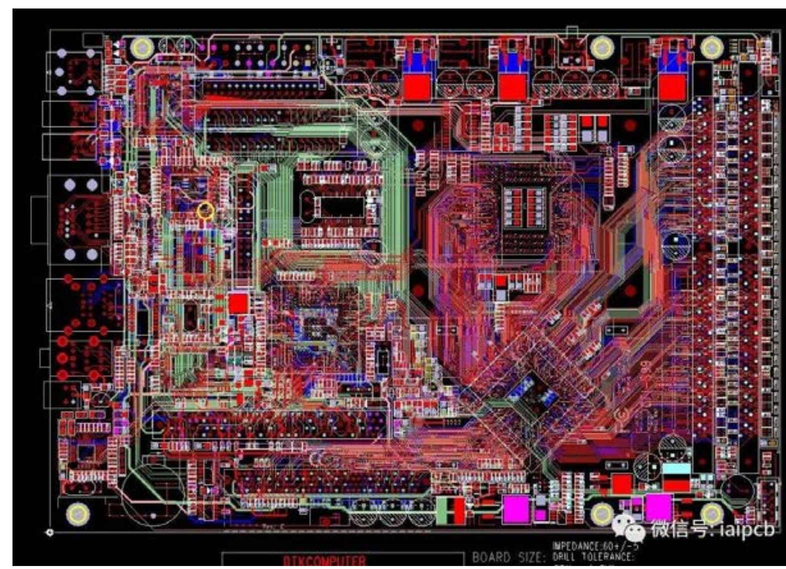
Magnetic Circuit

Vehicle path

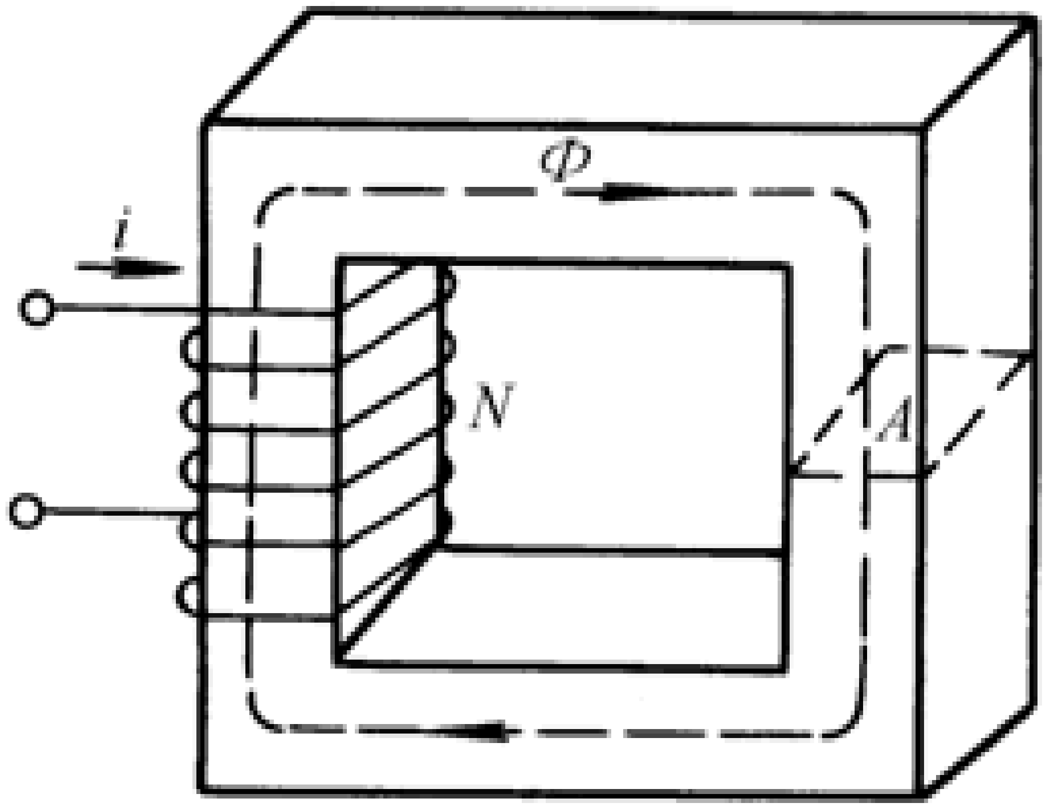
Water path

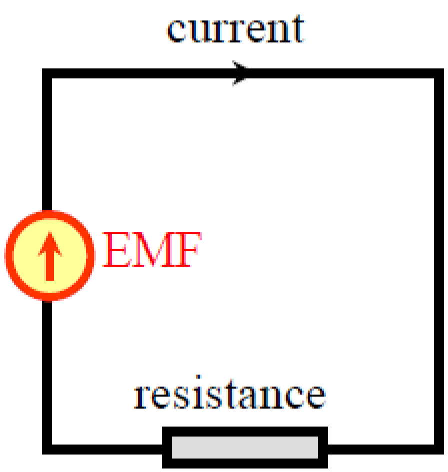
Oil passage

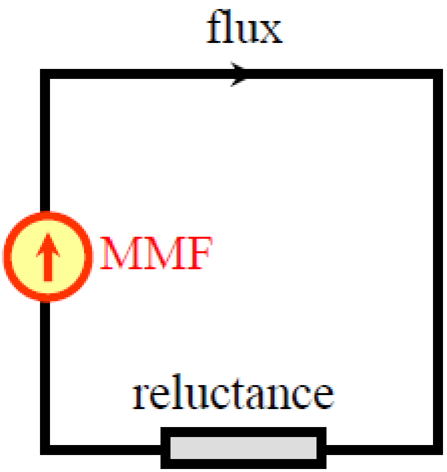


Electric path

Definition of Magnetic Circuit

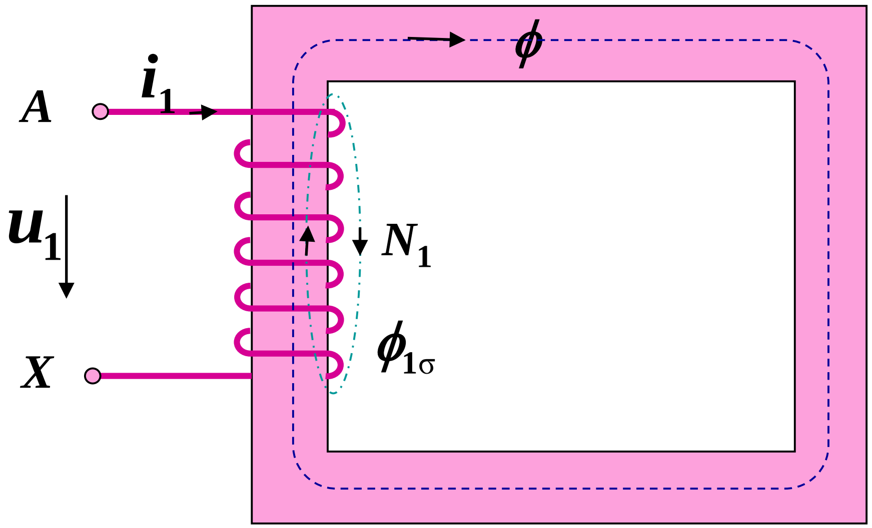






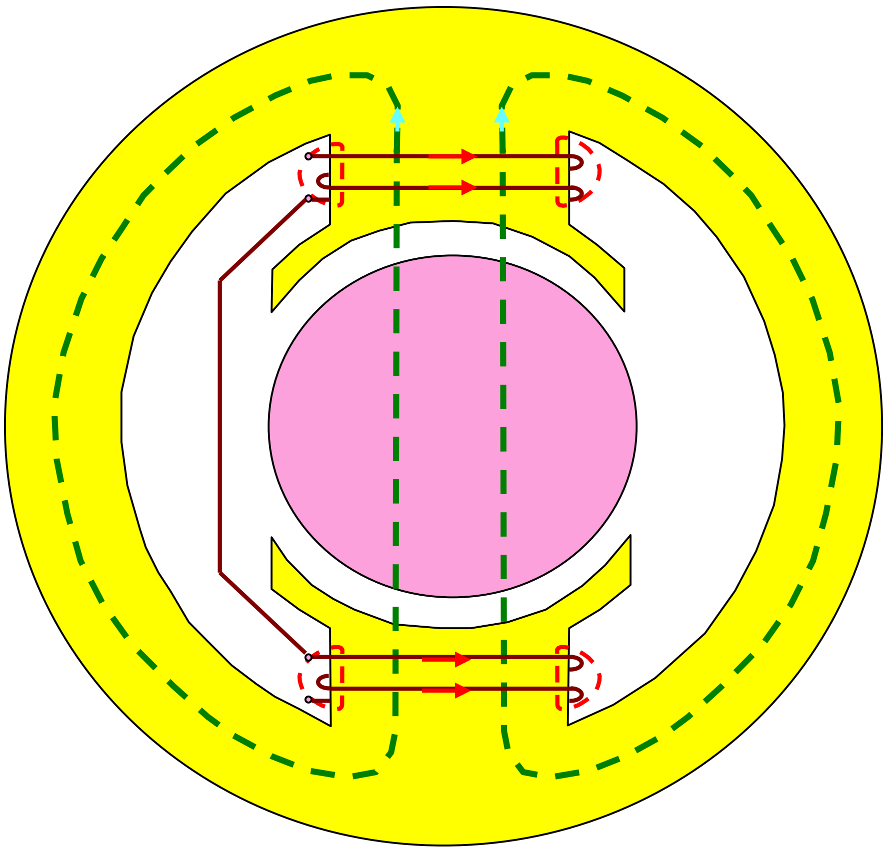
Electromotive Force
EMF: 电动势

Magnetomotive Force
MMF: 磁动势



Main Flux: couples with the primary and the secondary windings, contributes to the energy transmission or conversion.

