Modelling the magnetic Permeability of Non-linear Laminated Materials

Ewa Napieralska-Juszczak

Universite Artois France

RÉGION Nord-Pas de Calais

UNIVERSITÉ D'ARTOIS

LSEE

MEDEE

. The hierarchy of descriptive levels of magnetically ordered materials

5. Magnetic Hysteresis, or Magnetization Curve
Describing the *average magnetization* vector of a sample as a function of the external field (always applicable)

4. Phase, or Magnetic Texture Analysis
Collecting domains of equal magnetization direction in "phases". More generally, describing the distribution function (*texture*) of magnetization directions (> 0.1 mm)

3. Domain, or Magnetic Microstructure Analysis
Describing the *magnetic microstructure* of a sample, the shape and detailed spatial arrangement of domains and domain boundaries (1–1000 μm)

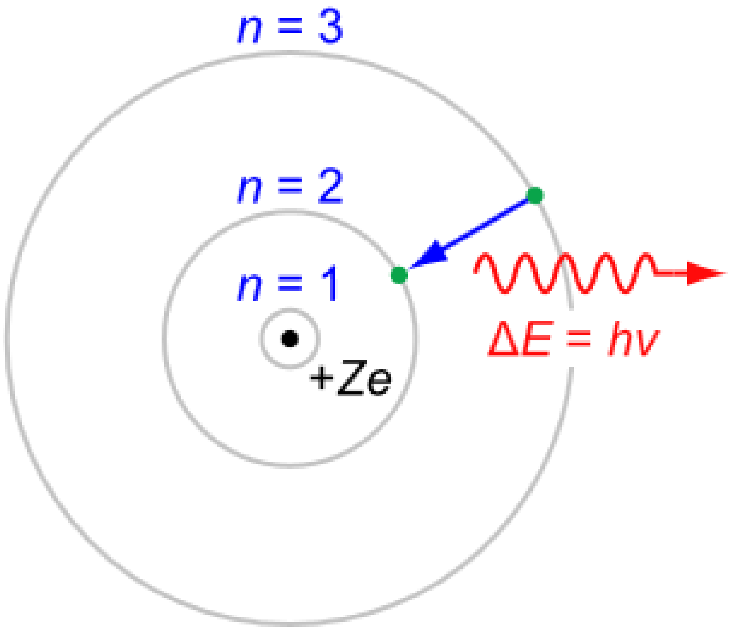
2. Micromagnetic Analysis
Describing the *internal structure of domain walls* and their substructures in terms of a continuum theory of a classical magnetization vector field (1–1000 nm)

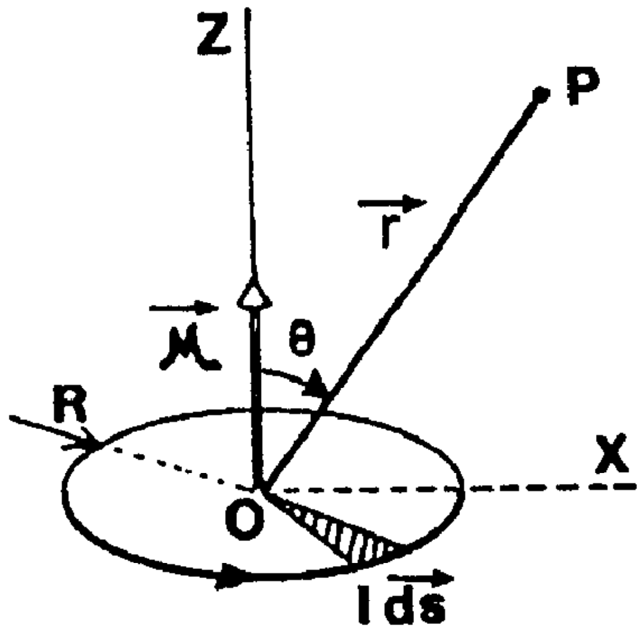
1. Atomic Level Theory
Describing the origin, the interactions, the mutual arrangement and the statistical thermodynamics of elementary magnetic moments (< 1 nm)

ATOM

- The **atom** is a basic unit of matter that consists of a dense central nucleus surrounded by a cloud of negatively charged electrons.
- molecule strives to hold a minimum of energy
- binding energy = energy of the isolated atoms - energy of the particles

