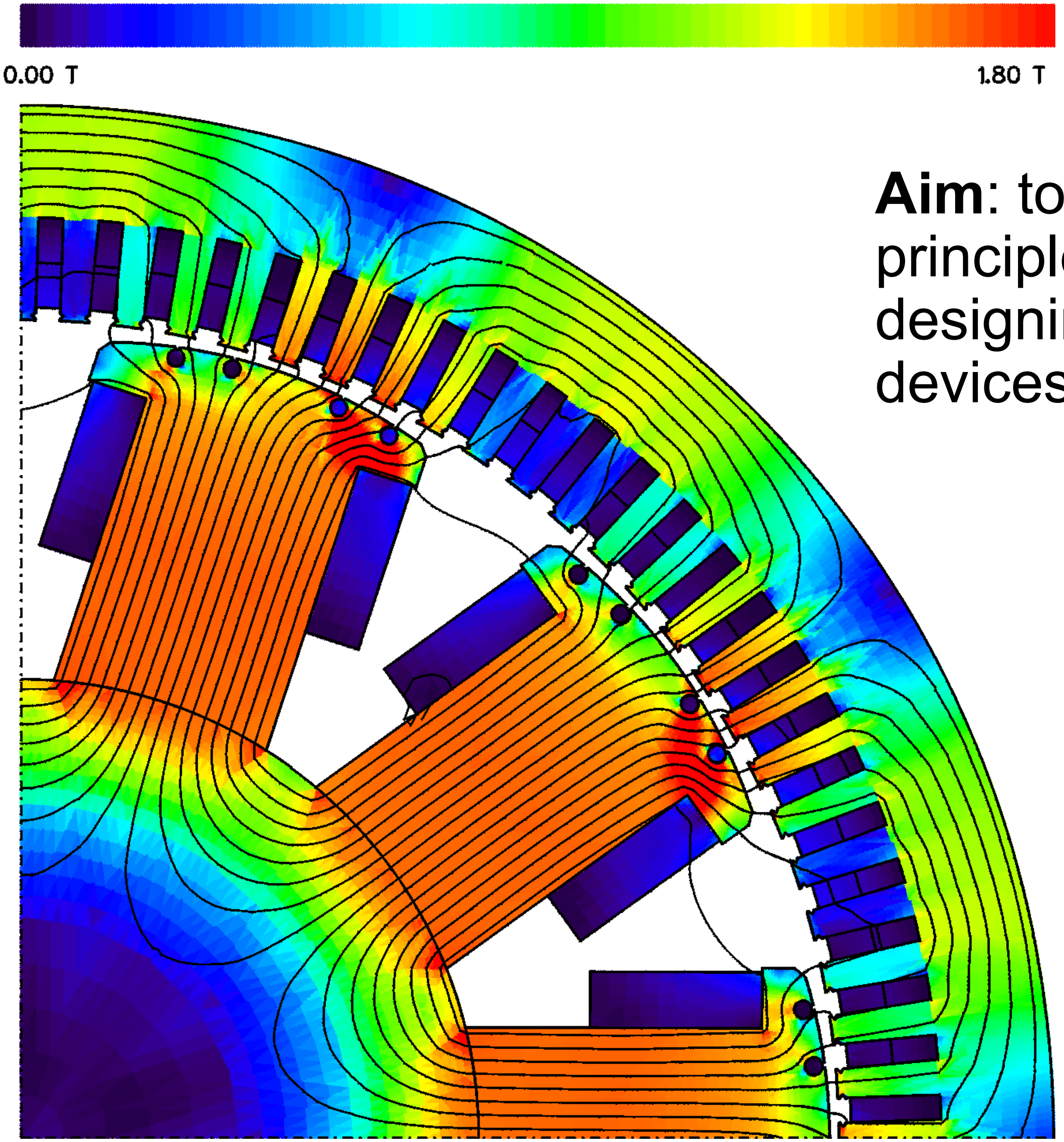
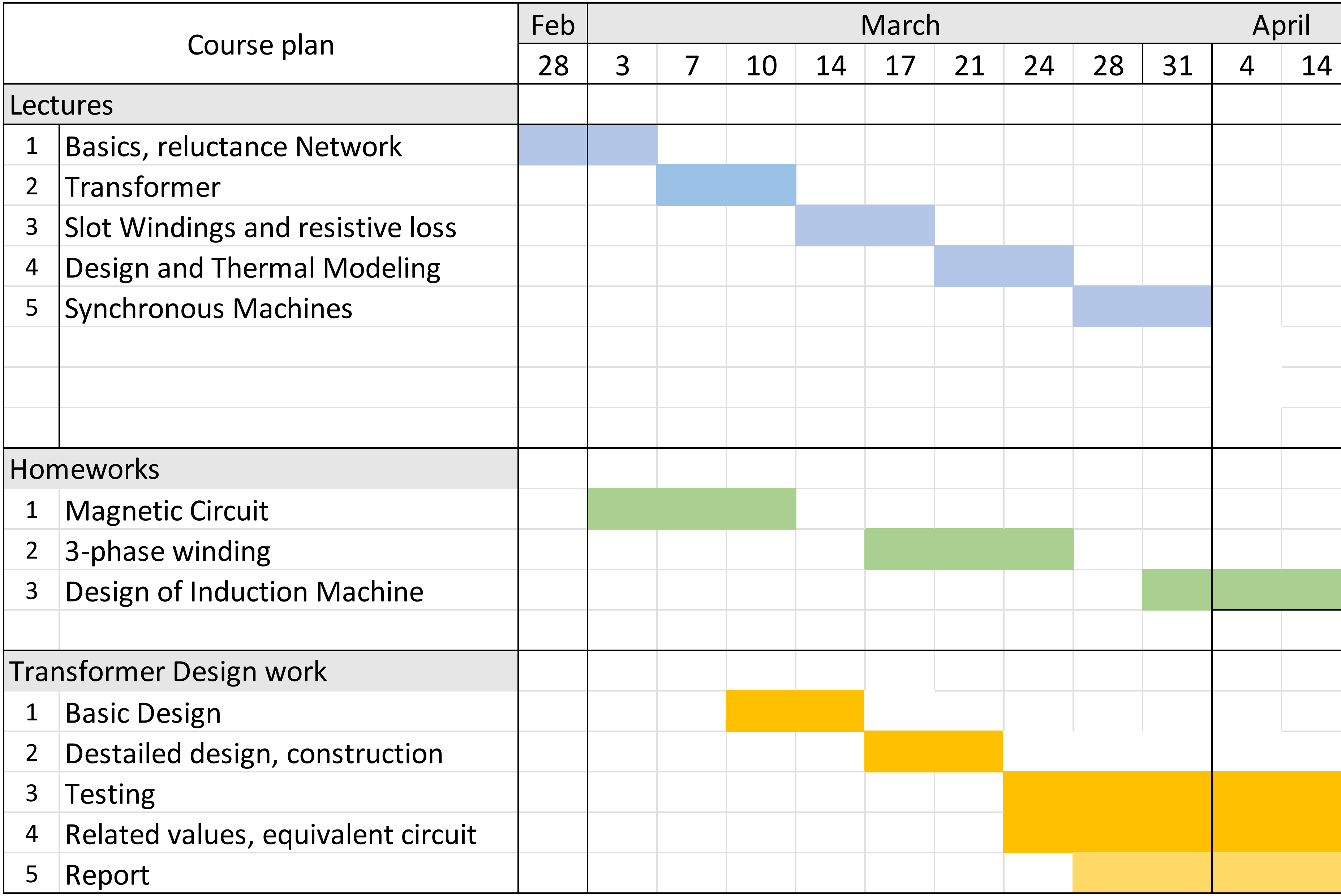
ELEC-E8404 Design of Electrical Machines



Aim: to learn the basic principles and methods for designing electromagnetic devices.

