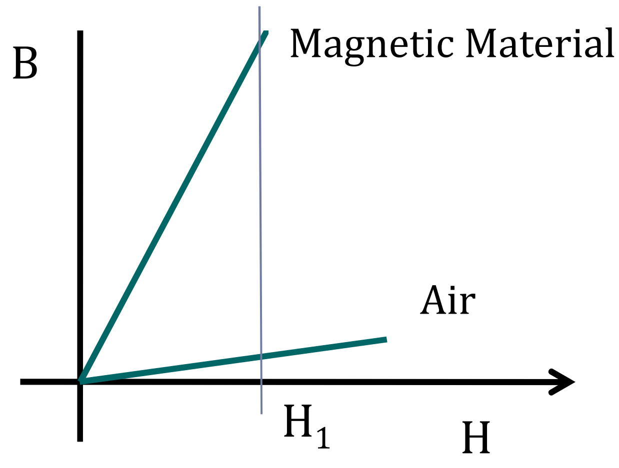
The **Energy** per volume (J/m³), **w**, can be given in terms of B and H, for a particular space location:

$$w = \int H \cdot dB$$

Isotropic material, magnetic permeability **μ** constant.

$$w = H \cdot B = \mu \cdot H^2 = \frac{B^2}{\mu}$$



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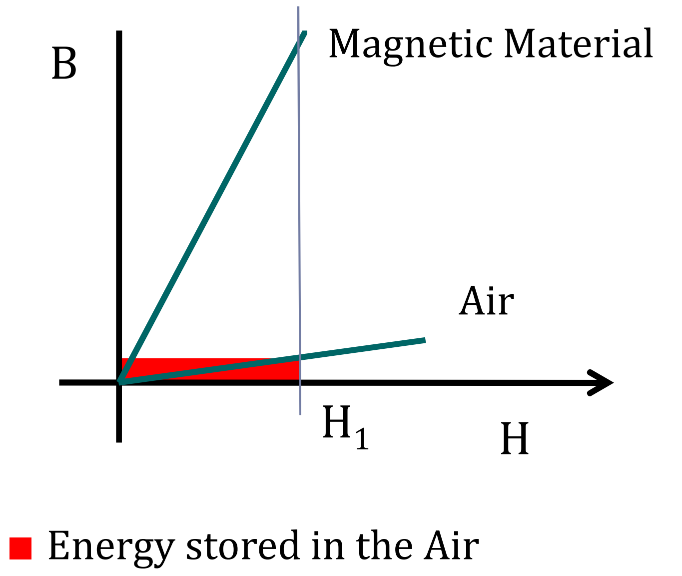

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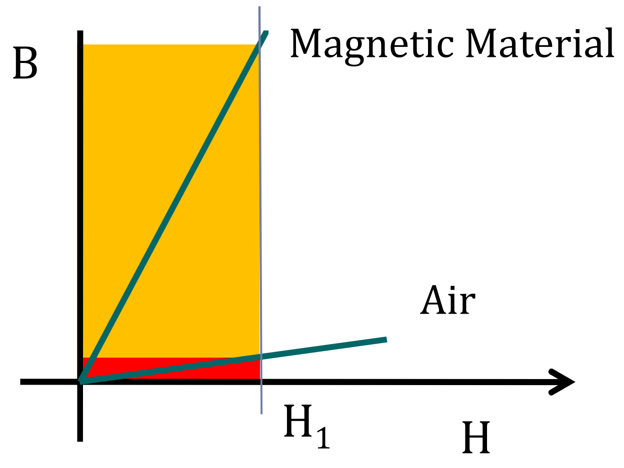


- Energy stored in the Air
- Energy stored in Magnetic Material

Physical background

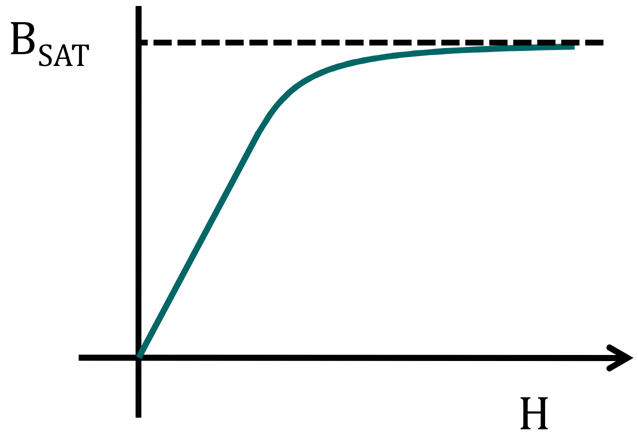
Relationship between B and H. Saturation

Thus, **H is a space magnetic field**, independent of the material, that appears whenever there is a curret flowing nearby.

The **magnetic density, B**, appears when there is a magnetic field in a material , given by its **permeability** μ, and takes into account the force that the sensitive element to this field (another current) will experiment.

Magnetic materials have an intrinsic limitation of the magnetic density, B, that they can withstand. For higher B values, they get **saturated**.

Then, at that point, increasing current means increasing the magnetic field, H, **BUT IT DOES NOT IMPLY INCREASING THE MAGNETIC DENSITY, B.**



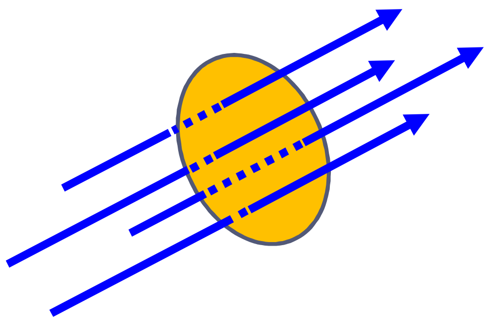
SATURATION: The maximum magnetic density value, B_{MAX} , is limited for a given material (see material datasheets)

Physical background

Magnetic Density (B) and Magnetic Flux, (Φ)

Magnetic Flux, Φ, can be defined as the amount of magnetic density (**B**) that crosses a given area, A, multiplied by that area. The higher the flux, the more dense the magnetic density, B, is.

$$\Phi = \iint_A \vec{B} \cdot \vec{dA} \qquad \Phi = B \cdot A$$



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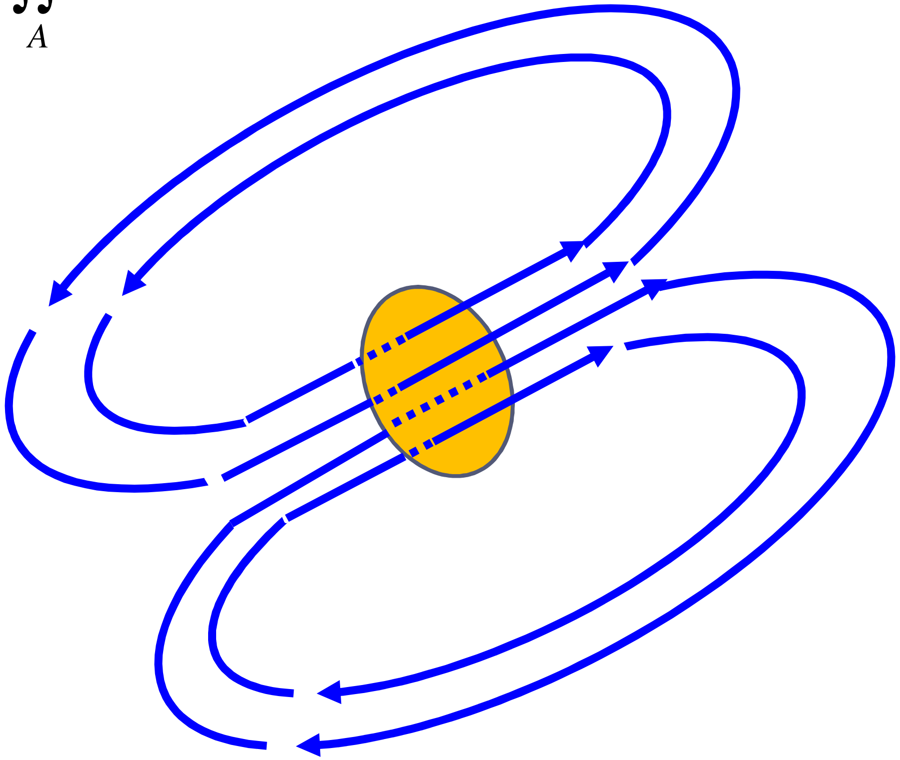


In any case, these magnetic density (B) lines, are closed lines

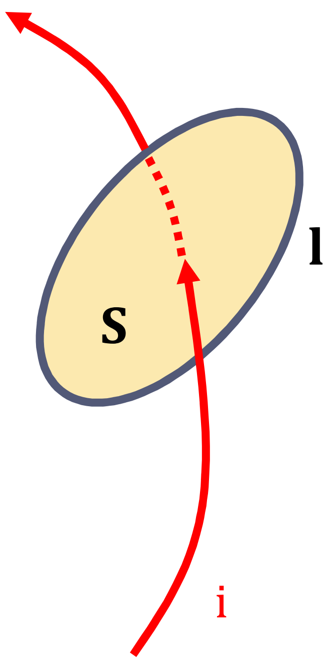
$$div \vec{B} = 0$$

Physical background

Ampère's Law and Magnetic Field (H)

Ampère's Law states that for a given closed path, **l**, the integral of the magnetic field across the path equals the overall current that crosses the surface **S** created by the path.

The overall current s called Magnetomotrice Force (mmf)



$$\oint_{\ell} \overrightarrow{H} \cdot \overrightarrow{dl} = i$$

Physical background

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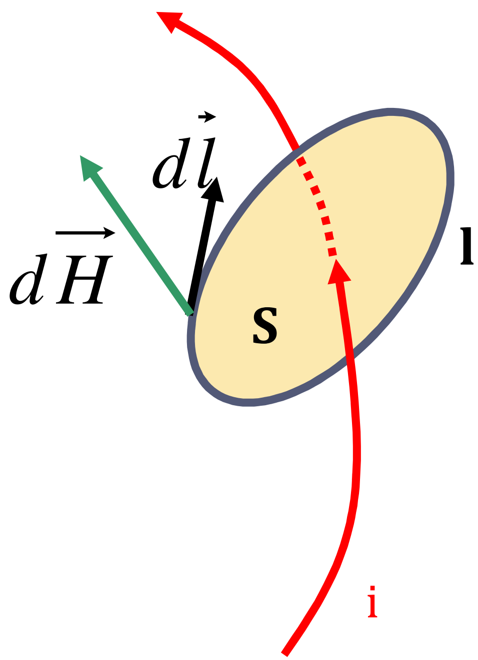

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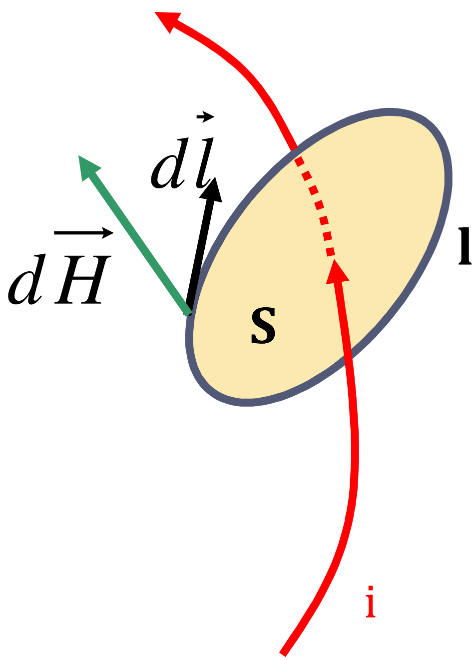
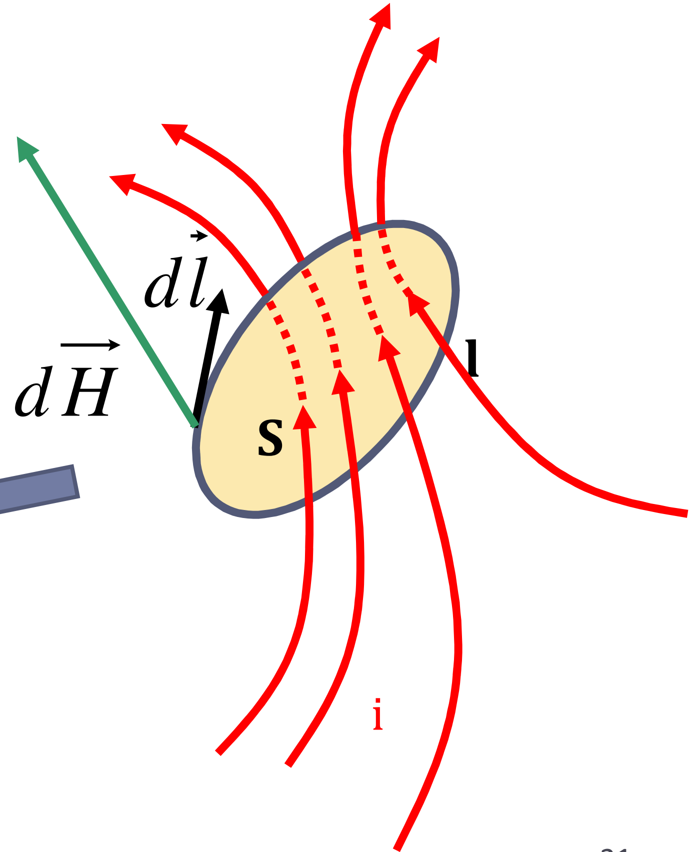


$$\oint_{\ell} \vec{H} \cdot \vec{dl} = i$$

$$\oint_{\ell} \vec{H} \cdot \vec{dl} = N \cdot i$$



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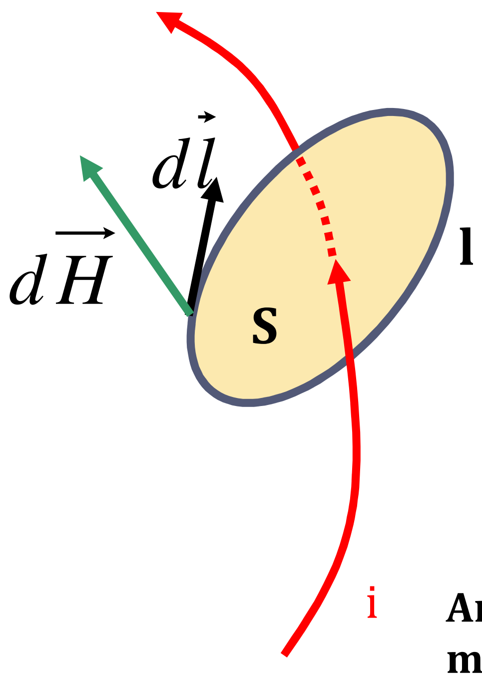

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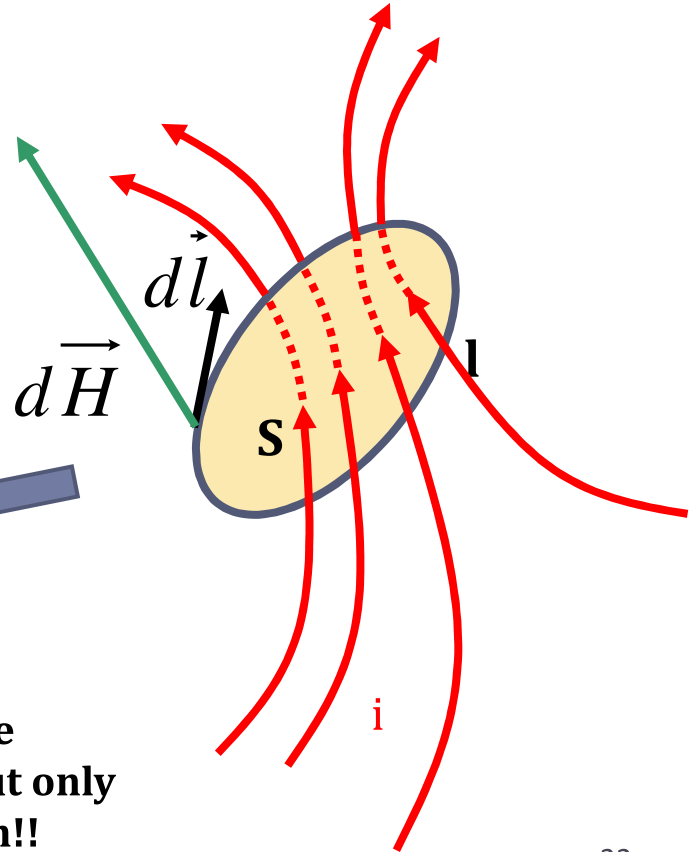
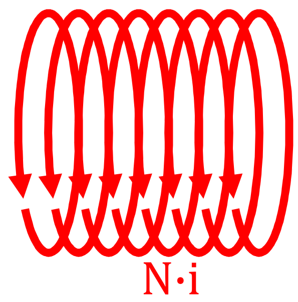


Ampére's Law does not define the magnetic field in all the space, but only its integral across the closed path!!

Physical background

Ampère’s Law and Magnetic Field (H)

Magnetic elements usually operate with turns of wire, that allow to enclose the magnetic field. Consider a fixed number of turns, **N**, and a current, **i**, that flows through all the turns



Physical background

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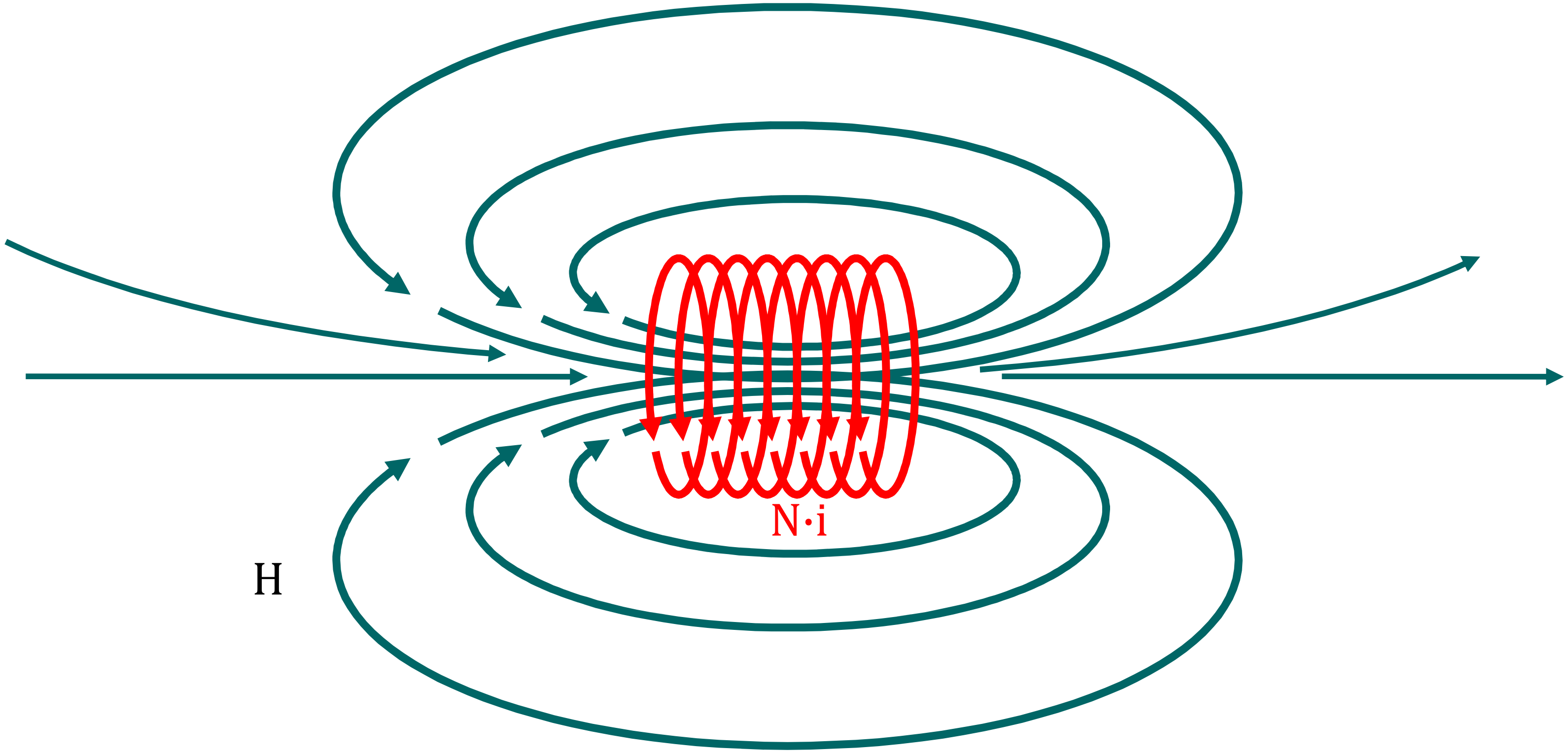
In such a configuration, a magnetic field is generated, that gets expanded outside the turns geometry. The magnetic field lines (and magnetic density lines) are **closed lines**.



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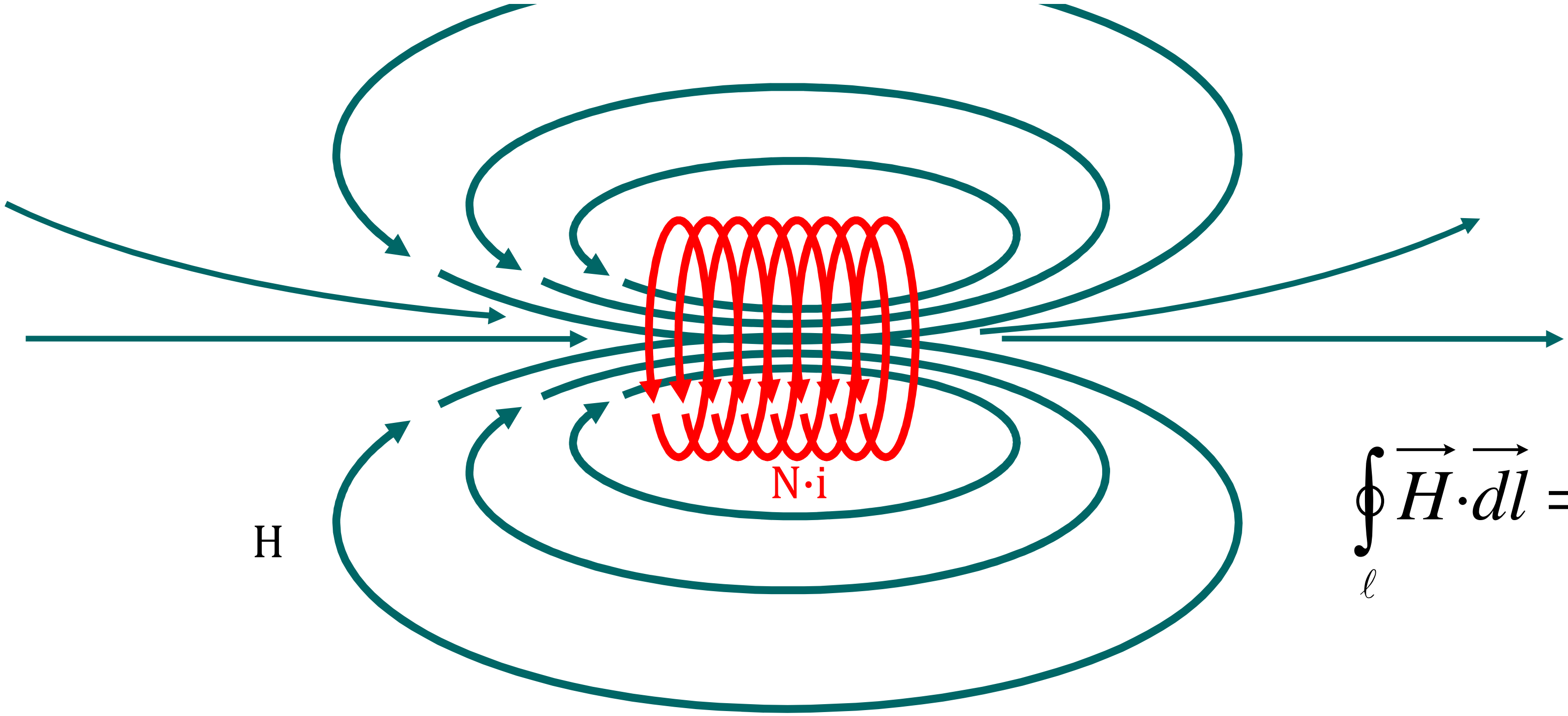
Ampère’s Law can be then applied. However, the integral can be hard to calculate.

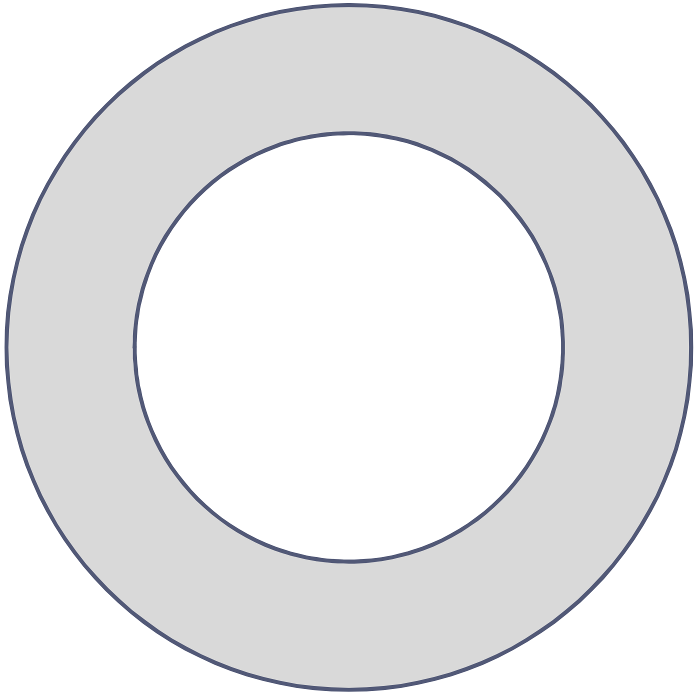


$$\oint_{\ell} \vec{H} \cdot \vec{dl} = N \cdot i$$

Physical background

Ampère's Law and Magnetic Field (H)

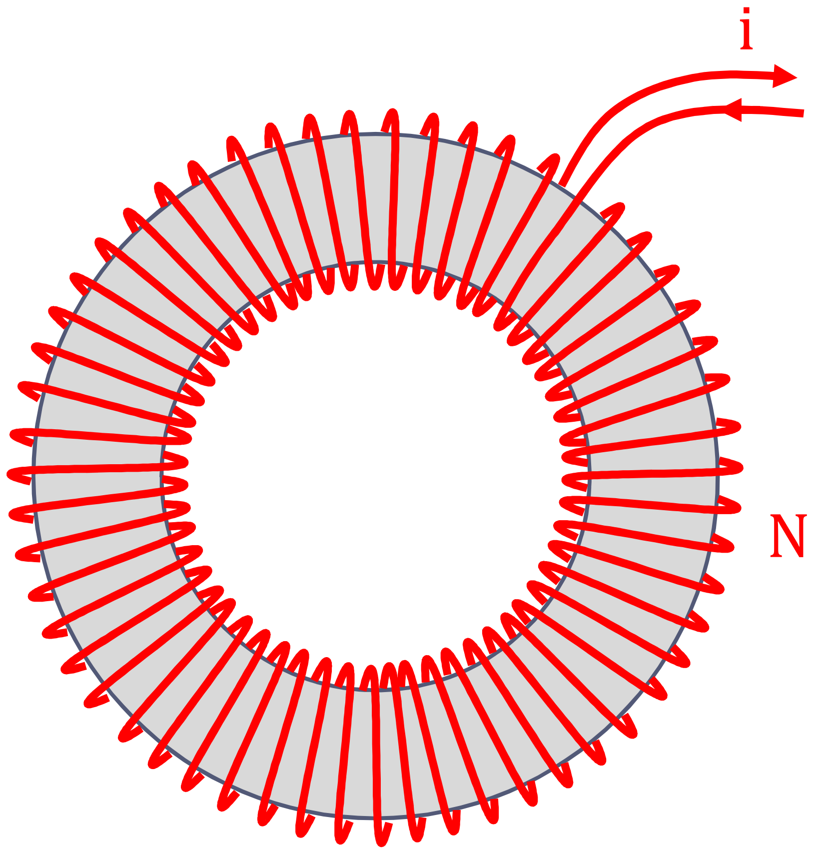
Let us consider an easy geometry, called magnetic toroid.



Physical background

Ampère’s Law and Magnetic Field (H)

Let us consider an easy geometry, called magnetic toroid. Consider N wire turns winded around such magnetic material, with a magnetic permeability much higher than the surrounding material ($\mu >>> \mu_0$)



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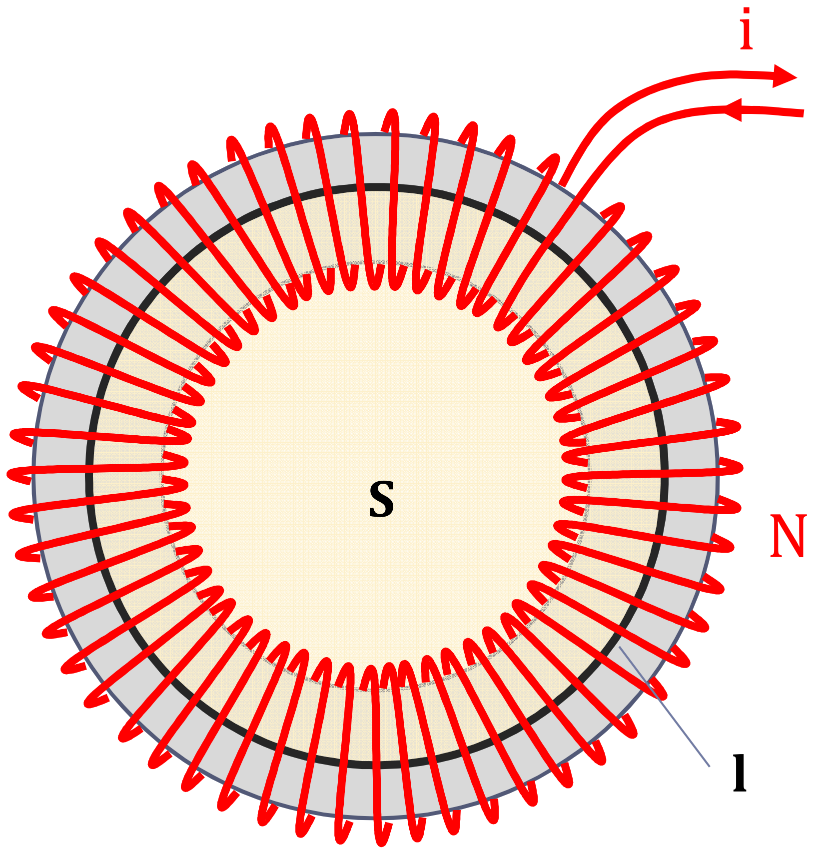

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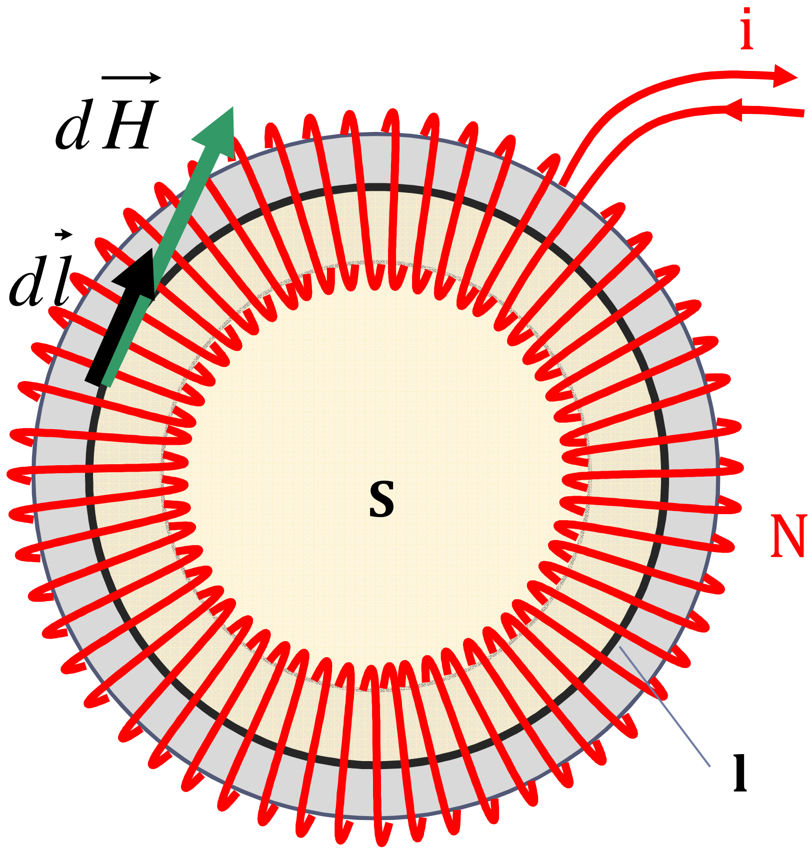

In this geometry, the magnetic field will be constant inside the toroid

$$H = \frac{N \cdot i}{\ell}$$

Physical background

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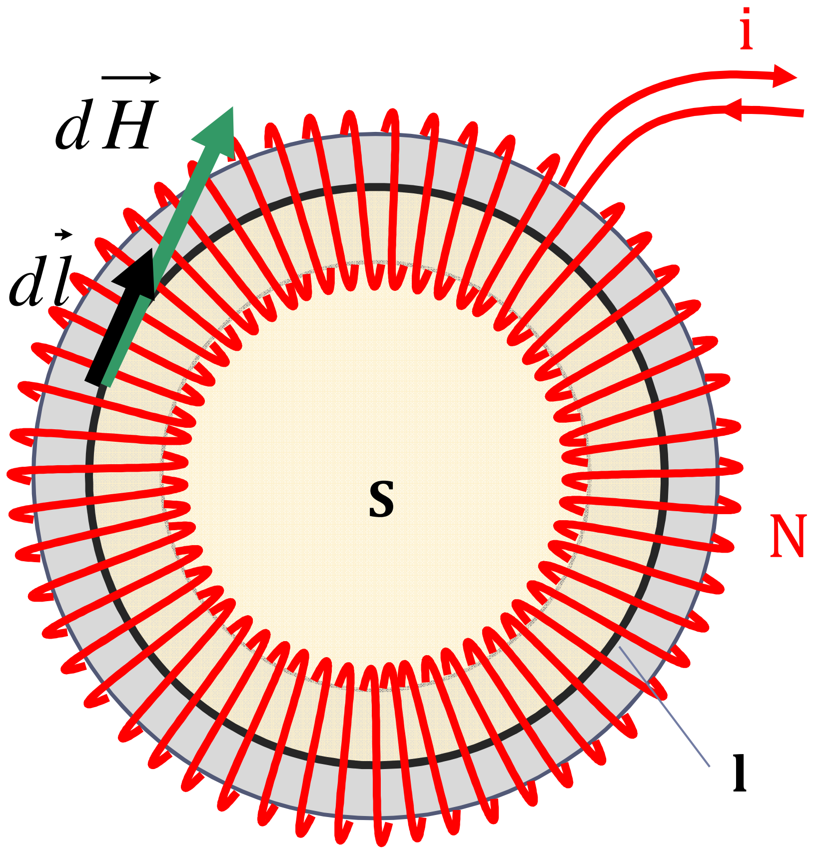