Leakage Flux: only couples with one winding, no contributes to the energy conversion, only leads to the voltage drop.



Main Flux: couples with the primary and the secondary windings, contributes to the energy transmission or conversion.

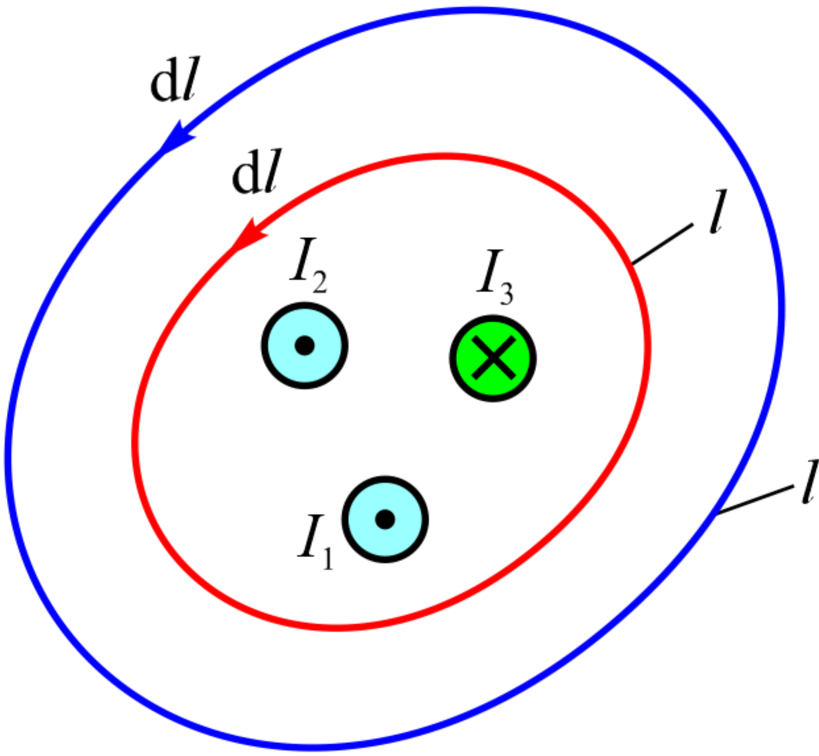
Leakage Flux: only couples with one winding, no contributes to the energy conversion, only leads to the voltage drop.

Flux	Function	Value	MC	Symbol
Main Flux	Energy transmission or conversion	Large	Main magnetic circuit	Φ_0
Leakage Flux	Not	Small	Leakage magnetic circuit	Φ_σ

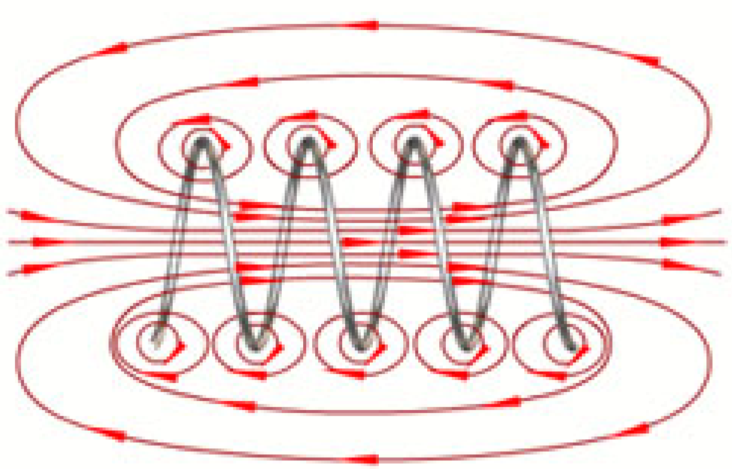
Ampere's Circuital Law

$$\oint_l \boldsymbol{H} \cdot \mathrm{d}\boldsymbol{l} = \oint_{l'} \boldsymbol{H} \cdot \mathrm{d}\boldsymbol{l} = \sum i$$

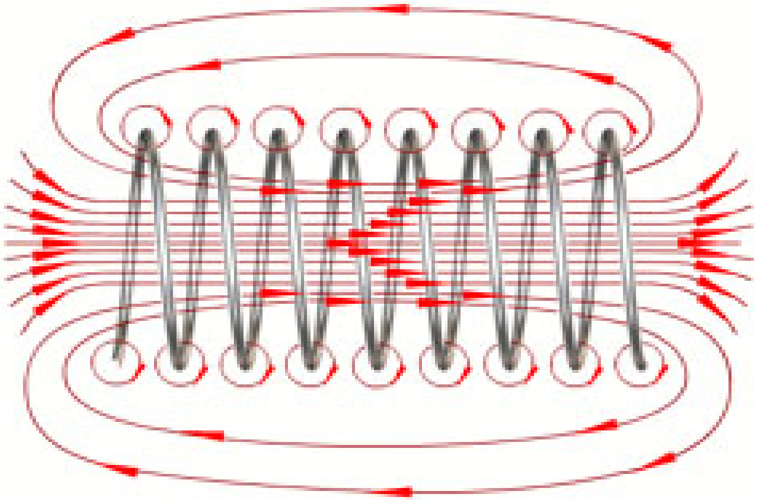
$$\oint_l \boldsymbol{H} \cdot \mathrm{d}\boldsymbol{l} = I_1 + I_2 - I_3$$



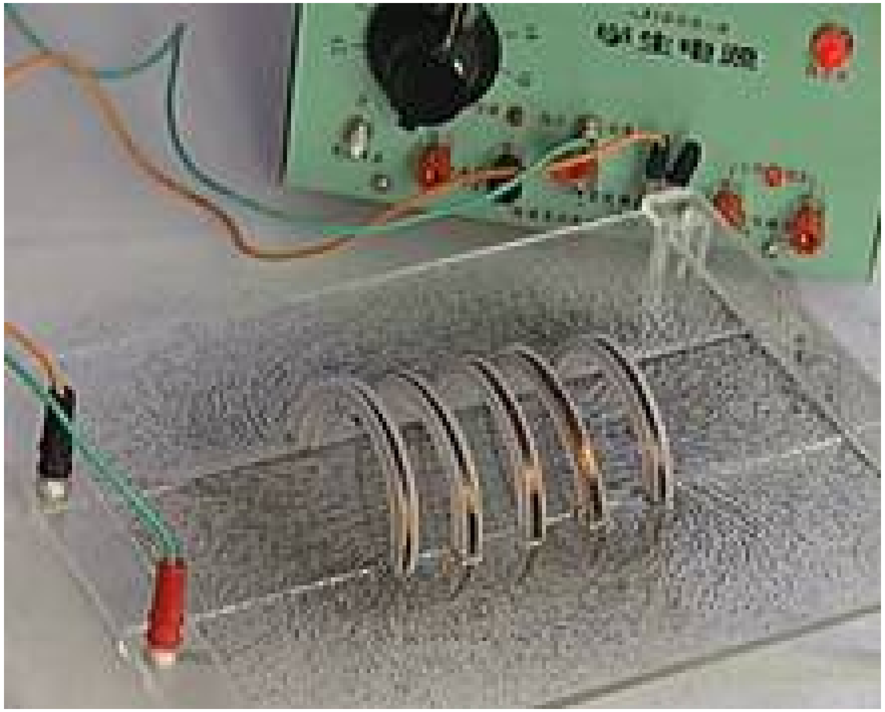
➢**Current is the source of magnetic field**