Plan


Course plan
Feb
March
April
28
3
7
10
14
17
21
24
28
31
4
14
Lectures
1 Basics, reluctance Network
2 Transformer
3 Slot Windings and resistive loss
4 Design and Thermal Modeling
5 Synchronous Machines
Homeworks
1 Magnetic Circuit
2 3-phase winding
3 Design of Induction Machine
Transformer Design work
1 Basic Design
2 Destailed design, construction
3 Testing
4 Related values, equivalent circuit
5 Report

Schedule

Feb	28	Principles of Design, Reluctance Model	
March	3	Relcutance model (contd.)	Homework 1 Introduction
	7	Transformer	
	10	Transformer (contd.)	**Submission : Homework 1**
	14	**Groups start preparing for transformer design**	
		Three phase slot winding	
	17	Three phase slot winding (contd.)	Homework 2 Introduction
	21	Design and Thermal Modeling	
	24	Thermal Modeling (contd.)	**Submission : Homework 2**
	28	Synchronous Machines	
	31	Synchronous Machine (contd.)	Homework 3 Introduction
April	4		
	14		**Submission : Homework 3**
	12..15	**Submit Report**	

Assessment

- Three assignments (contributes to 1/3rd of final grade)
- Trasformer design task and report (contributes to 2/3rd of final grade)

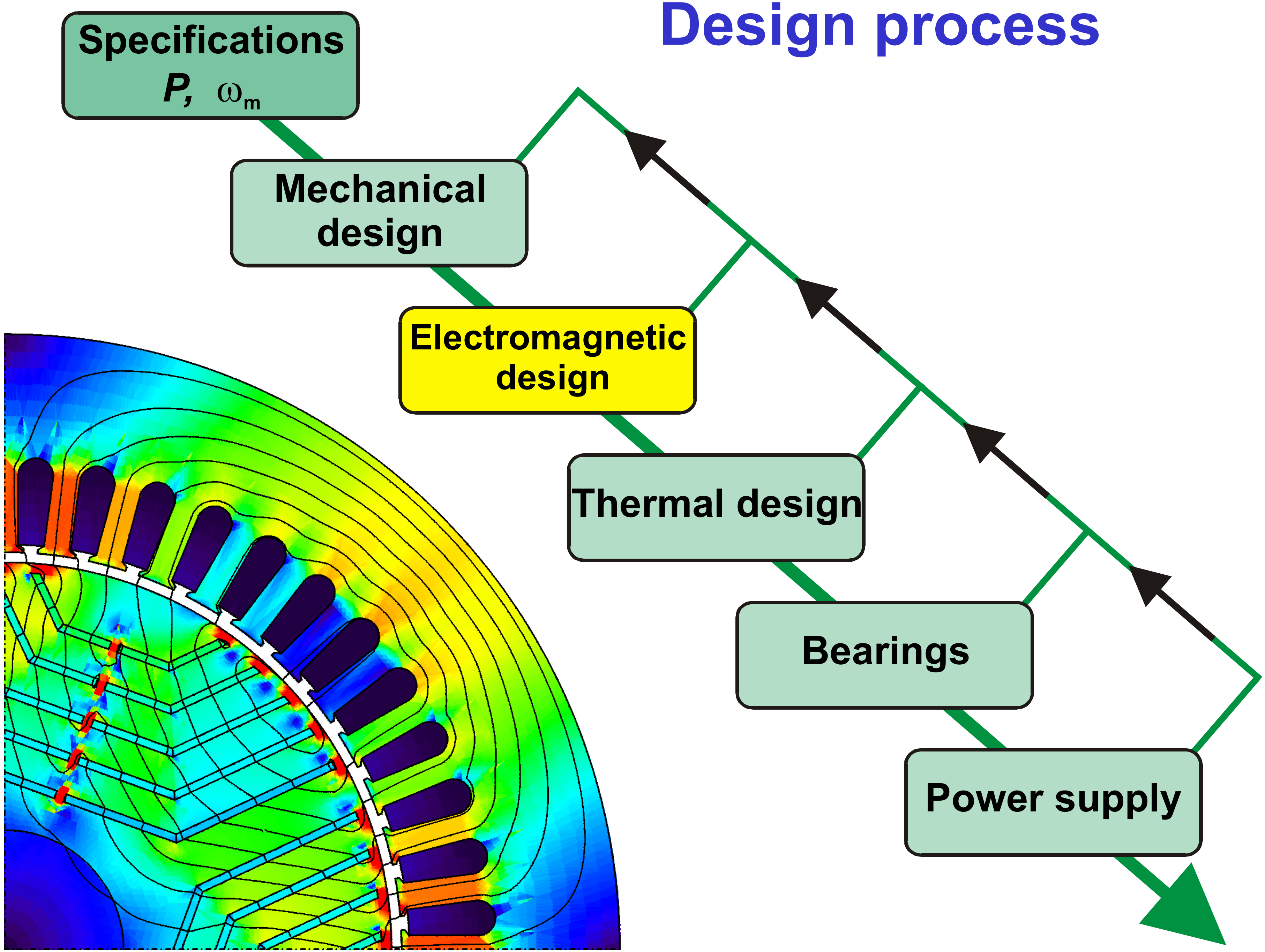
Course reading

- Lecture slides, course handouts
- ”Design of Electrical Machines” , Juha Pyrhonen, Tapani Jokinen, Valeria Hrabovcova.

Course Schedule

- On Friday, 31st of March, the lecture will start at 14:45.

Design process



Electromagnetic and thermal modelling

Maxwell's equations

$$\nabla \cdot \boldsymbol{D} = \rho$$

$$\nabla \cdot \boldsymbol{B} = 0$$

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

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t}$$

Material equations

$$\boldsymbol{D} = \varepsilon \boldsymbol{E}$$

$$\boldsymbol{J} = \sigma \boldsymbol{E}$$

$$\boldsymbol{B} = \mu \boldsymbol{H}$$

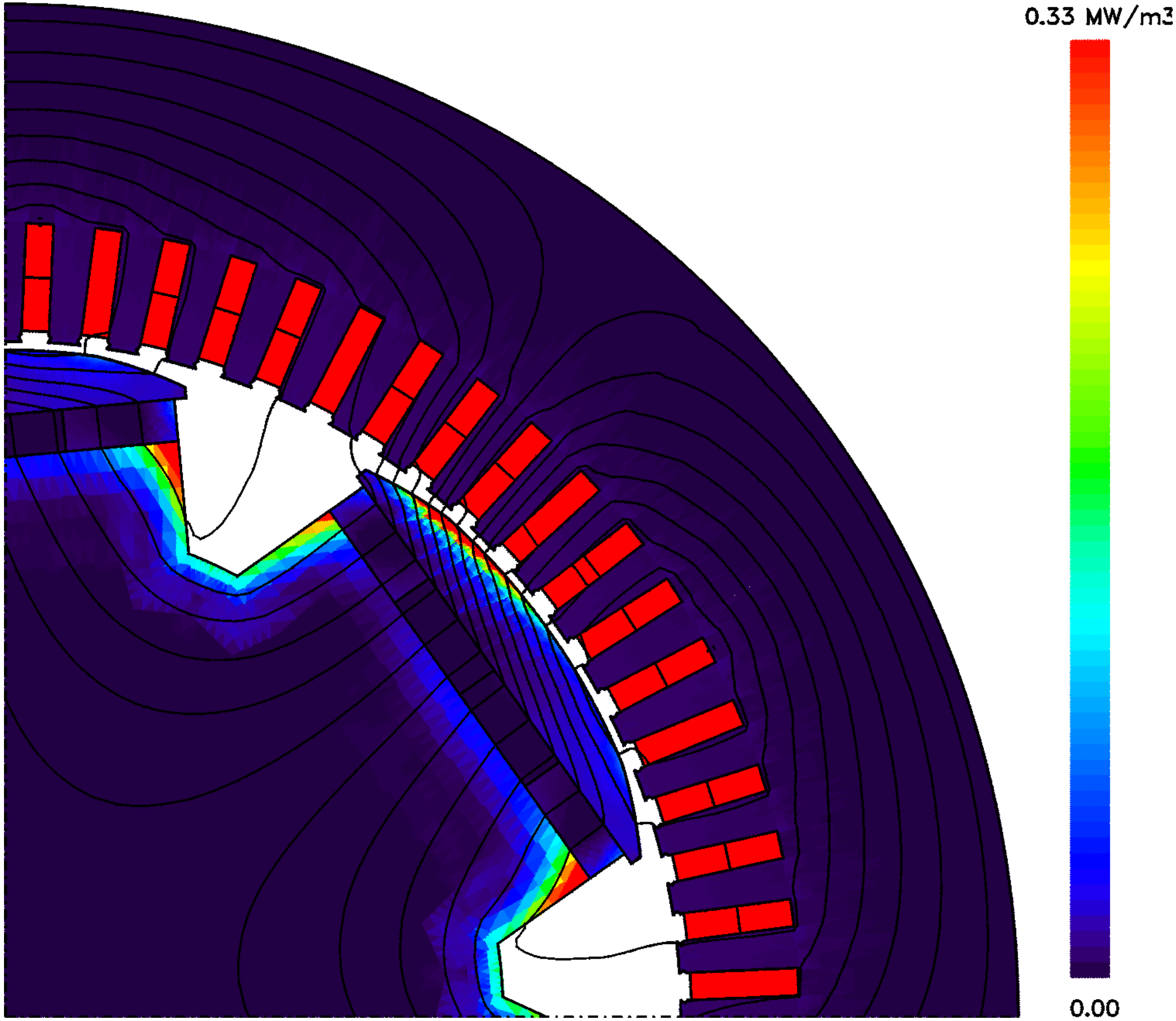
Heat transfer

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (\lambda \nabla T) = p_{\mathrm{h}}$$