In this geometry, the magnetic field will be constant inside the toroid

$$H = \frac{N \cdot i}{\ell}$$

The magnetic density will be:

$$B = \mu H = \mu \frac{N \cdot i}{\ell}$$

Physical background

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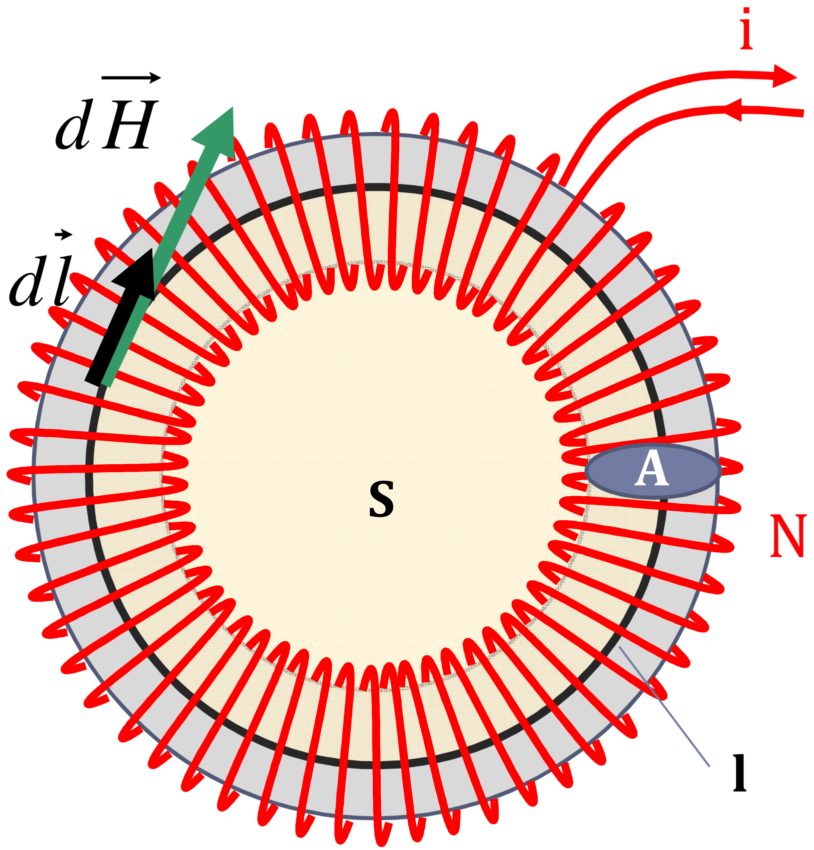


In this geometry, the magnetic field will be constant inside the toroid

$$H = \frac{N \cdot i}{\ell}$$

The magnetic density will be:

$$B = \mu H = \mu \frac{N \cdot i}{\ell}$$

And the magnetic flux will be:

$$\Phi = B \cdot A = \mu \frac{N \cdot i \cdot A}{\ell}$$

Physical background

Magnetic circuit

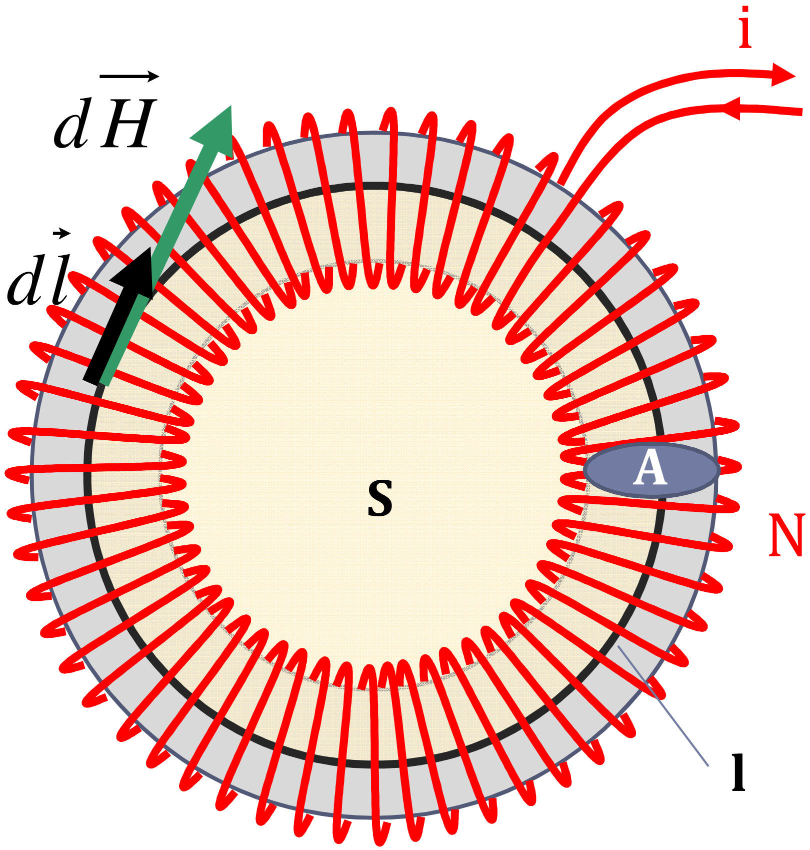
A magnetic circuit can be defined, considering the mmf, the flux, and the **RELUCTANCE**

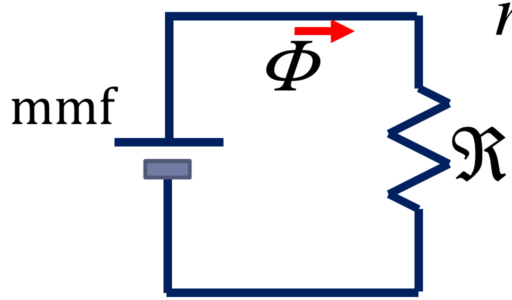
$$\Phi = \mu \frac{N \cdot i \cdot A}{\ell}$$

$$mmf = N \cdot i$$

$$\Re = \frac{\ell}{A \cdot \mu}$$

$$mmf = \Re \cdot \Phi$$





$$\Re = \frac{\ell}{A \cdot \mu}$$

Physical background

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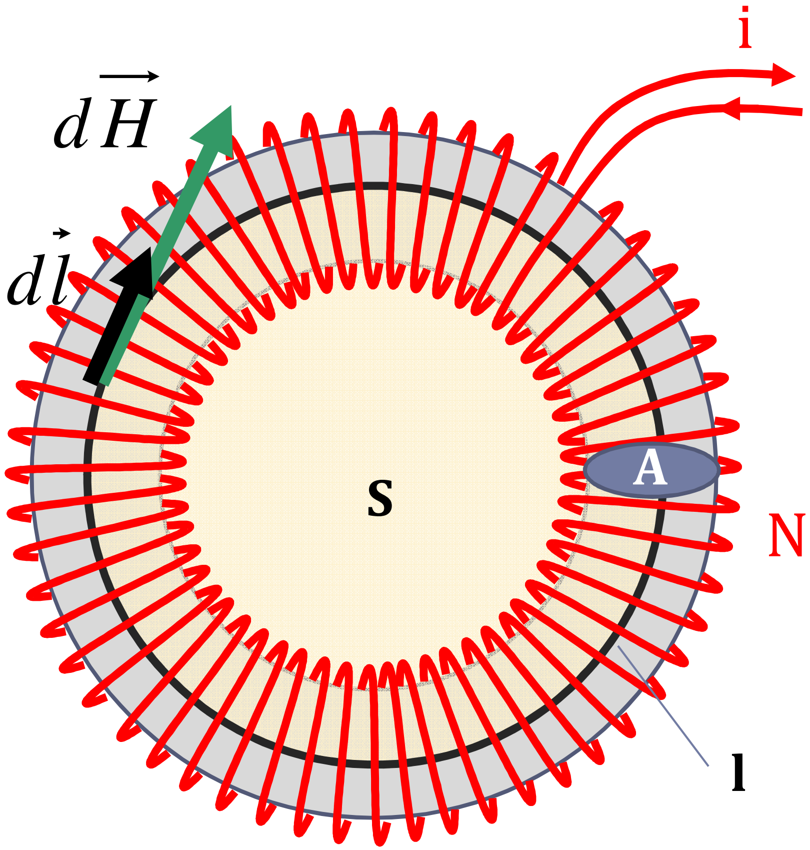
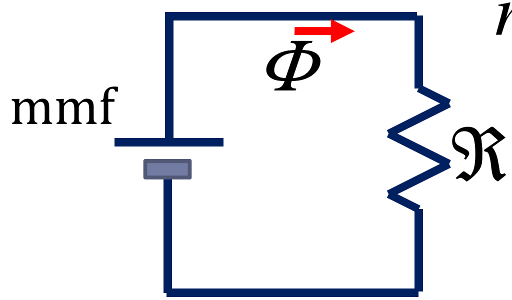
$$mmf = N \cdot i$$

$$\Re = \frac{\ell}{A \cdot \mu}$$

$$mmf = \Re \cdot \Phi$$





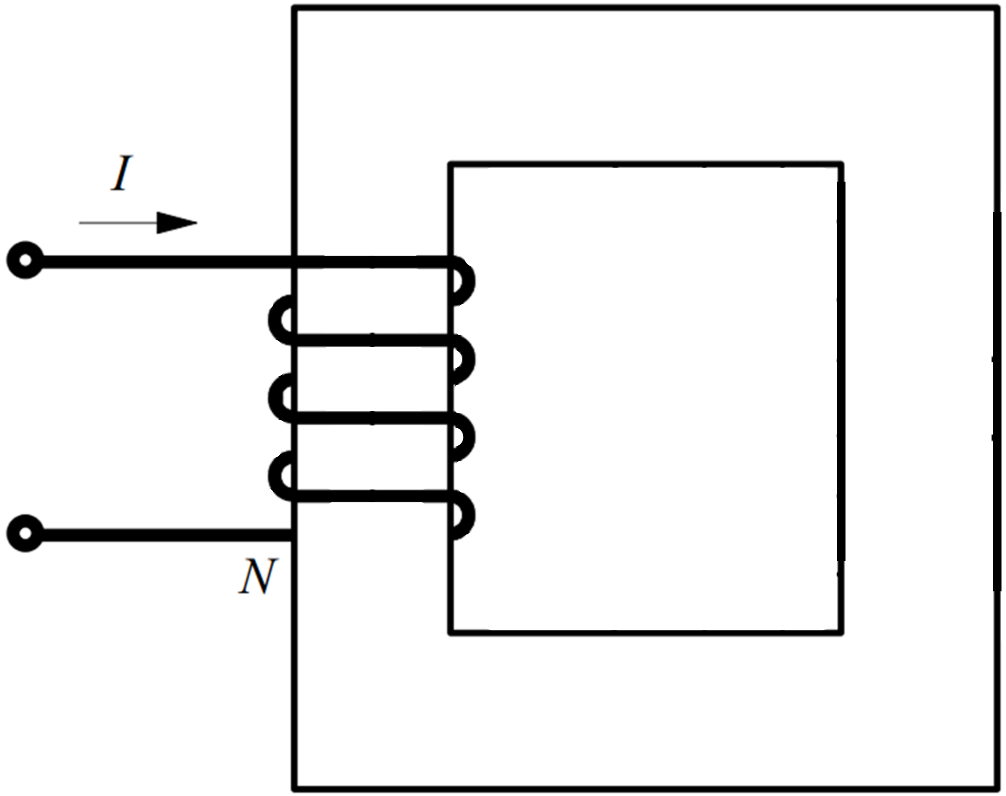
$$\Re = \frac{\ell}{A \cdot \mu}$$

The higher the **Reluctance** of a magnetic path, the smaller the magnetic flux generated by a **mmf.**

Physical background

Flux distribution in a real magnetic circuit

In a real magnetic circuit, the reluctance of the magentic core is smaller than the reluctance of the air.

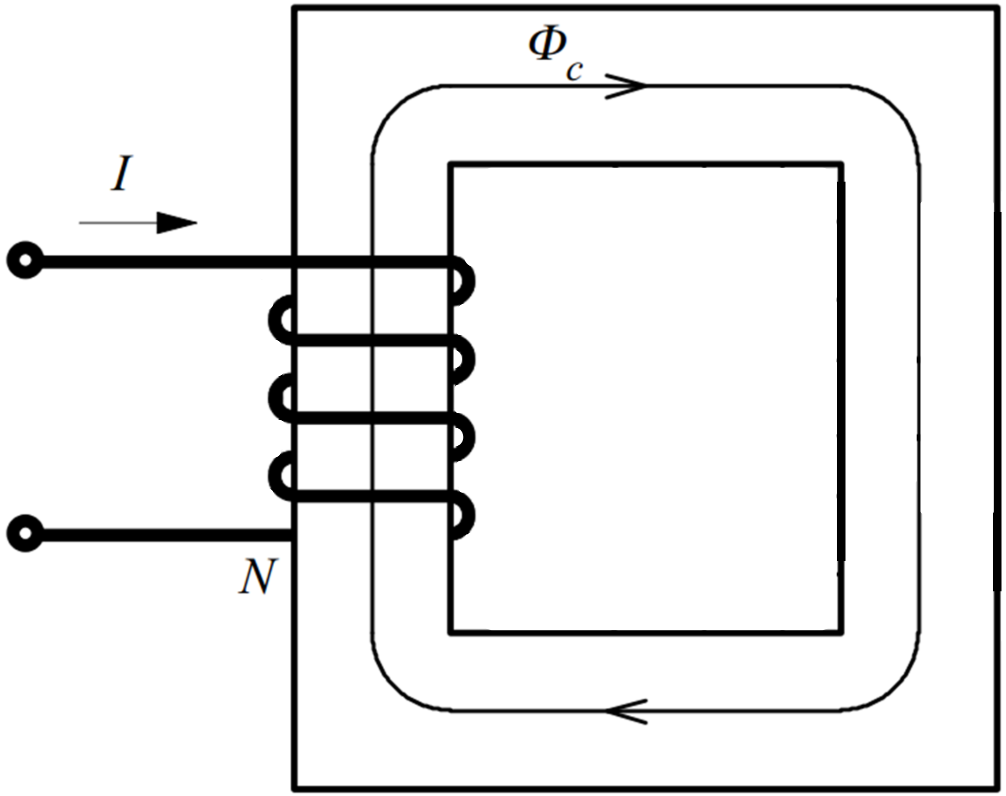


Physical background

Flux distribution in a real magnetic circuit

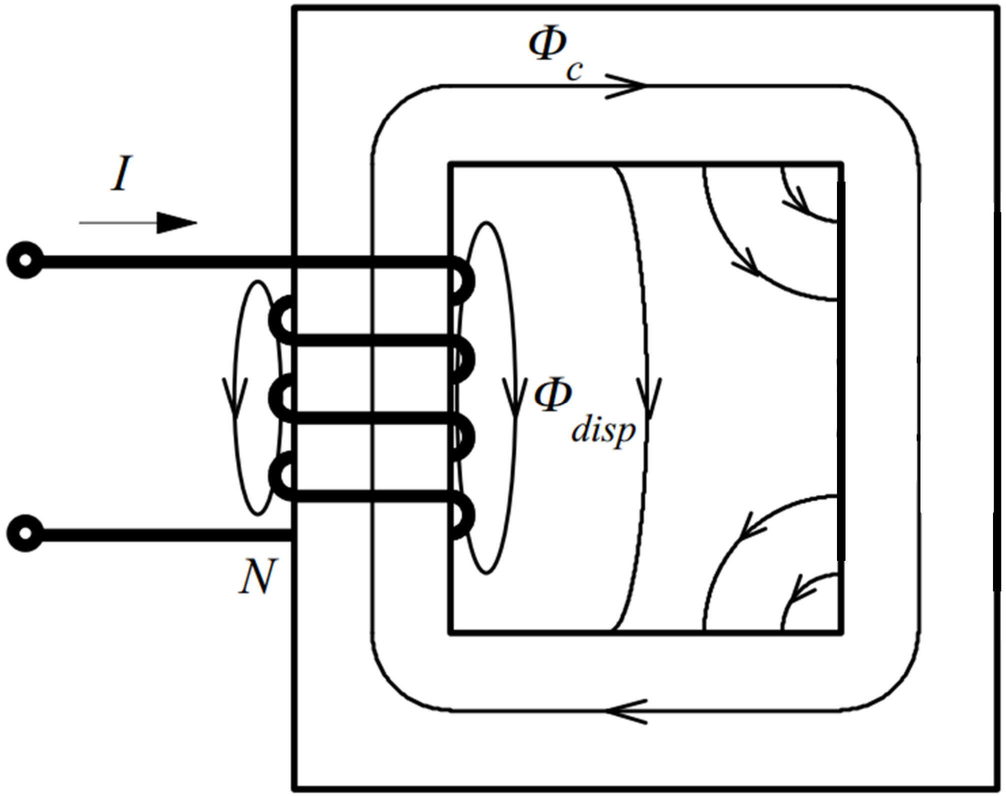
In a real magnetic circuit, the reluctance of the magentic core is smaller than the reluctance of the air.

Thus the magnetic flux is confined in the core.



Physical background

Flux distribution in a real magnetic circuit



In a real magnetic circuit, the reluctance of the magentic core is smaller than the reluctance of the air.

Thus the magnetic flux is confined in the core.

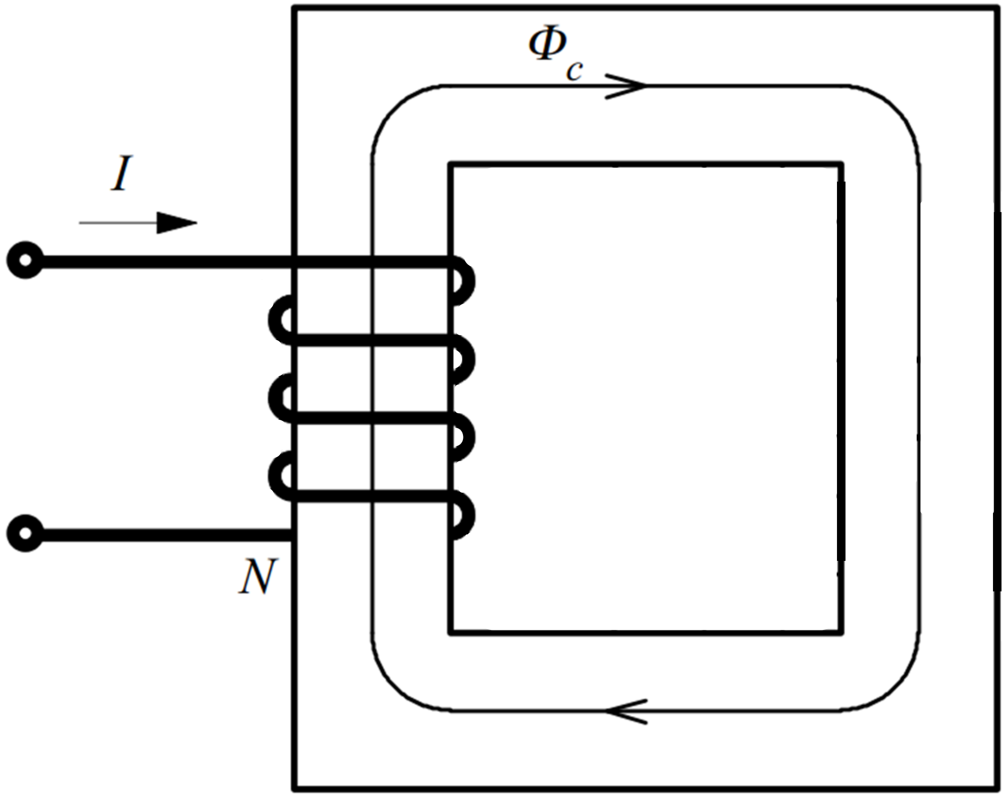
However, some flux is found outside the core. It is called **dispersion flux.**

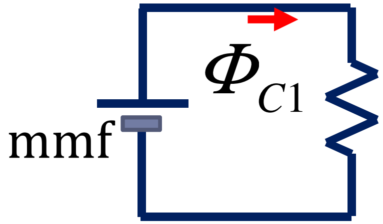
This dispersion flux will be very important when **considering losses** in an inductor.

Physical background

Air Gap and magnetic saturation

Consider a magnetic circuit with a given mmf, an consider that the obtained H implies **SATURATION**.





$$\Re_C = \frac{\ell}{A \cdot \mu}$$

Looking at the equivalent circuit, it is needed a final reluctance that provides a smaller flux (and hence **B**) than in the original.

Physical background

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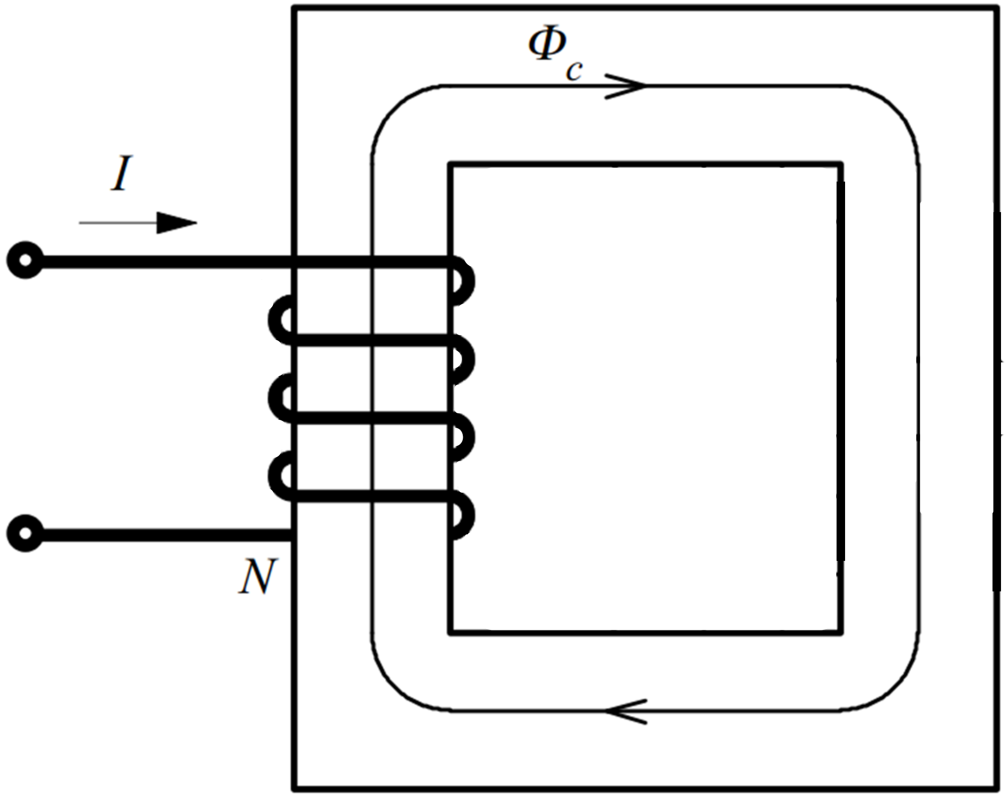

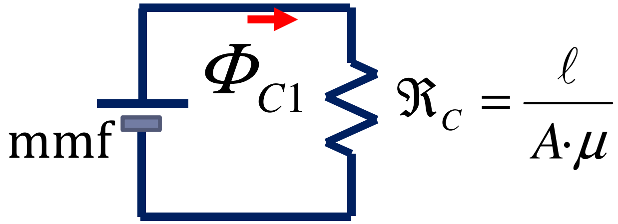

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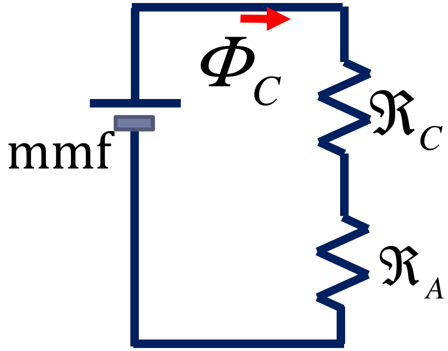

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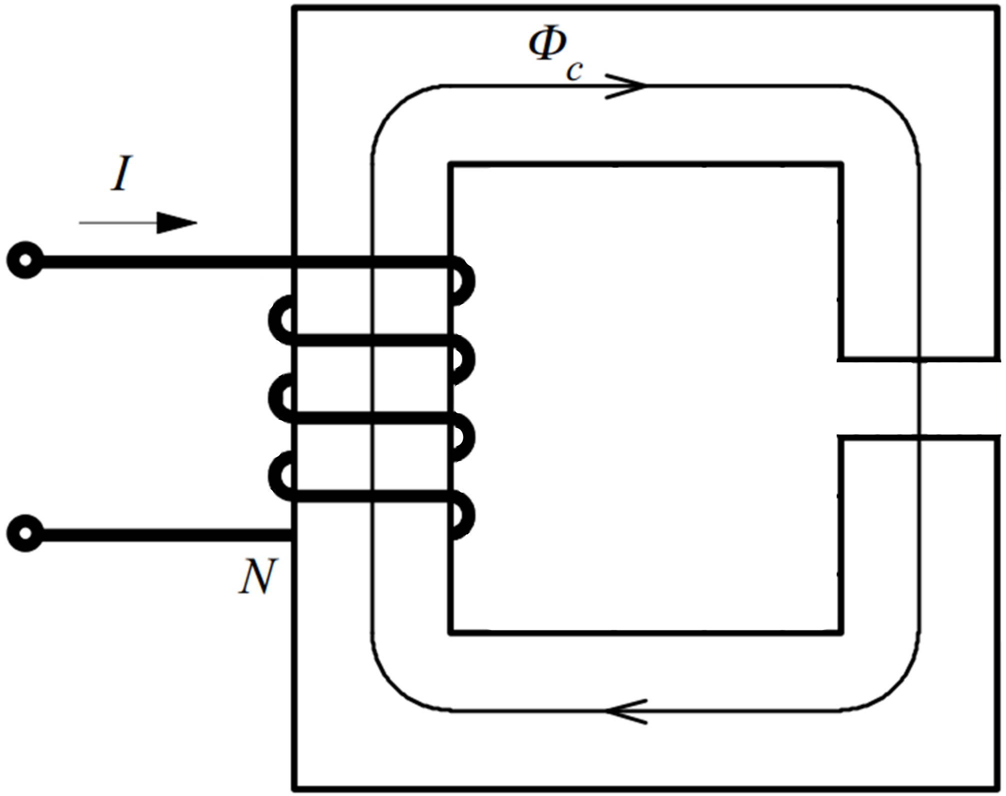

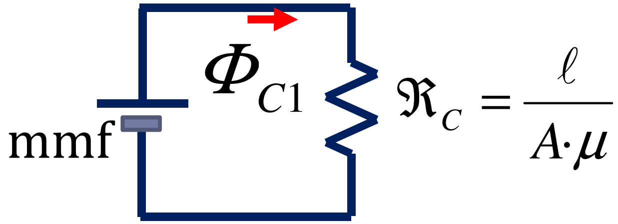

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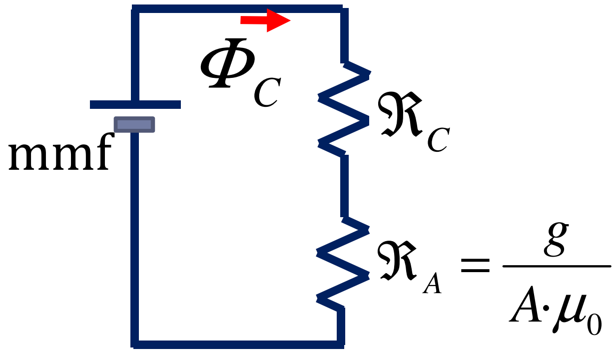

The **AIR GAP** ensures a much smaller flux (and hence B)

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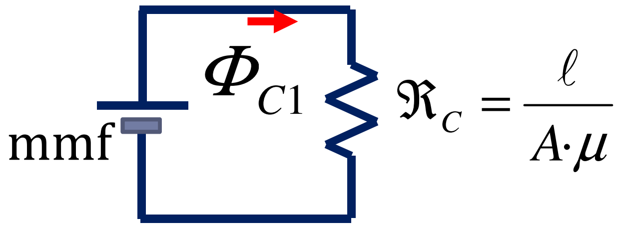

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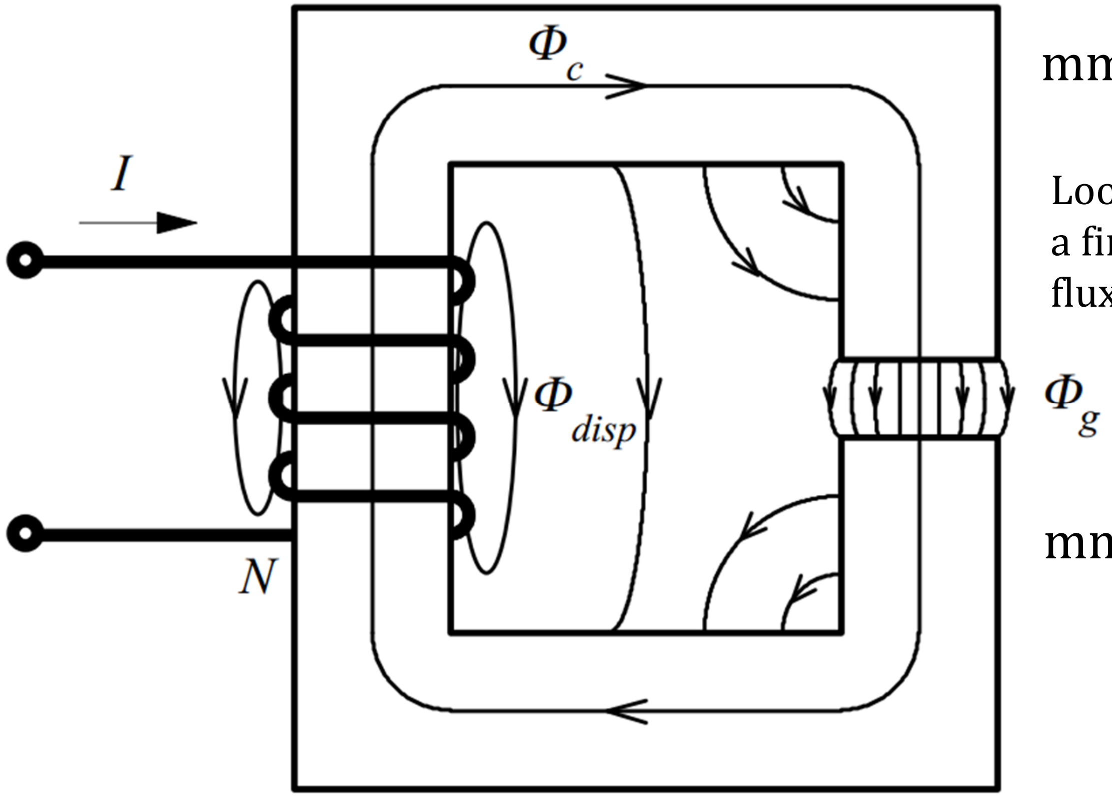
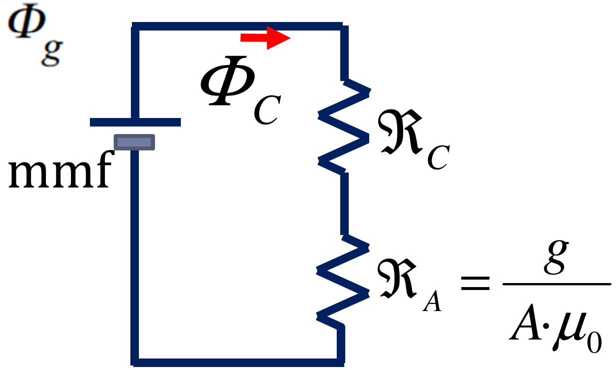




Final flux distribution ($\Phi_{DISP} << \Phi_C$)

The **AIR GAP** ensures a much smaller flux (and hence B)

Introduction

How to design a magnetic component

Current **i** in a number of turns, **N**

Ampère's Law

Magnetic Field (H)