图A



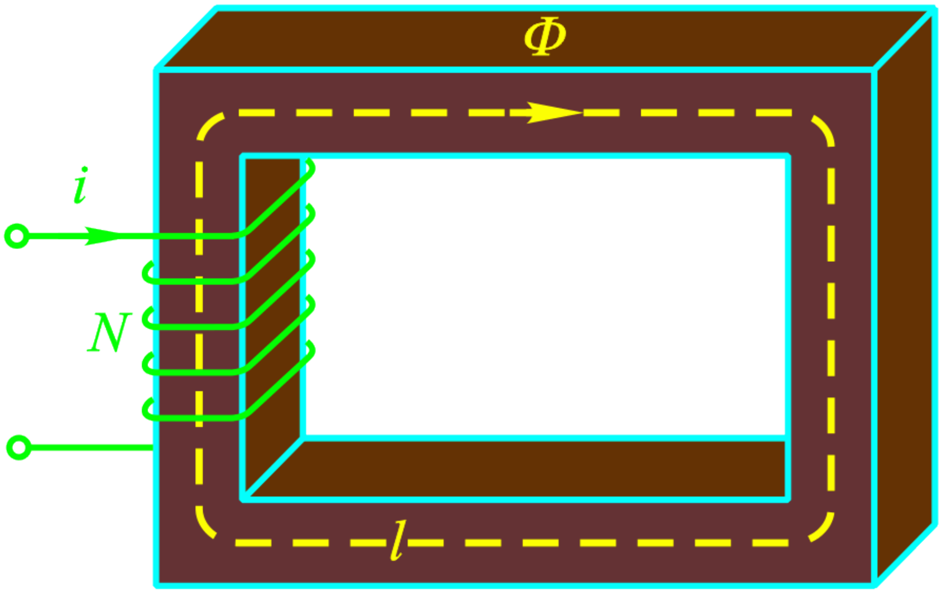
图B



图C

Ohm's Law

$$\oint_l H \cdot dl = Hl = Ni$$



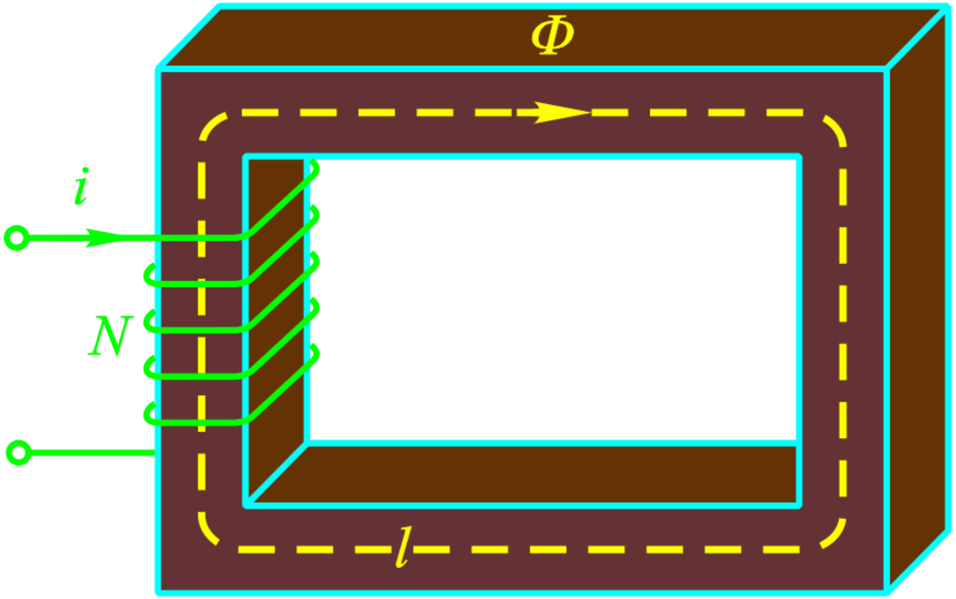
Ohm's Law

MMF $$F = Ni$$

Relutance $$R_{\mathrm{m}} = \frac{l}{\mu A}$$

Permeance $$\Lambda_{\mathrm{m}} = 1/R_{\mathrm{m}}$$

Flux $$\phi = F / R_{\mathrm{m}}$$



Discussion

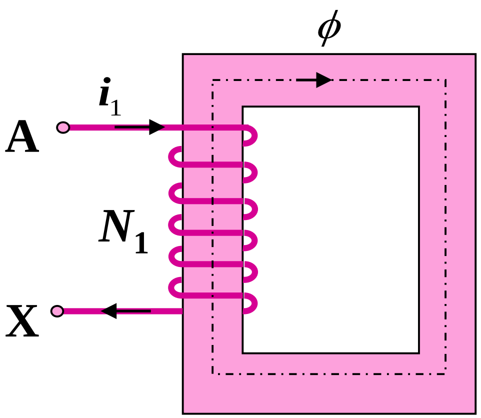


Figure 1

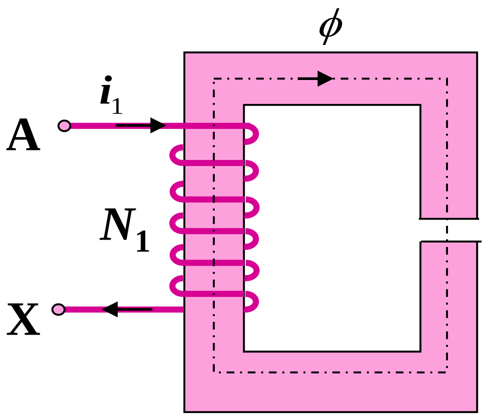
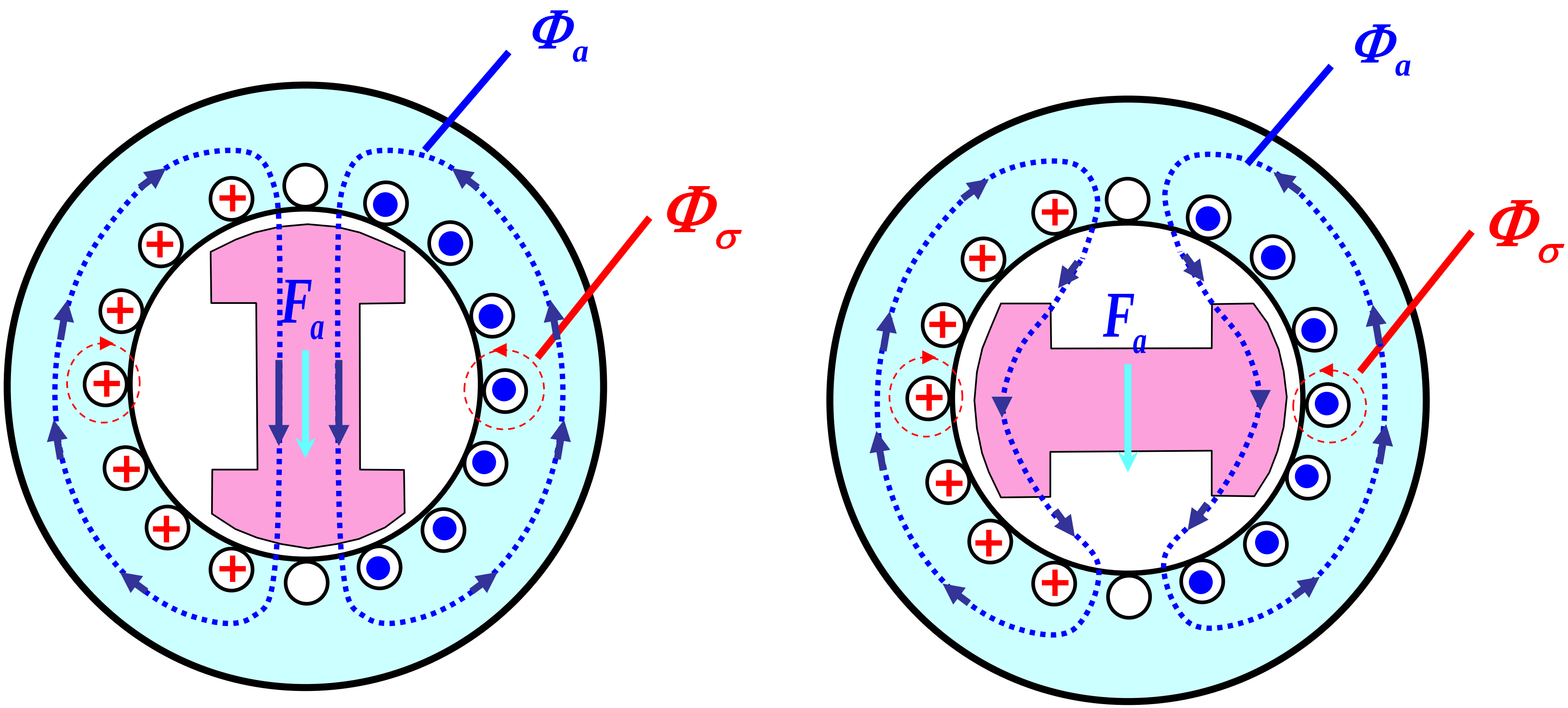