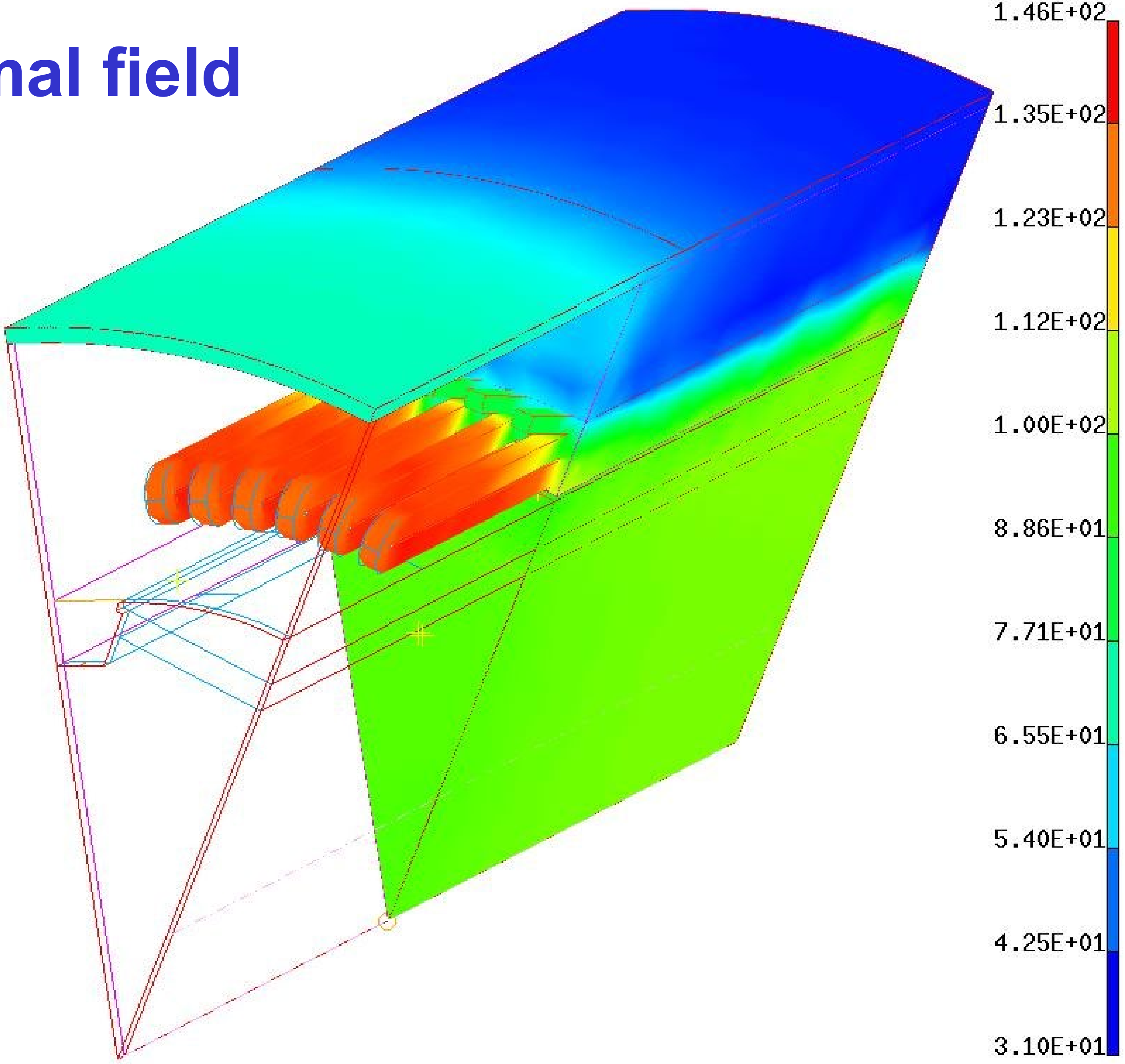
$$\boldsymbol{q} = -\lambda \nabla T$$

In addition, boundary conditions have to be specified.

Electrical losses of a prototype …

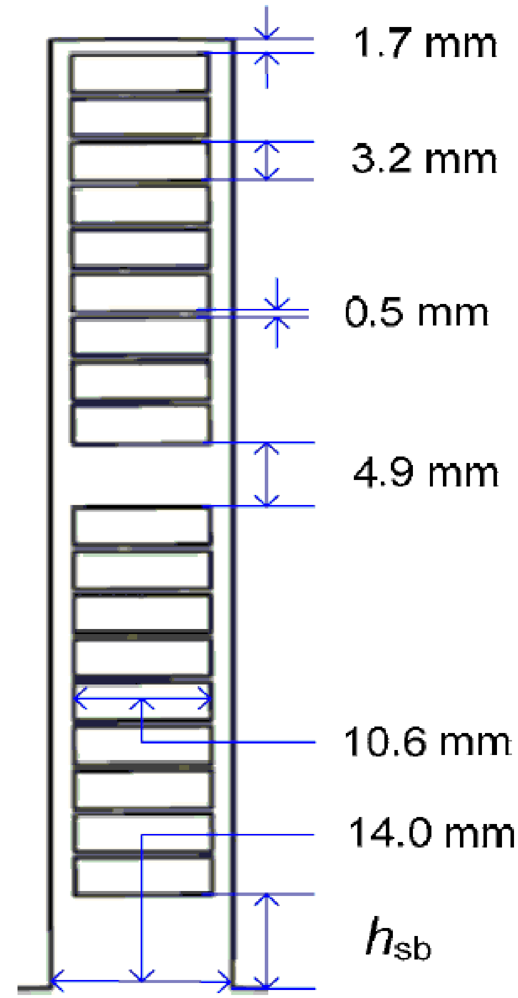


and thermal field



Raw Materials

- Conductors
  - – Copper, aluminium, brass
  - – Insulation layers
- Insulators
  - – Foils, tapes, bars
  - – Supports and frames
  - – Castable compounds

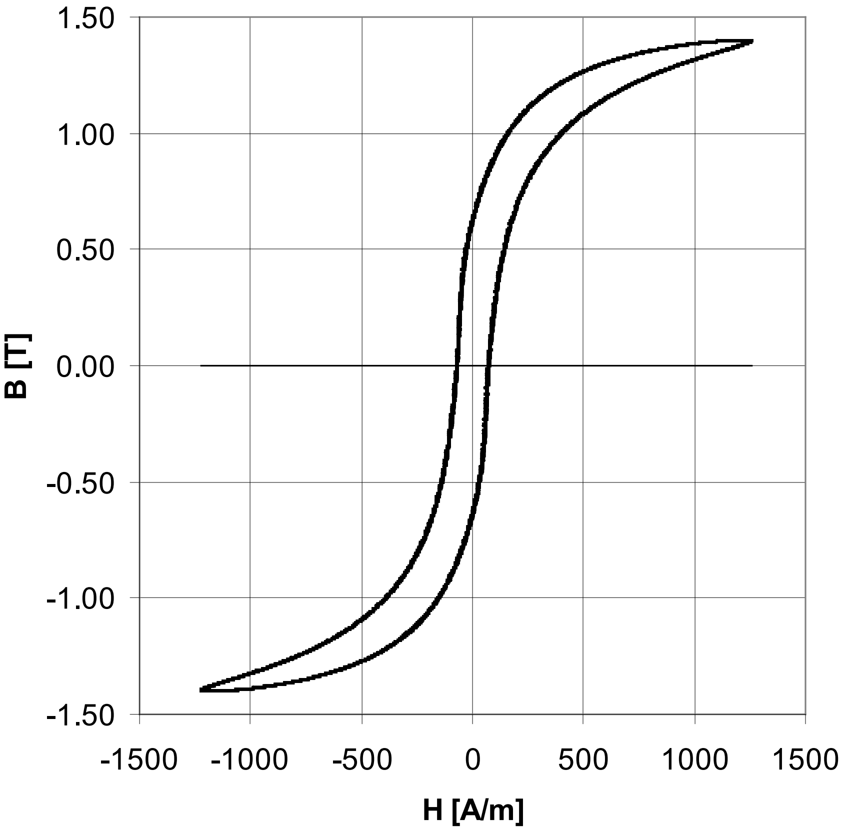


Form-wound coils in a low-voltage machine

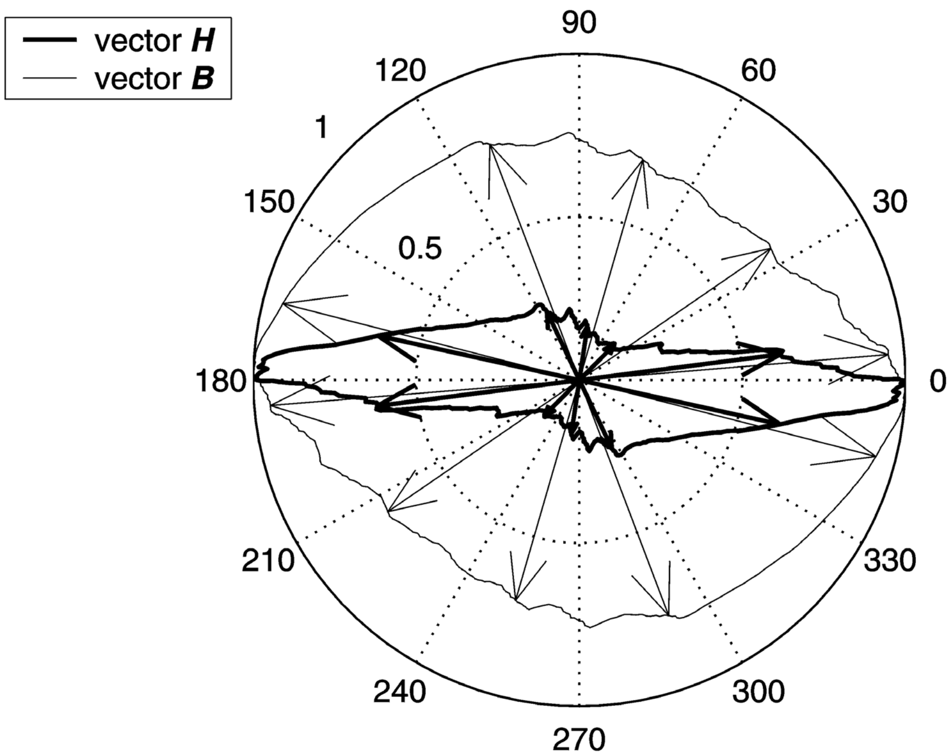
Raw Materials II

- Electrical steel sheets
  - Standard dimensions
  - Ready-made, punched sheets available
  - Insulation coating
  - Magnetic characteristics
    - Oriented steel sheets
    - Non-oriented steel sheets