Given material, μ

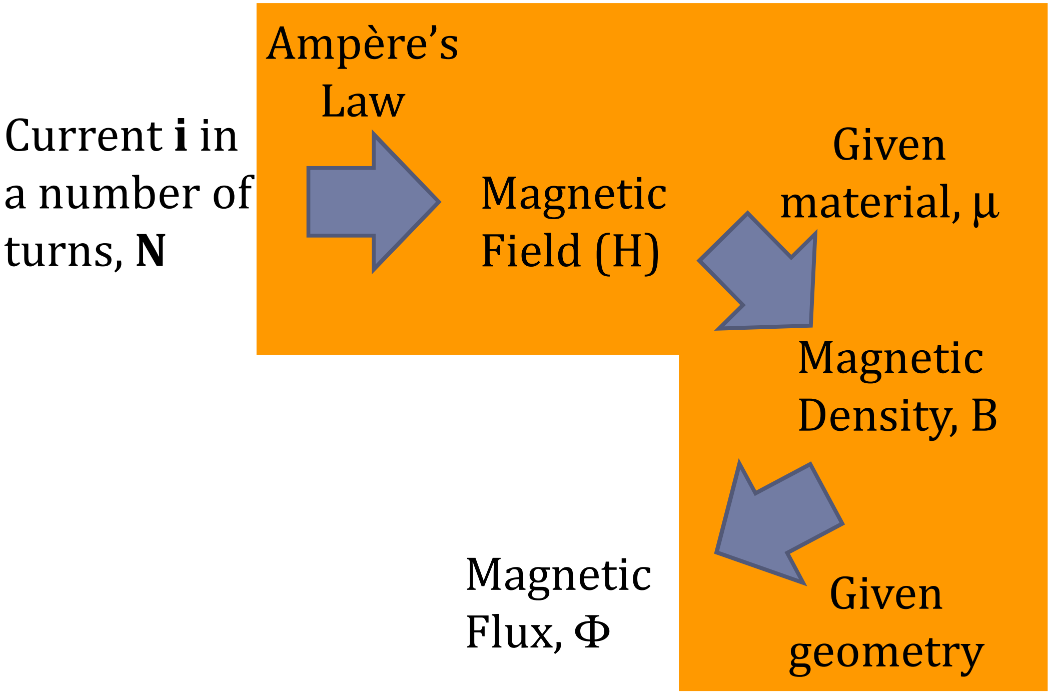
Magnetic Density, B

Given geometry

Magnetic Flux, Φ

Introduction

How to design a magnetic component



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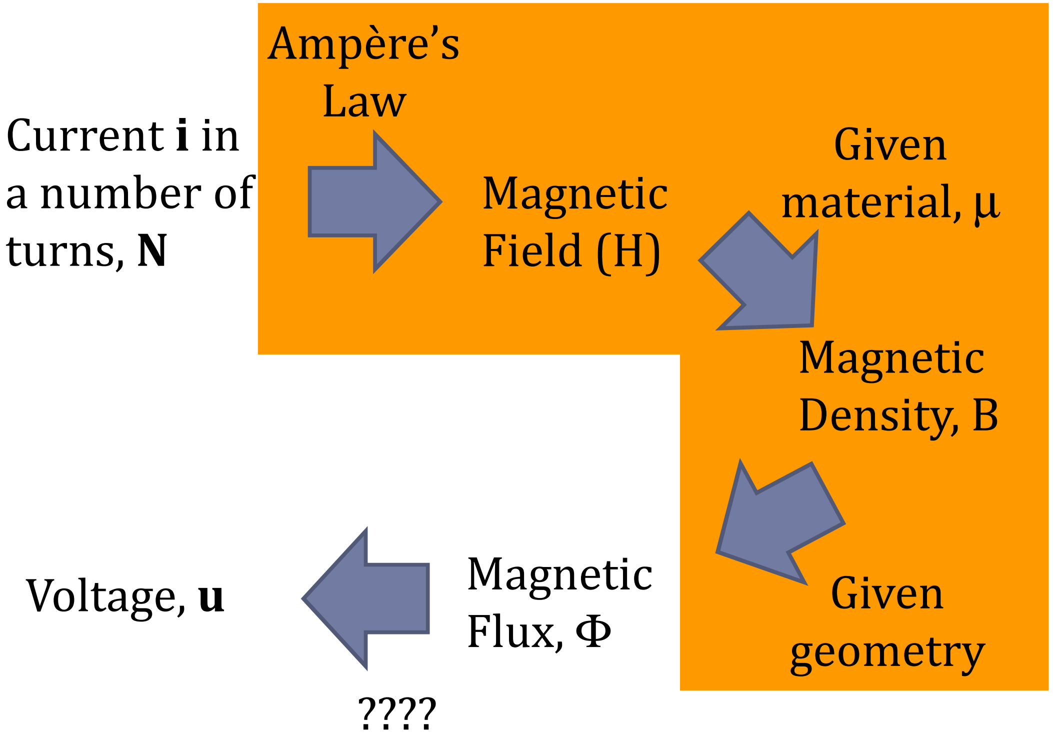
$$mmf = N \cdot i = \Re \cdot \Phi$$

Introduction

How to design a magnetic component



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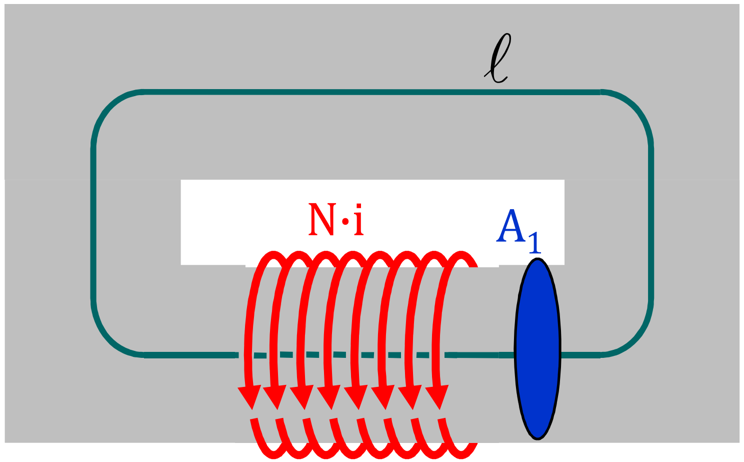
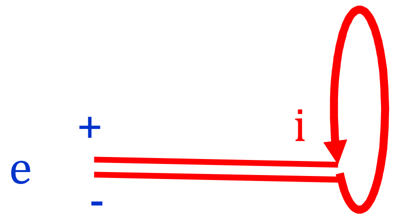
Physical background

Magnetic Flux and Faraday's Law

There is a relationship between the flux variation in a turn and the voltage in that turn. It is the **Faraday's Law**, that states that each turn in a winding generates a induced voltage (considered then as a **voltage source**) that equals the variation of the magnetic flux traversing that turn (-).



$$e = -\frac{d\Phi}{dt}$$



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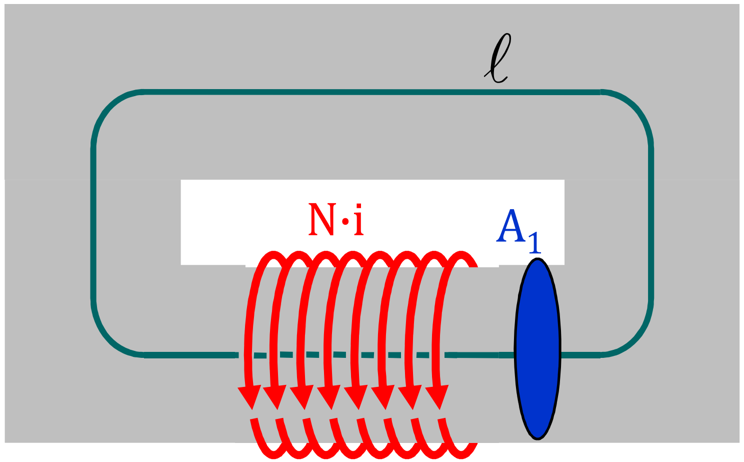

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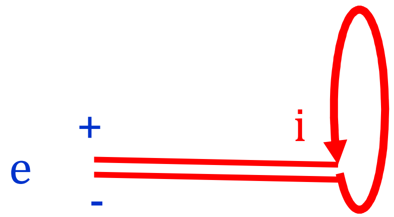

$$e = -\frac{d\Phi}{dt} = -A \cdot \frac{dB}{dt} = -A \cdot \mu \cdot \frac{dH}{dt} = -\frac{A \cdot \mu}{\ell} \cdot N \cdot \frac{di}{dt}$$

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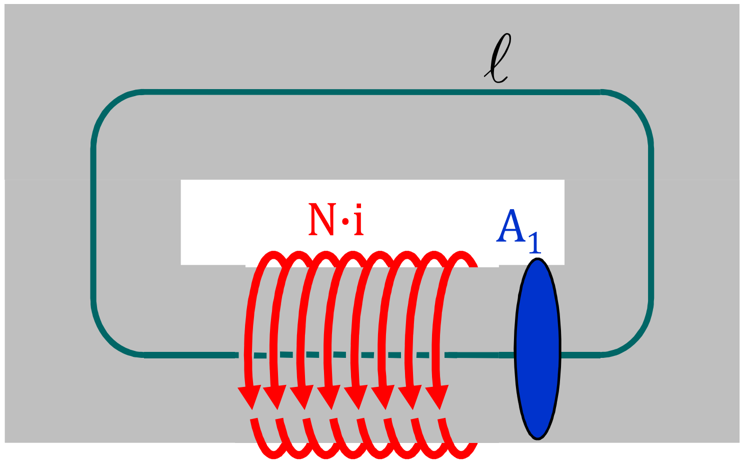
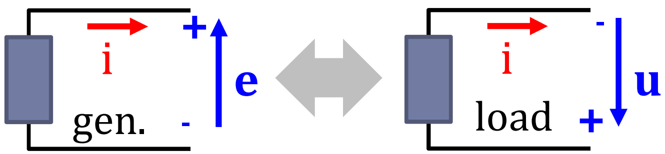
This induced voltage is for a single turn (multiply by N to get the winding voltage).

The induced voltage (generator) can be considered in the load references systems (**e** to **u**)





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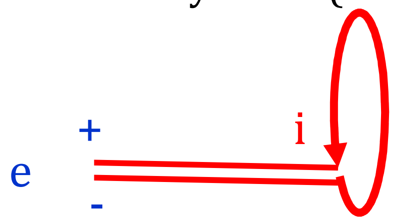

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$$\boxed{u = -N \cdot e = \frac{A \cdot \mu \cdot N^2}{\ell} \cdot \frac{di}{dt}}$$

Physical background

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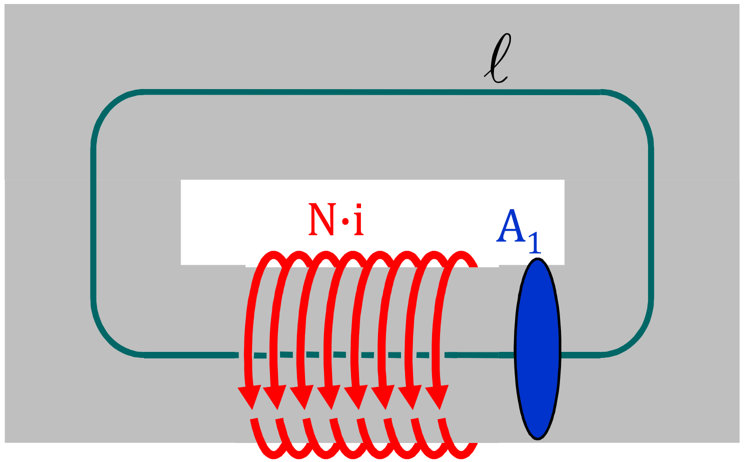
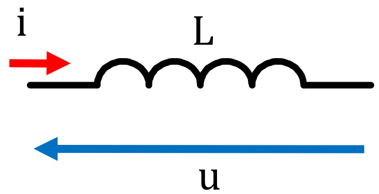


Therefore, the voltage and current in such a winding are related. This relationship is called the Self-Inductance (or **Inductance**), **L**.

$$u = \frac{A \cdot \mu \cdot N^2}{\ell} \cdot \frac{di}{dt} = L \cdot \frac{di}{dt}$$



Physical background

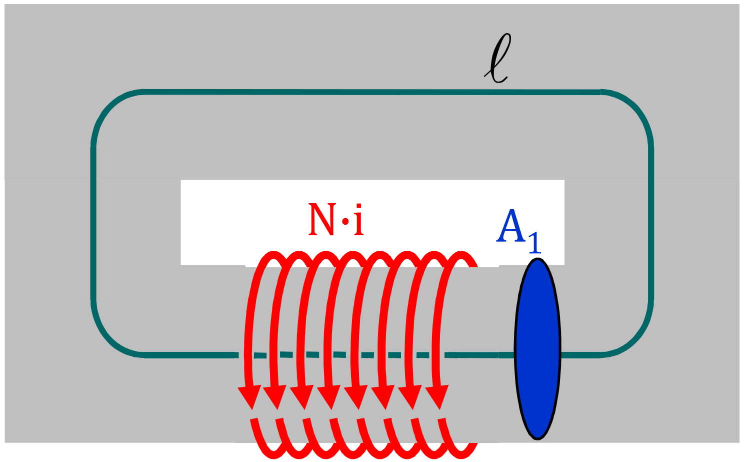
INDUCTANCE

Inductance, L, depends on magnetic parameters (magnetic permeability), geometric parameters (length of the magnetic loop, surface of the winding) and electrical parameters (number of turns).

The inductance can be expressed as a function of the Reluctance.

$$u = L \cdot \frac{di}{dt}$$

$$L = \frac{A \cdot \mu \cdot N^2}{\ell}$$



$$L = \frac{N^2}{\Re}$$

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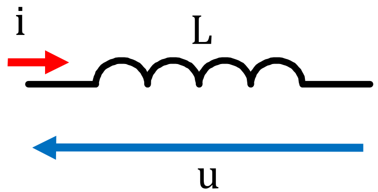


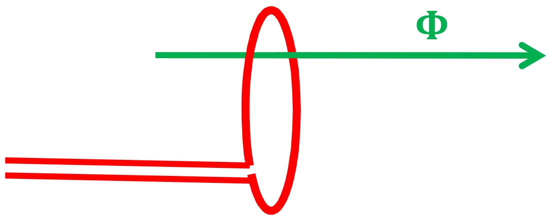
Physical background

Lenz's Law (power losses in an inductor, transformer's design)

Faraday's Law is a particular case of Lenz's Law: Consider a flux variation in a turn. An induced flux appears in that turn that tends to oppose to the original flux variation. The induced flux generates a current in the turn and a induced voltage, e, in the turn.

Consider a turn without current flowing, but having a flux changing in time.

$$e = -\frac{d\Phi}{dt}$$



Φ: Magnietc Flux (Suppose it is **DECREASING**).

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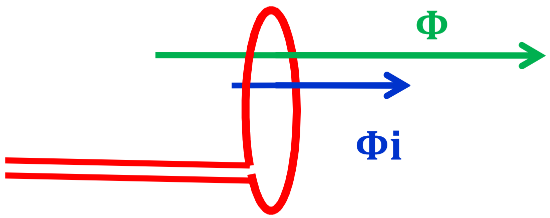

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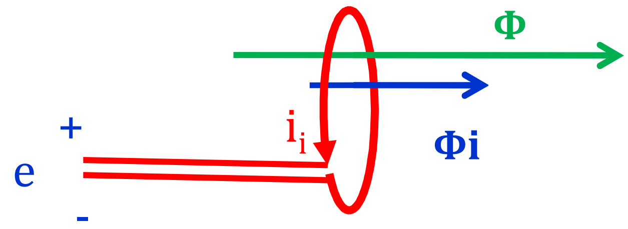

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This induced flux generates a current and voltage with the references depicted.

Sign "-" implies that the voltage tends to oppose the original field (if a flux with the direction of Φ is desired, a opposite polarity voltage must be placed).

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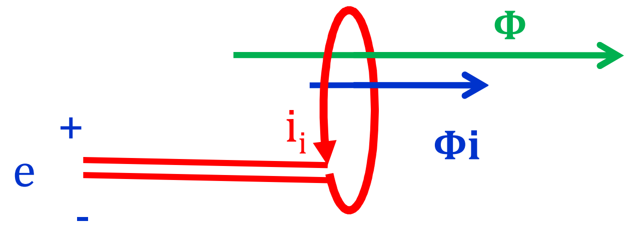

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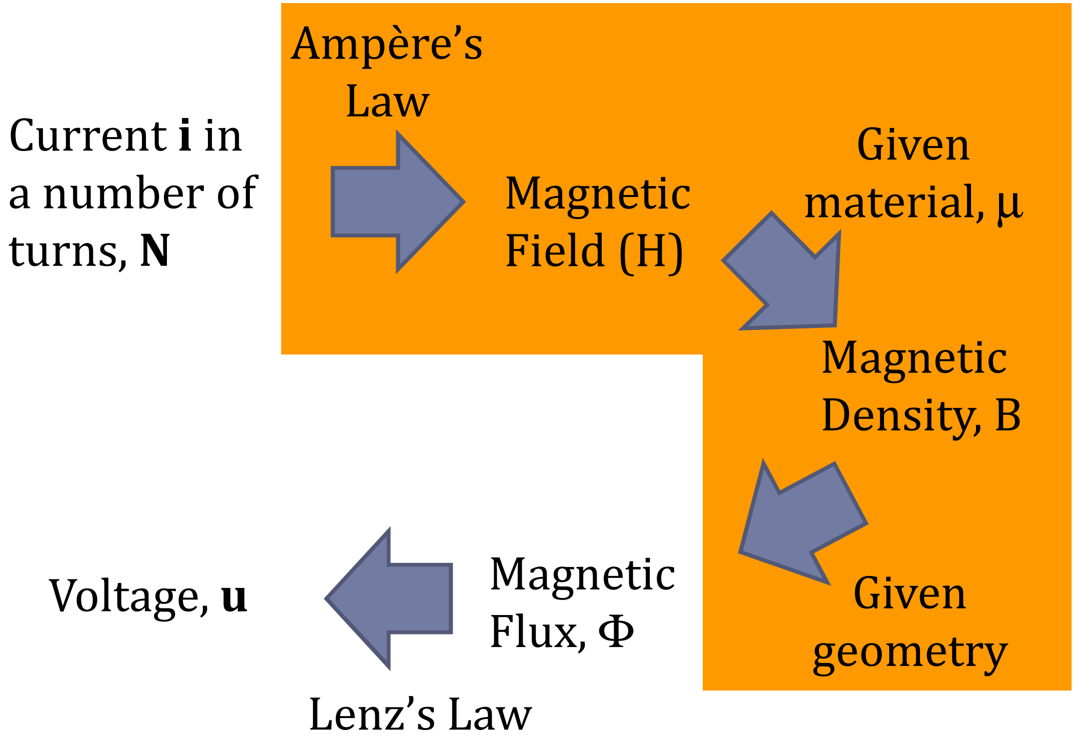
In an inductor, the voltage at the turn is SELF-INDUCED by the variation of the flux produced by the induced current. (Transformers consider other currents and voltages at the magnetic geometry)

Introduction

How to design a magnetic component



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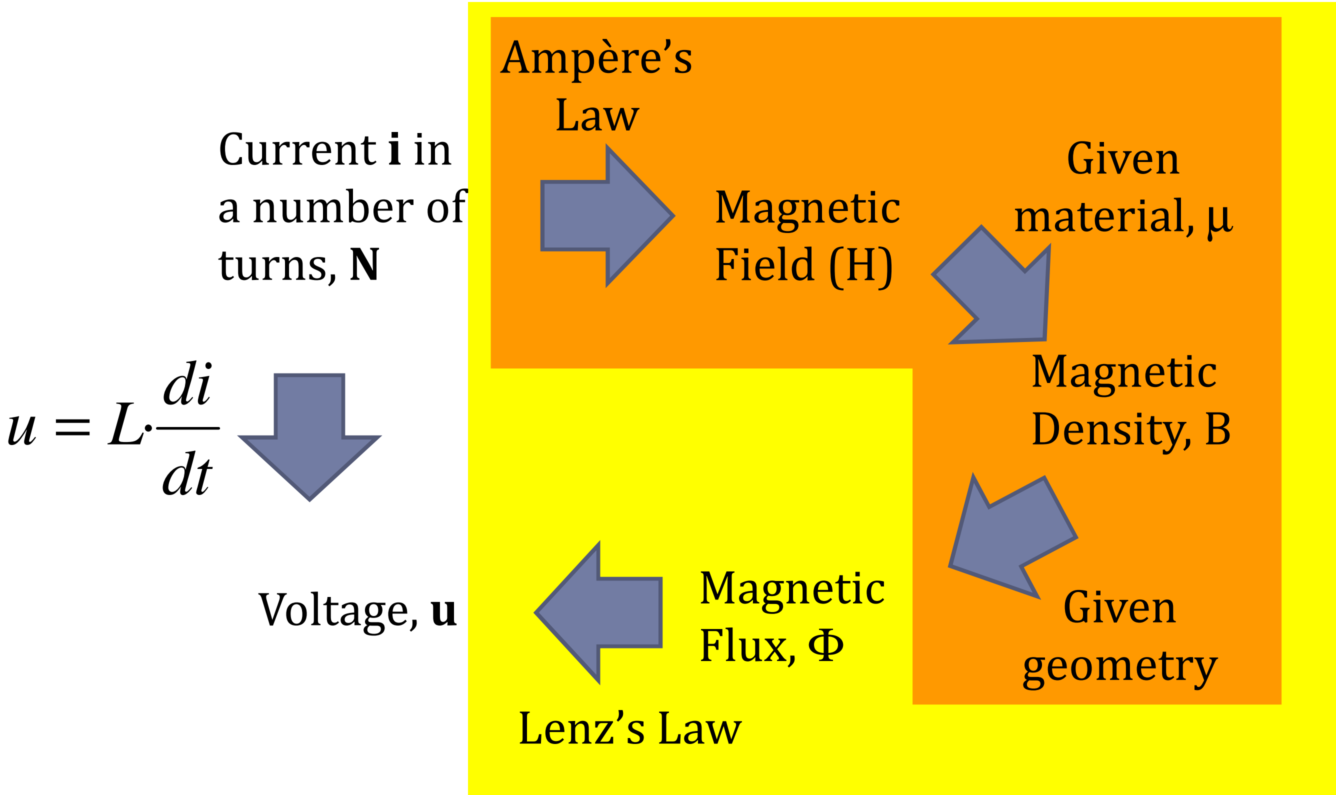

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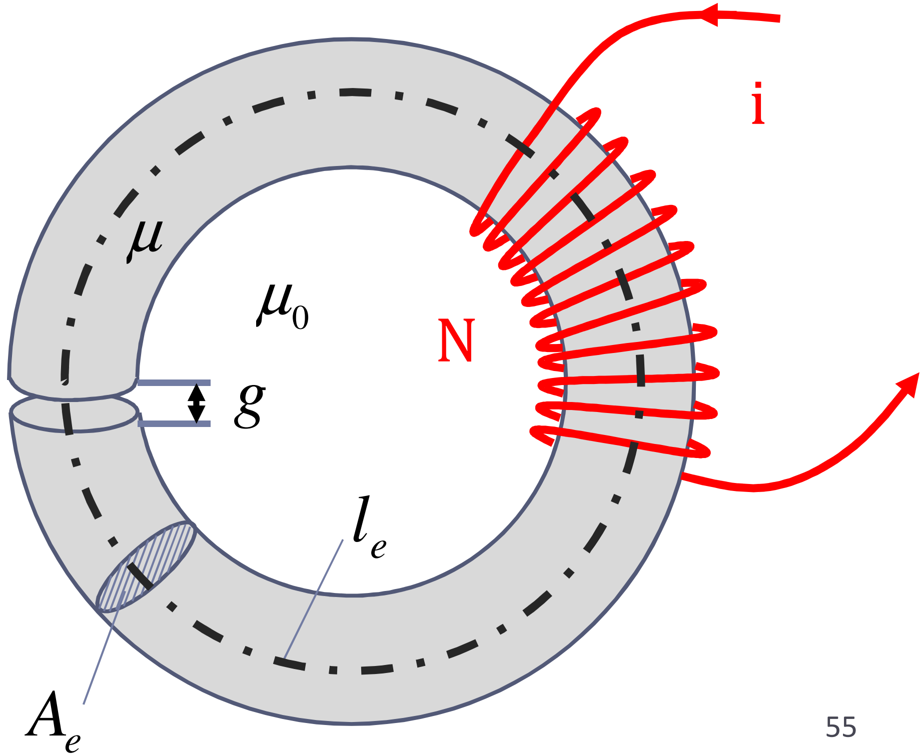
Inductance

Design of inductors: Equivalent Toroid Method

$$L = \frac{1}{\Re_{EQ}} \cdot N^2$$



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Design of inductors: Equivalent Toroid Method

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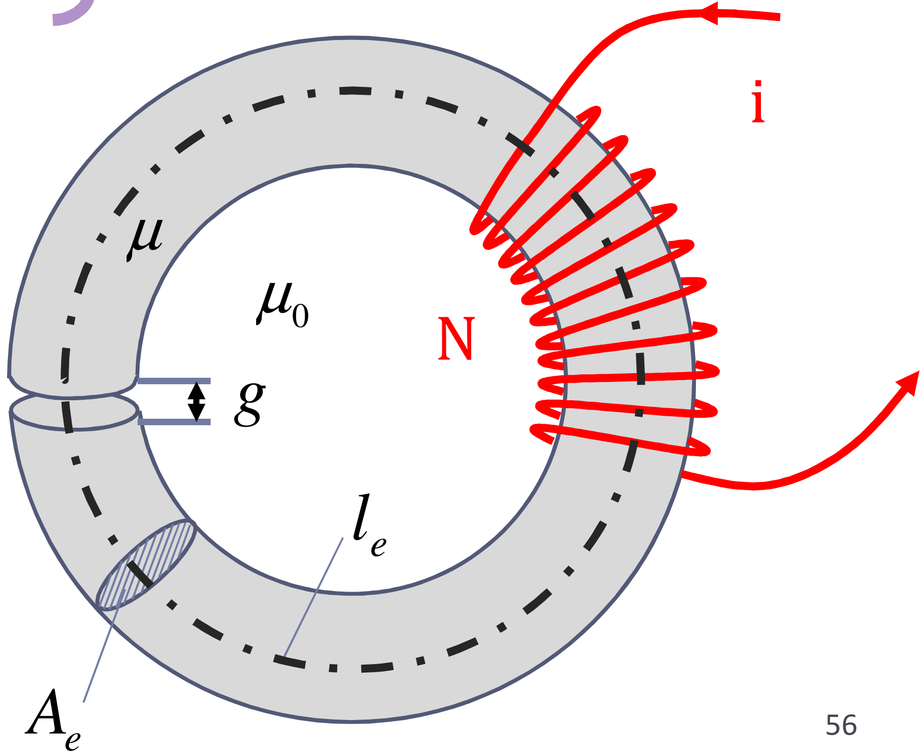
$$\Re_{EQ} = \oint_L \frac{dl}{\mu \cdot A} = \Re_a + \Re_c = \frac{g}{\mu_0 \cdot A_e} + \frac{l_e}{\mu \cdot A_e}$$

$$L = \frac{\mu_0 \cdot A_e \cdot N^2}{\dfrac{l_e}{\mu_r} + g}$$



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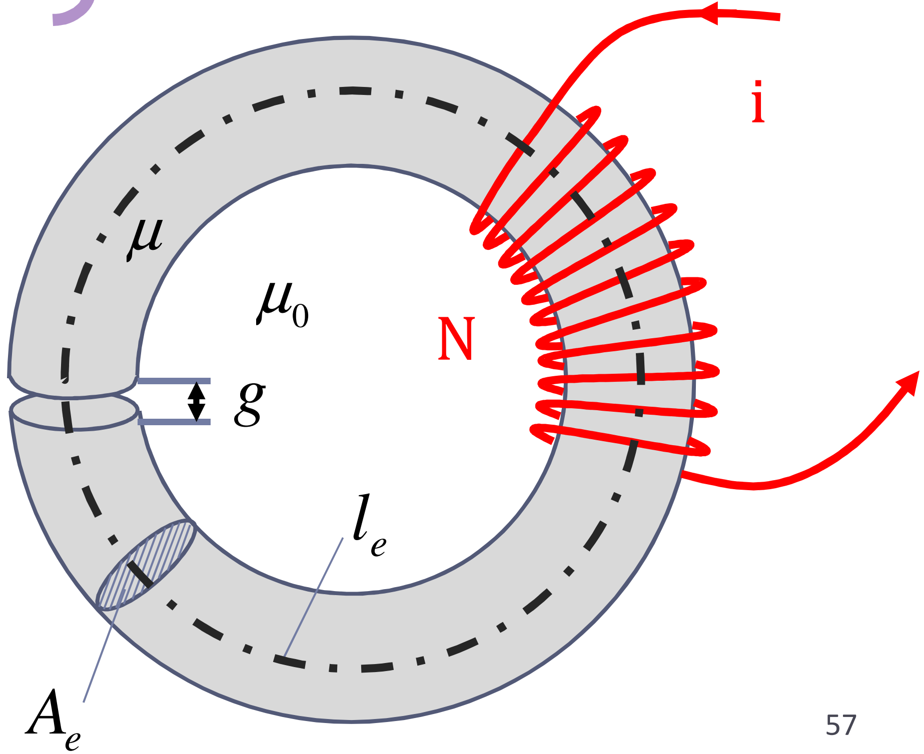
$$B = \frac{\Phi}{A_e} = \frac{N \cdot i}{\Re_{EQ}} \cdot \frac{1}{A_e} = \frac{N \cdot \mu_0 \cdot i}{\frac{l_e}{\mu_r} + g}$$



Physical background

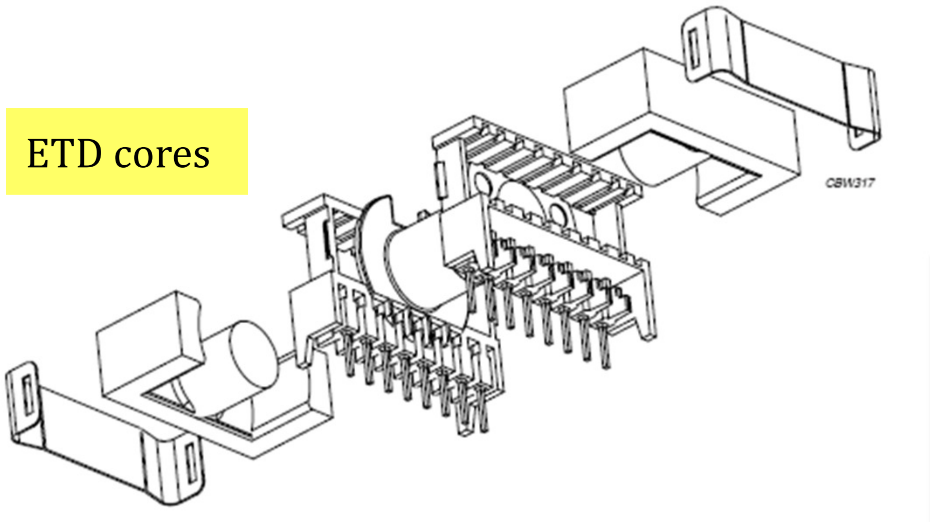
Summary:

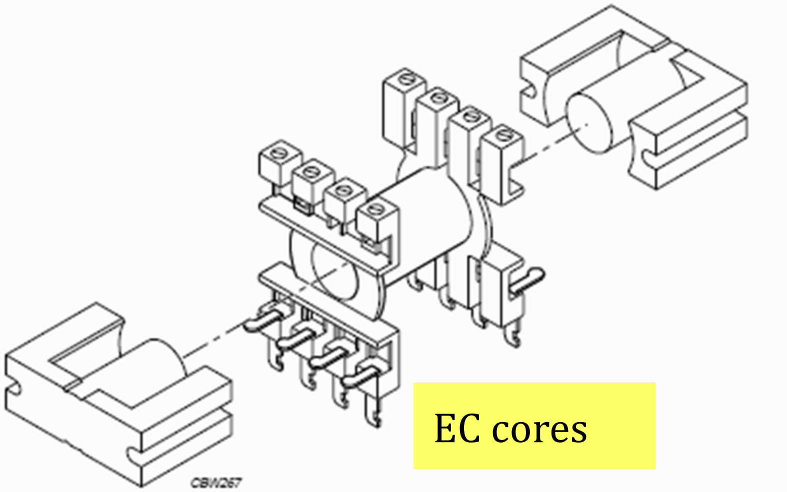
- Biot-Savart: Currents flowing in conductors create magnetic field that implies a force in other current elements.
- This force is a function of the magnetic behaviour of the material (magnetic permeability, **μ**)
- The magnetic force per unit of sensitive element formes a space-field (magnetic density, **B**)
- The effect of magnetism can be studied independently of the material itself (magnetic field, **H**)
- For a given material, there is a limit in the amount of magnetic density that is capable to withstand (**Saturation**)
- Ampère's Law relates the magnetic field, H and the current, i, in a given magnetic circuit $H = \frac{N \cdot i}{\ell}$
- The magnetic flux that gives idea of the overall energy stored in a magnetic material $\Phi = B \cdot A$
- Faraday's Law relates the flux variation in a turn and the voltage in that turn. $e = -\frac{d\Phi}{dt}$
- The **inductance L** relates the current and the voltage in a given winding in a magnetic circuit. Thus, the behavior of the magnetic circuit can be modelled in terms of an electric circuit (in the end it is an **electrical impedance**)

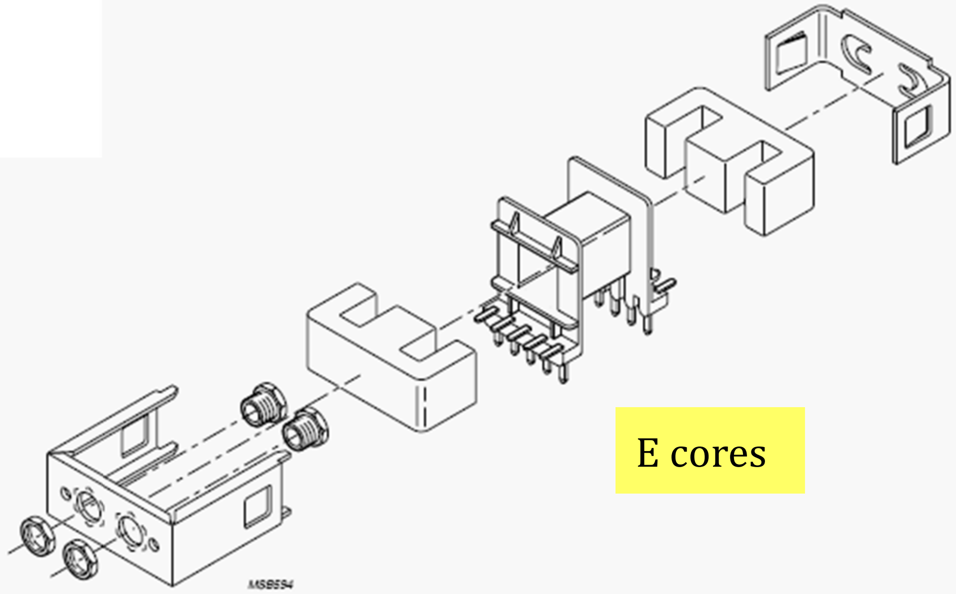
$$u = L \cdot \frac{di}{dt}$$

Inductors

Magnetic materials: Geometries and coil formers,



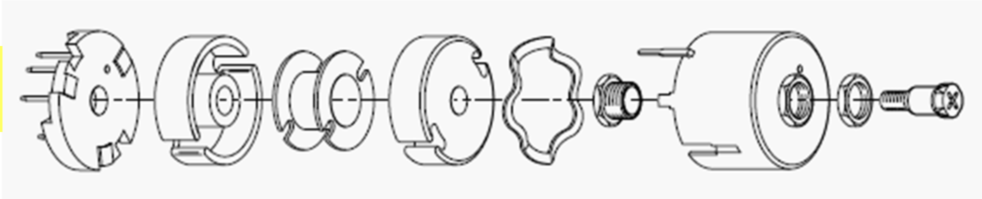




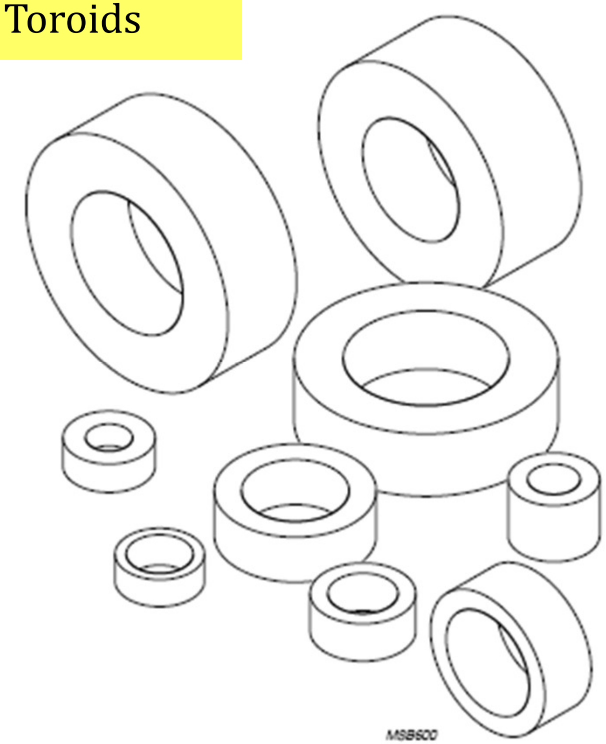
Inductors

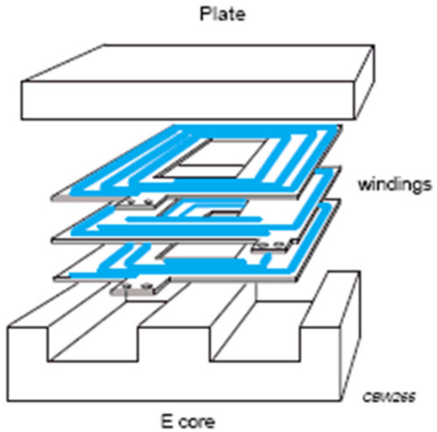
Magnetic materials: Geometries and coil formers,