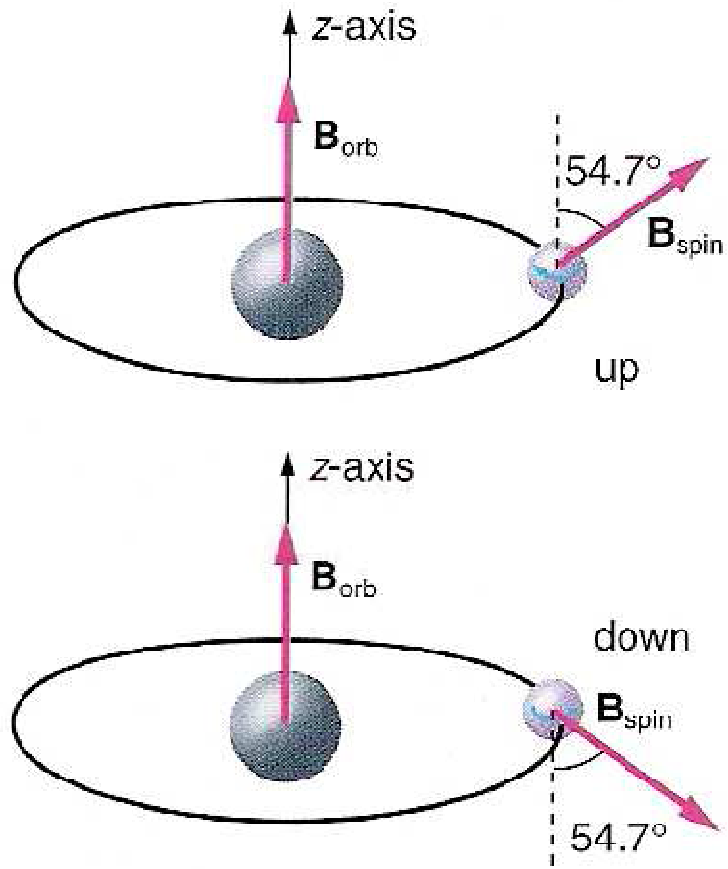
Bohr model of atom





SPIN

- **spin** is a fundamental characteristic property of elementary particles, composite particles and atomic nuclei



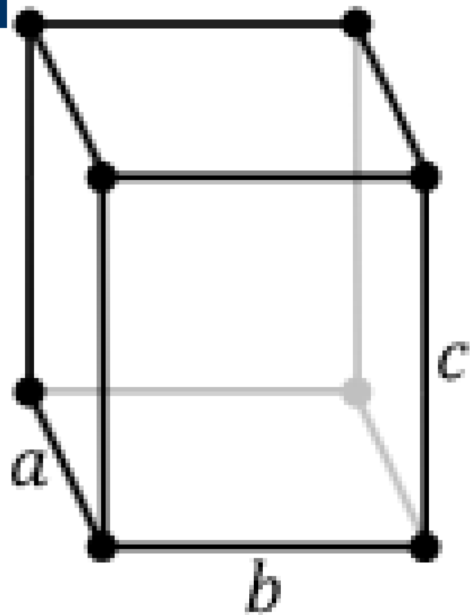
Magnetic moments

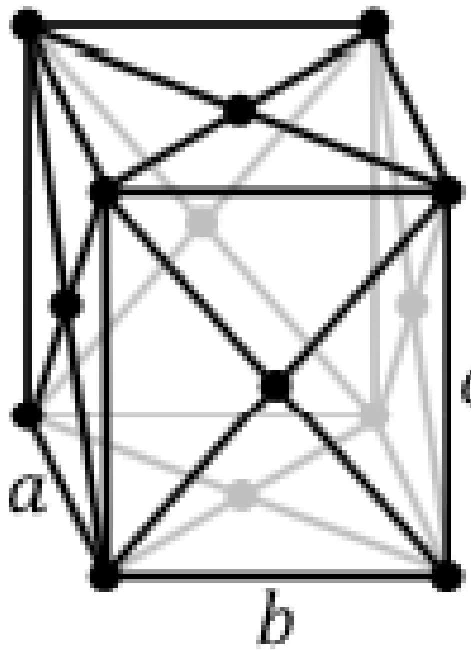
- Particles with spin can possess a magnetic dipole moment,, just like a rotating electrically charged body in classical electrodynamics.
- A **magnetic field** is a field produced by moving electric charges, by electric fields that vary in time and by the 'intrinsic' magnetic field of elementary particles associated with the spin of the particle.

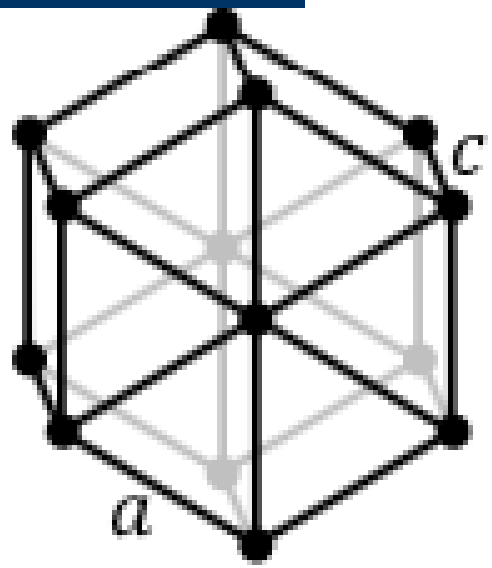
electrostatic interaction

- Van der Waals forces include attractions between atoms, molecules, and surfaces. They differ from covalent and jonic bonding in that they are caused by correlations in the fluctuating polarizations of nearby particles
- Heisenberg model - the dominant coupling between two dipoles may cause nearest-neighbors to have lowest energy when they are *aligned*.