Magnetic characteristics of iron

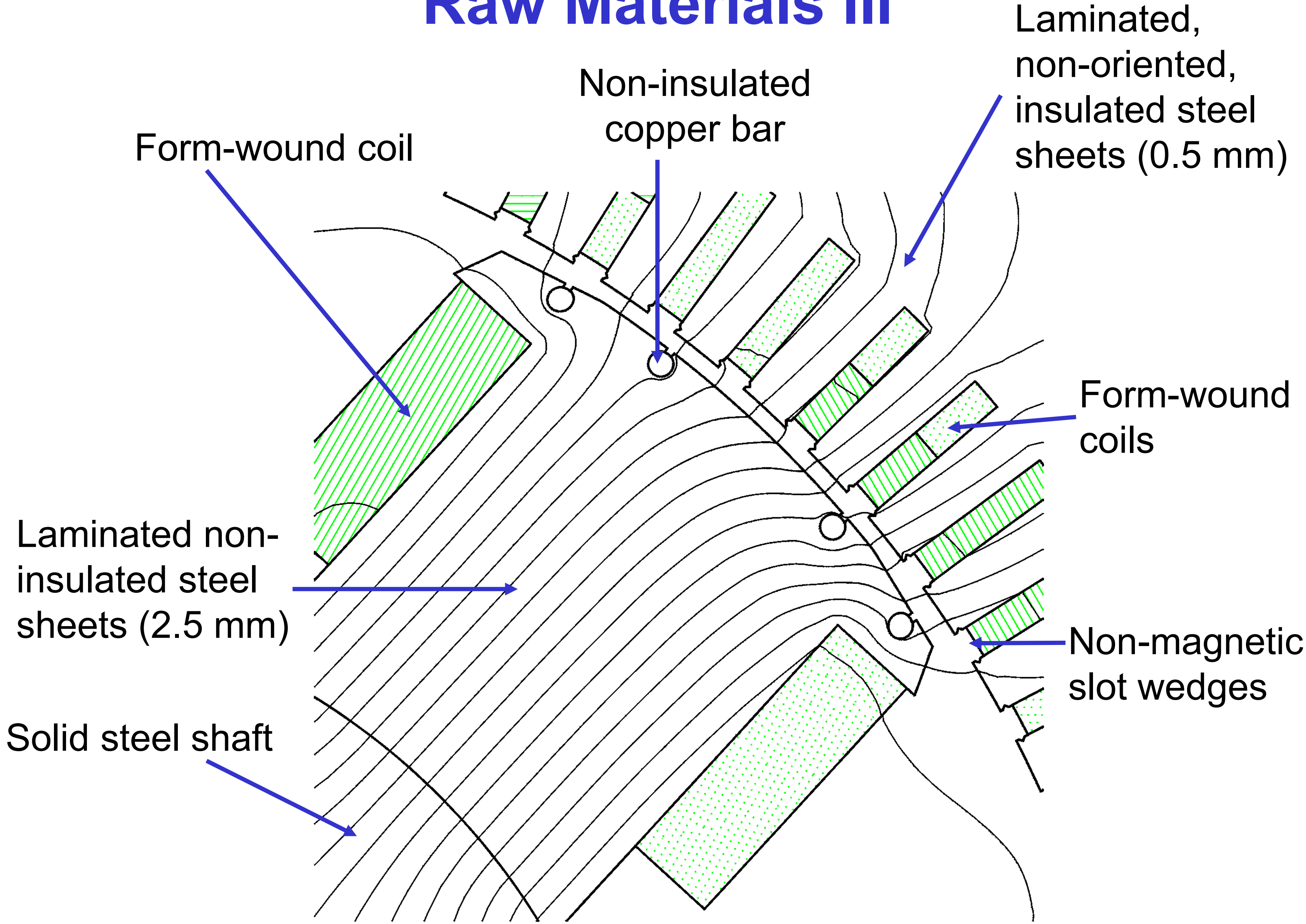


Alternating field



Fields in an electrical machine

Raw Materials III



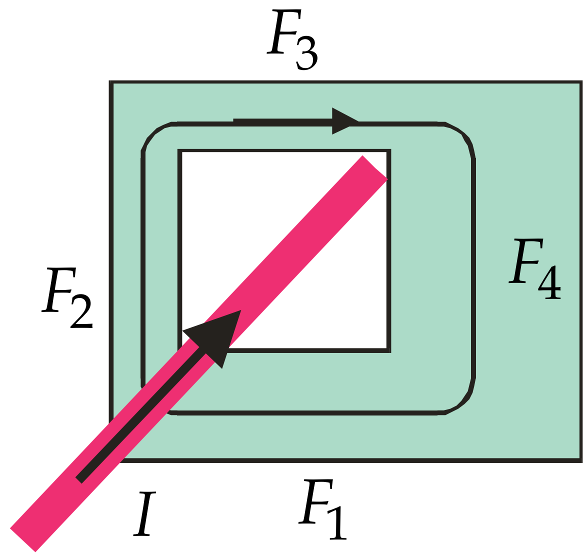
Tools for the design process

- Computer
- Design codes developed by experts
  - A coupled electromagnetic, thermal and mechanical problem has to be solved
  - Typically, semi-analytical models for routine design, FEA for designing new products
- Test results from previous products
  - Provide verification and possible correction factors between the theoretical models and real world

Magnetic circuits

$$\oint_s \boldsymbol{H}\cdot \mathrm{d}\boldsymbol{s} = \sum_i F_i = I$$

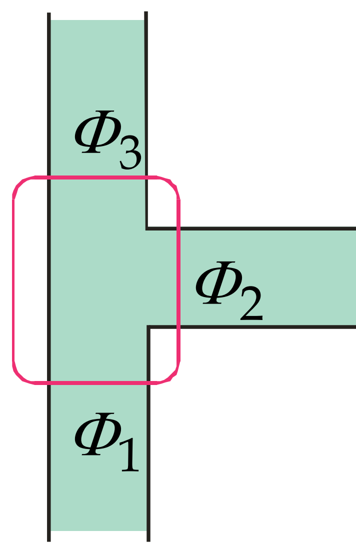
$$F_i = \int_{a_i}^{b_i} \boldsymbol{H}\cdot \mathrm{d}\boldsymbol{s}$$



$$F_1 + F_2 + F_3 + F_4 = I$$

$$\oint_S \boldsymbol{B}\cdot \mathrm{d}\boldsymbol{S} = \sum_i \Phi_i = 0$$

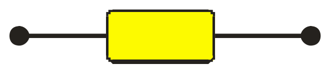
$$\Phi_i = \int_{S_i} \boldsymbol{B}\cdot \mathrm{d}\boldsymbol{S}$$