PT cores

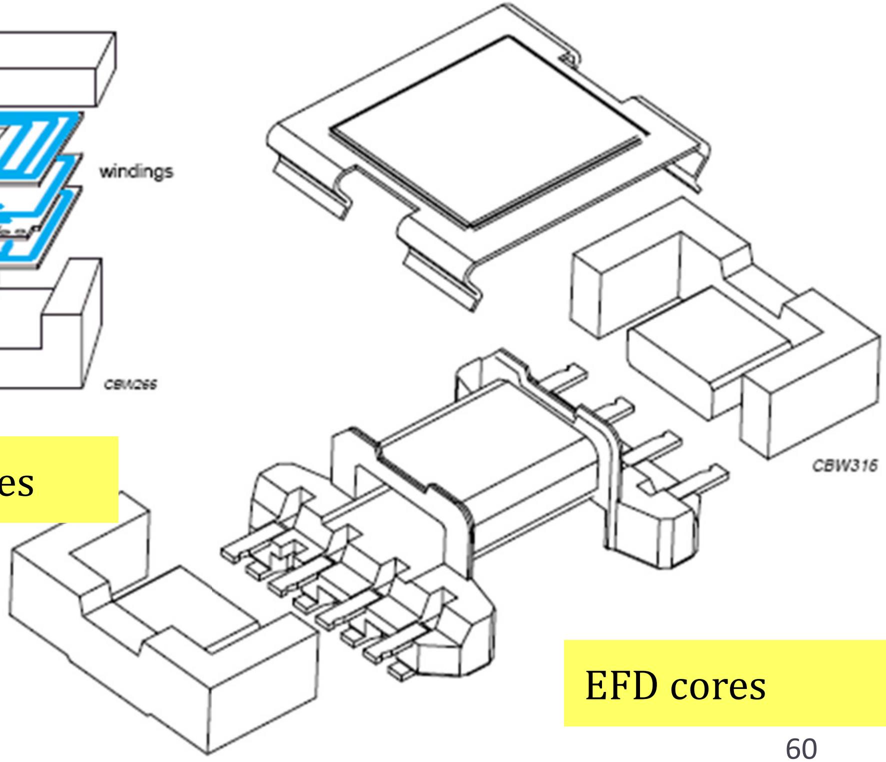


Toroids





Planar E cores

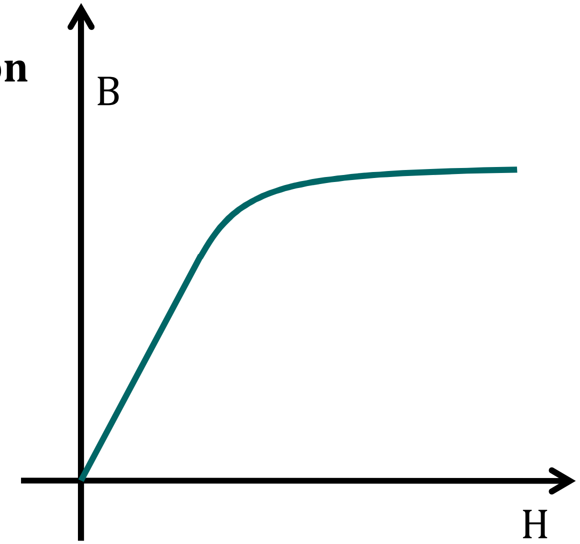


EFD cores

Inductors

Magnetic materials: B-H Characteristics

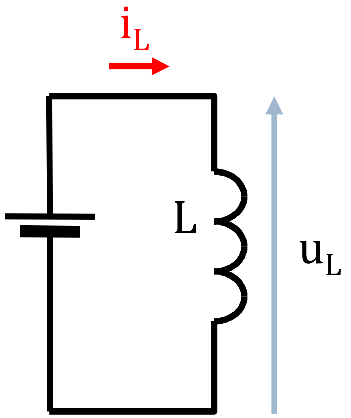
Saturation

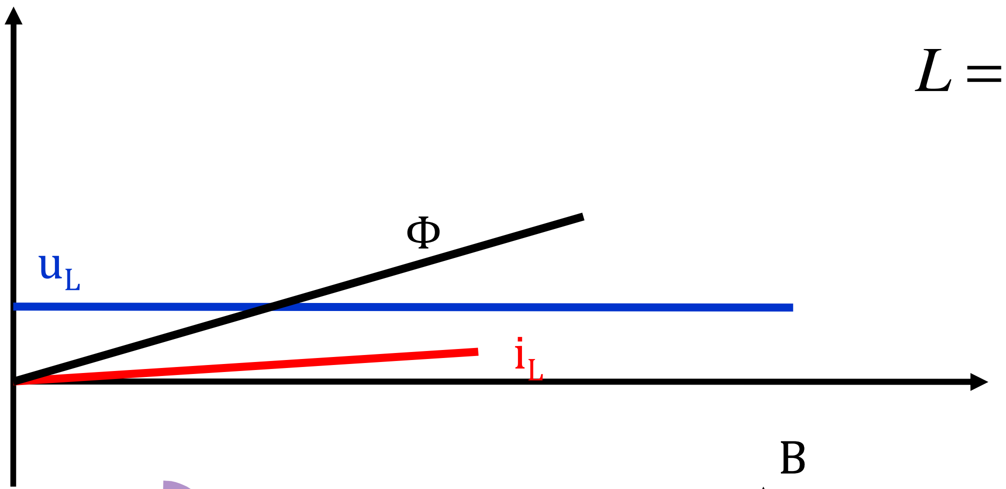


Saturation: The maximum value of magnetic density (B_{MAX}) in a core has a physical limit. The value is given in the datasheets.

Inductors

Electrical behaviour of inductors: DC signals





$$L = \frac{A \cdot \mu \cdot N^2}{\ell}$$

Faraday

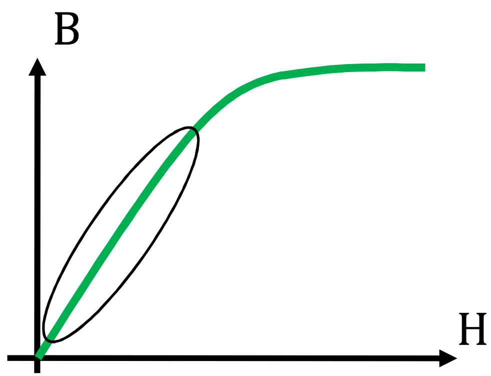
$$u_L = \frac{d\Phi}{dt}$$

Ampére

$$B = \mu \cdot H$$

$$\Phi = \frac{N \cdot i}{\Re}$$

$$u_L = L \cdot \frac{di_L}{dt}$$



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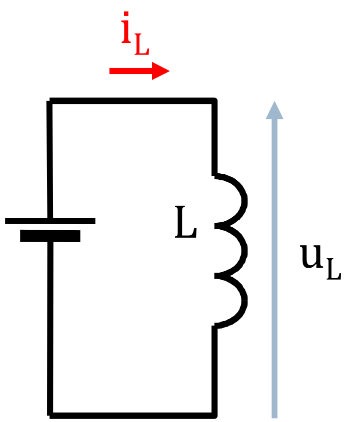
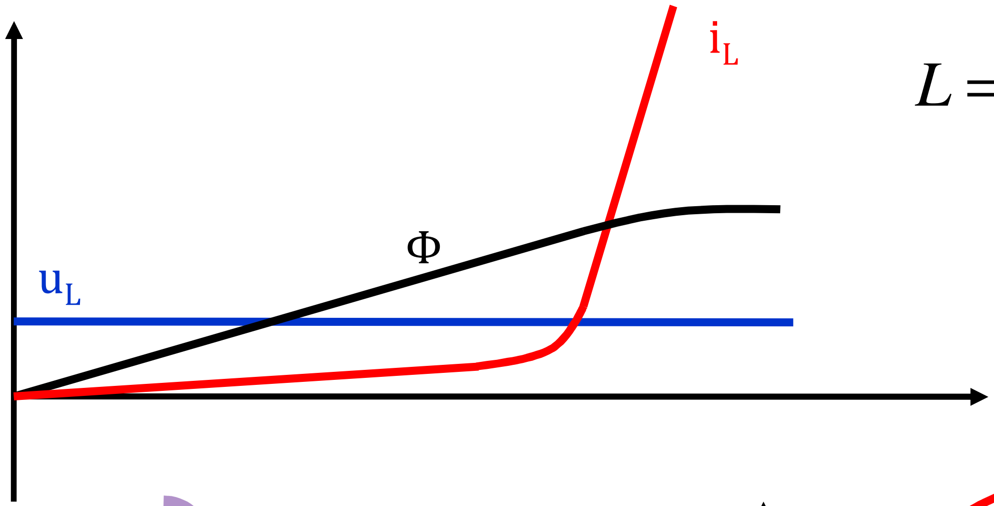




$$L = \frac{A\cdot\mu\cdot N^2}{\ell}$$

Faraday

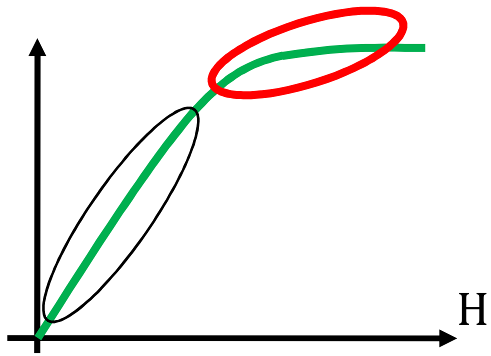
$$u_L = \frac{d\Phi}{dt}$$

Ampére

$$\cancel{B = \mu\cdot H}$$

$$\cancel{\Phi = \frac{N\cdot i}{\Re}}$$

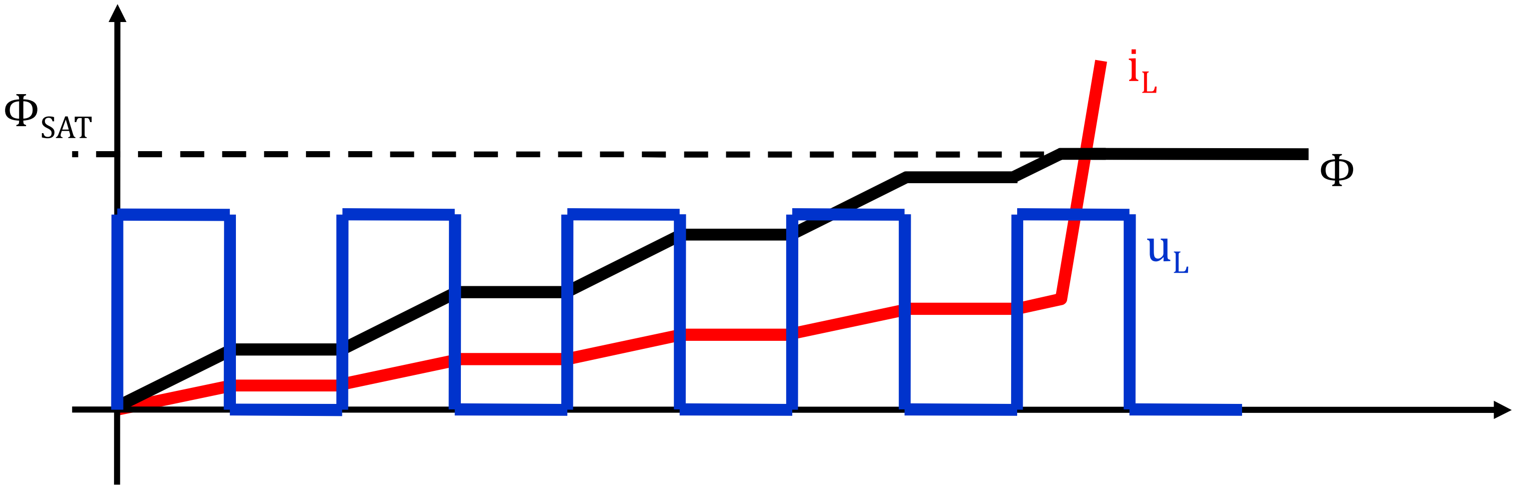
$$u_L = \cancel{L}\cdot\frac{di_L}{dt}$$



$$\mu\downarrow\downarrow\Rightarrow \Re\uparrow\uparrow\Rightarrow L\downarrow\downarrow\Rightarrow i\uparrow\uparrow$$

Inductors

Electrical behaviour of inductors: Squarewaves

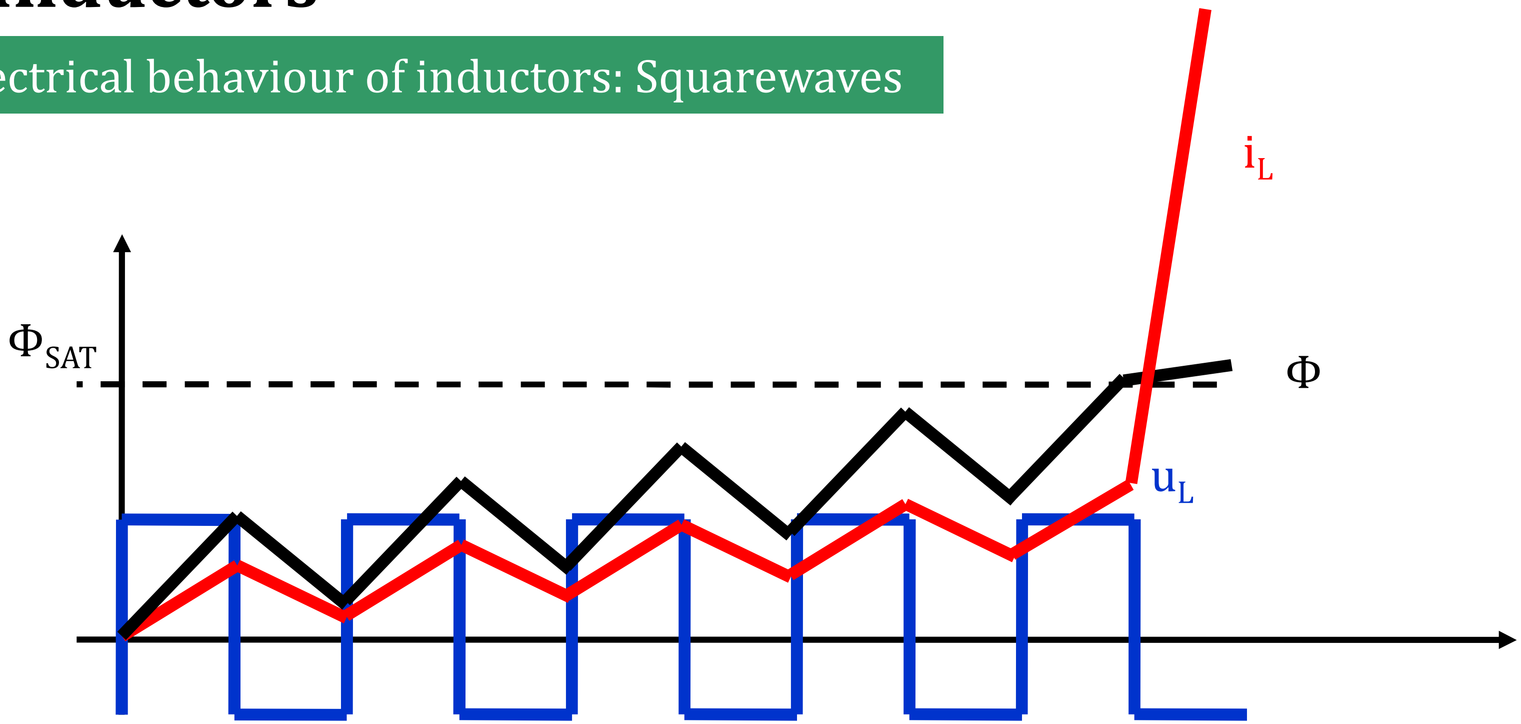


As there is not demagnetization, after a number of cycles the flux reaches saturation.

Then, the inductor behaves as a short-circuit.

Inductors

Electrical behaviour of inductors: Squarewaves

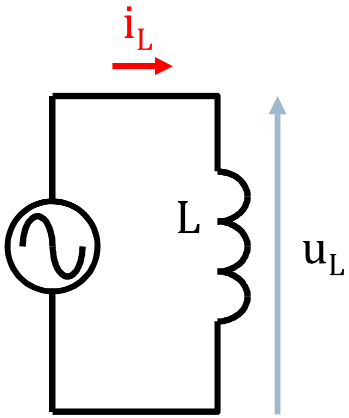


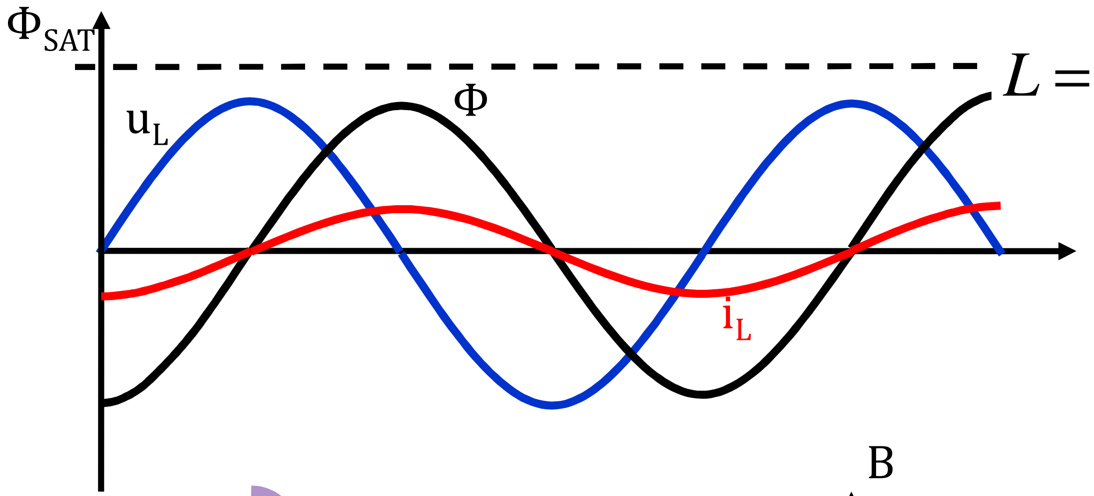
Even for a small DC value, after a number of cycles the flux reaches saturation.

Then, the inductor behaves as a short-circuit.

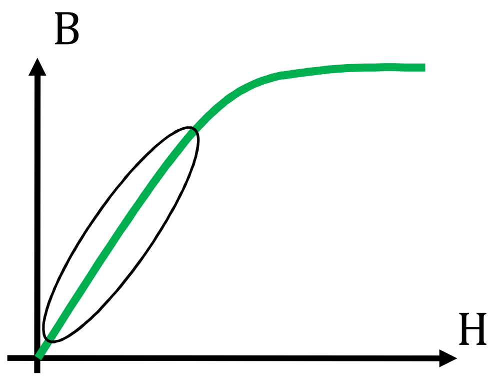
Inductors

Electrical behaviour of inductors: sinewaves





$$L = \frac{A \cdot \mu \cdot N^2}{\ell}$$



Faraday

$$u_L = \frac{d\Phi}{dt}$$

$$u_L = L \cdot \frac{di_L}{dt}$$

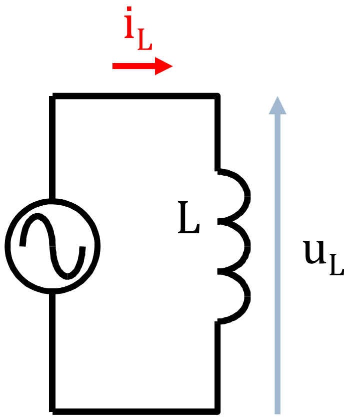
Ampére

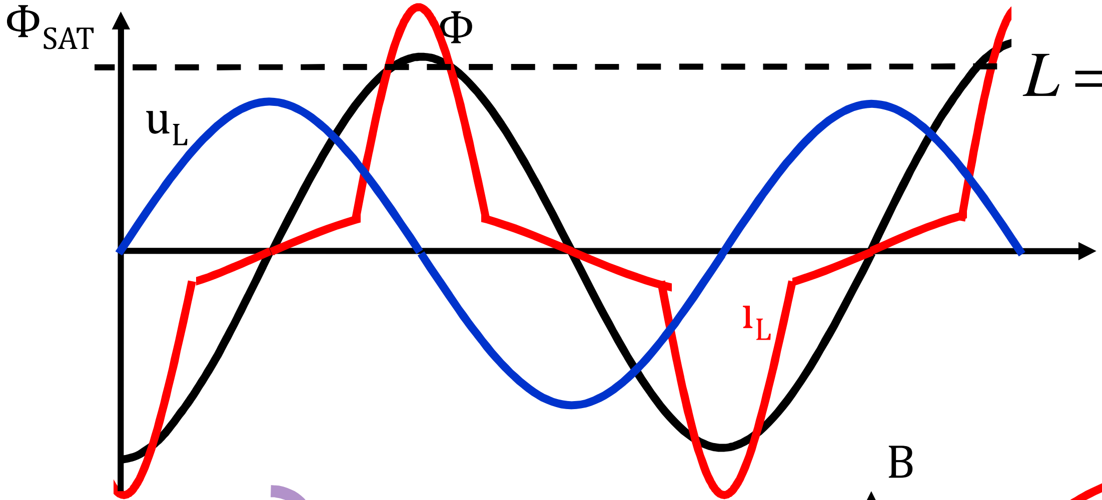
$$B = \mu \cdot H$$

$$\Phi = \frac{N \cdot i}{\Re}$$

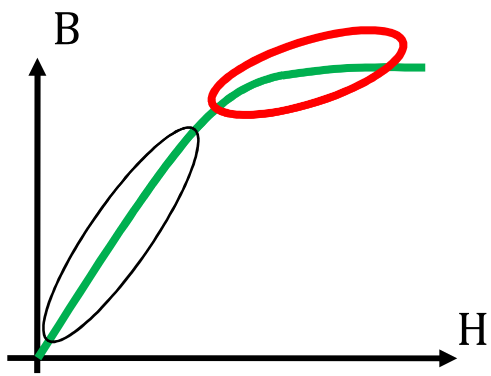
Inductors

Electrical behaviour of inductors: sinewaves





$$L = \frac{A \cdot \mu \cdot N^2}{\ell}$$



Faraday

$$u_L = \frac{d\Phi}{dt}$$

$$u_L = \cancel{L} \cdot \frac{di_L}{dt}$$

Ampére

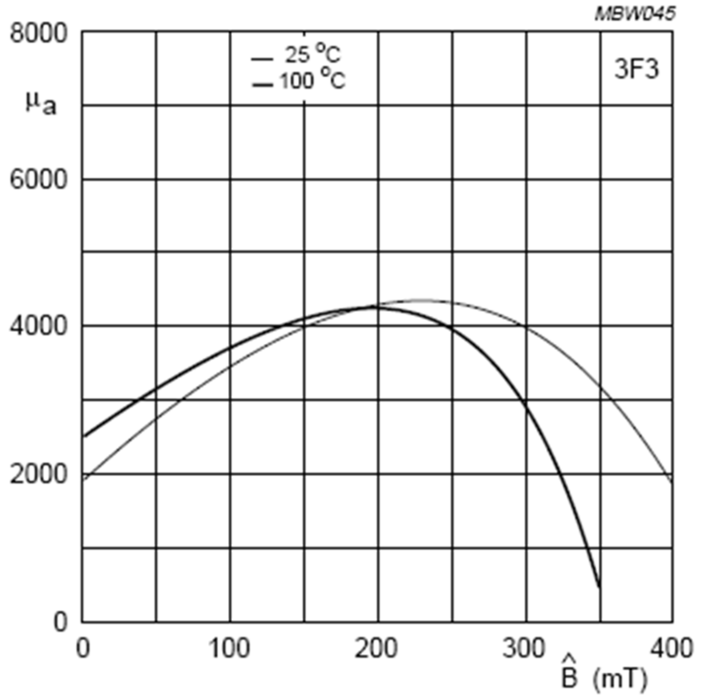
$$\cancel{B = \mu \cdot H}$$

$$\cancel{\Phi = \frac{N \cdot i}{\Re}}$$

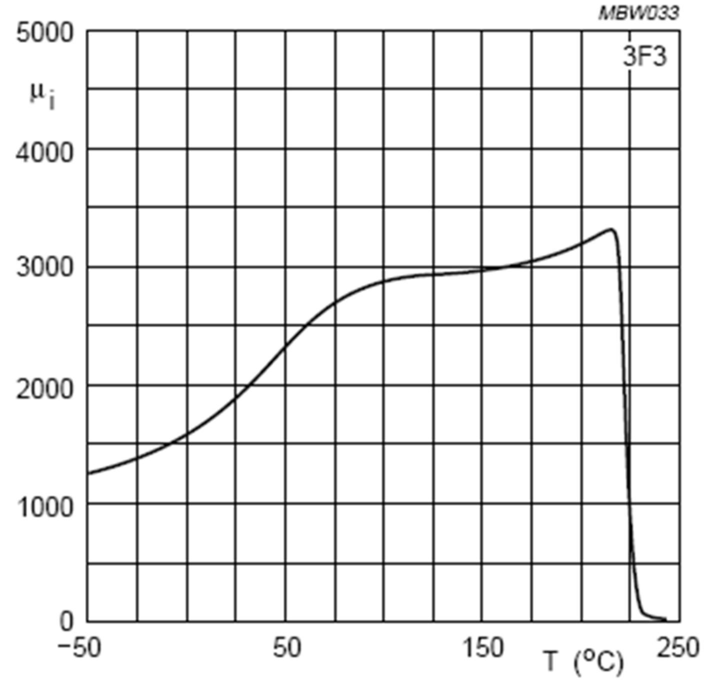
$$\mu \downarrow\downarrow \Rightarrow \Re \uparrow\uparrow \Rightarrow L \downarrow\downarrow \Rightarrow i \uparrow\uparrow$$

Inductors

Magnetic materials: Permeability Characteristics



Relationship between **µ** and **B (saturation)**.



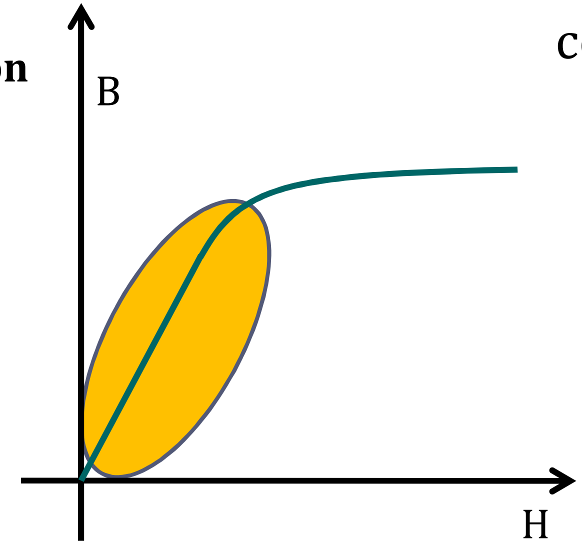
Curie Temperature: At temperatures higher than Curie Temp., the material losses its magnetic properties.

Inductors

DESIGN OF INDUCTORS

All the design procedure is based on **AVOIDING SATURATION OF THE MAGNETIC CORE,** while keeping size, costs and **losses** as low as possible.

Saturation

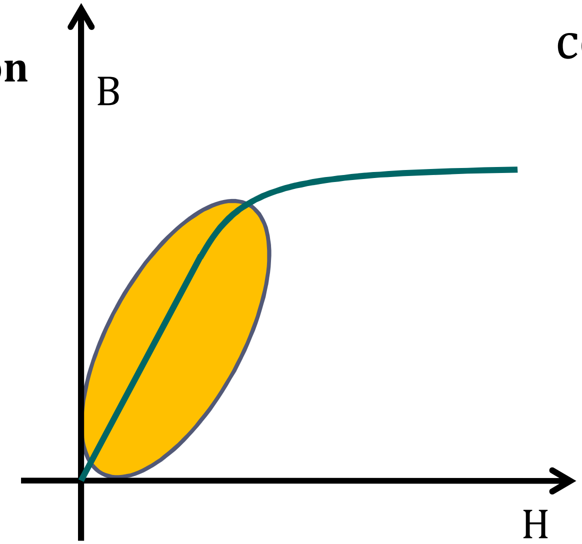


Saturation: The maximum value of magnetic density (B_{MAX}) in a core has a physical limit. The value os given in the datasheets.

Inductors

DESIGN OF INDUCTORS

Saturation



All the design procedure is based on **AVOIDING SATURATION OF THE MAGNETIC CORE,** while keeping size, costs and **losses** as low as possible.

LOSSES?

Magnetic Core Losses

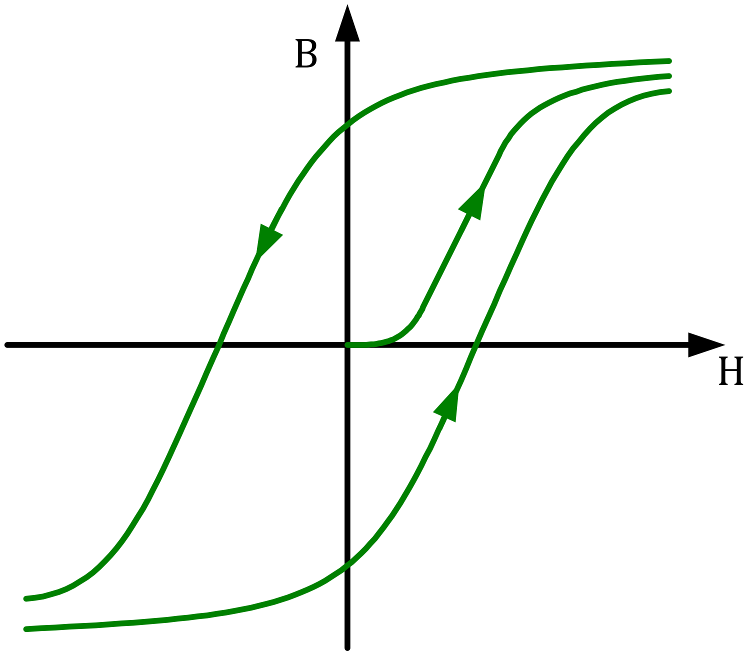
and

Copper Wire Losses

Saturation: The maximum value of magnetic density (B_{MAX}) in a core has a physical limit. The value os given in the datasheets.

Inductors: Core Losses

Magnetic materials: B-H Characteristics



Hysteresis: In an **altern evolution of H**, the value of B is different if H rises or falls.

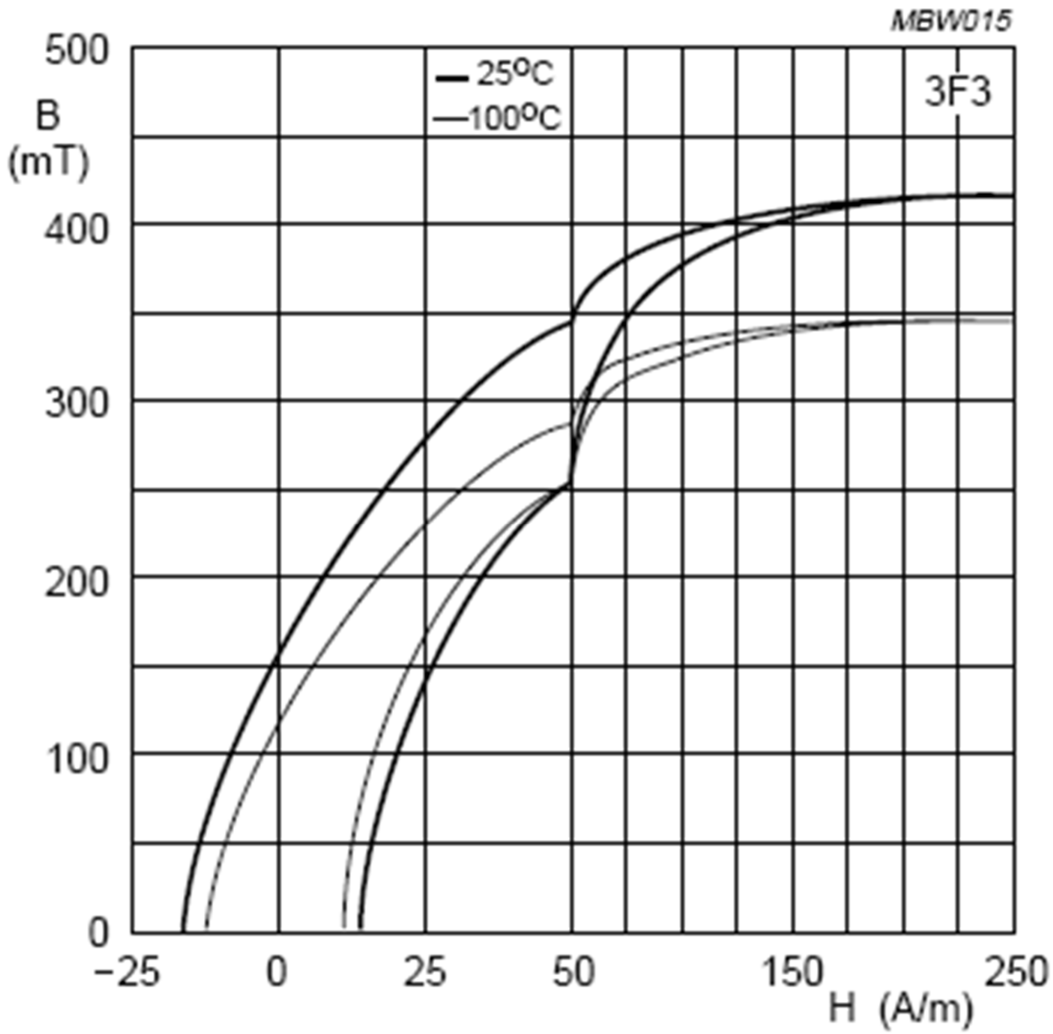
The inner area of the obtained curve is related with the core losses (heat in the core).