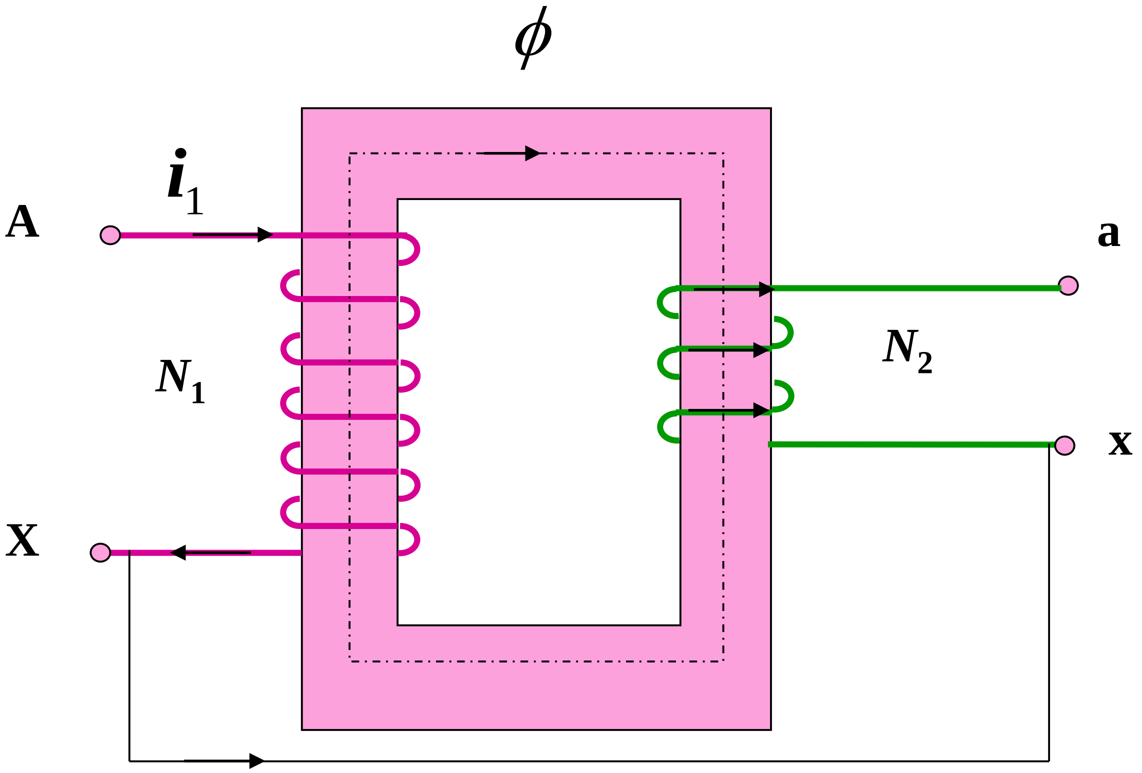
Figure 2

Question: Comparing Figure 1, there is only one opening on the core in the Figure 2. The cross-sectional area, exciting current and number of turns are unchanged. Please analyze the difference of main flux and the leakage flux between two samples.



Φa
Φσ
Fa
Φa
Φσ
Fa

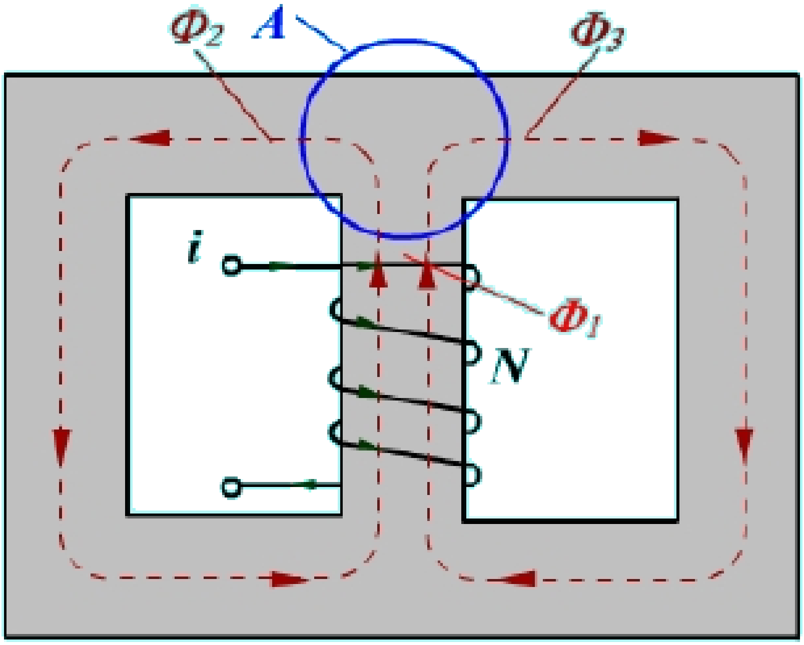
Valid number of turns



The First Kirchhoff's Law

$$\oint_S \boldsymbol{B} \cdot \mathrm{d}a = 0$$

Flux continuity theorem



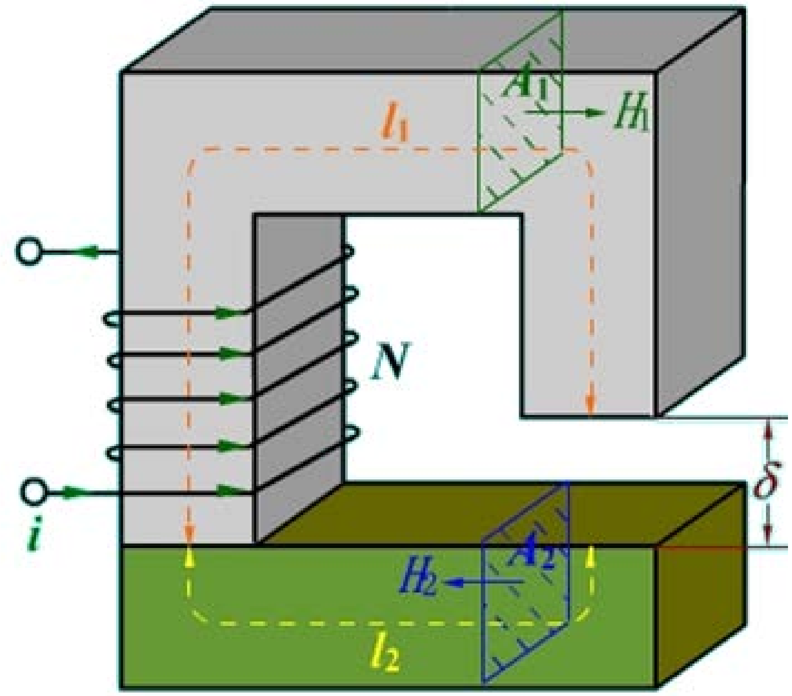
$$\sum \phi = \mathbf{0}$$

$$-\phi_1 - \phi_2 + \phi_3 = 0$$

The Second Kirchhoff's Law

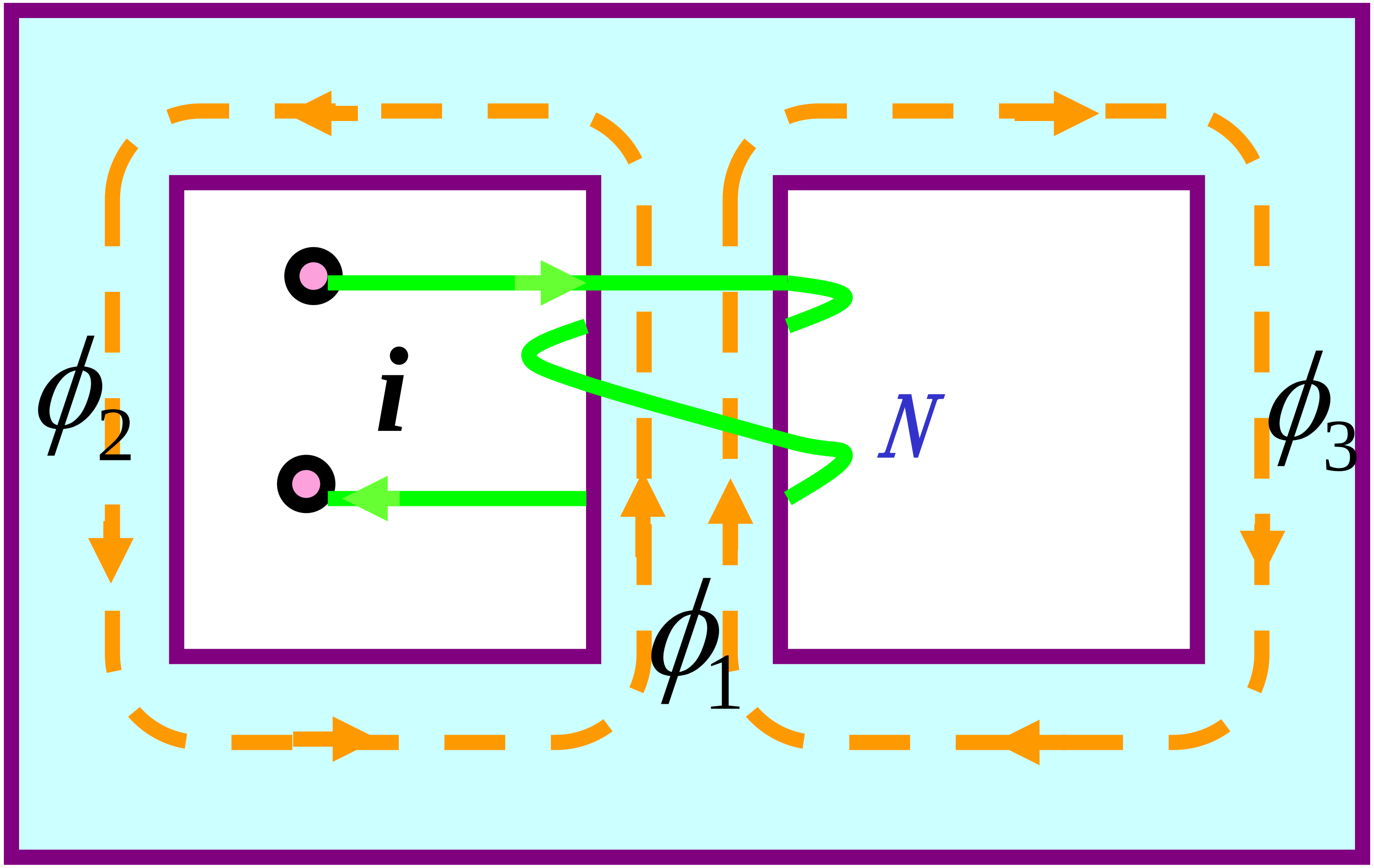
$$Ni = \sum_{k=1}^{3} H_k l_k =$$

$$\phi_1 R_{m1} + \phi_2 R_{m2} + \phi_\delta R_\delta$$



Electrical Circuit		Magnetic Circuit	
Items	**Units**	**Items**	**Units**
Current: I	**A**	**Flux:** Φ	**Wb**
EMF: E	**V**	**MMF:** $F=NI$	**A**
Voltage drop: IR	**V**	**Magnetic potential difference:** $\Phi R_m=Hl$	**A**
Conductivity: σ	**S/m**	**Permeability:** μ	**H/m**
Resistance: $R=l/\sigma A$	**Ω**	**Reluctance:** $R_m=l/\mu A$	$\mathbf{H^{-1}}$
Conductance: $G=1/R$	**S**	**Permeance:** $\Lambda_m=1/R_m$	**H**
Ohm's Law: $E=IR$		**Ohm's Law:** $F=\Phi R_m$	
the First Kirchhoff's Law: $\Sigma I=0$		**the First Kirchhoff's Law:** $\Sigma\Phi=0$	
the Second Kirchhoff's Law: $\Sigma E=\Sigma U$		**the second Kirchhoff's Law:** $\Sigma F=\Sigma\Phi R_m=\Sigma Hl$	