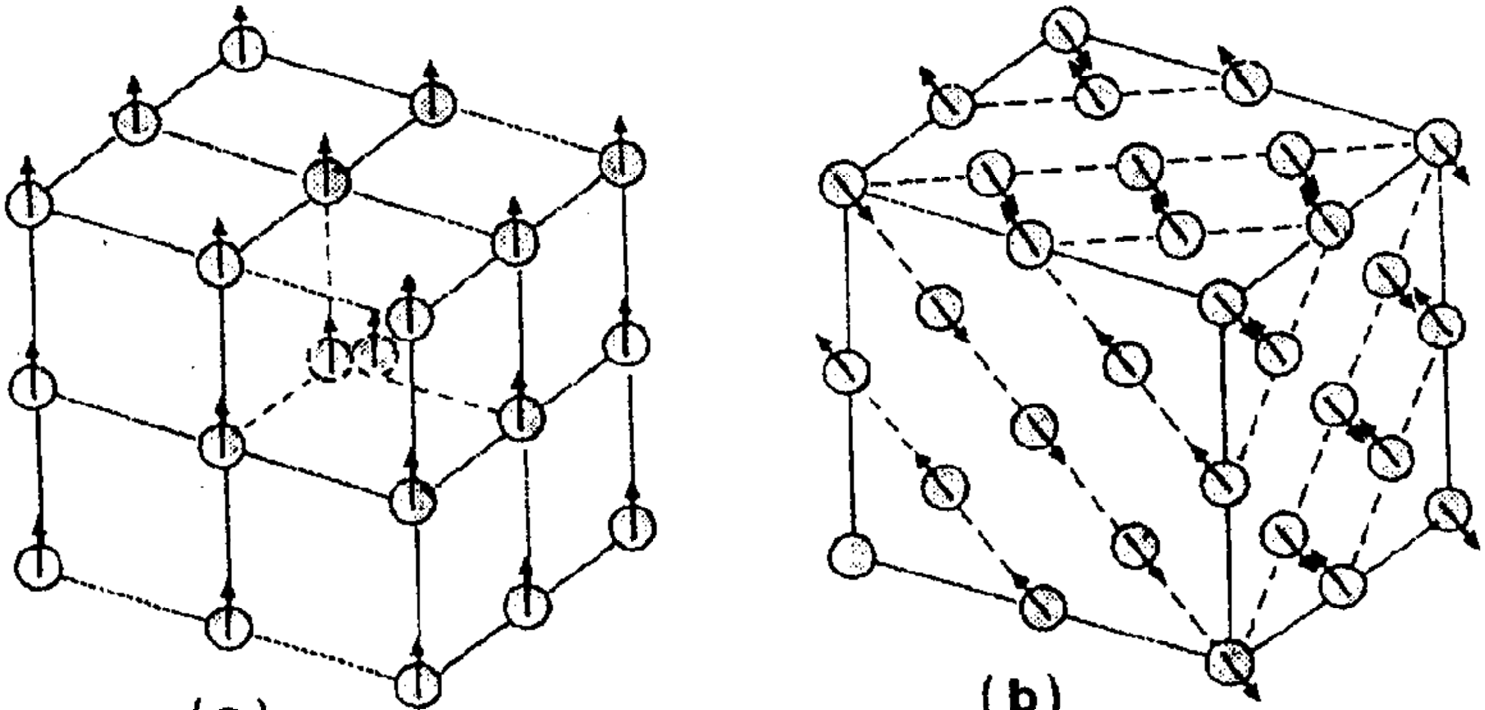
Cristal system of ferromagnetics





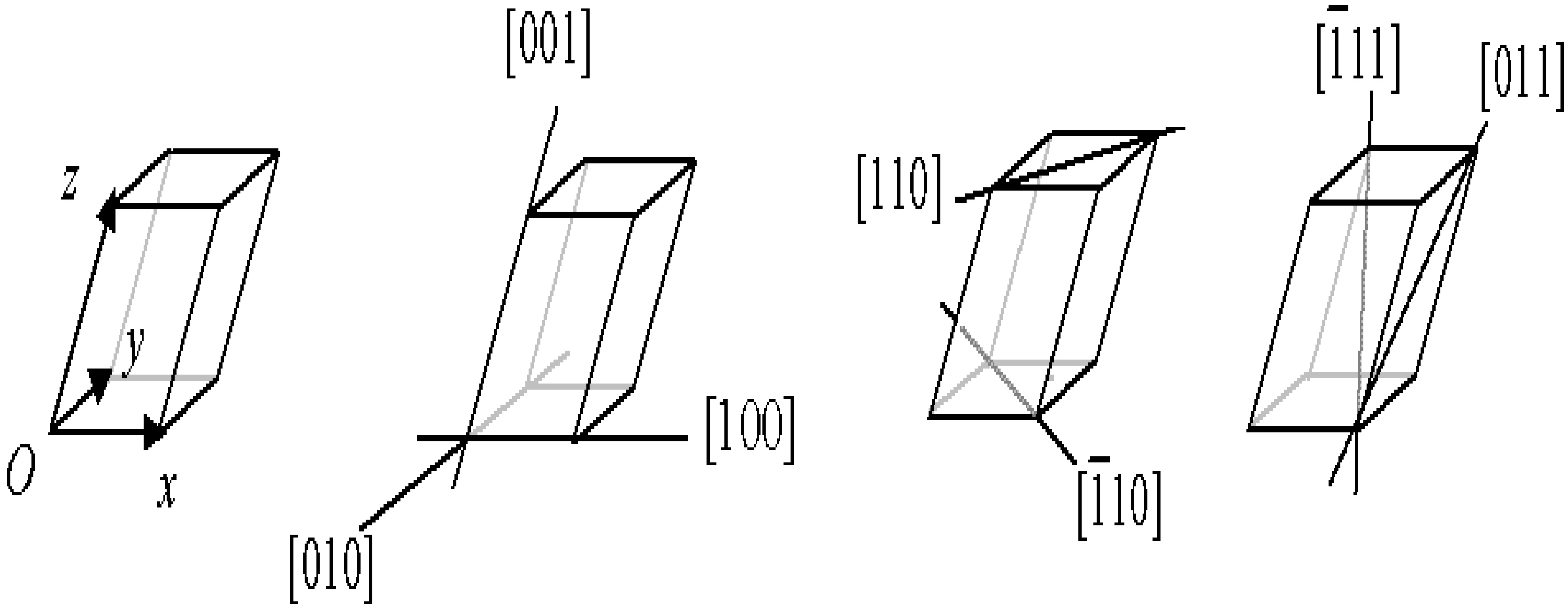