An altern evolution of H means altern current:

The core losses only take into account altern currents (altern H, altern B)

Inductors: Core Losses

Magnetic materials: B-H Characteristics

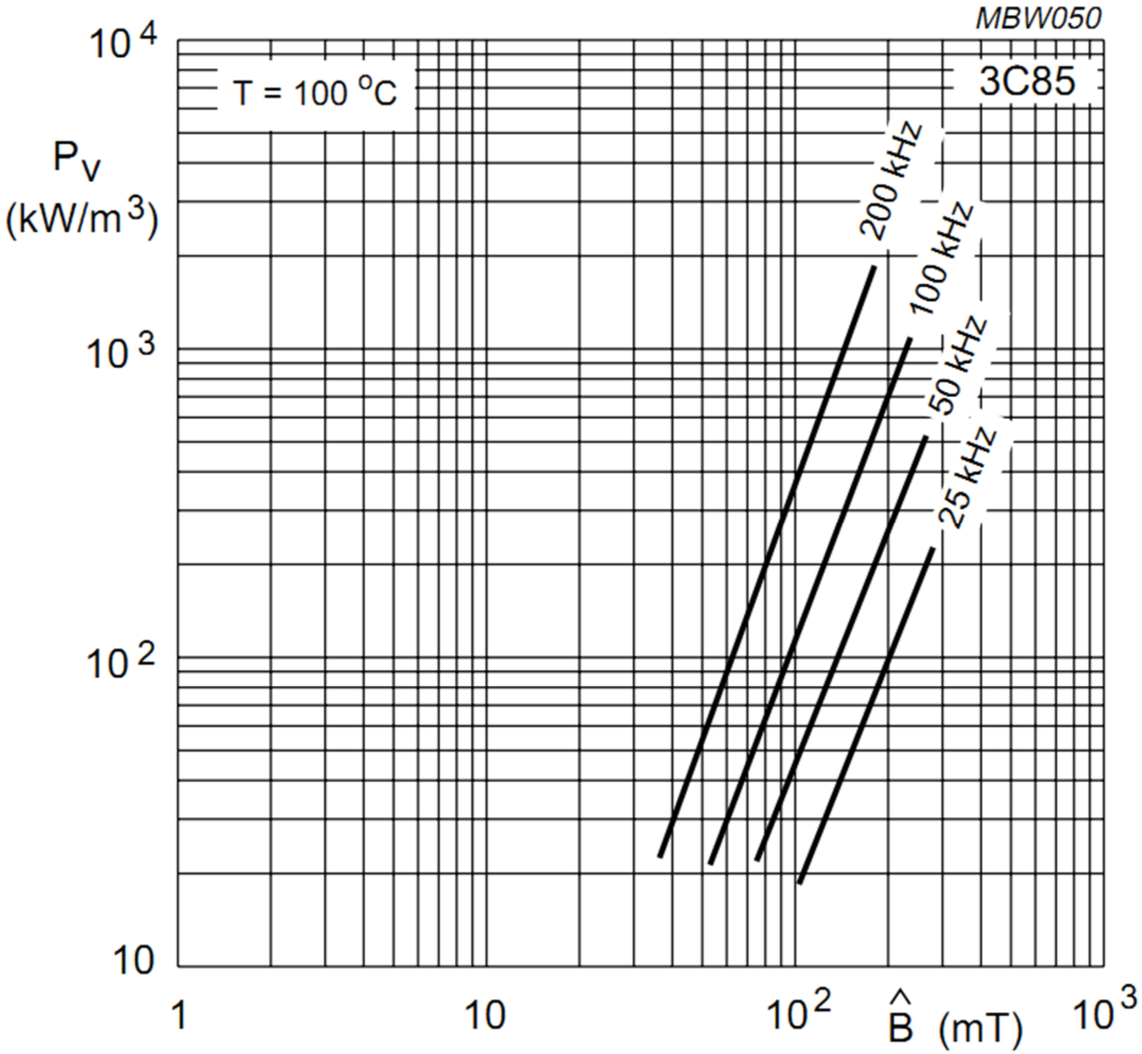


Very complicated expressions, **involving only the AC component of the Magnetic Density, B.**

$$P_{CORE} \cong k \cdot \hat{B}^2$$

Inductors: Core Losses

Magnetic materials: Hysteretic power losses



Inductors: Copper Losses

Copper losses

Copper losses depend on the frequency of the current.

LF copper losses consider the resistivity of the copper itself.

HF copper losses consider that an altern current produces an altern magnetic field, that induces new currents (Eddy currents or Foucault currents).
These currents increase the resistance of the wire and increase also the final current flowing, thus **dramatically increasing** the losses.

Inductors: Copper Losses

LF Copper losses

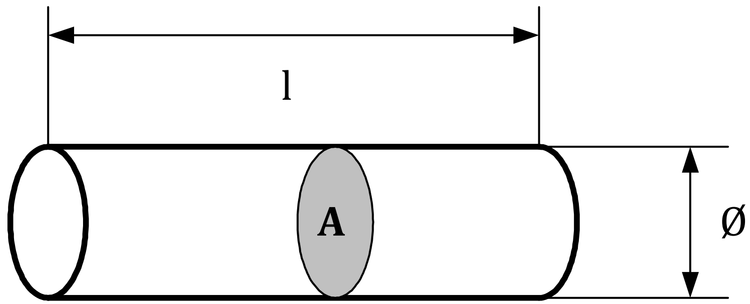
LF Copper losses: Copper resistivity

$$R_{cu} = \rho \frac{l_{TURN}}{A_{cu}} \cdot N$$

$$P_{cu} = i_{RMS}{}^{2} \cdot R_{cu}$$

$$P_{cu} = i_{RMS}{}^{2} \cdot \rho \cdot \frac{l_{esp}}{A_{cu}} \cdot N$$

The greater the diameter, the lower the copper LF power losses



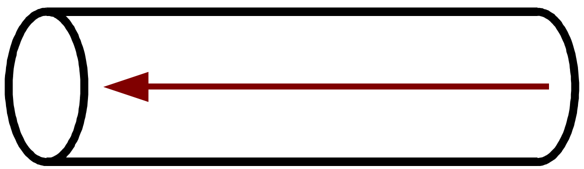
Thus, minimizing the LF copper losses means **maximizing the wire diameter**, using the maximum window area of the core.
But this does not take into account **HF** losses, and these losses can be **extremely high**.

Inductors: Copper Losses

HF Copper losses

HF Copper losses: Skin Effect

Consider a AC current in a wire **(dark red)**

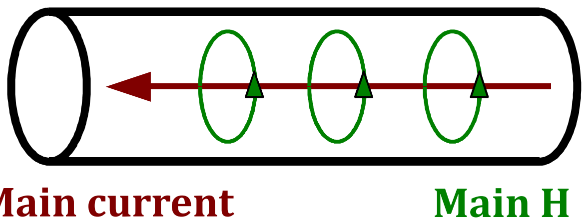


Inductors: Copper Losses

HF Copper losses

HF Copper losses: Skin Effect

Consider a AC current in a wire **(dark red)**
It generates a magnetic field, H **(green)**

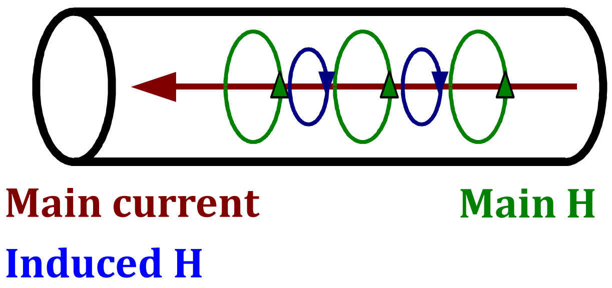


Inductors: Copper Losses

HF Copper losses

HF Copper losses: Skin Effect

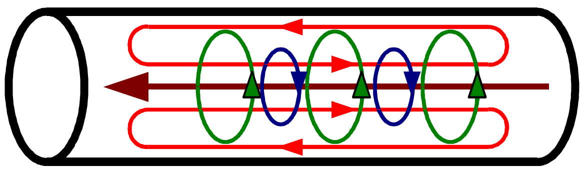
Consider a AC current in a wire **(dark red)**
It generates a magnetic field, H **(green)**
This magnetic field, by **Lenz's law**, generates an induced field, Hi (**blue**). This induced field tends to oppose the variation of H.



Inductors: Copper Losses

HF Copper losses

HF Copper losses: Skin Effect

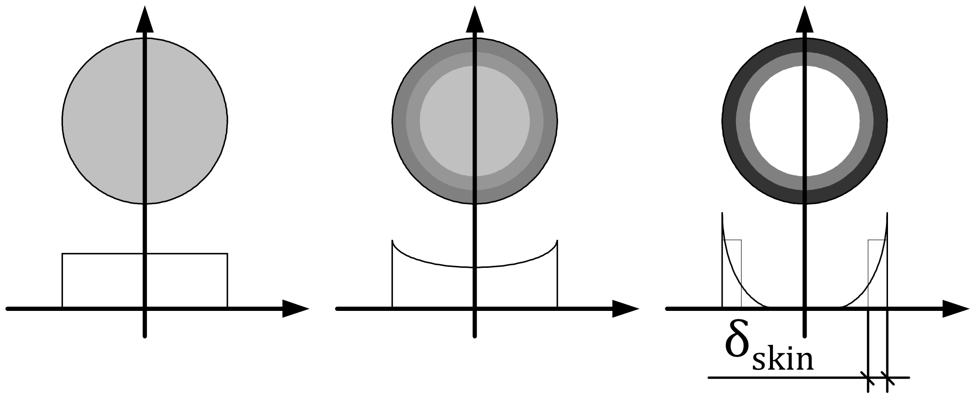


Consider a AC current in a wire **(dark red)**
It generates a magnetic field, H **(green)**
This magnetic field, by **Lenz's law**, generates an induced field, Hi (**blue**). This induced field tends to oppose the variation of H.
This induced field, generates an induced current, (**bright red**). The induced current is **added** to the main current in the **edge** of the wire, and is **substracted** in the **middle** of the wire.

Inductors: Copper Losses

HF Copper losses

HF Copper losses: Skin Effect



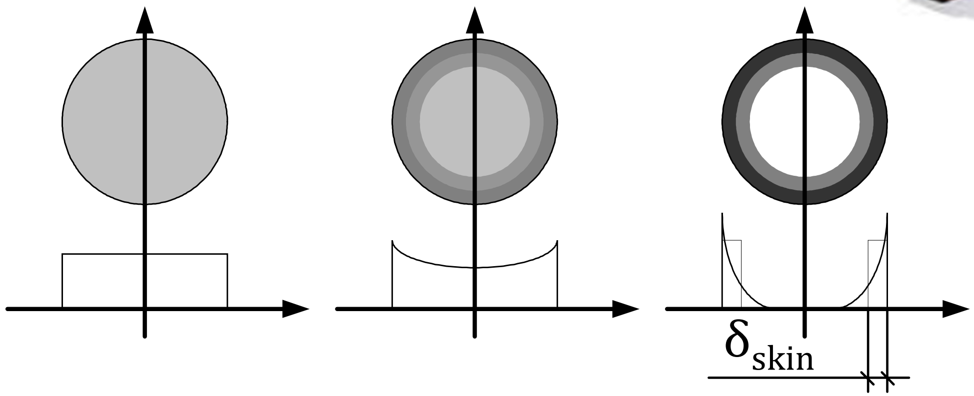
The diameter cannot be higher than twice the skin depth.

$$\delta_{skin} = \sqrt{\frac{\rho}{\pi \cdot \mu \cdot f}} \Rightarrow \delta_{skin}(cm) = \frac{7{,}5}{\sqrt{f(Hz)}}$$

Inductors: Copper Losses

HF Copper losses

HF Copper losses: Skin Effect



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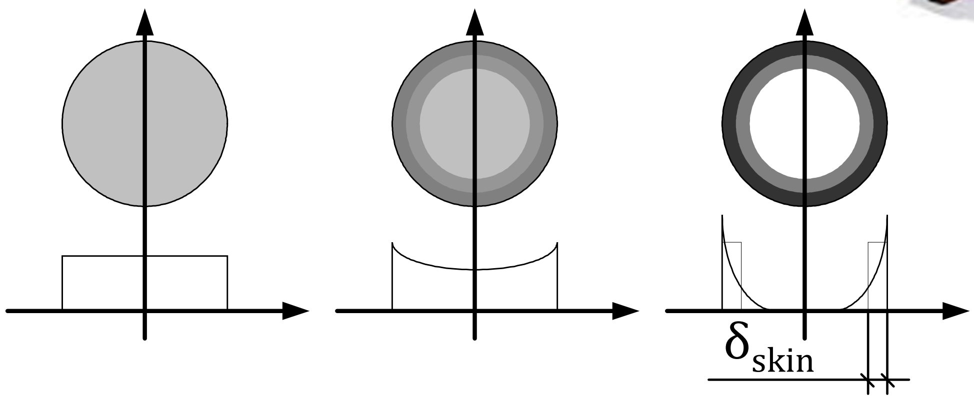


The diameter cannot be higher than twice the skin depth.

$$\delta_{skin} = \sqrt{\frac{\rho}{\pi \cdot \mu \cdot f}} \Rightarrow \delta_{skin}(cm) = \frac{7{,}5}{\sqrt{f\,(Hz)}}$$

The solution for the skin effect is to **split each turn in several wires in parallel**, and thus each wire would fulfill the skin depth condition. **LITZ wire** available from some manufactrers. However the *"use the whole window"* procedure still seems to be valid.

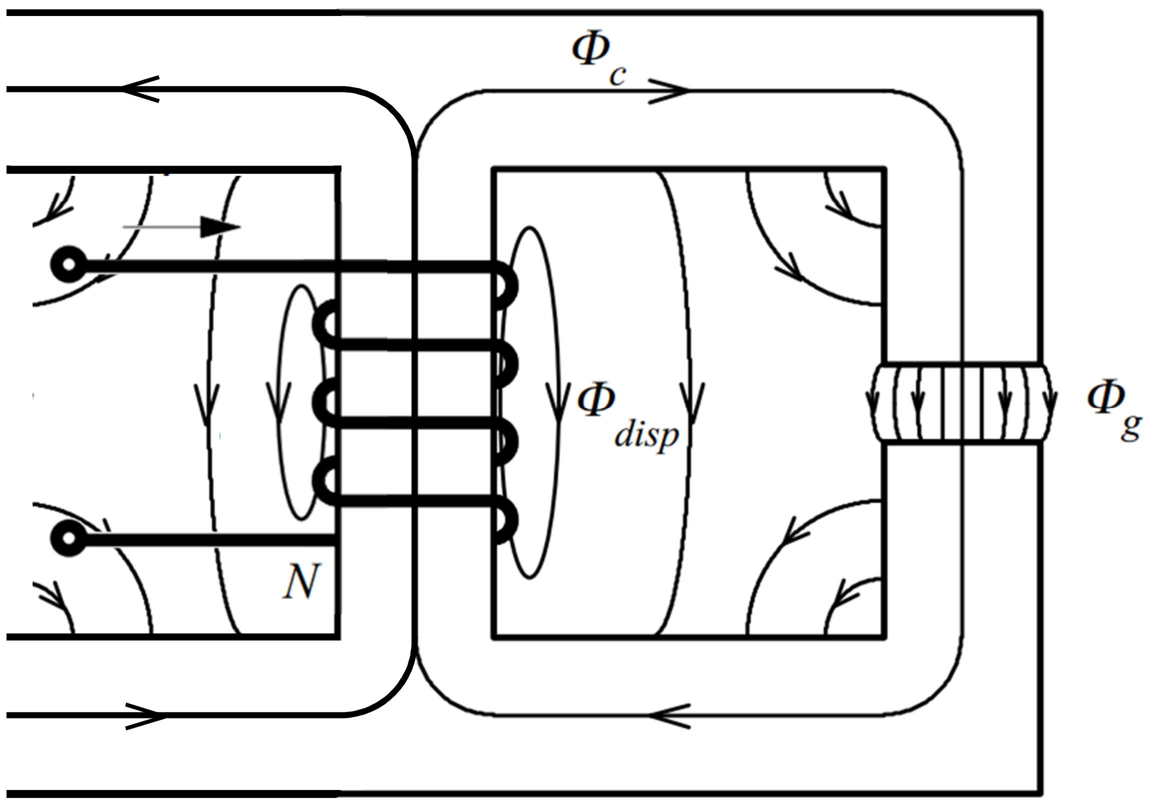
But this does not take into account other **HF** losses, called **proximity effect** losses, that can appear, **making such a design not valid.**

Inductors: Copper Losses

HF Copper losses

HF Copper losses: Proximity Effect

We suppose a one-dimensional distribution of H in the window area.

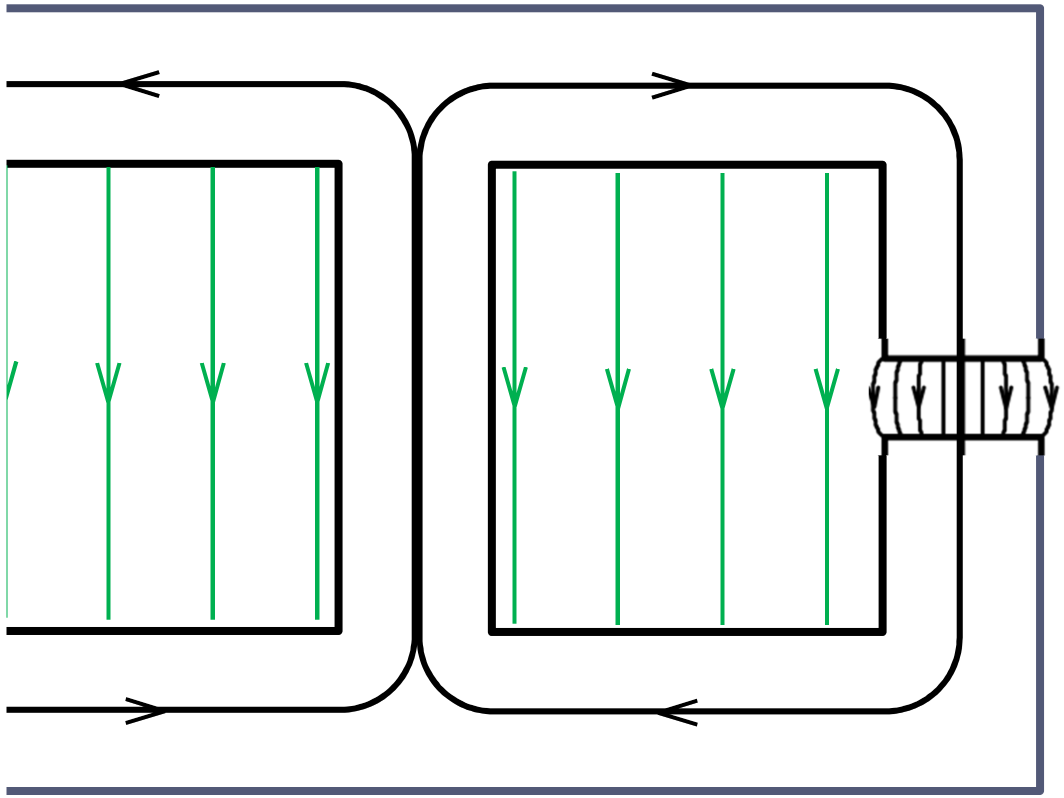


Inductors: Copper Losses

HF Copper losses

HF Copper losses: Proximity Effect

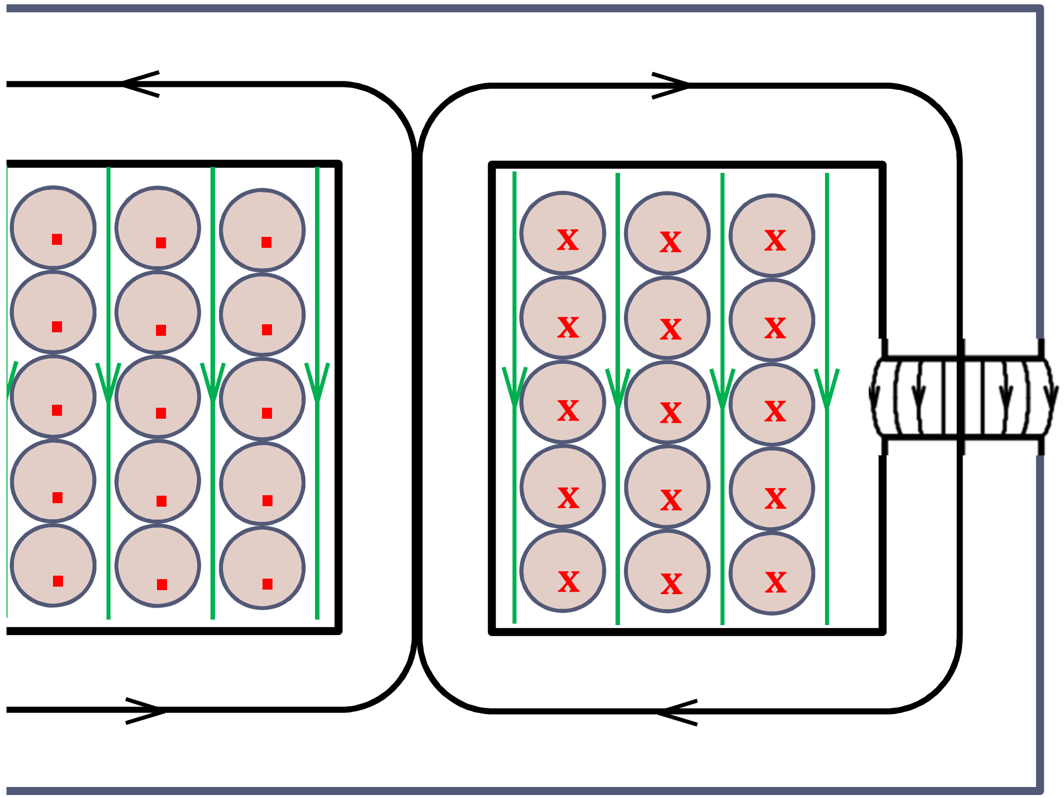
We suppose a one-dimensional distribution of H in the window area (**green** arrows).



Inductors: Copper Losses

HF Copper losses

HF Copper losses: Proximity Effect



We suppose a one-dimensional distribution of H in the window area (**green** arrows).

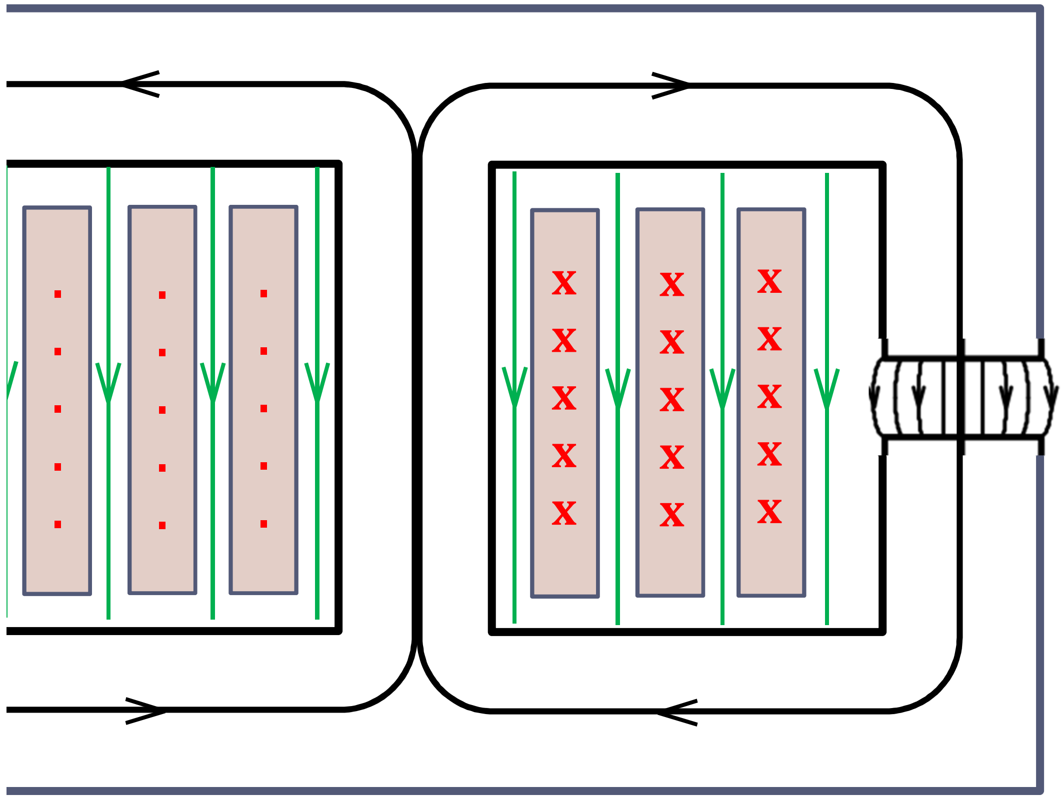
Consider a winding with a certain current flowing (**red**)

As the magnetic field has only one direction, then all the wires in a single layer can be considered to be a equivalent turn with a plane geometry, considering the equivalent area.

Inductors: Copper Losses

HF Copper losses

HF Copper losses: Proximity Effect



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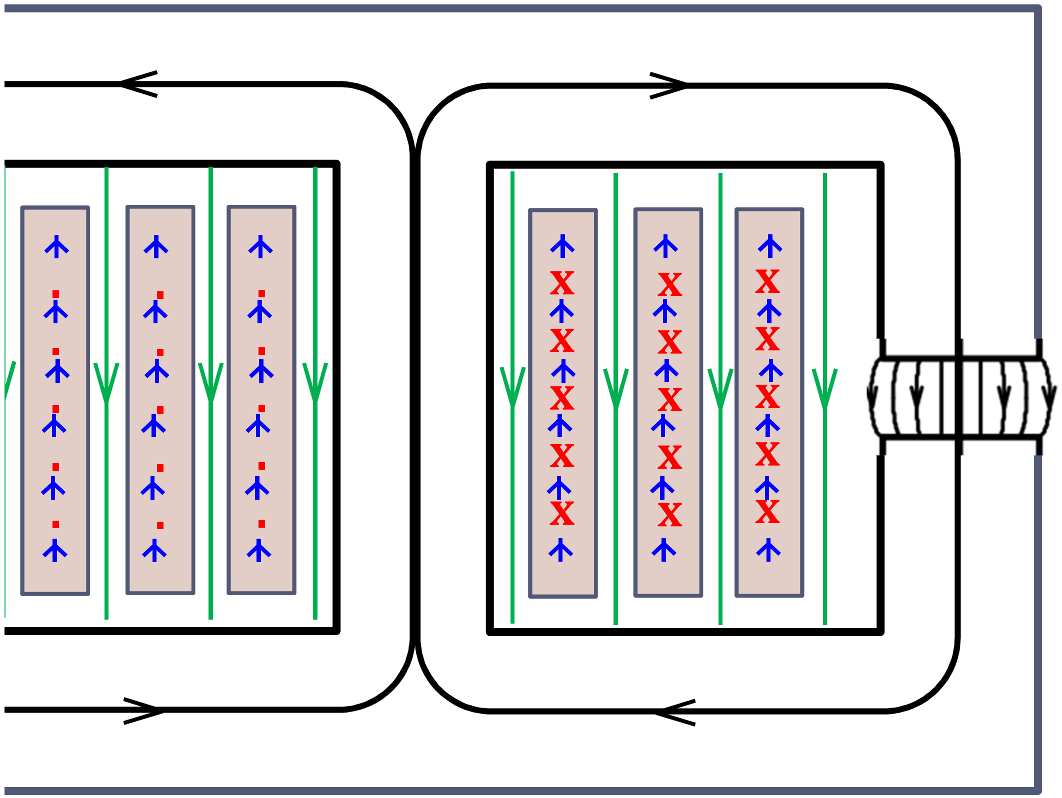
Inductors: Copper Losses

HF Copper losses

HF Copper losses: Proximity Effect



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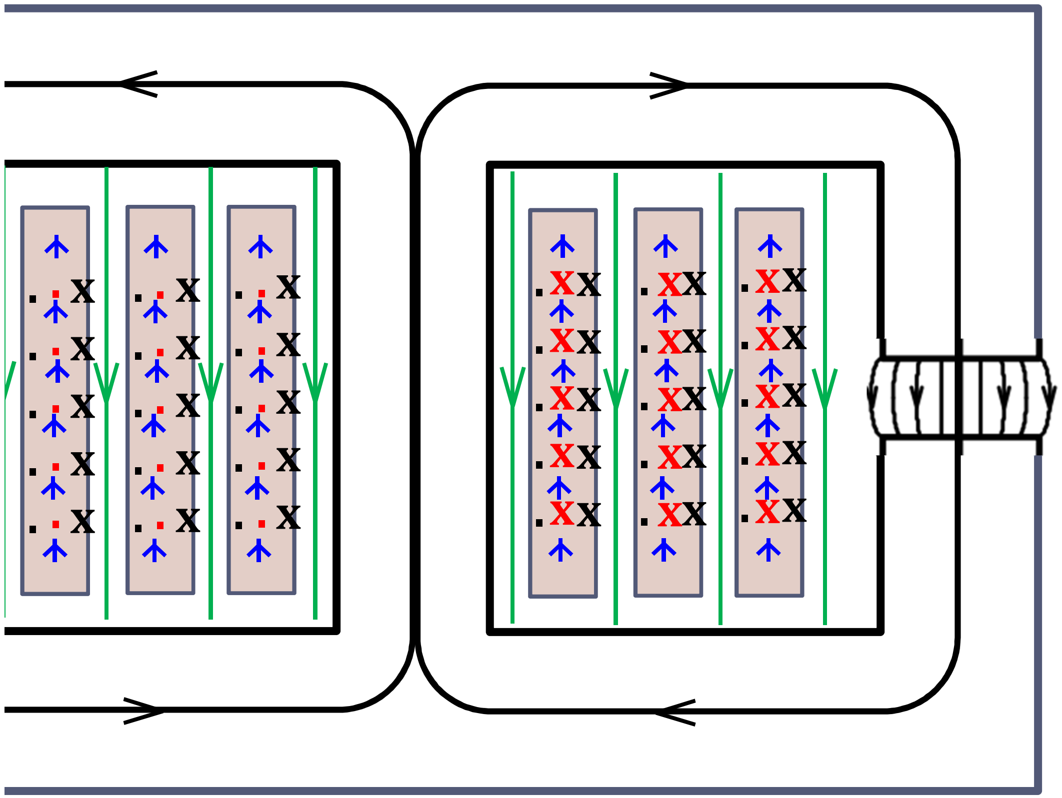
As the magnetic field has only one direction, then all the wires in a single layer can be considered to be a equivalent turn with a plane geometry, considering the equivalent area.

An induced field appears (**blue**)

Inductors: Copper Losses

HF Copper losses

HF Copper losses: Proximity Effect



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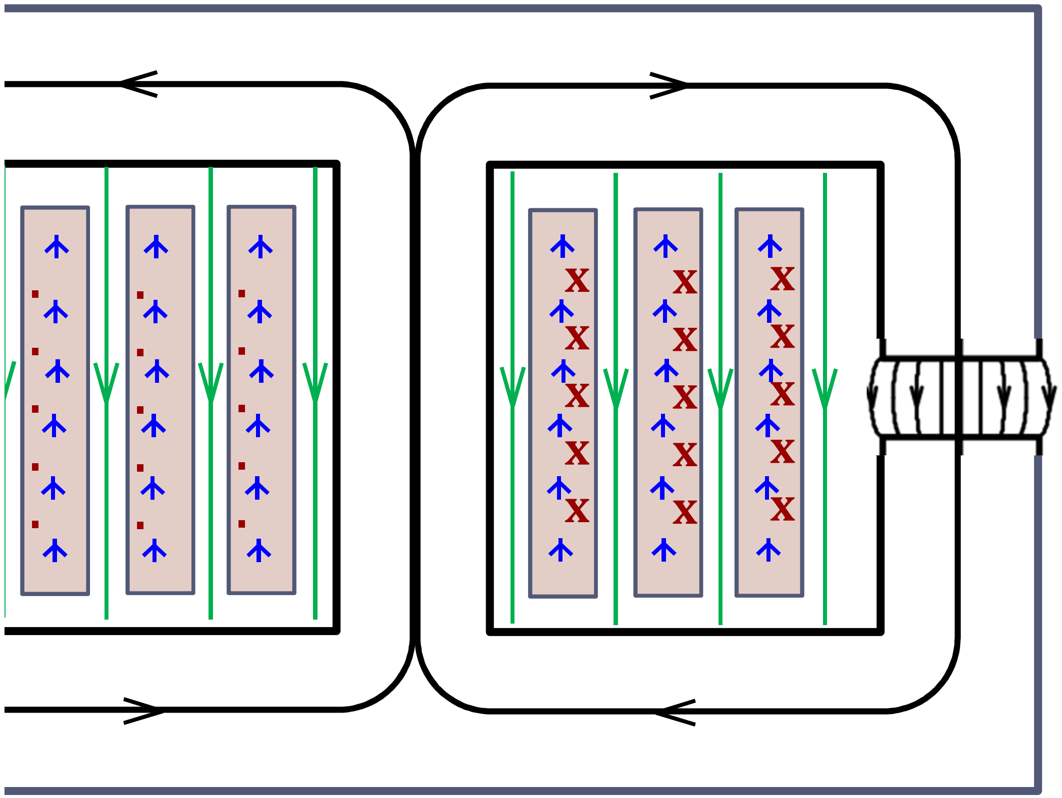
Effect of H_{ext}: The induced field provokes induced currents on the wire (**black**).