Discussion



$$\boldsymbol{F} = \boldsymbol{Ni} = \phi_1 \boldsymbol{R}_{\mathrm{m1}} + \phi_2 \boldsymbol{R}_{\mathrm{m2}} + \phi_3 \boldsymbol{R}_{\mathrm{m3}} \qquad ?$$

For a iron device， the section area is 9×10-4m2， the average length is 0.3m， the iron permeability is 5000μ0， the winding turns is *N*=500.

Question: If the flux density is 1T, what is the demanded MMF and the exciting current?。

Solutions:

Mangnetic intensity:

$$\boldsymbol{H} = \frac{\boldsymbol{B}}{\boldsymbol{\mu}_{\mathrm{Fe}}} = \frac{1}{5000\times 4\pi\times 10^{-7}} = 159\,\mathrm{A/m}$$

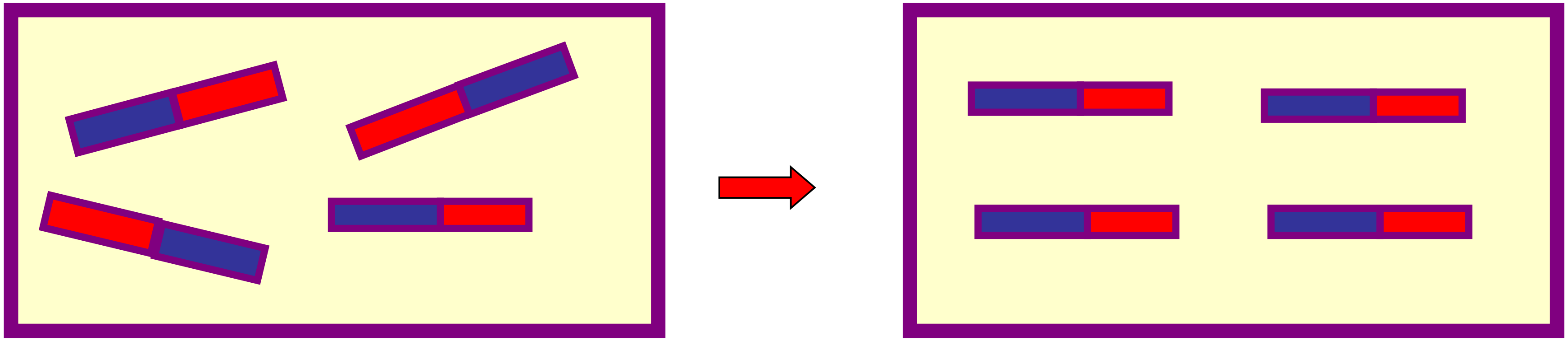
MMF: $F = Hl = 159\times 0.3\mathrm{A} = 47.7\mathrm{A}$

Exciting current: $i = F/N = 9.54\times 10^{-2}\mathrm{A}$

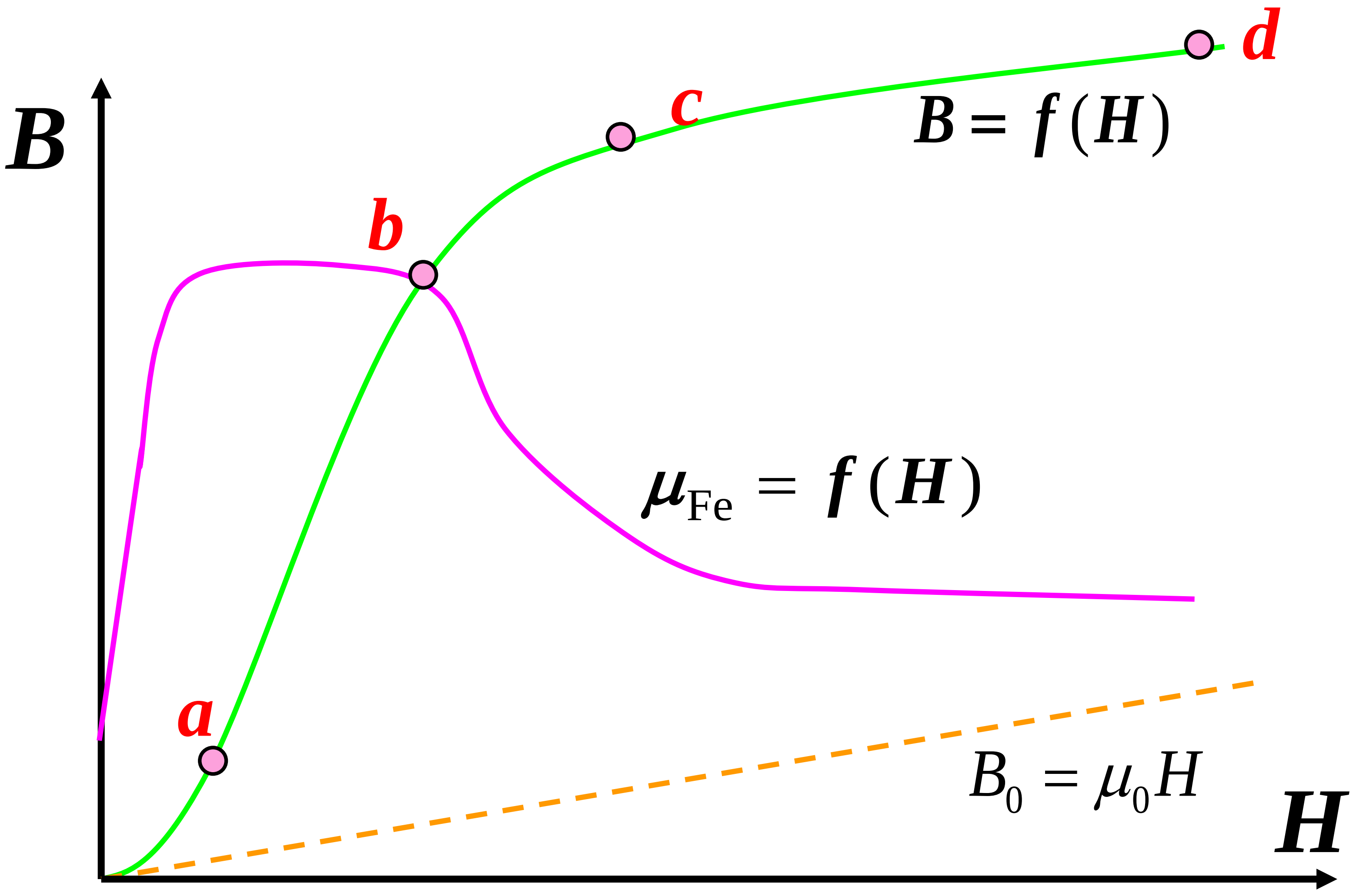
Magnetic Materials and Their Characteristic