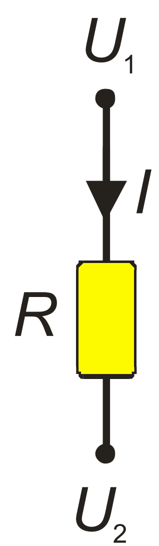
$$\Phi_1 + \Phi_2 + \Phi_3 = 0$$

Analogy between electric and magnetic circuits

Resistance

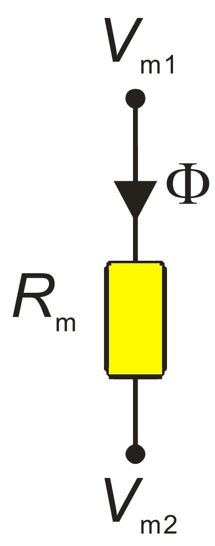


$$R = \frac{l}{\sigma A}$$

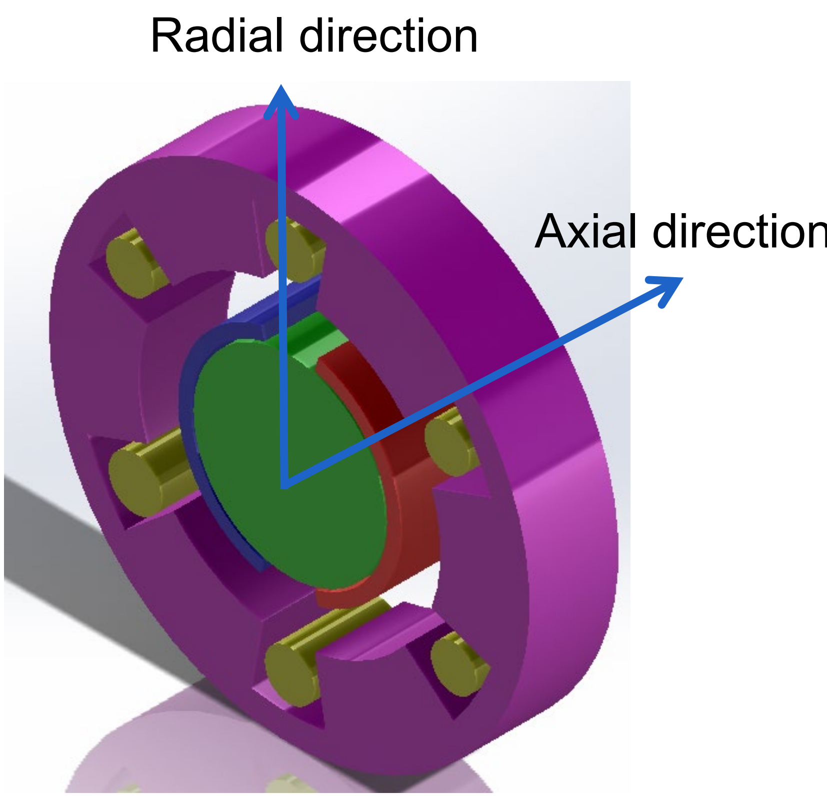


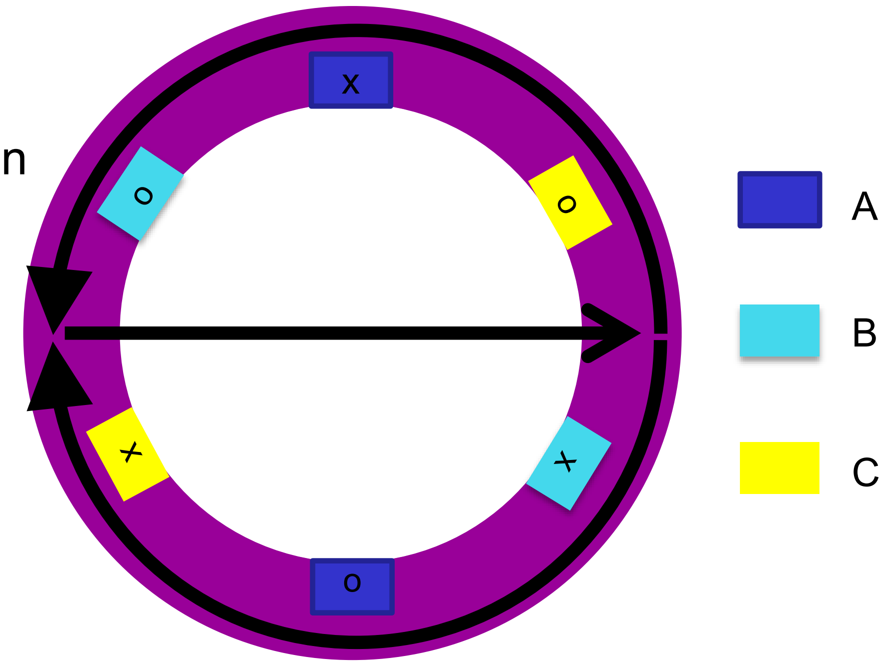
Reluctance

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



Radial Flux Permanent Magnet Machines





Front view

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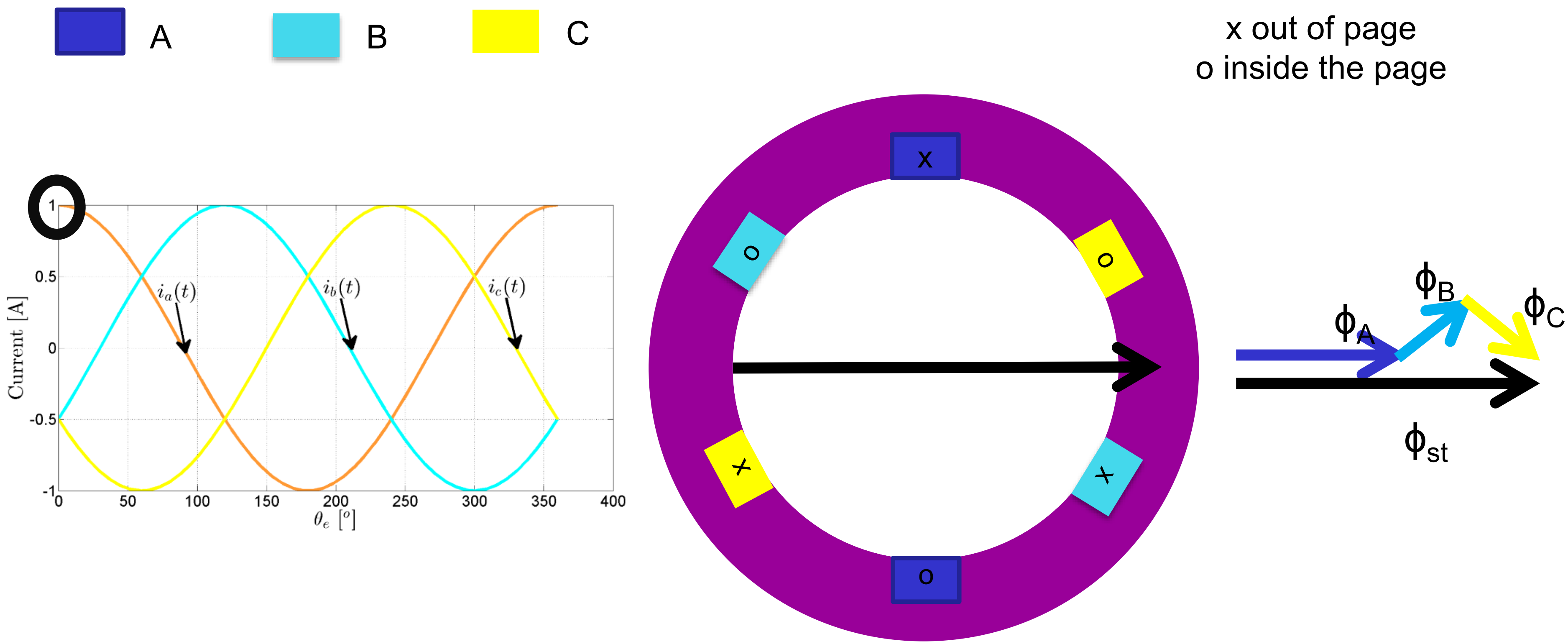
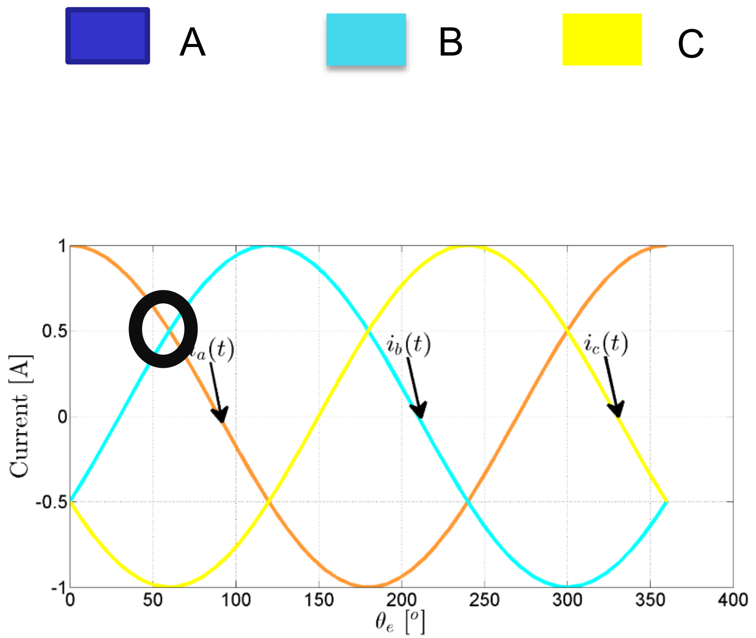
Flux flows in the stator yoke.