Inductors: Copper Losses

HF Copper losses

HF Copper losses: Proximity Effect



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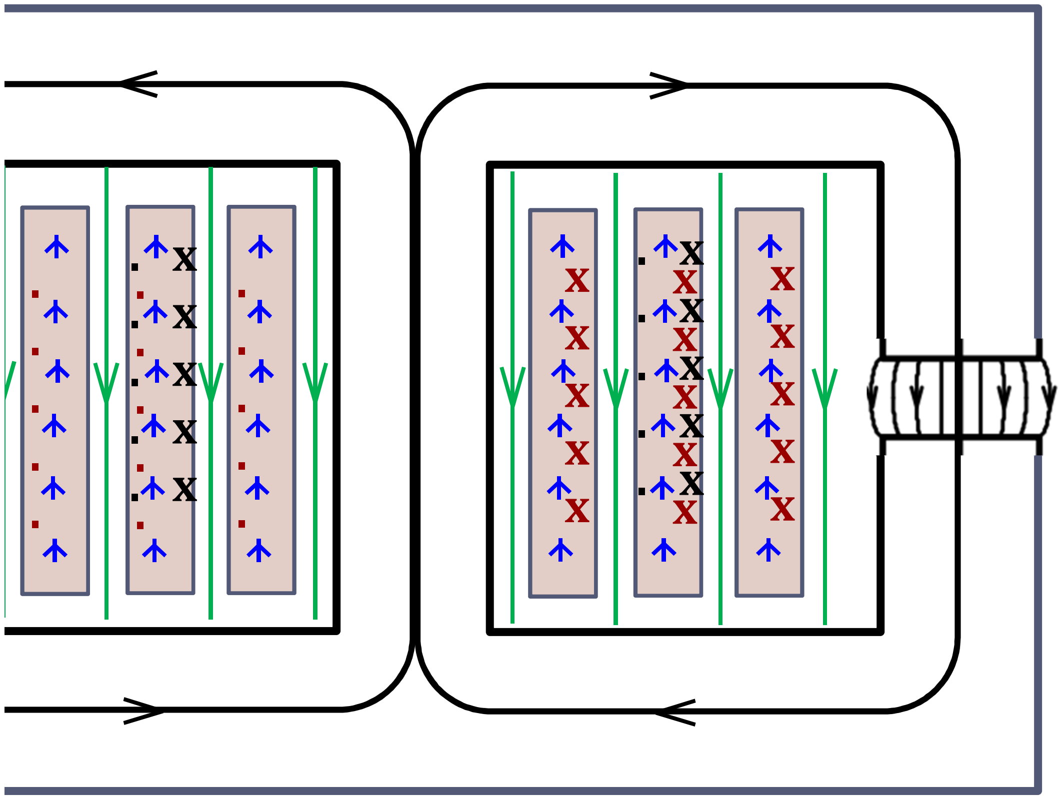
An induced field appears (**blue**)

Effect of H_{ext}: The induced field provokes induced currents on the wire (**black**). The overall effect moves the current towards the outer area of the wire (**dark red**).

Inductors: Copper Losses

HF Copper losses

HF Copper losses: Proximity Effect



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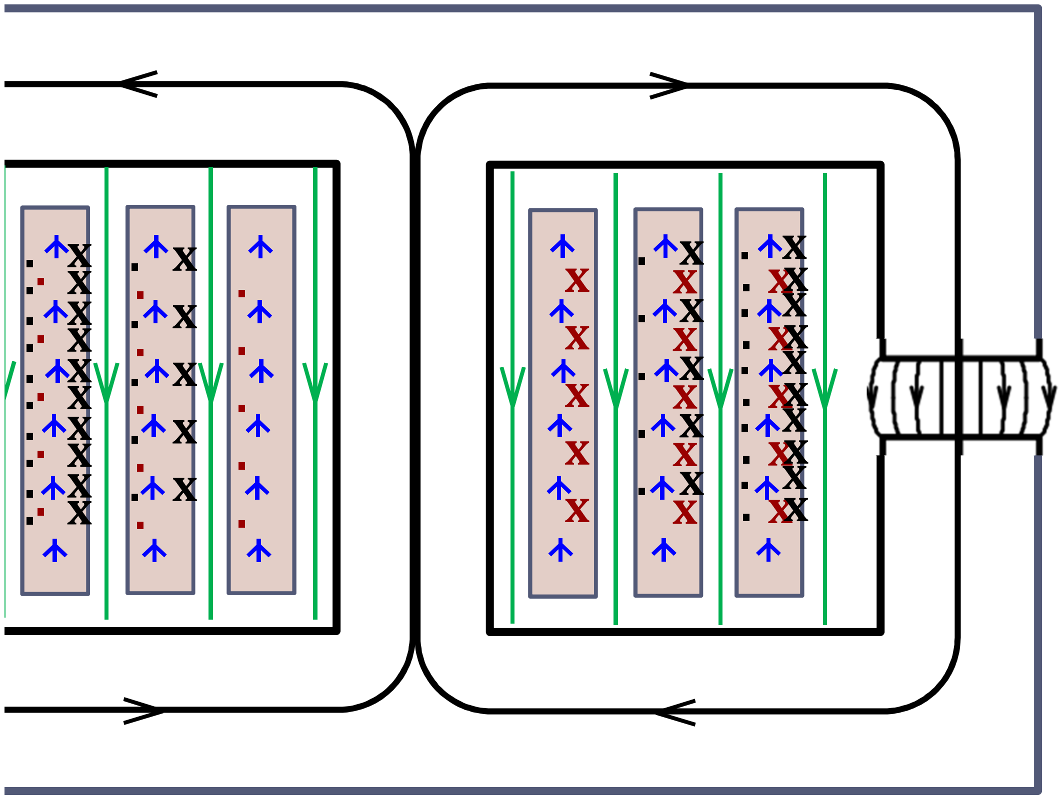
In the second layer, the nearby currents of the first layer induce a extra currents…

Inductors: Copper Losses

HF Copper losses

HF Copper losses: Proximity Effect



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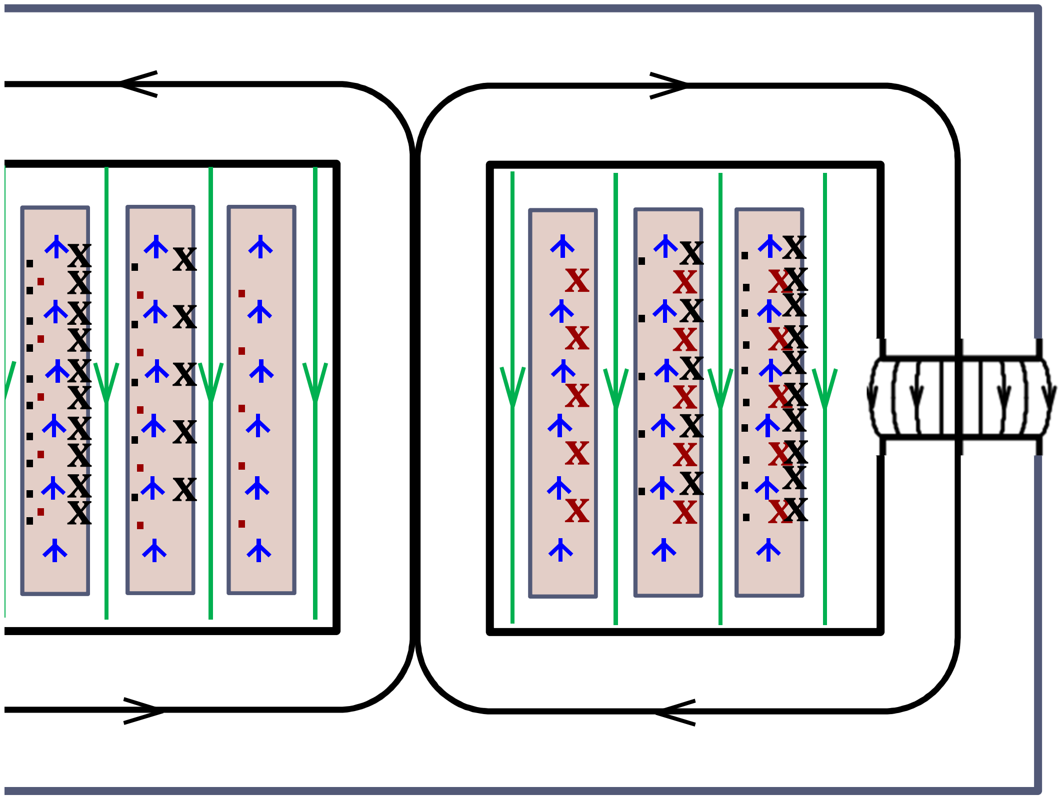
Effect of H_{ext}: The induced field provokes induced currents on the wire (**black**). The overall effect moves the current towards the outer area of the wire (**dark red**).
In the second layer, the nearby currents of the first layer induce a extra currents... And so on...

Inductors: Copper Losses

HF Copper losses

HF Copper losses: Proximity Effect



As a result of the proximity effect, and although the net current flowing through the windings is the same, **additional AC Eddy currents** are flowing through a **small wire area**.

As the losses increase with the square of the current, then **the overall losses increase exponentially with the number of layers in a winding**.

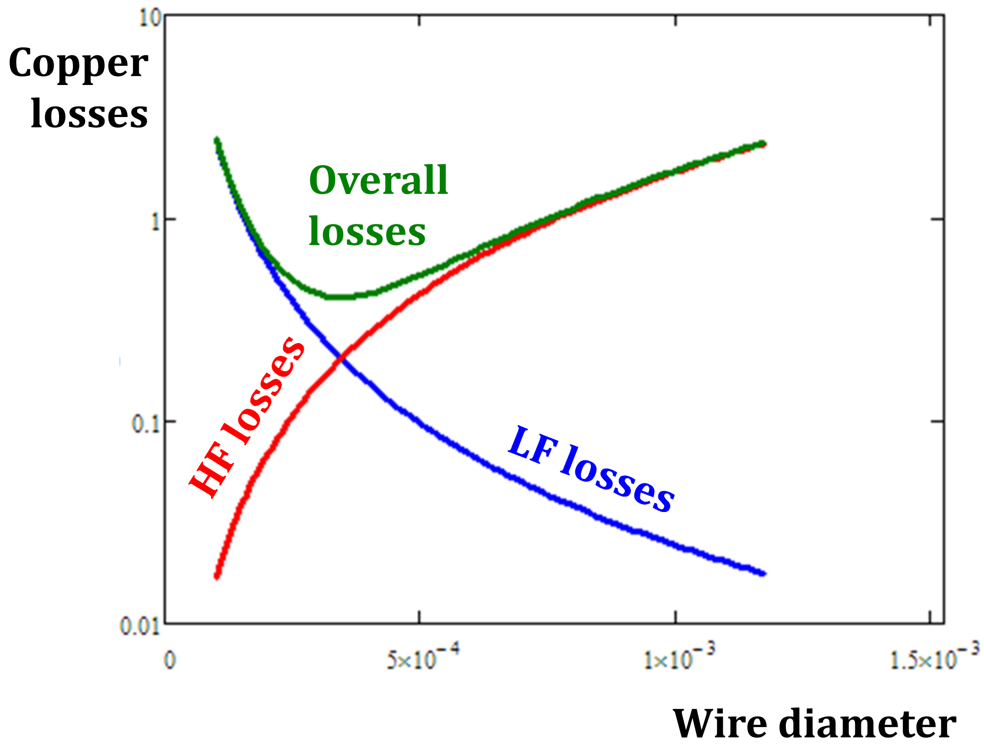
This is the effect that has **a higher contribution** in HF wire losses.

It is hard to calculate, **and numeric calculations** must be carried out to evaluate the windings disposition.

Inductors: Copper Losses

HF Copper losses

HF Copper losses: Proximity Effect



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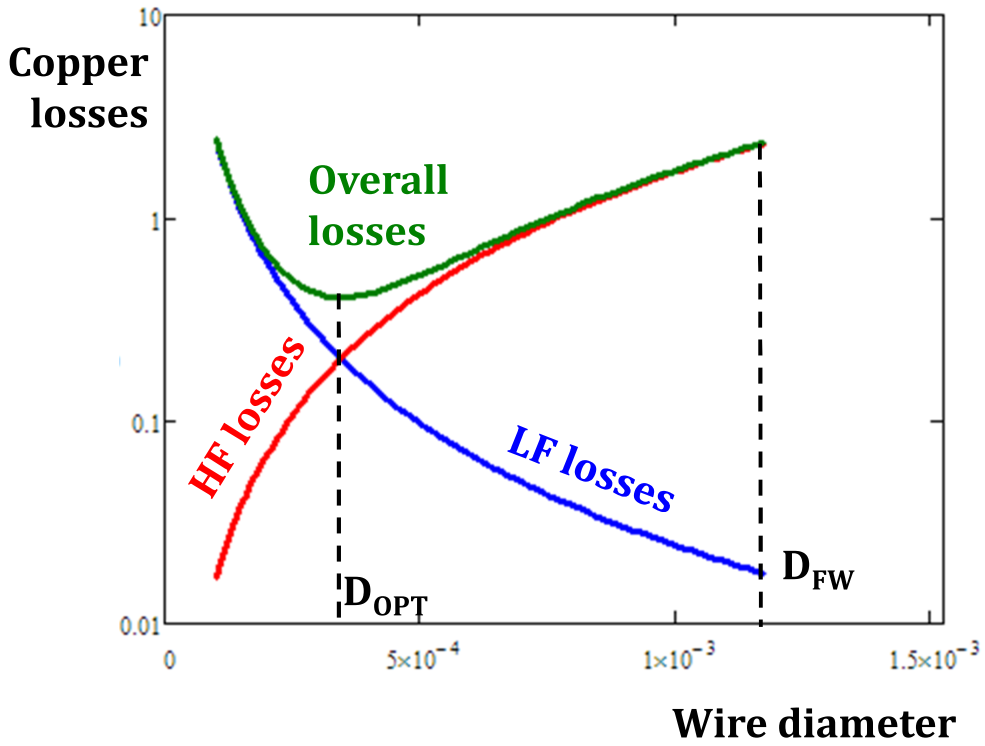

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This is the effect that has **a higher contribution** in HF wire losses.

It is hard to calculate, **and numeric calculations** must be carried out to evaluate the windings disposition.

As a **general procedure**, it is better to use smaller diameter wires, thus reducing the number of layers, although this increases a bit the LF wire losses.

Inductors

DESIGN EXAMPLE

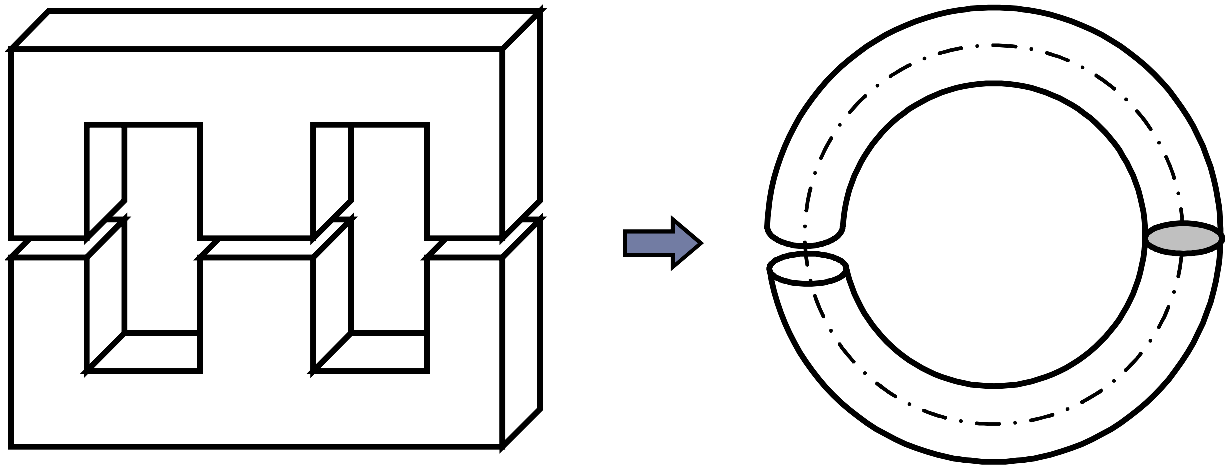
Inductors

Design of inductors: Equivalent Toroid Method

The method is based in considering the magnetic circuit as a toroid with an equivalent lenght, le, and an equivalent area, Ae.

Good aproximation for small air gap.

Very used in a first approach.



$$L = \frac{N^2}{\Re_{EQ}}$$

$$\Re_{EQ} = \oint_L \frac{dl}{\mu \cdot A} = \Re_a + \Re_c = \frac{g}{\mu_0 \cdot A_e} + \frac{l_e}{\mu \cdot A_e}$$

Inductors

Design of inductors: Equivalent Toroid Method

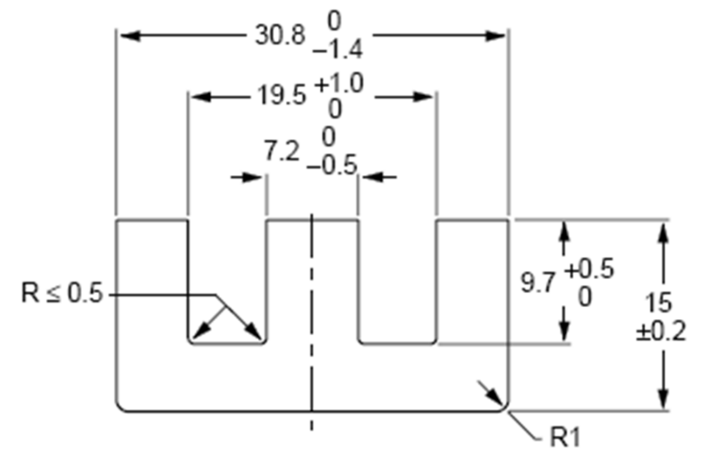
Philips Components — Product specification

E cores and accessories — E30/15/7

CORE SETS

Effective core parameters

SYMBOL	PARAMETER	VALUE	UNIT
$\Sigma(l/A)$	core factor (C1)	1.12	mm^{-1}
V_e	effective volume	4000	mm^3
l_e	effective length	67.0	mm
A_e	effective area	60.0	mm^2
A_{min}	minimum area	49.0	mm^2
m	mass of core half	≈11	g



Inductors

Design of inductors: Equivalent Toroid Method

Value of inductance, L:

$$L = \frac{1}{\Re_{EQ}} \cdot N^2$$

$$\Re_{EQ} = \oint_L \frac{dl}{\mu \cdot A} = \Re_a + \Re_c = \frac{g}{\mu_0 \cdot A_e} + \frac{l_e}{\mu \cdot A_e}$$

$$L = \frac{\mu_0 \cdot A_e \cdot N^2}{\frac{l_e}{\mu_r} + g}$$

Magnetic Density, B:

$$B = \frac{\Phi}{A_e} = \frac{N \cdot i}{\Re_{EQ}} \cdot \frac{1}{A_e} = \frac{N \cdot \mu_0 \cdot i}{\frac{l_e}{\mu_r} + g}$$

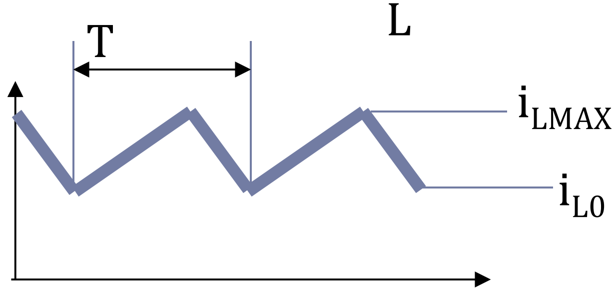
Valid for PEAK values, but also valid for only AC values, etc.

Inductors

Optimal Design of Inductors:

Parameters:

Power topology
(power level)
inductance
Current waveform



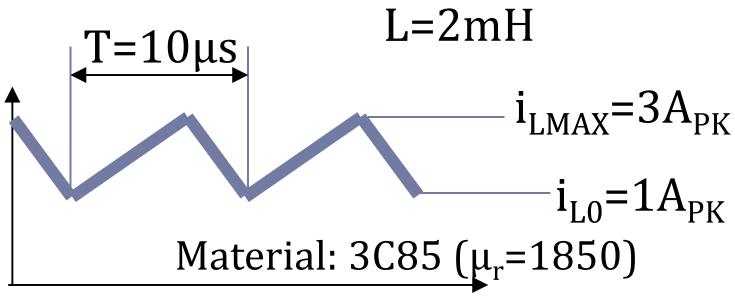
Inductors

EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

Step 1: Core Type and Size?

The manufacturers provide initial estimations for both the core type and the size.

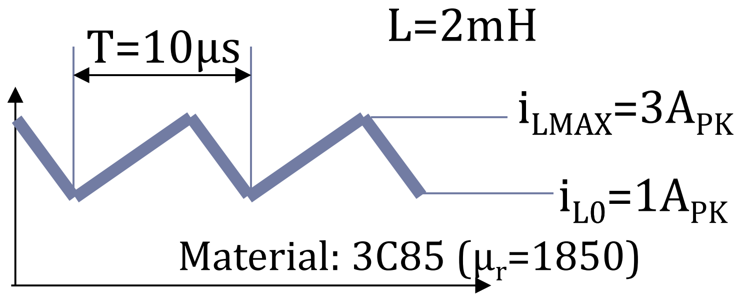
Inductors

EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

Step 1: Core Type and Size?

The manufacturers provide initial estimations for both the core type and the size.

Converter design selection chart(II)

FUNCTION	TYPE OF CONVERTER CIRCUIT[1]		
	BUCK-BOOST FLYBACK	BUCK BOOST FORWARD	PUSH-PULL
E cores	+	+	0
Planar E cores	–	+	0
EFD cores	–	+	+
ETD cores	0	+	+
EC cores	–	0	+
U cores	+	0	0
RM cores	0	+	0
EP cores	–	+	0
P cores	–	+	0
Ring cores	–	+	+

Note

1. "+" = Favourable; "0" = Average; "-" = Unfavourable.

Inductors

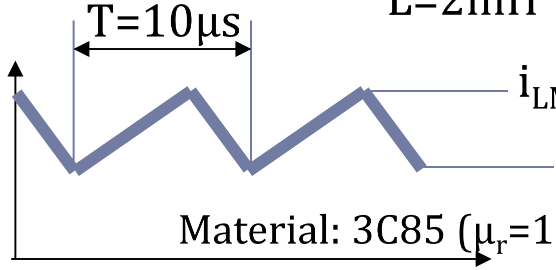
EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology
(power level)
inductance
Current waveform

L=2mH



Material: 3C85 (μ_r=1850)

BOOST Converter, 200 W

Step 1: Core Type and Size?

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Converter design selection chart(II)

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EC cores	–	0	+
U cores	+	0	0
RM cores	0	+	0
EP cores	–	+	0
P cores	–	+	0
Ring cores	–	+	+

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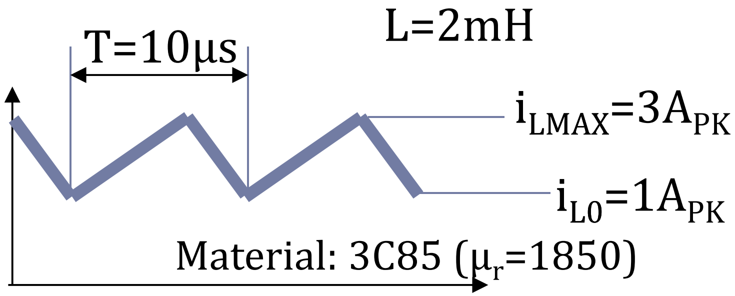
Inductors

EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

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RM cores	0	+	0
EP cores	–	+	0
P cores	–	+	0
Ring cores	–	+	+

Note

1. "+" = Favourable; "0" = Average; "-" = Unfavourable.

Power throughput for different core types (at 100 kHz switching frequency)

POWER RANGE (W)	CORE TYPE
<5	RM4; P11/7; R14; EF12.6; U10
5 to 10	RM5; P14/8
10 to 20	RM6; E20; P18/11; R23; U15; EFD15
20 to 50	RM8; P22/13; U20; RM10; ETD29; E25; R26/10; EFD20
50 to 100	ETD29; ETD34; EC35; EC41; RM12; P30/19; R26/20; EFD25
100 to 200	ETD34; ETD39; ETD44; EC41; EC52; RM14; P36/22; E30; R56; U25; U30; E42; EFD30
200 to 500	ETD44; ETD49; E55; EC52; E42; P42/29; U37
<500	E65; EC70; U93; U100

Inductors

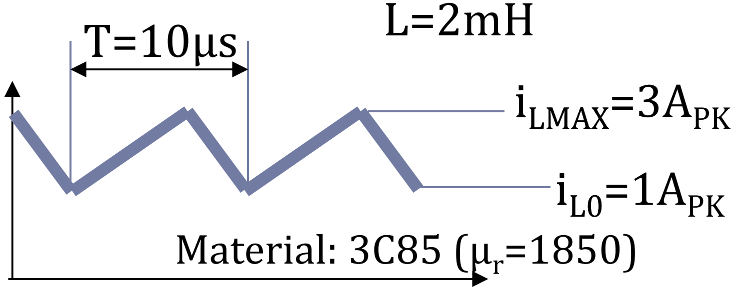
EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform

L=2mH



Material: 3C85 (μ_r=1850)

BOOST Converter, 200 W

Step 1: Core Type and Size?

The manufacturers provide initial estimations for both the core type and the size.

Converter design selection chart(II)

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E cores	+	+	0
Planar E cores	–	+	0
EFD cores	–	+	+
ETD cores	0	+	+
EC cores	–	0	+
U cores	+	0	0
RM cores	0	+	0
EP cores	–	+	0
P cores	–	+	0
Ring cores	–	+	+

Note

1. "+" = Favourable; "0" = Average; "-" = Unfavourable.

Power throughput for different core types (at 100 kHz switching frequency)

POWER RANGE (W)	CORE TYPE
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200 to 500	ETD44; ETD49; E55; EC52; E42; P42/29; U37
<500	E65; EC70; U93; U100

PRODUCT OVERVIEW AND TYPE NUMBER STRUCTURE

Product overview ETD cores

CORE TYPE	V_e (mm^3)	A_e (mm^3)	MASS (g)
ETD29	5470	76.0	14
ETD34	7640	97.1	20
ETD39	11500	125	30
ETD44	17800	173	47
ETD49	24000	211	62
ETD54	35500	280	90
ETD59	51500	368	130

Inductors

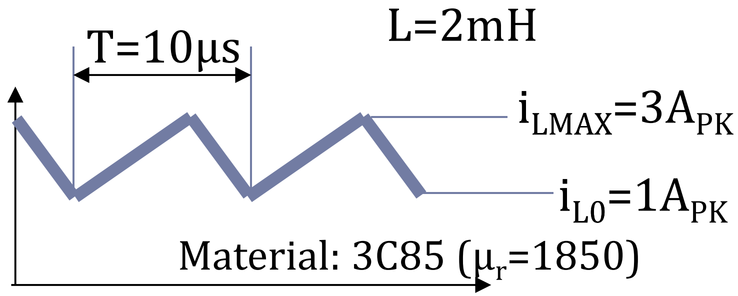
EXAMPLE

Optimal Design of Inductors:

Step 1: Core Type and Size: ETD44

Parameters:

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

Step 2: Estimation of Losses

$$P_L = P_{CORE} + P_{CU}$$

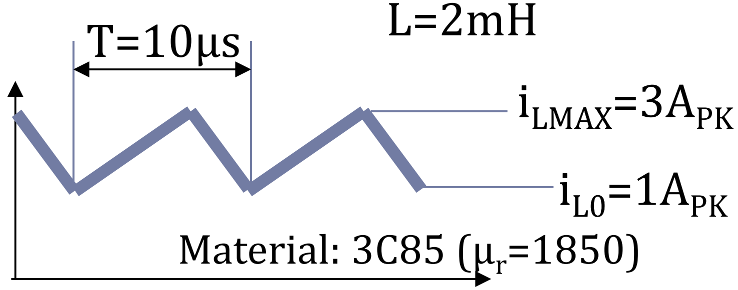
Inductors

EXAMPLE

Optimal Design of Inductors:

Parameters:

- Power topology (power level)
- inductance
- Current waveform



BOOST Converter, 200 W

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Losses

$$P_L = P_{CORE} + P_{CU}$$

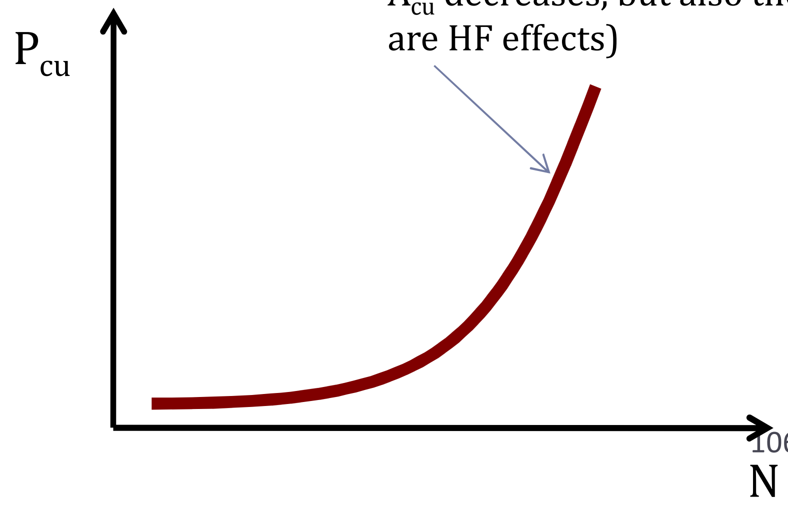
Cupper losses are higher if N increases

$$R_{cu} = \rho \frac{l_{TURN}}{A_{cu}} \cdot N$$

$$P_{cu} = i_{RMS}^{\,2} \cdot R_{cu}$$

$$P_{cu} = i_{RMS}^{\,2} \cdot \rho \cdot \frac{l_{esp}}{A_{cu}} \cdot N$$

Not linearly (If N increases, A_{cu} decreases, but also there are HF effects)



Inductors

EXAMPLE

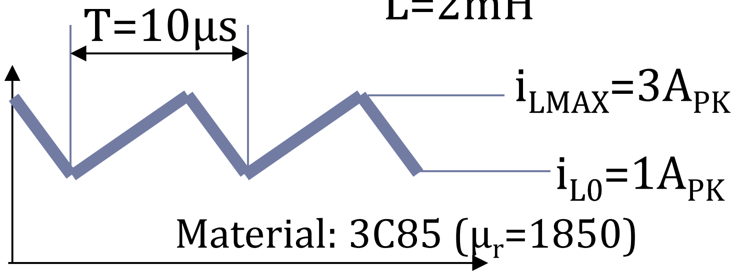
Optimal Design of Inductors:

Parameters:

Step 1: Core Type and Size: ETD44

Power topology
(power level)
inductance
Current waveform

L=2mH



Material: 3C85 (μ_r=1850)

BOOST Converter, 200 W

Step 2: Estimation of Losses

$$P_L = P_{CORE} + P_{CU}$$

Core losses are smaller if N increases

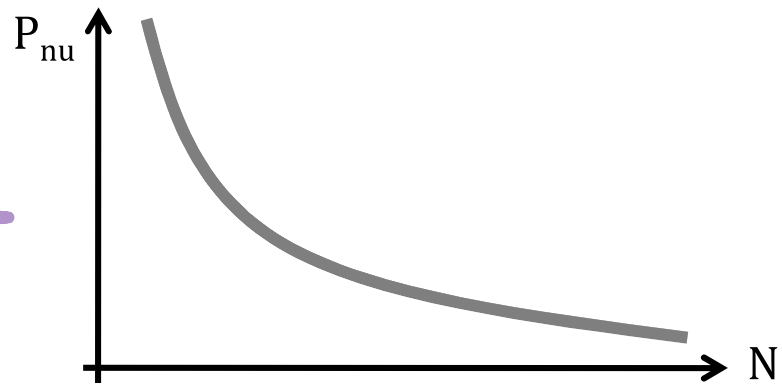
$$\hat{B} = \frac{N \cdot \mu_0 \cdot \hat{\imath}}{\frac{l_e}{\mu_r} + g}$$

$$L = \frac{\mu_0 \cdot A_e \cdot N^2}{\frac{l_e}{\mu_r} + g}$$

$$\hat{B} = \frac{L \cdot \hat{\imath}}{A_e \cdot N}$$

$$P_{CORE} \cong k \cdot \hat{B}^2$$

Hysteresis



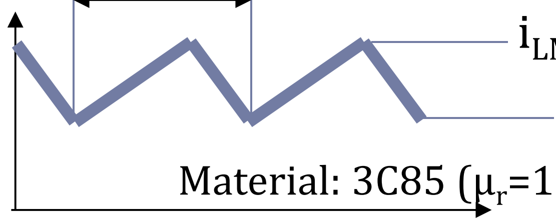
Inductors

EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Losses

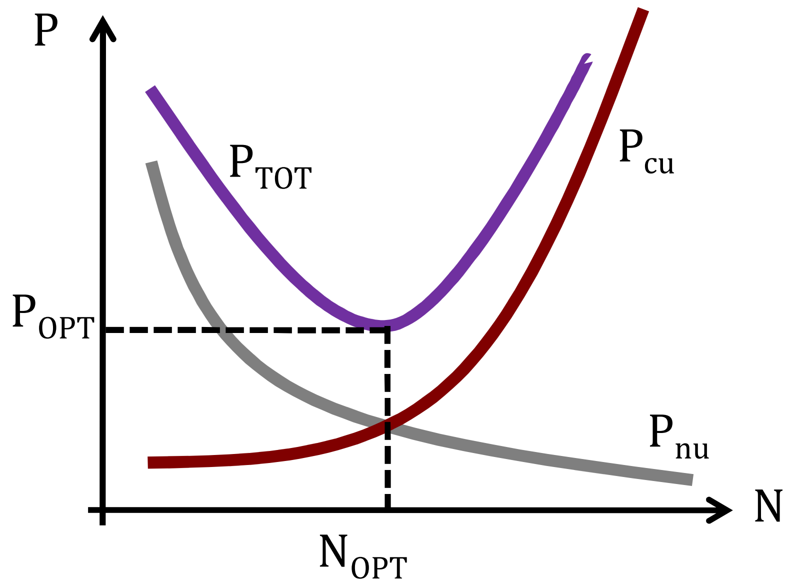
$$P_L = P_{CORE} + P_{CU}$$

$$N = N_{OPT}$$

$$P_{CORE} = P_{CU} = \frac{P_L}{2}$$

Usual value for P_L?