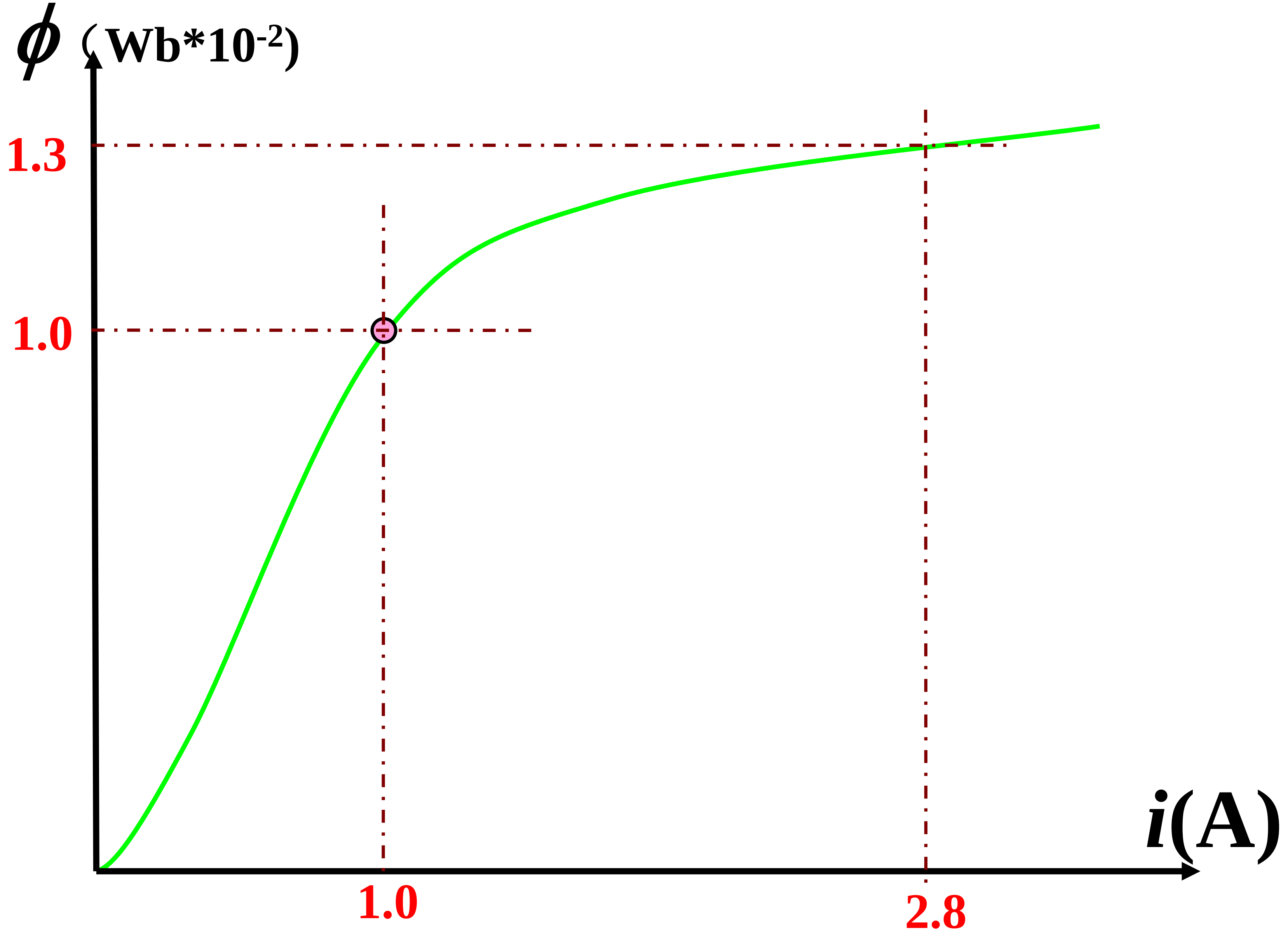
Permeability： $\mu = B/H$ **(H/m, T, A/m)**

$\mu_0 = 4\pi \times 10^{-7}$ **H/m** $\mu_{Fe} = (2000\sim 6000)\mu_0$



Initial Magnetization Curve





Q1: Plot the curve of current while $\phi(t)=0.013\sin(\omega t)$.

Q2: Plot the curve of flux while $i(t)=1.3\sin(\omega t)$

Discussion: Superposition principle

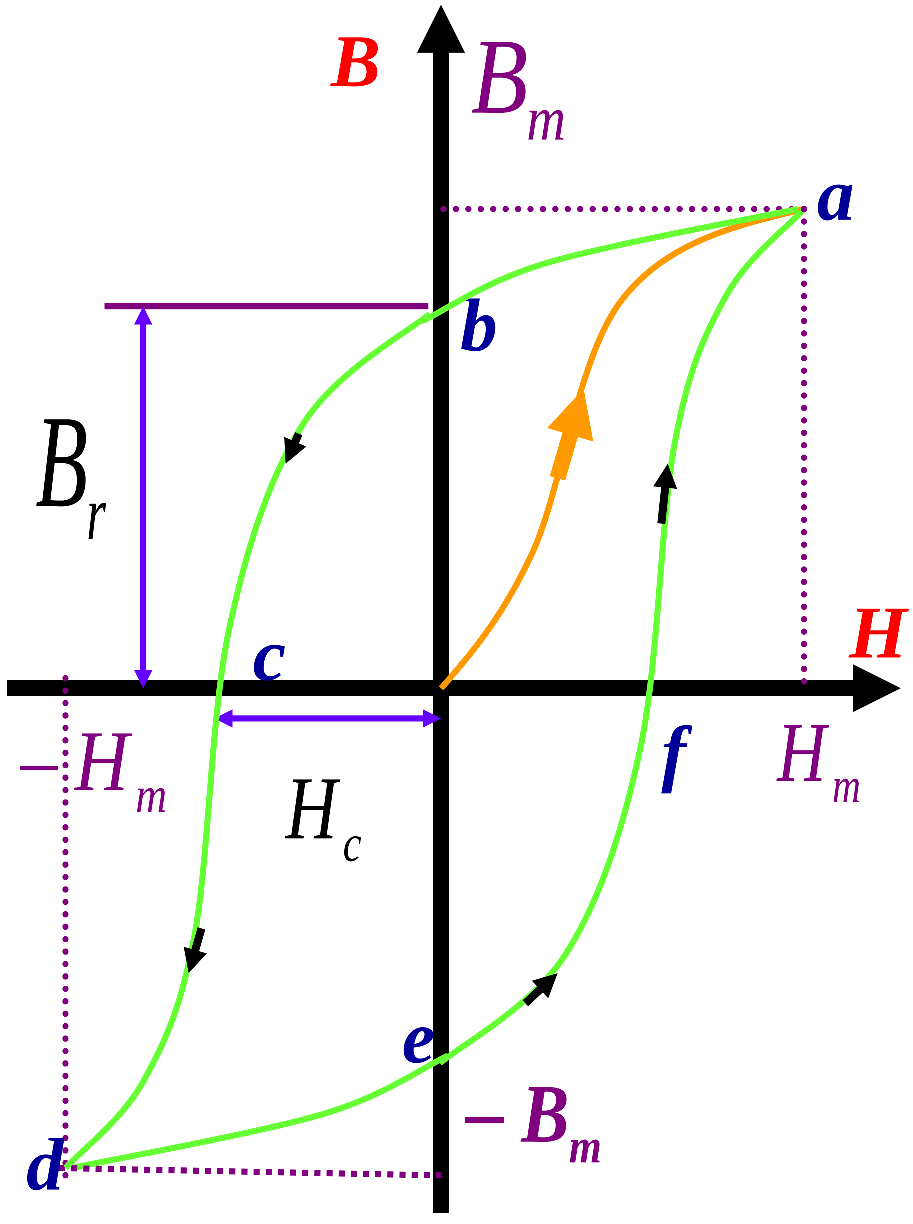
Hysteresis Loop

Residual Magnetism

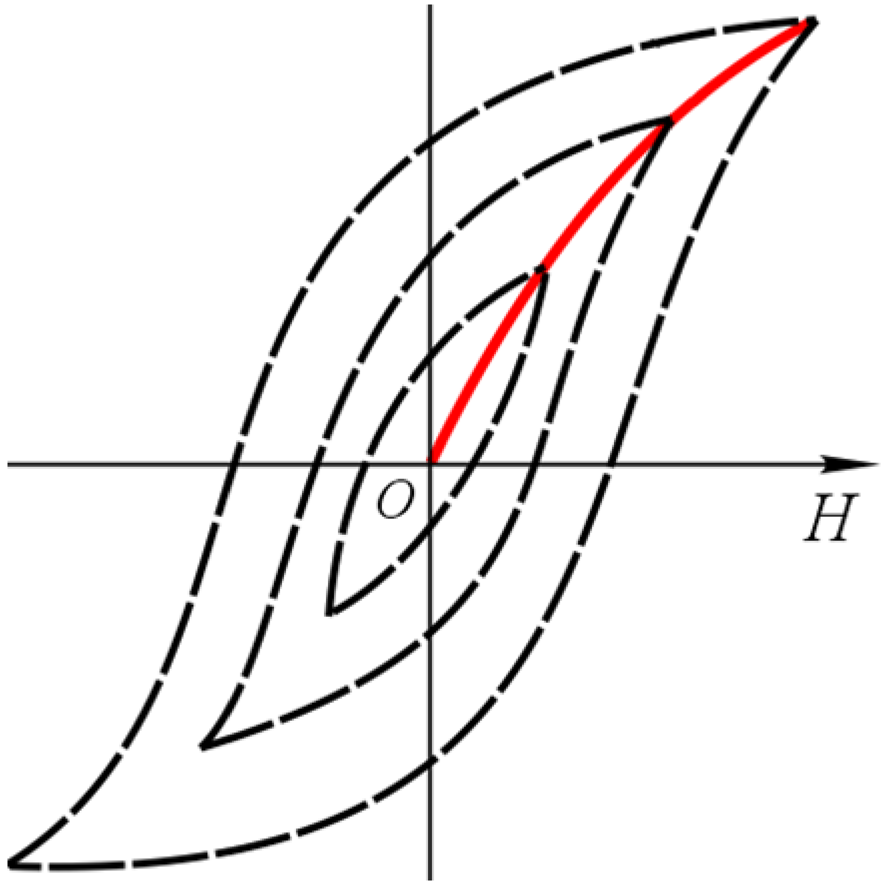
剩磁:B_r .