Radial Flux Permanent Magnet Machines



Radial Flux Permanent Magnet Machines



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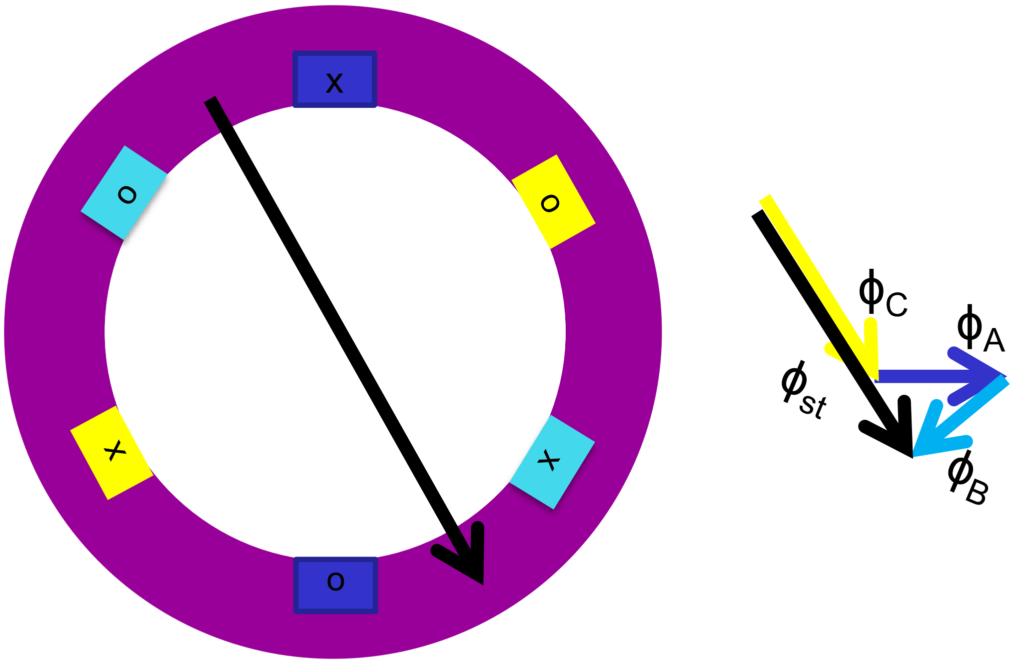
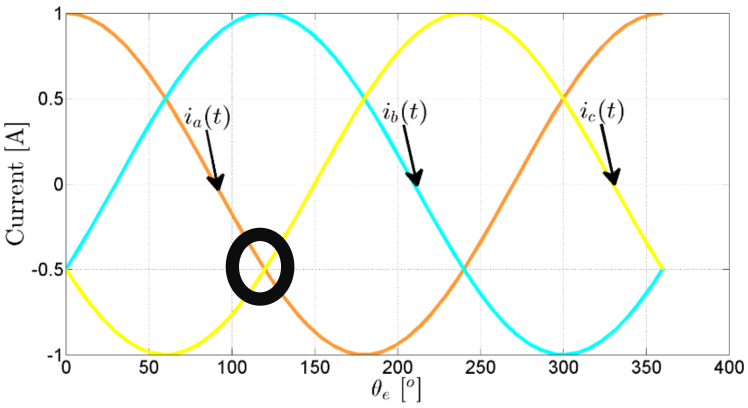
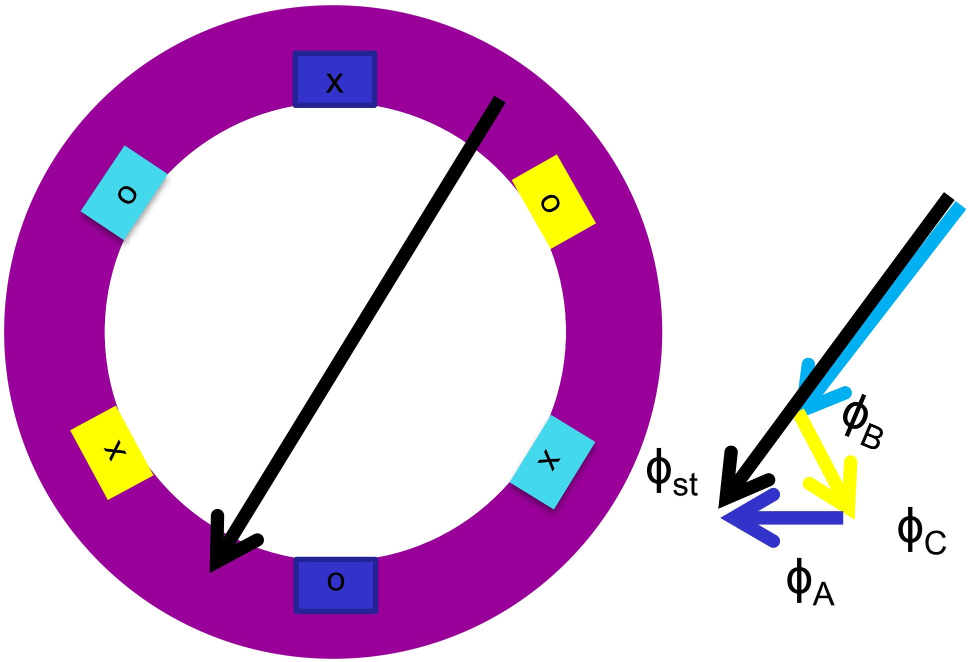
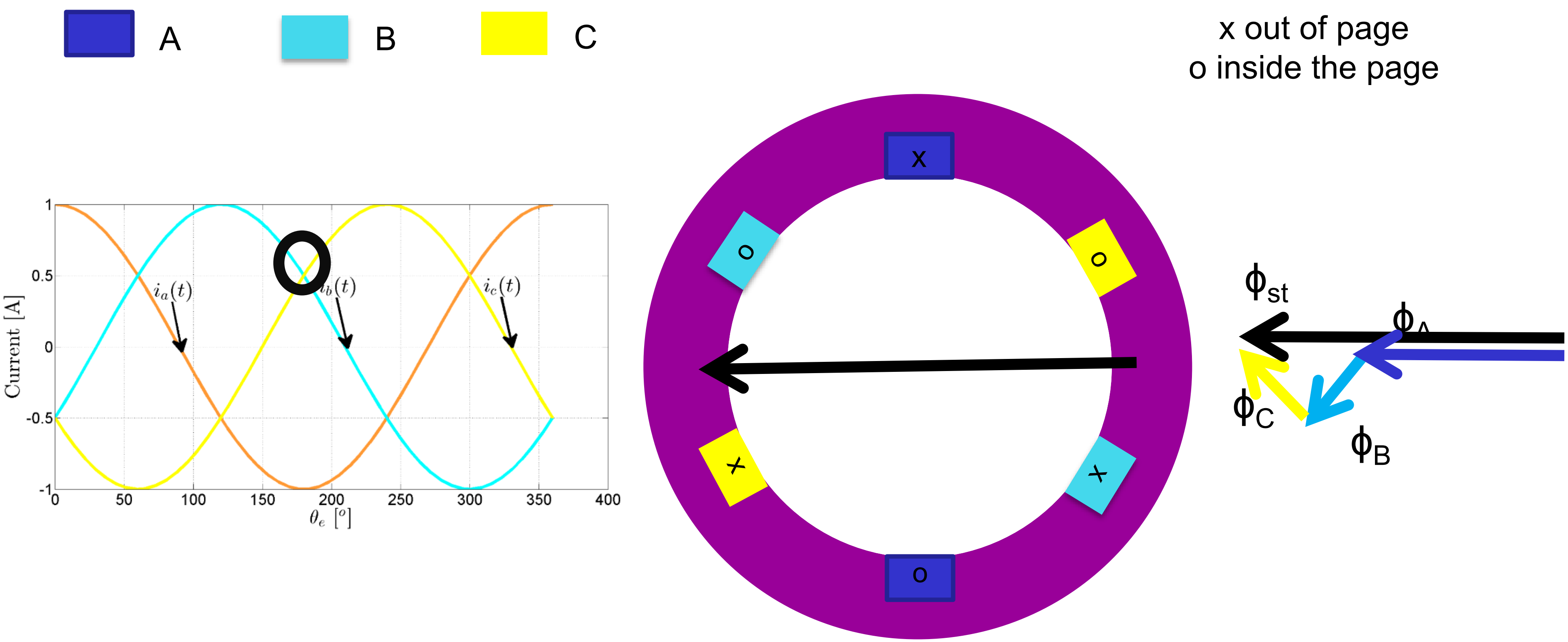