$$\frac{P_L}{P_{CONVERTER}} = 1\%$$



Inductors

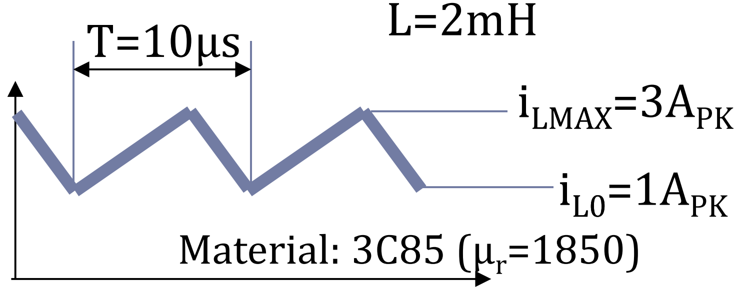
EXAMPLE

Optimal Design of Inductors:

Parameters:

Step 1: Core Type and Size: ETD44

Power topology
(power level)
inductance
Current waveform



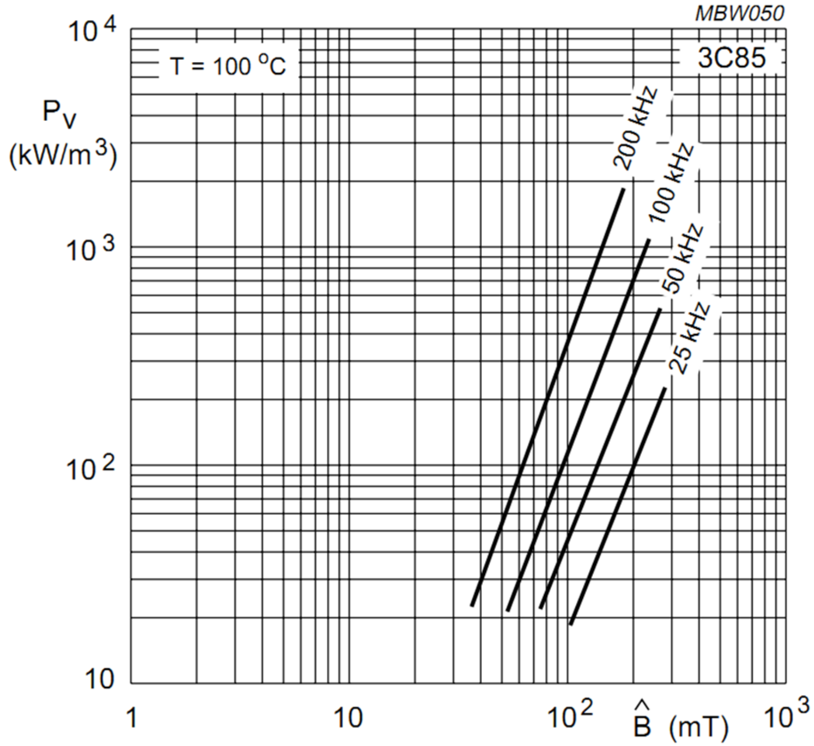
BOOST Converter, 200 W

Step 2: Estimation of Core Losses

Core losses are a function of the AC component of the magnetic density, B

$\hat{B} \Leftrightarrow P_{CORE}$

$$P_{CORE} = 1.0W$$



Inductors

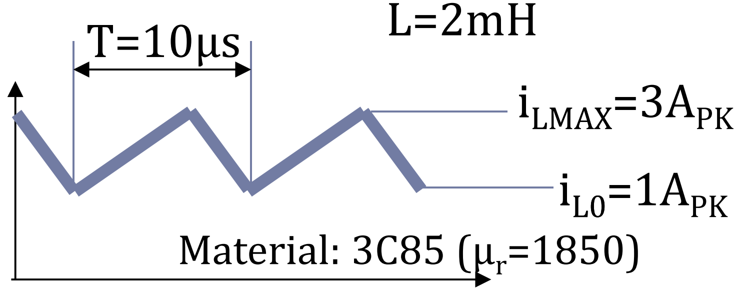
EXAMPLE

Optimal Design of Inductors:

Step 1: Core Type and Size: ETD44

Parameters:

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

Step 2: Estimation of Core Losses

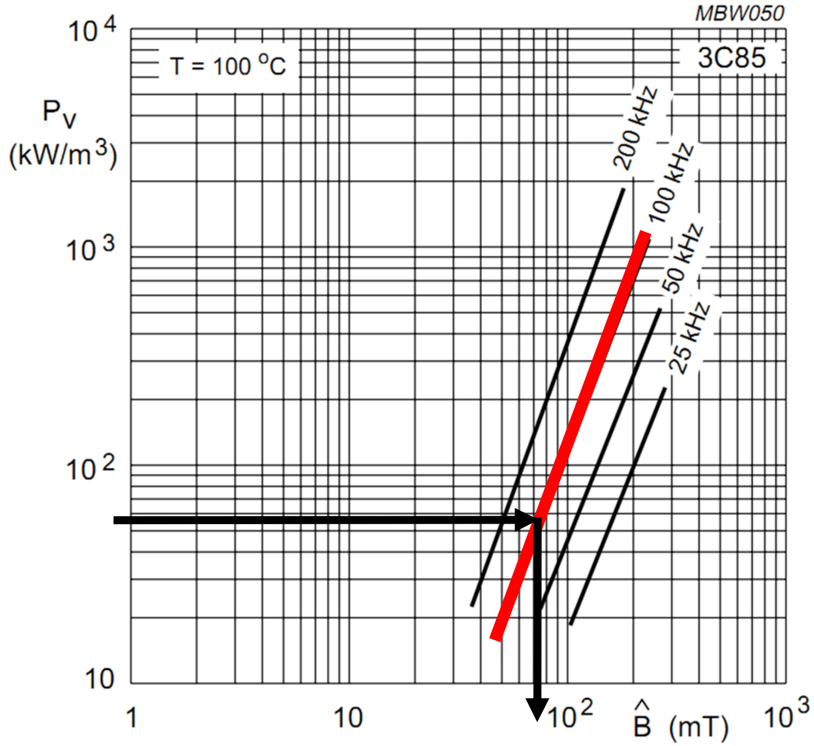
Core losses are a function of the AC component of the magnetic density, B

$\hat{B} \Leftrightarrow P_{CORE}$

$$P_{CORE} = 1.0W$$

$$Pv = \frac{P_{CORE}}{V_e} = \frac{1.0W}{17800mm^3} = 56.1kW/m_3$$

$$\hat{B} = 77mT$$



Inductors

EXAMPLE

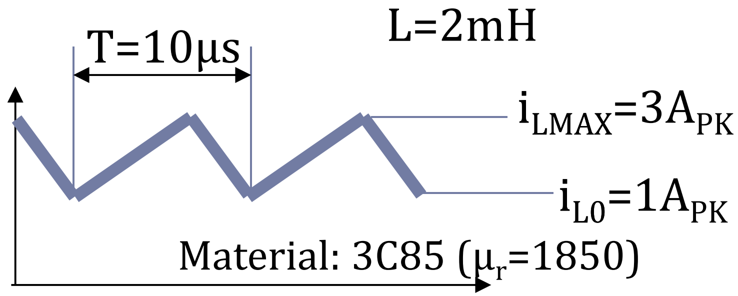
Optimal Design of Inductors:

Parameters:

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

Step 3: Calculation of N

$$\hat{B} = 77mT$$

$$\left.\begin{aligned} \hat{B} &= \frac{N\cdot\mu_0\cdot\hat{\imath}}{\frac{l_e}{\mu_r}+g} \\ L &= \frac{\mu_0\cdot A_e\cdot N^2}{\frac{l_e}{\mu_r}+g} \end{aligned}\right\} \quad \hat{B} = \frac{L\cdot\hat{\imath}}{A_e\cdot N} \Rightarrow N = \frac{L\cdot\hat{\imath}}{A_e\cdot\hat{B}}$$

$$N = \frac{2mH\cdot\left(\frac{3A-1A}{2}\right)}{173mm^2\cdot 77mT} = 150.1 \Rightarrow 151$$

Inductors

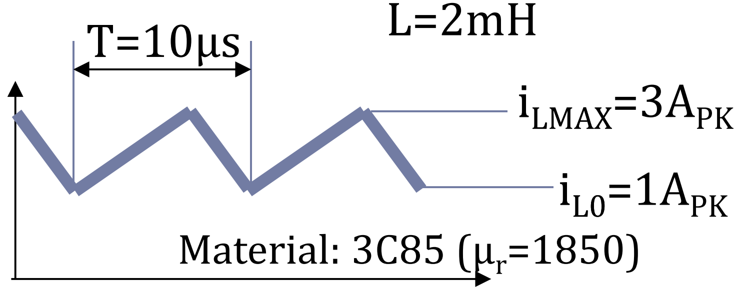
EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform

L=2mH



BOOST Converter, 200 W

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

Step 3: Calculation of N=151

Step 4: Calculation of Air Gap

$$\hat{B} = \frac{N \cdot \mu_0 \cdot \hat{i}}{\frac{l_e}{\mu_r} + g} \Rightarrow g = \frac{N \cdot \mu_0 \cdot \hat{i}}{\hat{B}} - \frac{l_e}{\mu_r}$$

$$g = \frac{151 \cdot 4 \cdot \pi \cdot 10^{-7} \cdot 1A}{77mT} - \frac{103mm}{1850} \Rightarrow 2.43mm$$

Inductors

EXAMPLE

Optimal Design of Inductors:

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

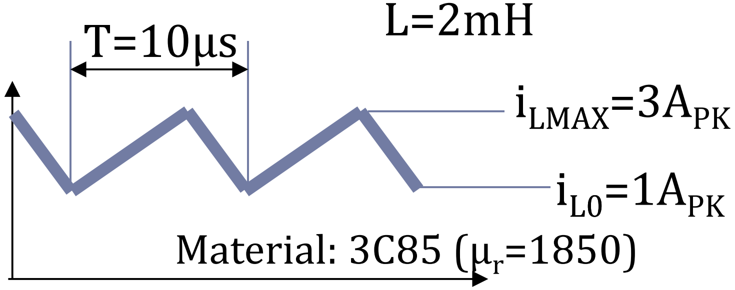
Step 3: Calculation of N=151

Step 4: Calculation of Air Gap g=2.43mm

Parameters:

Power topology
(power level)
inductance
Current waveform

L=2mH



BOOST Converter, 200 W

Step 5: Check core saturation

$$B_{MAX} = \frac{N \cdot \mu_0 \cdot i_{MAX}}{\frac{l_e}{\mu_r} + g}$$

Inductors

EXAMPLE

Optimal Design of Inductors:

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

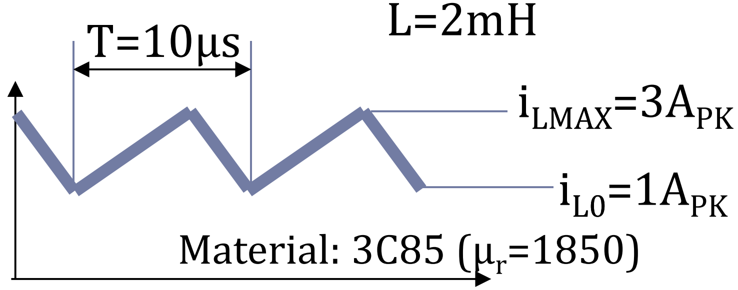
Step 3: Calculation of N=151

Step 4: Calculation of Air Gap g=2.43mm

Parameters:

Power topology (power level)
inductance
Current waveform

L=2mH



BOOST Converter, 200 W

Step 5: Check core saturation

$$B_{MAX}=\frac{N\cdot\mu_0\cdot i_{MAX}}{\dfrac{l_e}{\mu_r}+g} \Rightarrow B_{MAX}=\frac{151\cdot 4\cdot\pi\cdot 10^{-7}\cdot 3A_{PK}}{\dfrac{0.103m}{1850}+0.00243m}=0.23T$$

Inductors

EXAMPLE

Optimal Design of Inductors:

Step 1: Core Type and Size: ETD44

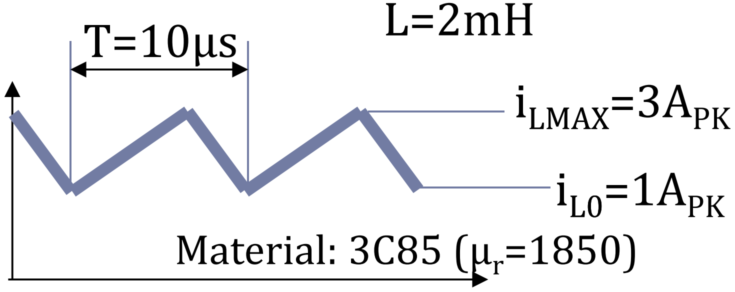
Step 2: Estimation of Core Losses

Step 3: Calculation of N=151

Step 4: Calculation of Air Gap g=2.43mm

Parameters:

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

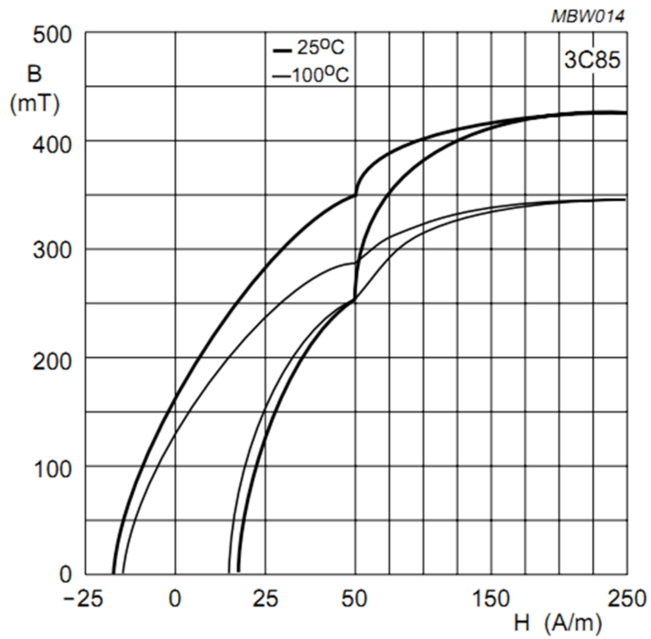
Step 5: Check core saturation

$$B_{MAX} = 230mT$$

Consider limit as 330 mT. If limit is surpassed, try to decrease core losses or move to a larger core.

3C85 SPECIFICATIONS

SYMBOL	CONDITIONS	VALUE	UNIT
μ_i	25 °C; ≤10 kHz; 0.1 mT	2000 ±20%	
μ_a	100 °C; 25 kHz; 200 mT	5500 ±25%	
B	25 °C; 10 kHz; 250 A/ m 100 °C; 10 kHz; 250 A/ m	≥400 ≥330	mT
P_V	100 °C; 25 kHz; 200 mT 100 °C; 100 kHz; 100 mT	≤140 ≤165	kW/m³
ρ	DC; 25 °C	≈2	Ωm
T_C		≥200	°C
density		≈4800	kg/m³



Inductors

EXAMPLE

Optimal Design of Inductors:

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

Step 3: Calculation of N=151

Step 4: Calculation of Air Gap g=2.43mm

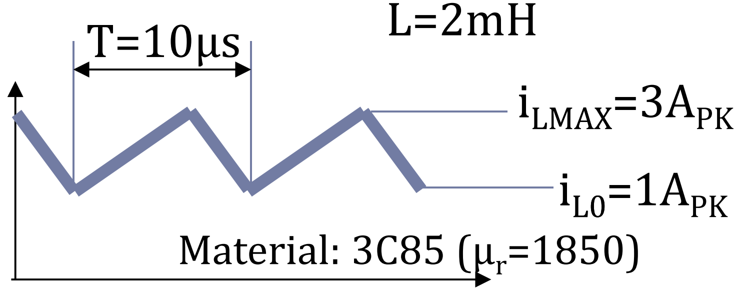
Step 5: Check core saturation. B_{MAX} =0.23T

Step 6: Calculation of Wire Diameter

Parameters:

Power topology (power level)
inductance
Current waveform

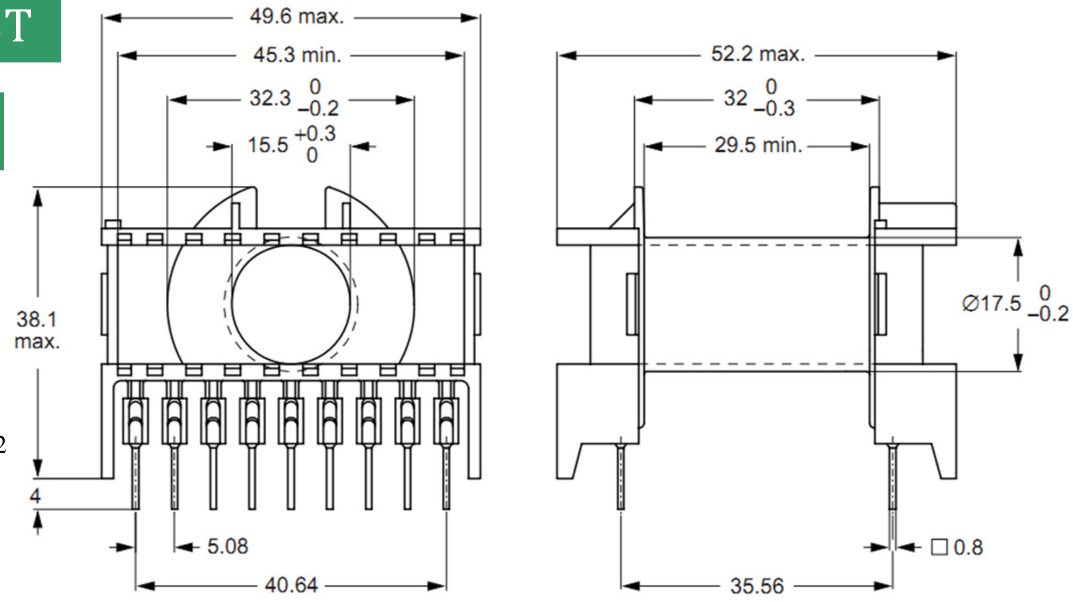
L=2mH



BOOST Converter, 200 W

FIRST APPROACH: consider to use all the window of the bobbin **(not optimized for proximity effect !!)**

$$Wd = \frac{32.1mm - 17.5mm}{2} x29.5mm = 215.35mm^2$$



Dimensions in mm.

Inductors

EXAMPLE

Optimal Design of Inductors:

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

Step 3: Calculation of N=151

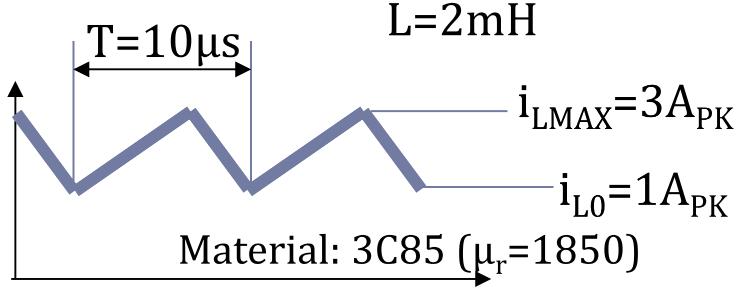
Step 4: Calculation of Air Gap g=2.43mm

Step 5: Check core saturation. B_{MAX} =0.23T

Parameters:

Power topology (power level)
inductance
Current waveform

L=2mH



BOOST Converter, 200 W

Step 6: Calculation of Wire Diameter

FIRST APPROACH: consider to use all the window of the bobbin **(not optimized for proximity effect !!)**

$$Wd = \frac{32.1mm - 17.5mm}{2} x29.5mm = 215.35mm^2$$

Select the effective area as 30% of the window area

$$EWd = 0.3x215.35mm^2 = 64.6mm^2$$

For the fixed number of turns, which is the diameter?

$$N \cdot \pi \cdot \left(\frac{D}{2}\right)^2 = EWd$$

Explicitly D:

$$D = \sqrt{\frac{EWd \cdot 4}{N \cdot \pi}} = \ldots = 0.836mm$$

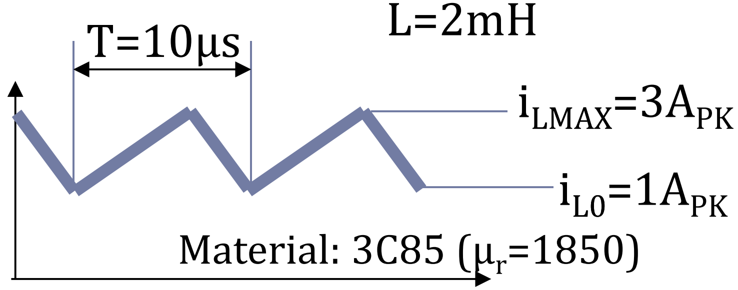
Inductors

EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

Step 3: Calculation of N=151

Step 4: Calculation of Air Gap g=2.43mm

Step 5: Check core saturation. B_{MAX} =0.23T

Step 6: Calculation of Wire Diameter $D = 0.836mm$

Does it fulfill the skin effect condition?

$$\delta_{skin}(cm) = \frac{7{,}5}{\sqrt{f(Hz)}} = \frac{7{,}5}{\sqrt{100000}} = 2.37 \cdot 10^{-2}\,cm$$

$$\delta_{skin}(mm) = 0.237mm$$

$$D_{skin}(mm) = 0.474mm$$

Inductors

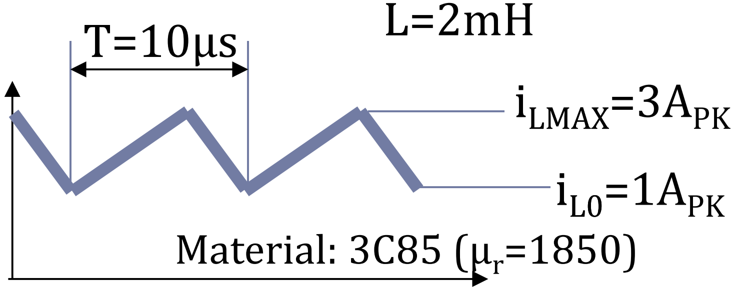
EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level) inductance Current waveform

L=2mH



Material: 3C85 (μ_r=1850)

BOOST Converter, 200 W

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

Step 3: Calculation of N=151

Step 4: Calculation of Air Gap g=2.43mm

Step 5: Check core saturation. B_{MAX} =0.23T

Step 6: Calculation of Wire Diameter

$$D = 0.836mm$$

Does it fulfill the skin effect condition?

$$\delta_{skin}(cm) = \frac{7,5}{\sqrt{f(Hz)}} = \frac{7,5}{\sqrt{100000}} = 2.37{\cdot}10^{-2}\,cm$$

$$\delta_{skin}(mm) = 0.237mm$$

$$D_{skin}(mm) = 0.474mm \boxed{<= 0.836mm}$$

Inductors

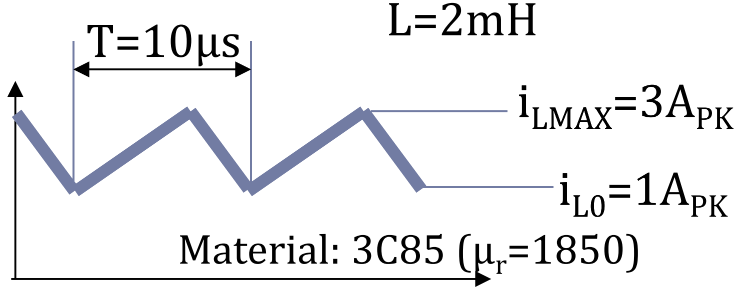
EXAMPLE

Optimal Design of Inductors:

- Step 1: Core Type and Size: ETD44
- Step 2: Estimation of Core Losses
- Step 3: Calculation of N=151
- Step 4: Calculation of Air Gap g=2.43mm
- Step 5: Check core saturation. B_{MAX} =0.23T

Parameters:

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

Step 6: Calculation of Wire Diameter

$$D = 0.836mm$$

Does it fulfill the skin effect condition?

$$\delta_{skin}(cm) = \frac{7{,}5}{\sqrt{f(Hz)}} = \frac{7{,}5}{\sqrt{100000}} = 2.37 \cdot 10^{-2}\, cm$$

$$\delta_{skin}(mm) = 0.237mm$$

$$D_{skin}(mm) = 0.474mm \boxed{<= 0.836mm}$$

The necesary diameter is greater than the skin limit…

Use more than one conductor per turn…

$$D = \sqrt{\frac{EWd \cdot 4}{N \cdot \pi}} \Rightarrow D = \sqrt{\frac{EWd \cdot 4}{\boxed{4 \cdot N} \pi}} = \ldots = 0.418mm$$

$$D = 0.4mm$$

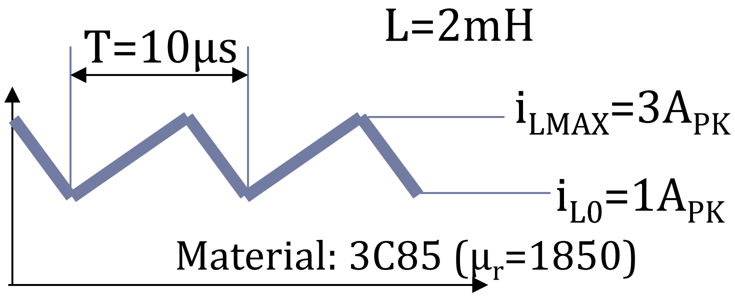
Inductors

EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

Step 3: Calculation of N=151

Step 4: Calculation of Air Gap g=2.43mm

Step 5: Check core saturation. B_{MAX} =0.23T

Step 6: Calculation of Wire Diameter: D=0.4mm, 4 wires/turn

Step 7: Check losses

$$P_{CORE} = 1.01W$$

(If $\hat{B}$ has been changed or core increased, this value changes)

Inductors

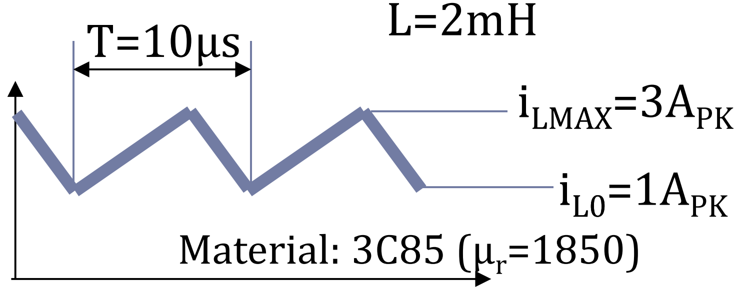
EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform

L=2mH



BOOST Converter, 200 W

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

Step 3: Calculation of N=151

Step 4: Calculation of Air Gap g=2.43mm

Step 5: Check core saturation. B_{MAX} =0.23T

Step 6: Calculation of Wire Diameter: D=0.4mm, 4 wires/turn

Step 7: Check losses

$$P_{CORE} = 1.01W$$

(If $\hat{B}$ has been changed or core increased, this value changes)

$$P_{cu} = i_{RMS}{}^2 \cdot \rho \cdot \frac{l_{esp}}{A_{cu}} \cdot N = 2^2 \cdot \frac{1}{5.7\cdot 10^7} \cdot \frac{75mm}{4\cdot 0.125664\, mm^2} \cdot 151 = \boxed{1.919W}$$

Larger than 1W!

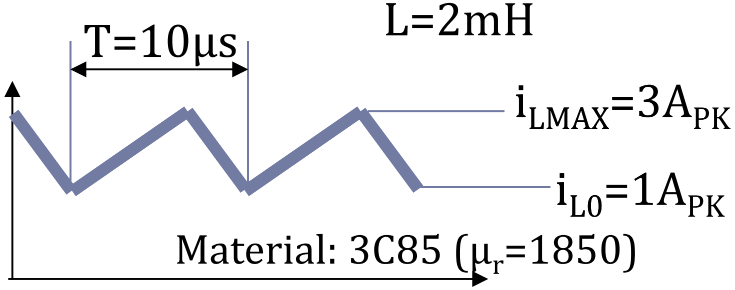
Inductors

EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

Step 3: Calculation of N=151

Step 4: Calculation of Air Gap g=2.43mm

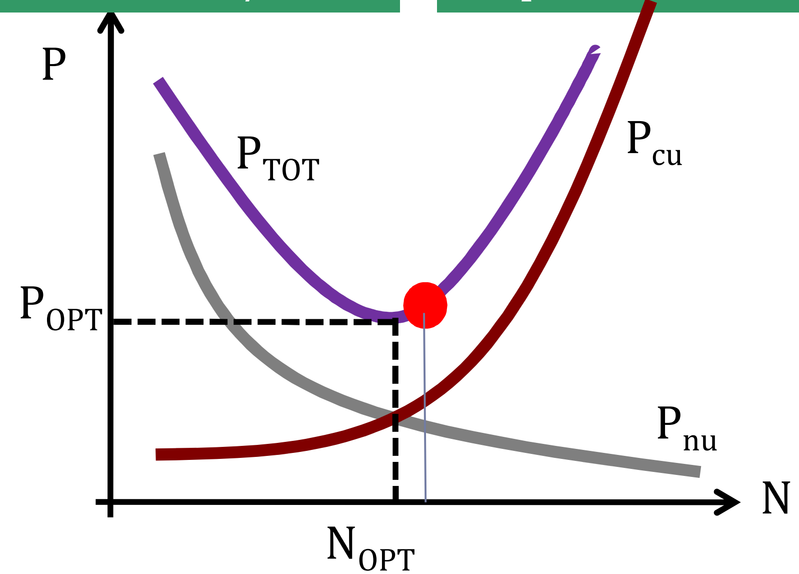
Step 5: Check core saturation. B_{MAX} =0.23T

Step 6: Calculation of Wire Diameter: D=0.4mm, 4 wires/turn

Step 7: Check losses

$$P_{CORE} = 1.01W$$

$$P_{cu} = 1.919W$$



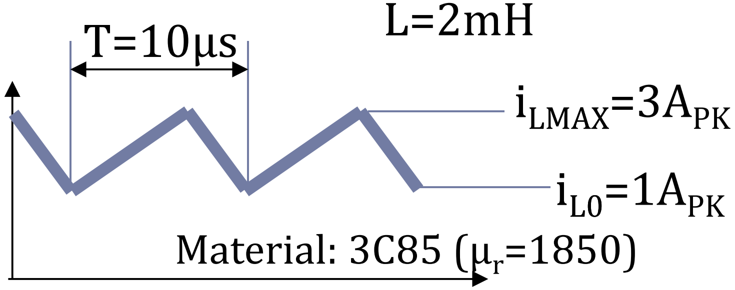
Inductors

EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

Step 3: Calculation of N=151

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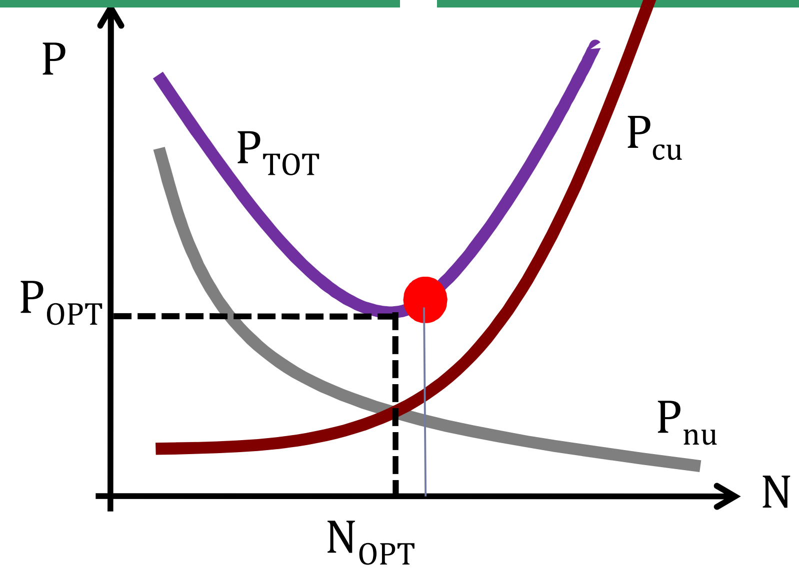
Step 7: Check losses

$$P_{CORE} = 1.01W$$

$$P_{cu} = 1.919W$$

In a real design THIS "COULD" BE ACCEPTABLE, only if it was true…



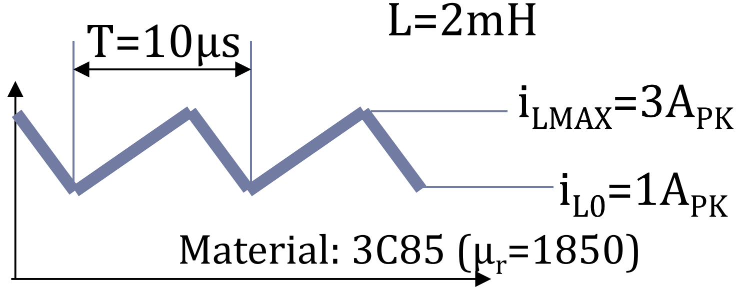
Inductors

EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

Step 3: Calculation of N=151

Step 4: Calculation of Air Gap g=2.43mm

Step 5: Check core saturation. B_{MAX} =0.23T

Step 6: Calculation of Wire Diameter: D=0.4mm, 4 wires/turn

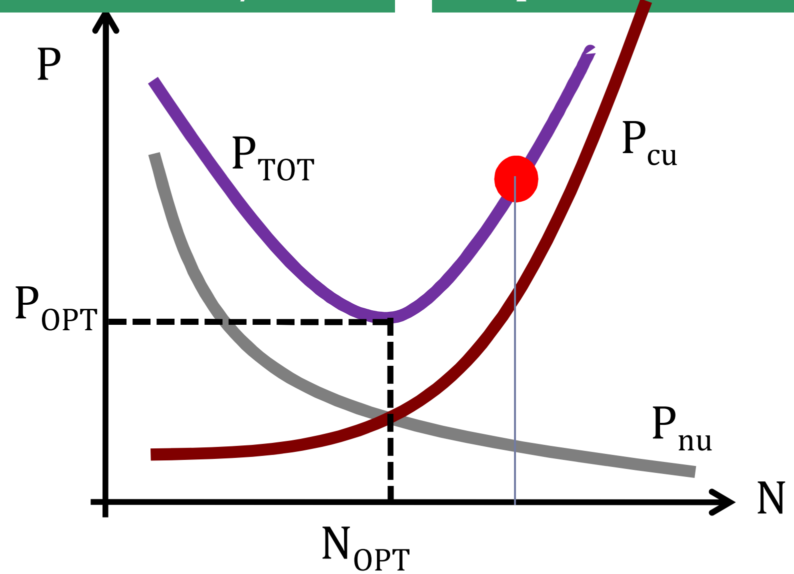
Step 7: Check losses

$$P_{CORE} = 1.01W$$

$$P_{cu} = 1.919W$$

In a real design THIS "COULD" BE ACCEPTABLE, only if it was true…

$$P_{cu(LF+HF)} = 4.207W$$



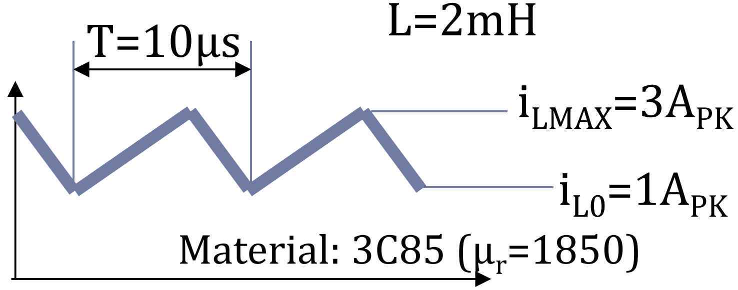
Inductors

EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

Step 3: Calculation of N=151

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Step 5: Check core saturation. B_{MAX} =0.23T