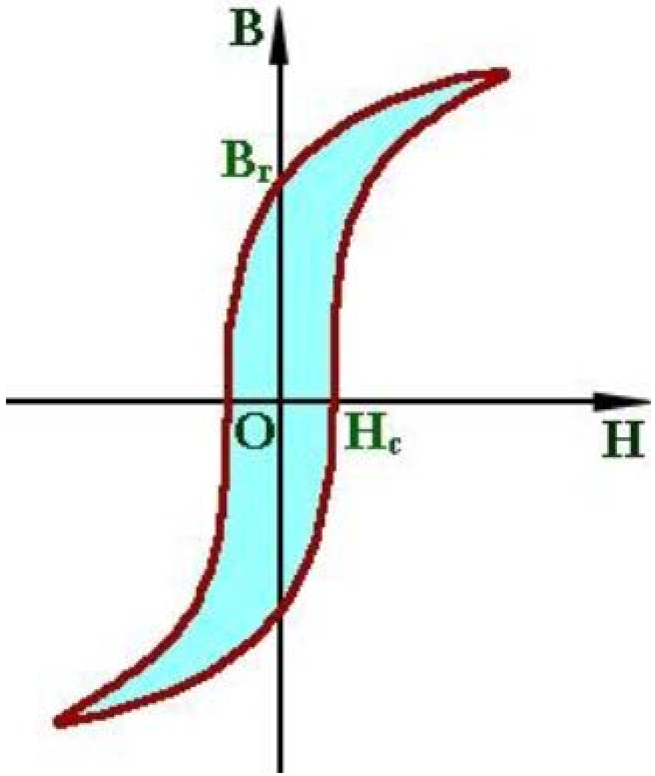
Coercive Force

矫顽力: H_c.



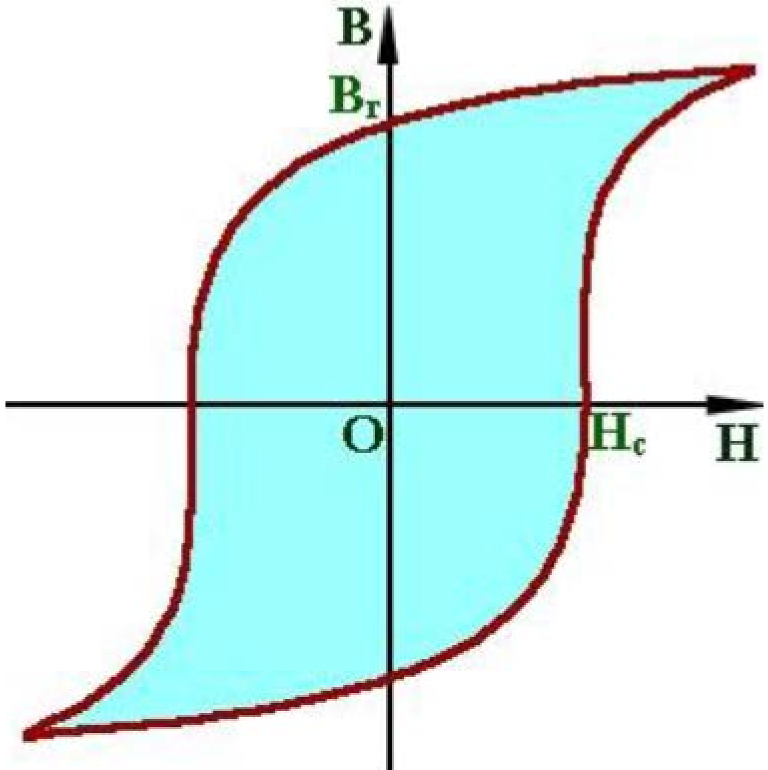
Basic magnetization curve





Soft magnetic material

Hard magnetic material



Core Losses

(1) Hysteresis loss

$$p_{\mathrm{h}} = C_{\mathrm{h}} f B_{\mathrm{m}}^{\mathrm{n}} V$$

(2) Eddy current loss

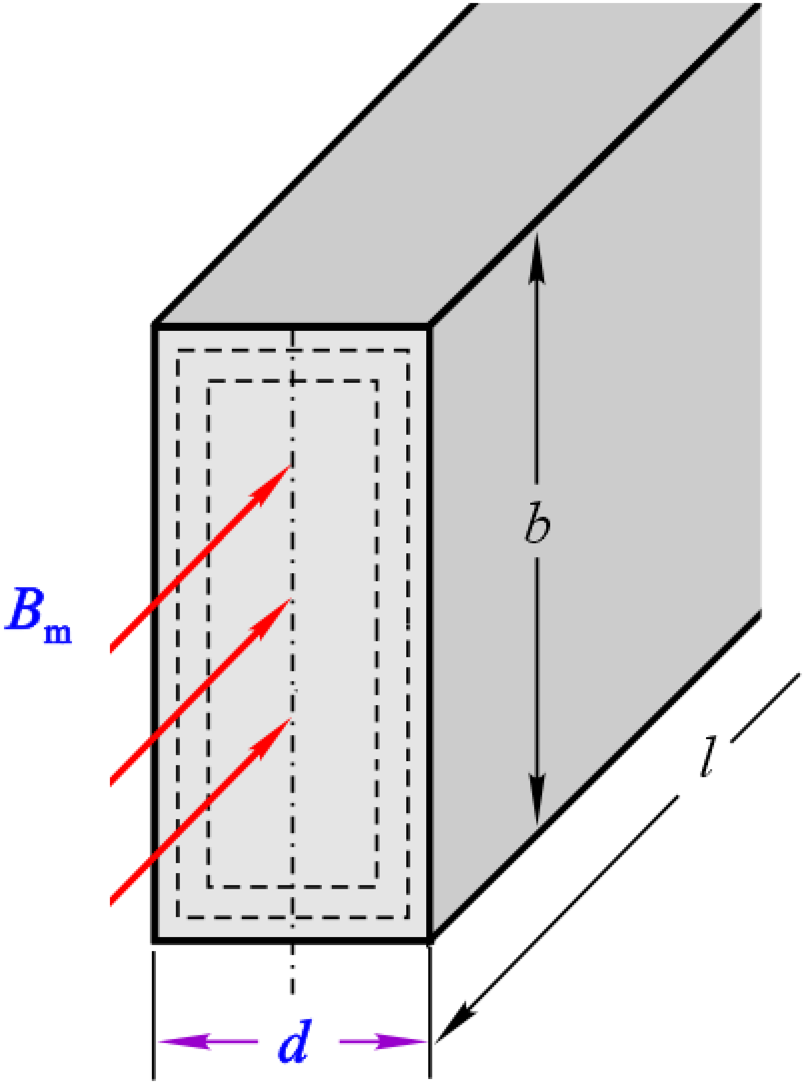
$$p_{\mathrm{e}} = C_{\mathrm{e}} d^2 f^2 B_{\mathrm{m}}^2 V$$

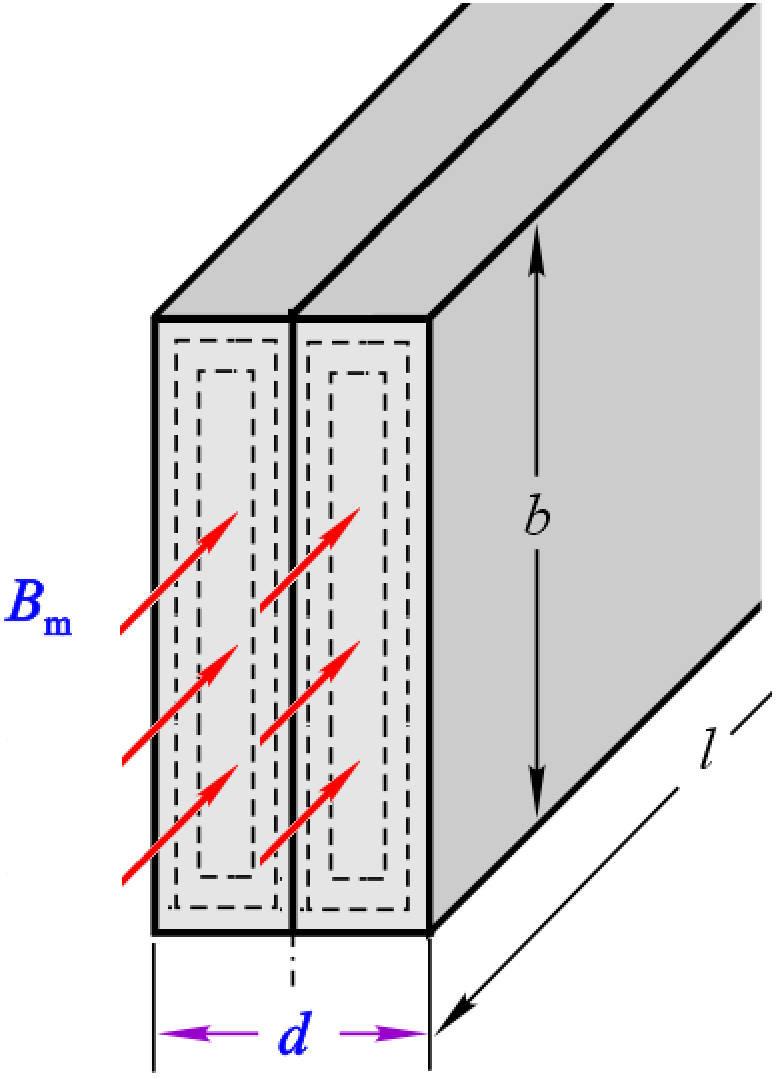
Core Losses:

$$p_{\mathrm{Fe}} = p_{\mathrm{h}} + p_{\mathrm{e}}$$

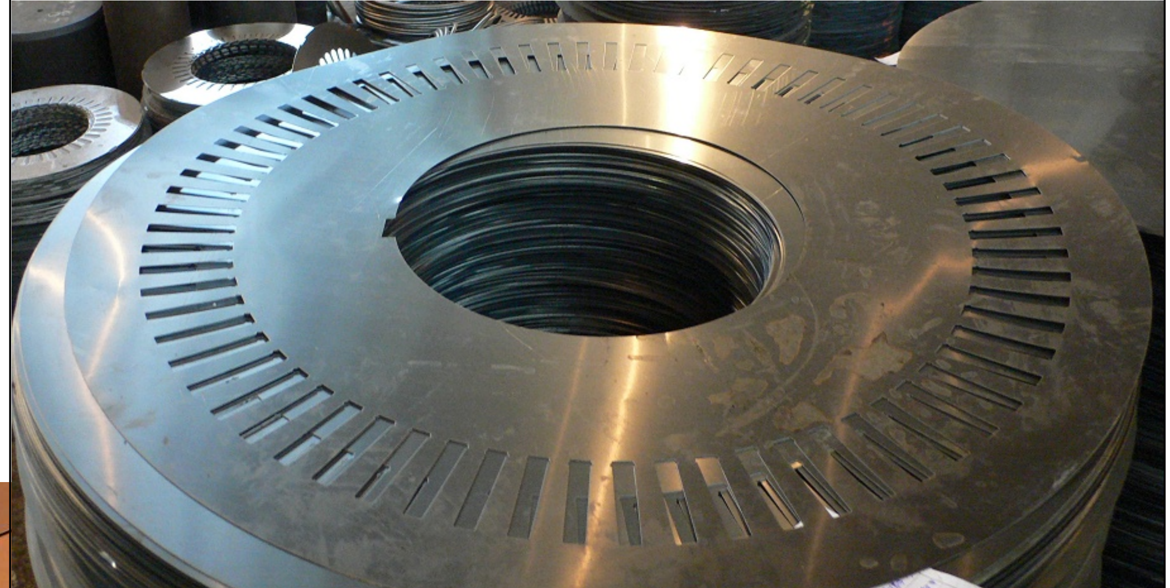
$$p_{\mathrm{Fe}} \approx C_{\mathrm{Fe}} f^{1.3} B_{\mathrm{m}}^2 G$$

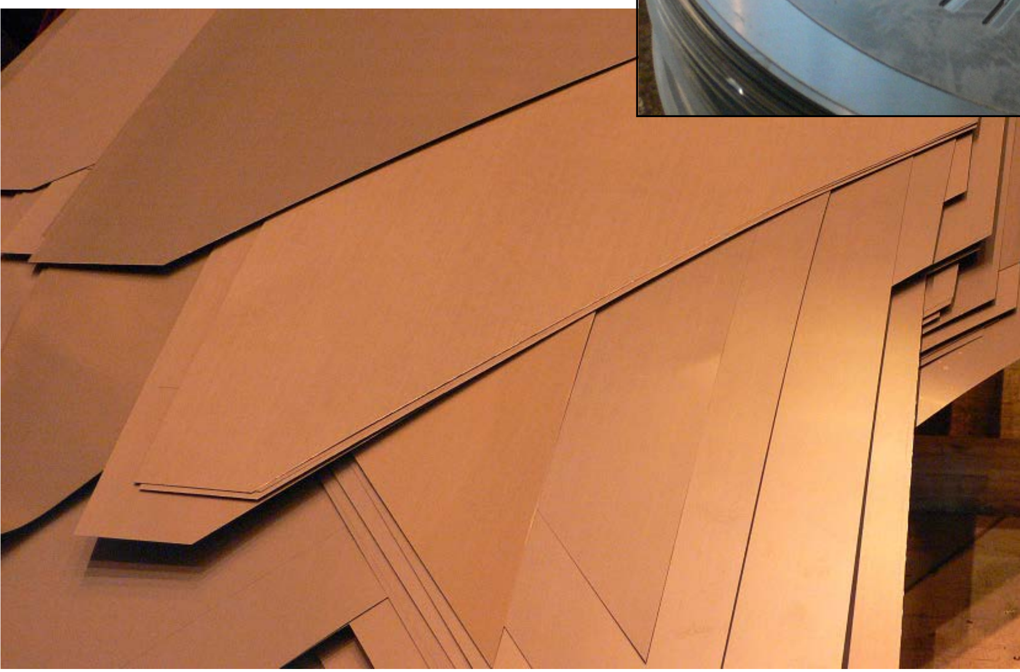
Eddy current loss

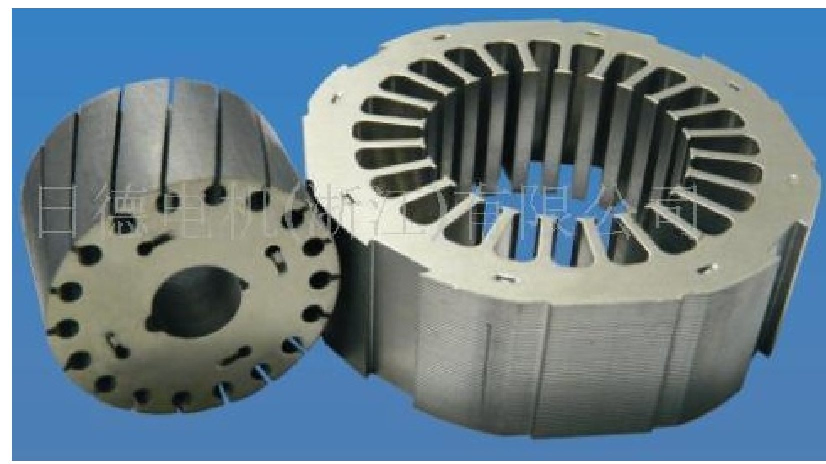




$$p_e = C_e d^2 f^2 B_m^2 V$$







Silicon steel sheet

Relationship between Inductance and MC

MMF

$$F = Ni = \Phi R_{\mathrm{m}}$$

Linkage

$$\Psi = N\Phi = N\frac{Ni}{R_{\mathrm{m}}} = Li$$

Inductance

$$L = \Psi / i = \frac{N^2}{R_{\mathrm{m}}} = N^2 \Lambda_{\mathrm{m}}$$

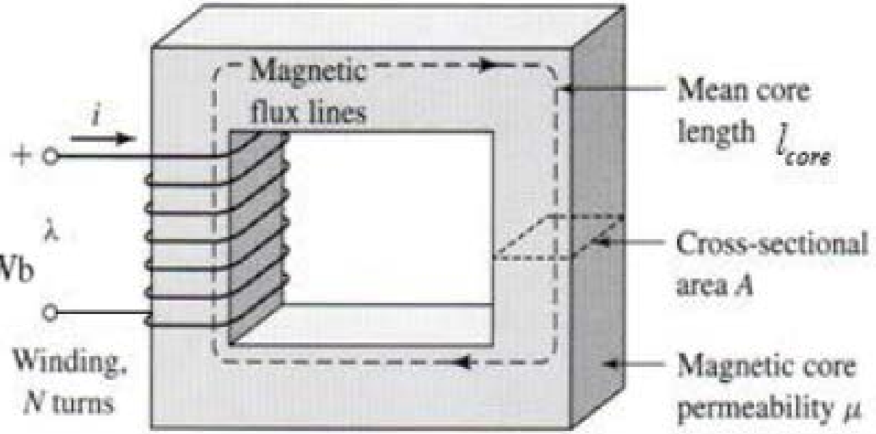
Reactance

$$X = \omega L = 2\pi f N^2 \Lambda_{\mathrm{m}}$$

Example 2.2

Inductance of a Core-and-Coil. Find the inductance of a core with length $l_{core} = 0.1\,\text{m}$, cross-sectional area $A = 0.001\ \text{m}^2$, and relative permeability μ_r somewhere between 15,000 and 25,000. It is wrapped with N = 10 turns of wire. What is the range of inductance for the core?

Solution. When the core's permeability is 15,000 times that of free space, it is



$$\mu_{core} = \mu_r \mu_0 = 15{,}000 \times 4\pi \times 10^{-7} = 0.01885 \text{ Wb/A-t-m}$$

so its reluctance is

$$\mathcal{R}_{core} = \frac{l_{core}}{\mu_{core} A} = \frac{0.1 \text{ m}}{0.01885 \text{ (Wb/A-t-m)} \times 0.001 \text{ m}^2} = 5305 \text{ A-t/Wb}$$

and its inductance is

$$L = \frac{N^2}{\mathcal{R}} = \frac{10^2}{5305} = 0.0188 \text{ henries} = 18.8 \text{ mH}$$

Similarly, when the relative permeability is 25,000 the inductance is

$$L = \frac{N^2}{\mathcal{R}} = \frac{N^2 \mu_r \mu_0 A}{l_{core}} = \frac{10^2 \times 25{,}000 \times 4\pi \times 10^{-7} \times 0.001}{0.1}$$

$$= 0.0314 \text{ H} = 31.4 \text{ mH}$$