Radial Flux Permanent Magnet Machines



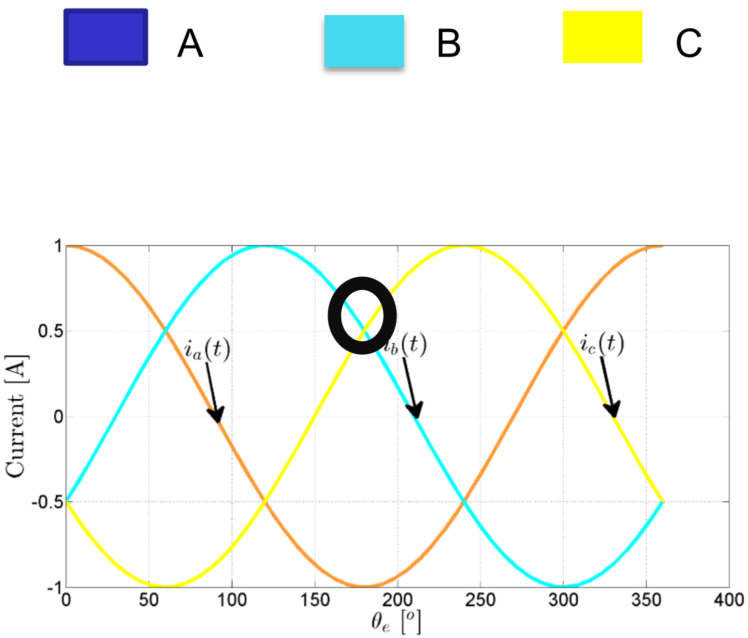


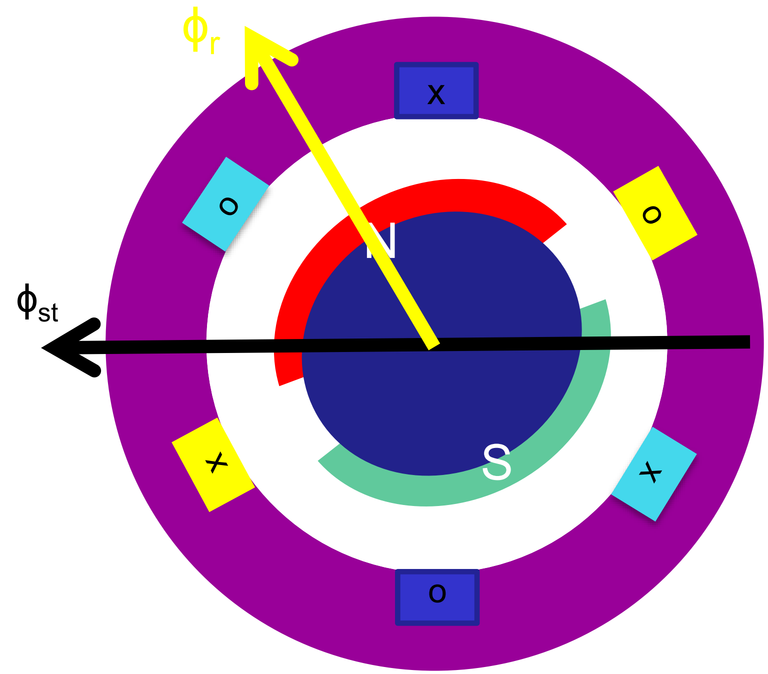
Radial Flux Permanent Magnet Machines



- Rotating magnetic field is produced.

Radial Flux Permanent Magnet Machines

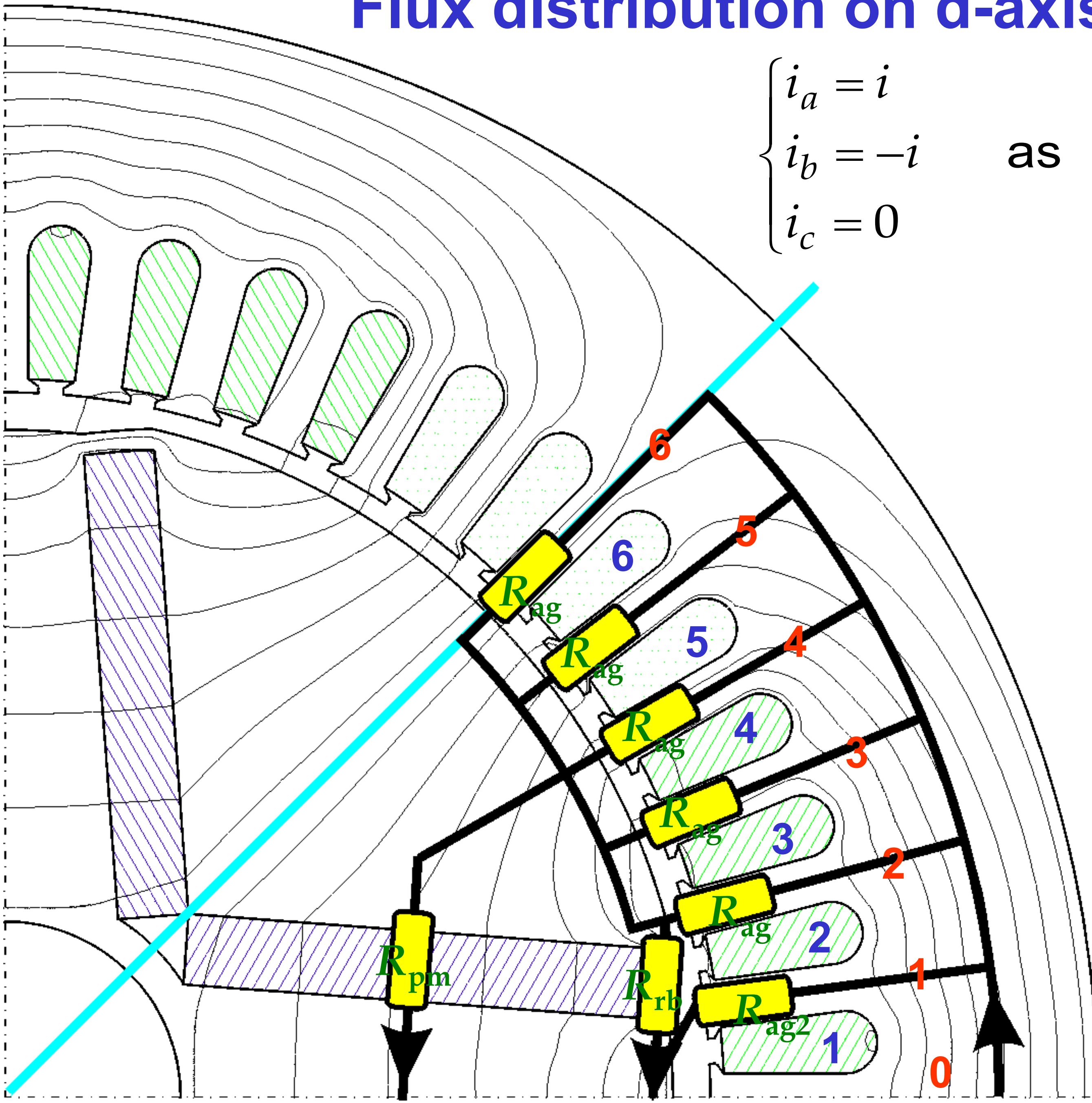




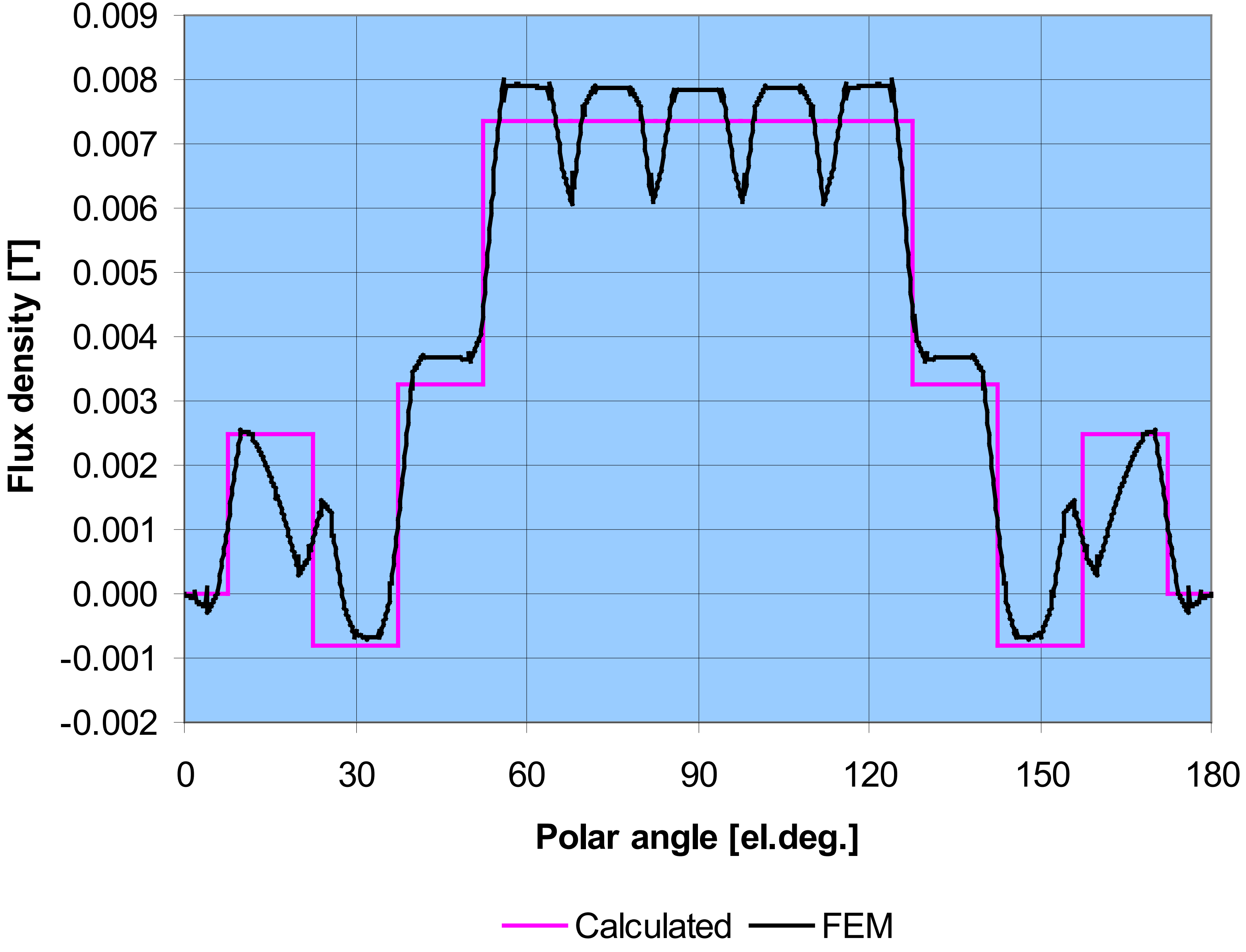
- The interaction between these two rotating fields produces torque.
- AFPMSM principle of operation is similar to RFPMSM.