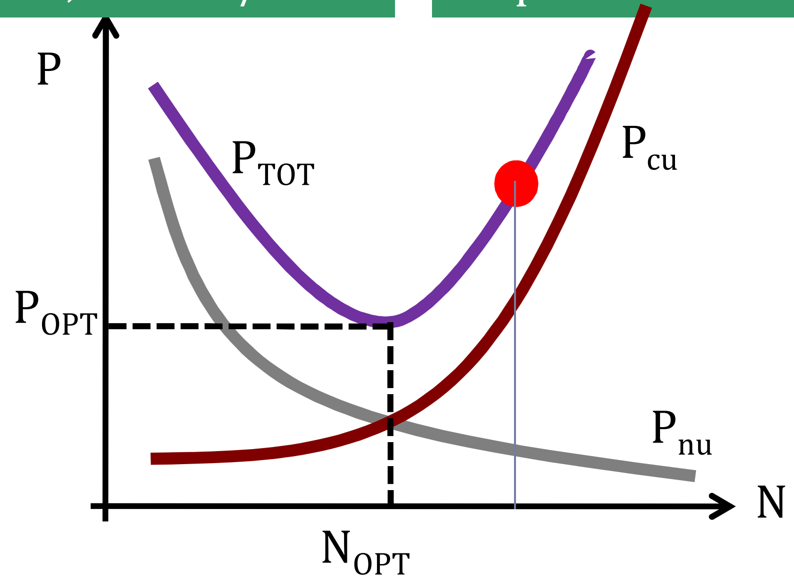
Step 6: Calculation of Wire Diameter: D=0.4mm, 4 wires/turn

Step 7: Check losses

$$P_{CORE} = 1.01W$$

$$P_{cu(LF+HF)} = 4.207W$$

DECREASE N:
Increase Target Losses
REPEAT FROM STEP 2



Inductors

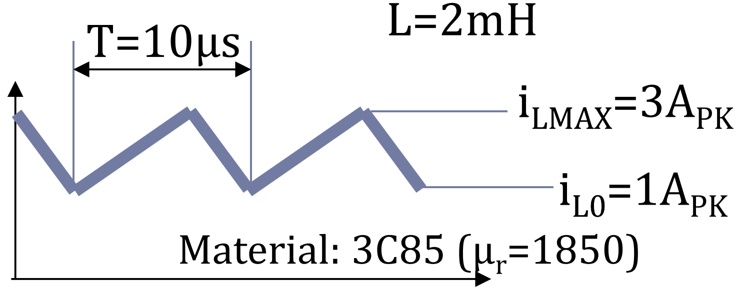
EXAMPLE

Optimal Design of Inductors:

Parameters:

Step 1: Core Type and Size: ETD44

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

Step 2: Estimation of Core Losses

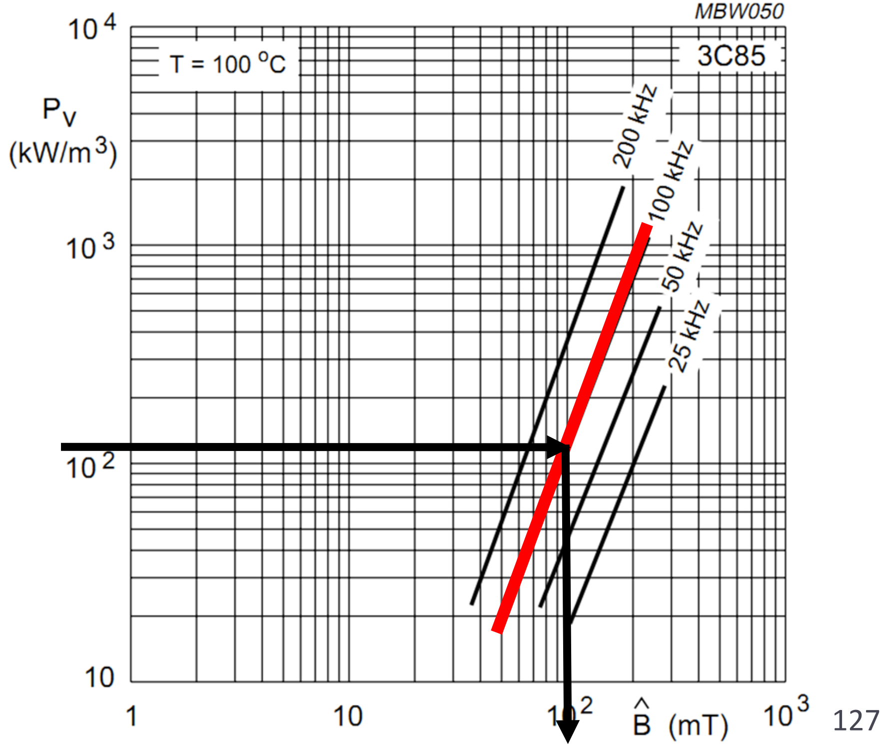
Core losses are a function of the AC component of the magnetic density, B

$\hat{B} \Leftrightarrow P_{CORE}$

$$P_{CORE} = 2.0W$$

$$Pv = \frac{P_{CORE}}{V_e} = \frac{2W}{17800mm^3} = 112.2kW/m_3$$

$$\hat{B} = 98mT$$



Inductors

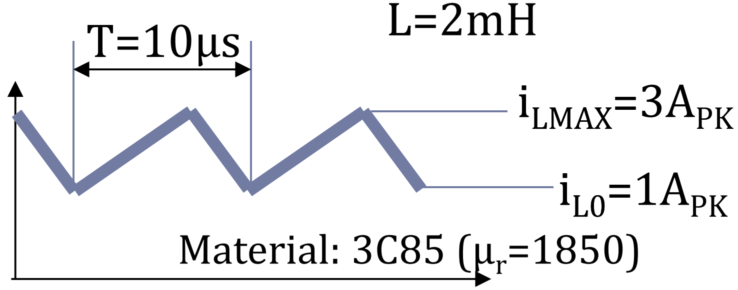
EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform

L=2mH



BOOST Converter, 200 W

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

Step 3: Calculation of N

$$\hat{B} = 98mT$$

$$\hat{B} = \frac{N \cdot \mu_0 \cdot \hat{\imath}}{\frac{l_e}{\mu_r} + g}$$

$$L = \frac{\mu_0 \cdot A_e \cdot N^2}{\frac{l_e}{\mu_r} + g}$$

$$\hat{B} = \frac{L \cdot \hat{\imath}}{A_e \cdot N} \Rightarrow N = \frac{L \cdot \hat{\imath}}{A_e \cdot \hat{B}}$$

$$N = \frac{2mH \cdot \left(\frac{3A - 1A}{2} \right)}{173mm^2 \cdot 98mT} = 116.9 \Rightarrow 117$$

Inductors

EXAMPLE

Optimal Design of Inductors:

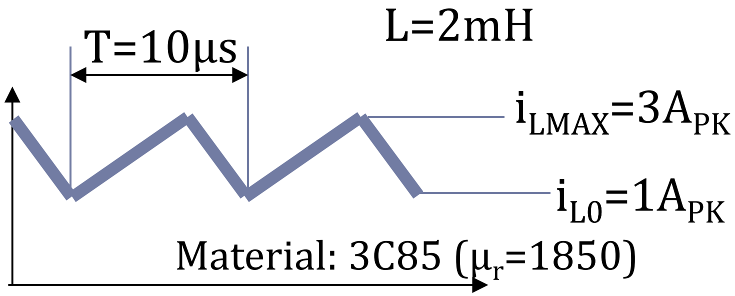
Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

Step 3: Calculation of ~~N=151~~ N=117

Parameters:

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

Step 4: Calculation of Air Gap

$$\hat{B}=\frac{N\cdot\mu_0\cdot\hat{i}}{\frac{l_e}{\mu_r}+g} \Rightarrow g=\frac{N\cdot\mu_0\cdot\hat{i}}{\hat{B}}-\frac{l_e}{\mu_r}$$

$$g=\frac{117\cdot 4\cdot\pi\cdot 10^{-7}\cdot 1A}{98mT}-\frac{103mm}{1850} \Rightarrow \boxed{1.44mm}$$

Inductors

EXAMPLE

Optimal Design of Inductors:

Parameters:

Step 1: Core Type and Size: ETD44

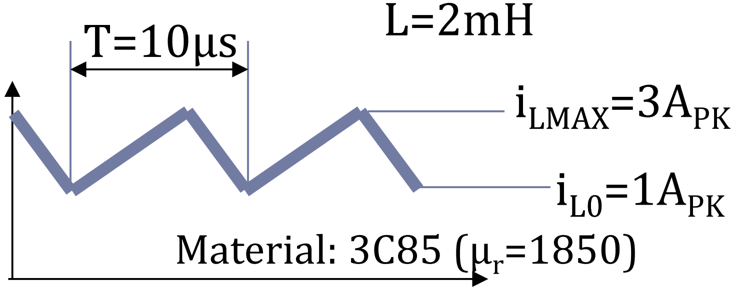
Step 2: Estimation of Core Losses

Step 3: Calculation of ~~N=151~~ N=117

Step 4: Calculation of Air Gap ~~g=2.43~~ g=1.44mm

Power topology (power level)
inductance
Current waveform

L=2mH



BOOST Converter, 200 W

Step 5: Check core saturation

$$B_{MAX} = \frac{N \cdot \mu_0 \cdot i_{MAX}}{\frac{l_e}{\mu_r} + g} \Rightarrow B_{MAX} = \frac{117 \cdot 4 \cdot \pi \cdot 10^{-7} \cdot 3A_{PK}}{\frac{0.103m}{1850} + 0.00144m} = 0.296T$$

$$B_{MAX} \leq 330mT$$

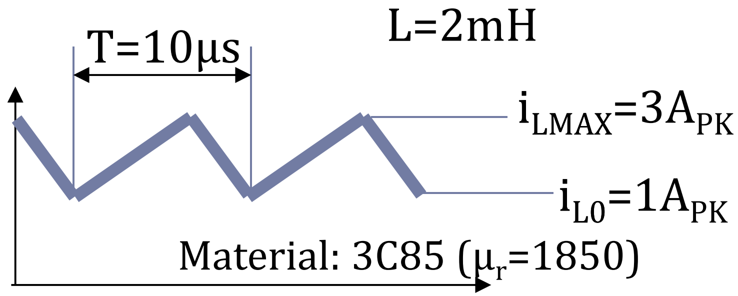
EXAMPLE

Inductors

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

Step 3: Calculation of ~~N=151~~ N=117

Step 4: Calculation of Air Gap ~~g=2.43~~ g=1.44mm

Step 5: Check core saturation. ~~B_{MAX}=0.23T~~ B_{MAX}=0.296T

Step 6: Calculation of Wire Diameter

Considering LF losses and full window

$$D = 0.916mm \rightarrow D_{Skin} = 0.45mm$$

6 LAYERS

$$NW_{Skin} = 4$$

Inductors

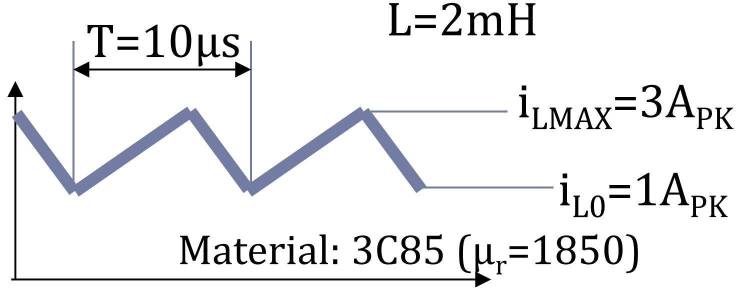
EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform

L=2mH



BOOST Converter, 200 W

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

Step 3: Calculation of ~~N=151~~ N=117

Step 4: Calculation of Air Gap ~~g=2.43~~ g=1.44mm

Step 5: Check core saturation. ~~B_{MAX}=0.23T~~ B_{MAX}=0.296T

Step 6: Calculation of Wire Diameter: ~~D=0.4mm, 4 wires/turn~~ D=0.45mm, 4 wires/turn

Step 7: Check losses $P_{CORE} = 1.916W$

Considering LF losses and full window $D_{Skin} = 0.45mm$ $NW_{Skin} = 4$ **6 LAYERS**

$P_{CU} = 0.96W$

$P_{TOT} = 2.876W$

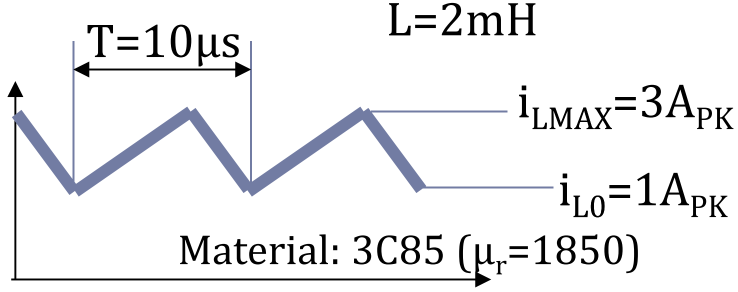
Inductors

EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform



BOOST Converter, 200 W

Step 1: Core Type and Size: ETD44

Step 2: Estimation of Core Losses

Step 3: Calculation of ~~N=151~~ N=117

Step 4: Calculation of Air Gap ~~g=2.43~~ g=1.44mm

Step 5: Check core saturation. ~~B_{MAX}=0.23T~~ B_{MAX}=0.296T

Step 6: Calculation of Wire Diameter: ~~D=0.4mm, 4 wires/turn~~ D=0.45mm, 4 wires/turn

Step 7: Check losses $P_{CORE} = 1.916W$

Considering LF losses and full window $D_{Skin} = 0.45mm$ $NW_{Skin} = 4$ **6 LAYERS**

$P_{CU} = 0.96W$ $P_{TOT} = 2.876W$

Considering HF losses $D_{Skin} = 0.4mm$ $NW_{Skin} = 4$ **5 LAYERS**

$P_{CU} = 2.526W$ $P_{TOT} = 4.495W$

EXAMPLE

Inductors

Opt

Step 1: C

Step 2: E

Step 3: C

Step 4: C

Step 5: C

Step 6: C

Step

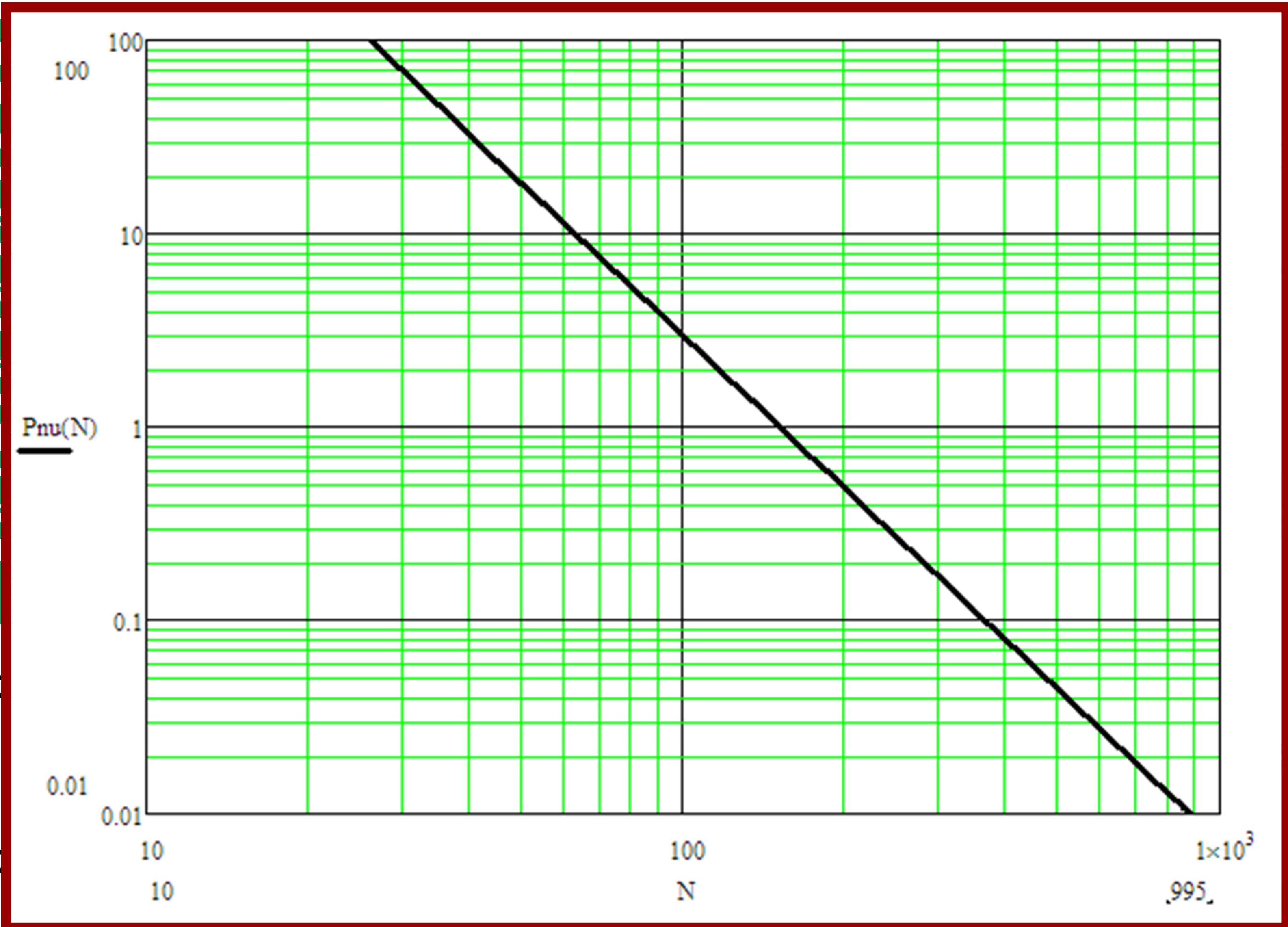
C

C

3A$_{PK}$

A$_{PK}$

76W



5 LAYERS

$P_{CU} = 2.526W$

$P_{TOT} = 4.495W$

EXAMPLE

Inductors

C

Step 1:

Step 2:

Step 3:

Step 4:

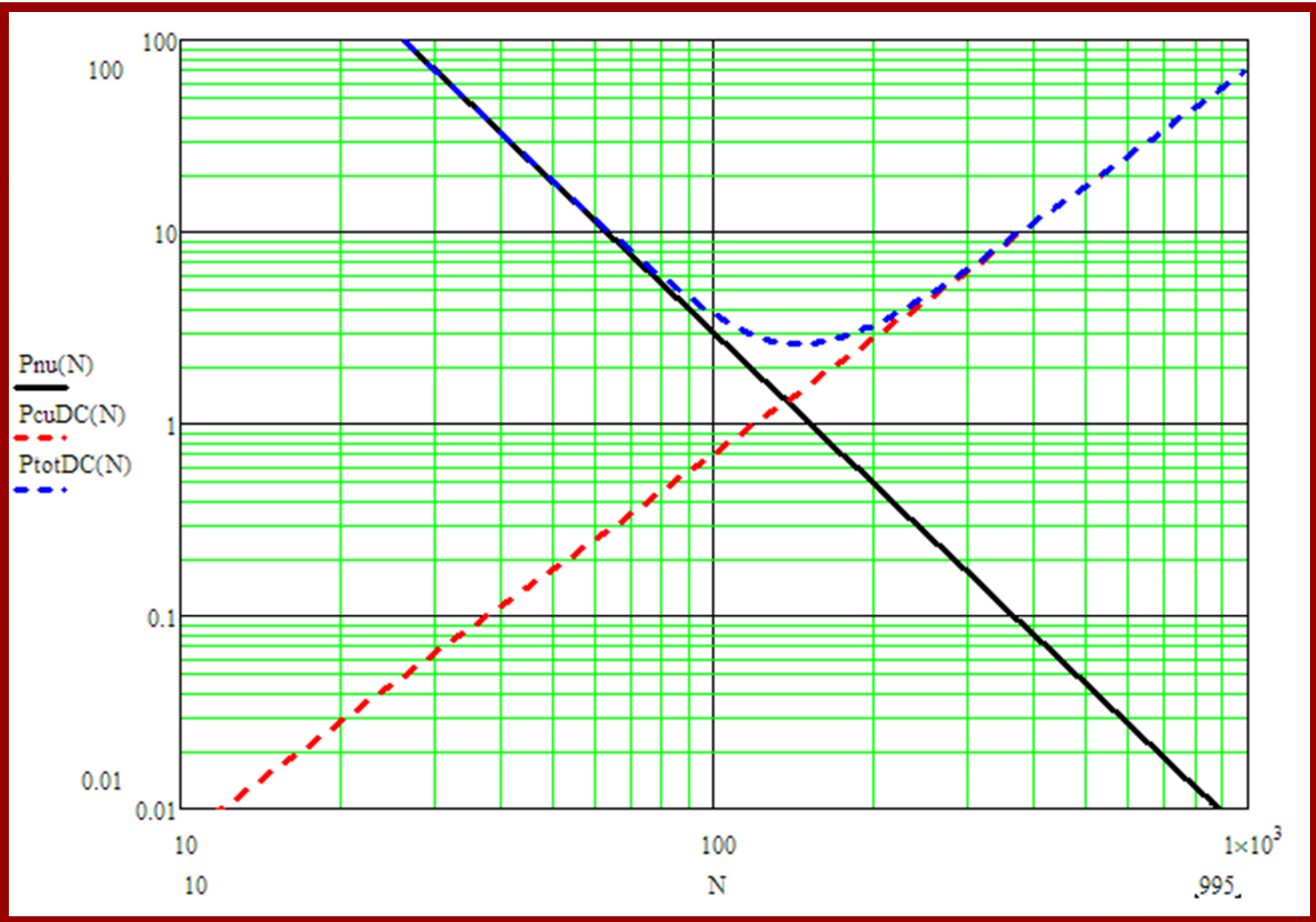
Step 5:

Step 6:

Ste

$3A_{PK}$

$1A_{PK}$



$76W$

5 LAYERS

$P_{CU} = 2.526W$

$P_{TOT} = 4.495W$

Inductors

EXAMPLE

C

Step 1:

Step 2:

Step 3:

Step 4:

Step 5:

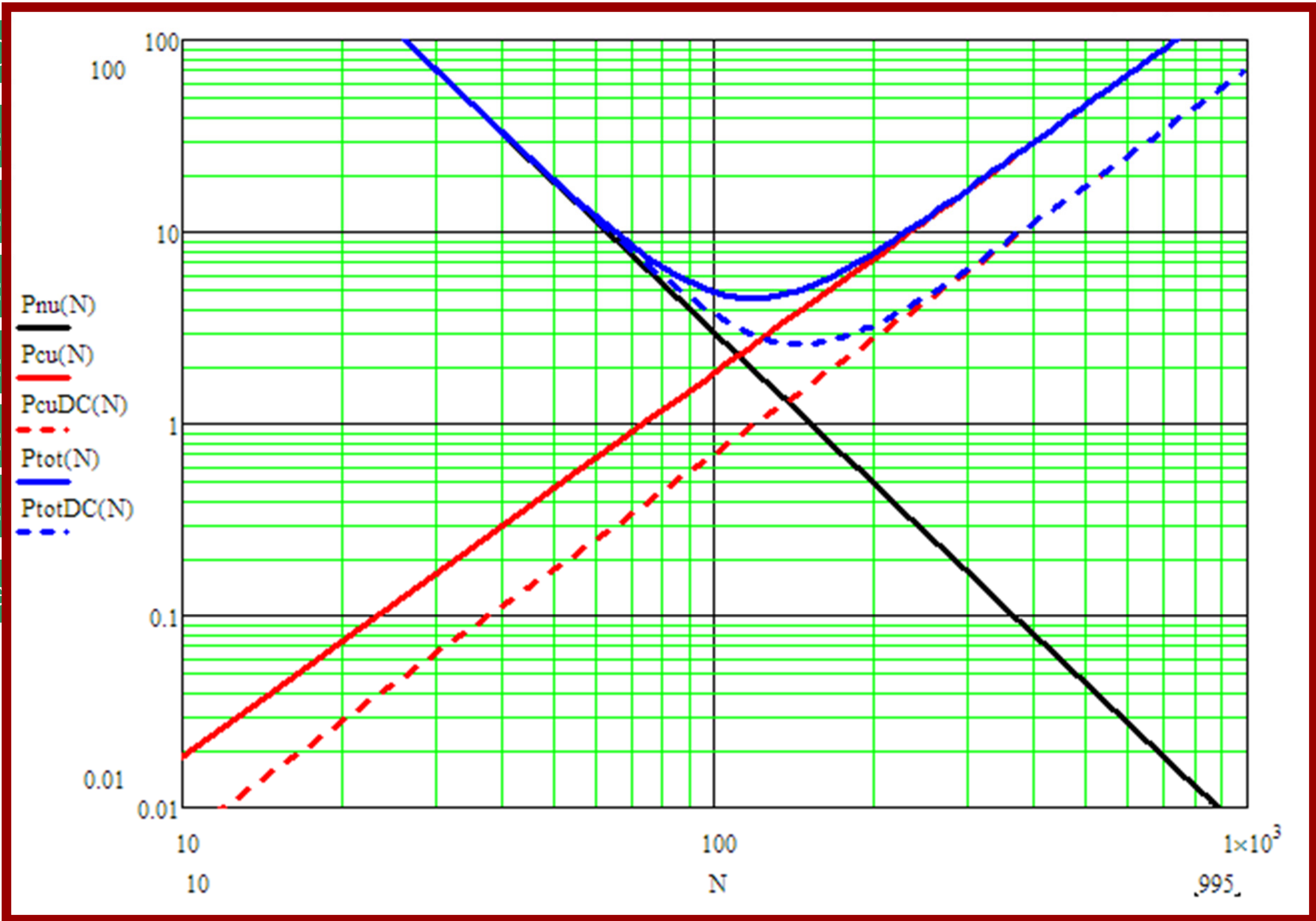
Step 6:

Ste

3A$_{PK}$

1A$_{PK}$

76W



5 LAYERS

$P_{CU} = 2.526W$

$P_{TOT} = 4.495W$

Indu

Optimal D

Step 1: Core Ty

Step 2: Estimati

Step 3: Calculat

Step 4: Calculat

Step 5: Check c

Step 6: Calculat

Step 7: Che

x=3A$_{PK}$

0=1A$_{PK}$

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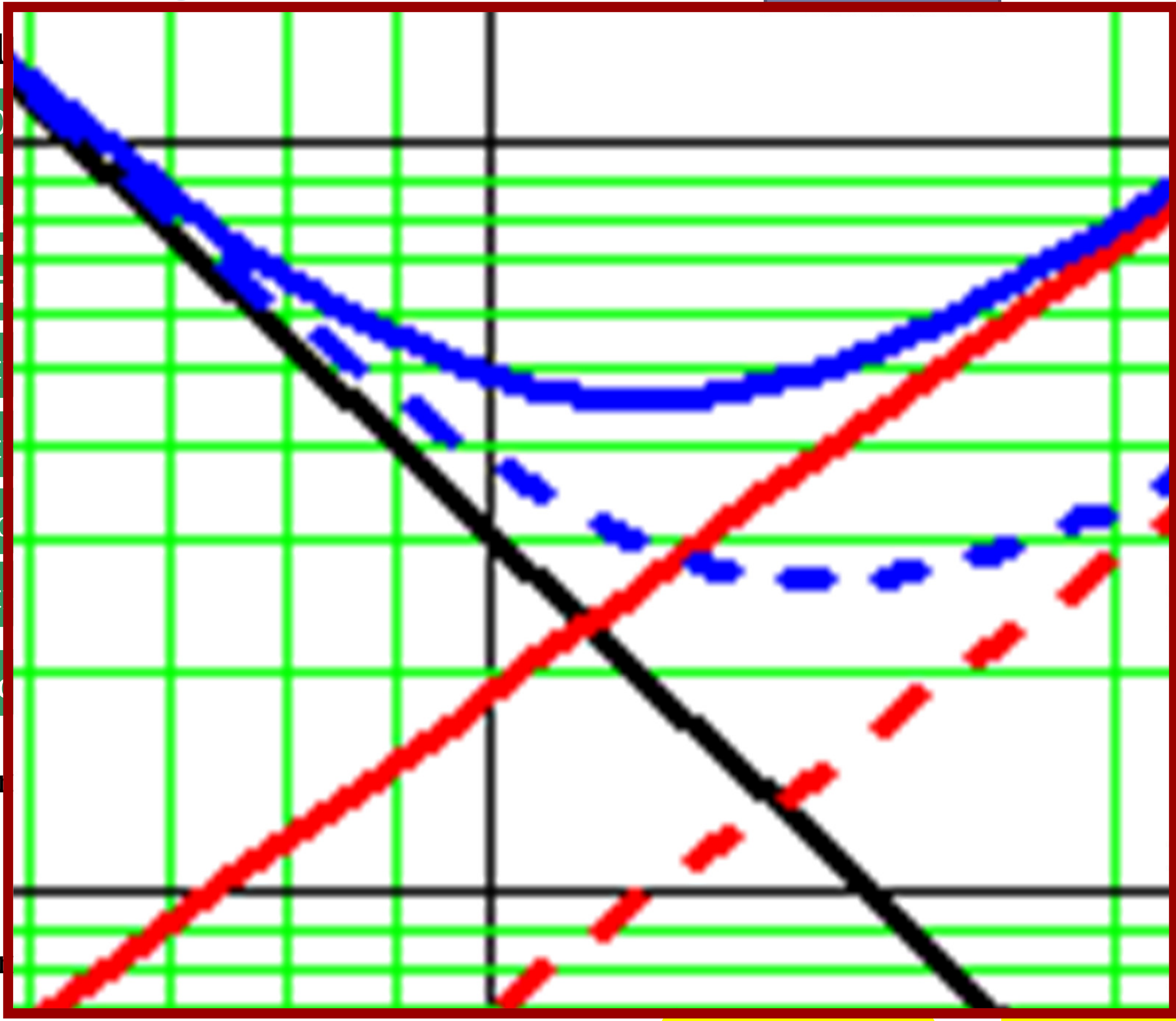
Conside

.876W

Conside



5 LAYERS

$P_{CU} = 2.526W$

$P_{TOT} = 4.495W$

Inductors

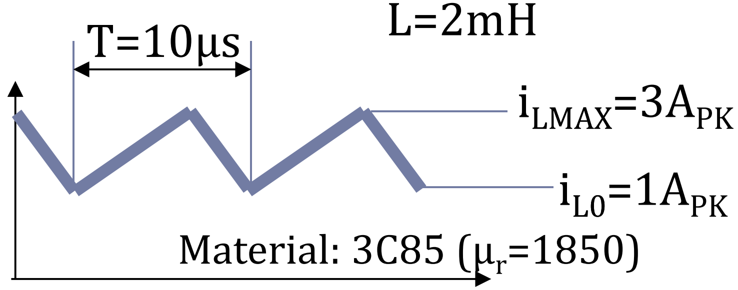
EXAMPLE

Optimal Design of Inductors:

Parameters:

Power topology (power level)
inductance
Current waveform

L=2mH



Material: 3C85 (μ_r=1850)

BOOST Converter, 200 W

DESIGN RESULTS

Core Type and Size: ETD44

N=117

Max. B (core saturation) B_{MAX}=0.296T

Air Gap g=1.44mm

D=0.4mm, 4 wires/turn

5 layers

Core losses: P_{CORE}=1.916W

Copper losses: P_{COPPER}=2.256W

TOTAL losses: P_{LOSS}=4.5W

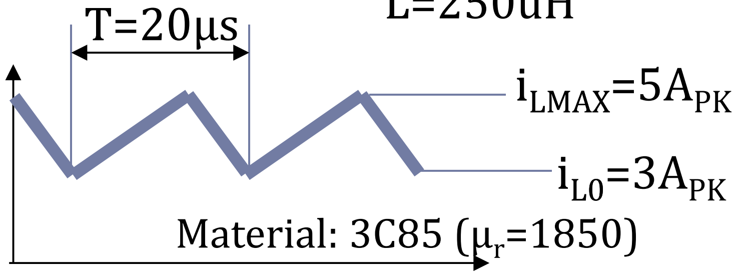
Inductors

TASK (Suggested): Propose an Optimal Design for an inductor fulfilling the following requirements:

Parameters:

Power topology (power level)
inductance
Current waveform

L=250uH



Material: 3C85 (μ_r=1850)

BUCK Converter, 500 W