Flux distribution on d-axis

$$\begin{cases} i_a = i \\ i_b = -i \\ i_c = 0 \end{cases} \quad \text{as} \quad i_a + i_b + i_c = 0$$

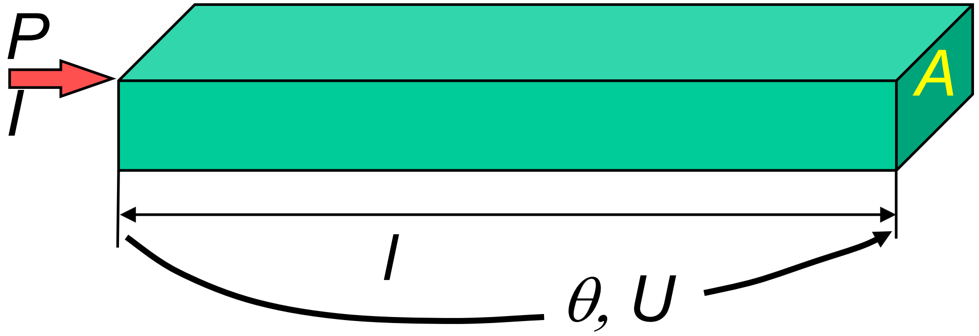


Flux distribution on d-axis II



Thermal resistance

A conductor having a constant cross-sectional area



P = Power,
$\theta =$ Temperature difference

Equations for the heat flow and electric current (p_h = 0)

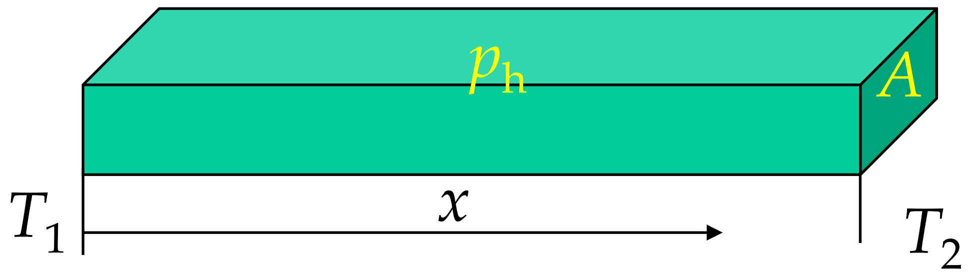
$$P = \int_A \vec{q} \cdot d\vec{A} = \int_A -\lambda \nabla T \cdot d\vec{A} = \lambda \frac{\theta}{l} A = \frac{\theta}{R}$$

$$R = \frac{l}{\lambda A}$$

$$I = \int_A \vec{J} \cdot d\vec{A} = \int_A -\sigma \nabla \phi \cdot d\vec{A} = \sigma \frac{U}{l} A = \frac{U}{R_e}$$

$$R_e = \frac{l}{\sigma A}$$

1D thermal network



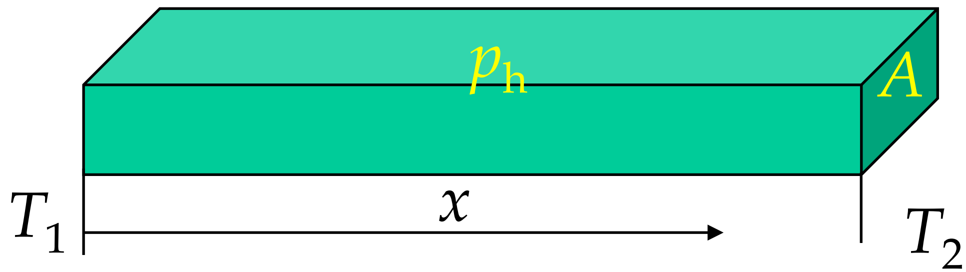
$$\nabla \cdot (\lambda \nabla T) = -p_h$$ λ = constant; p_h = constant

$$\frac{d^2T}{dx^2} = -\frac{p_h}{\lambda} \quad => T(x) = -\frac{p_h}{2\lambda}x^2 + c_1 x + c_2$$

$$\begin{cases} T(0) = T_1 \\ T(l) = T_2 \end{cases} => \quad T(x) = \frac{p_h}{2\lambda}x(l-x) + \frac{l-x}{l}T_1 + \frac{x}{l}T_2$$

Average temperature of a conductor

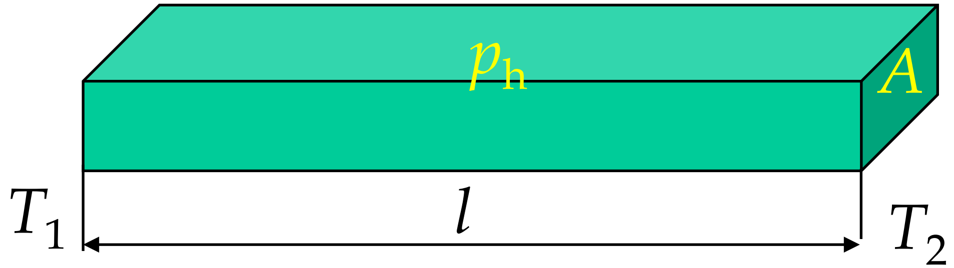
Knowledge of the average temperature is often sufficient



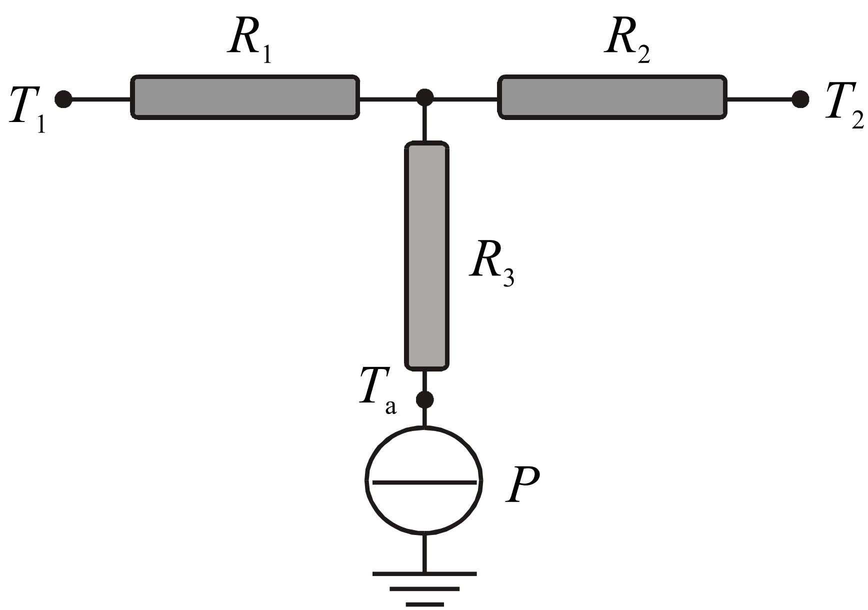
$$T_{ave} = \frac{1}{l}\int_0^l \left[\frac{p_h}{2\lambda}x(l-x) + \frac{l-x}{l}T_1 + \frac{x}{l}T_2\right]dx = \frac{p_h}{12\lambda}l^2 + \tfrac{1}{2}(T_1 + T_2)$$

Task: Define a simple thermal network, which models correctly the heat transfer and gives as a nodal value the average temperature of the conductor.

Thermal network for 1D heat flow



The thermal network below fulfils the requirements



$$R_1 = R_2 = \frac{l}{2\lambda A}$$

$$R_3 = -\frac{l}{6\lambda A}$$

Thermal network for a stator