Ferromagnetic and antyferromagnetic materials



(a) (b)

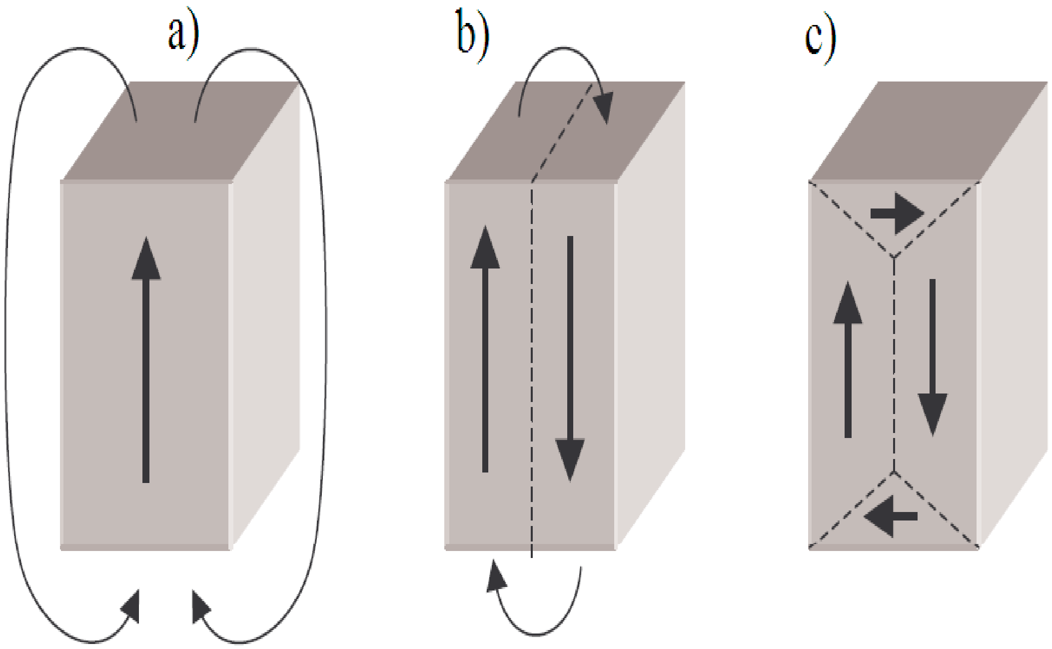
Basic directions



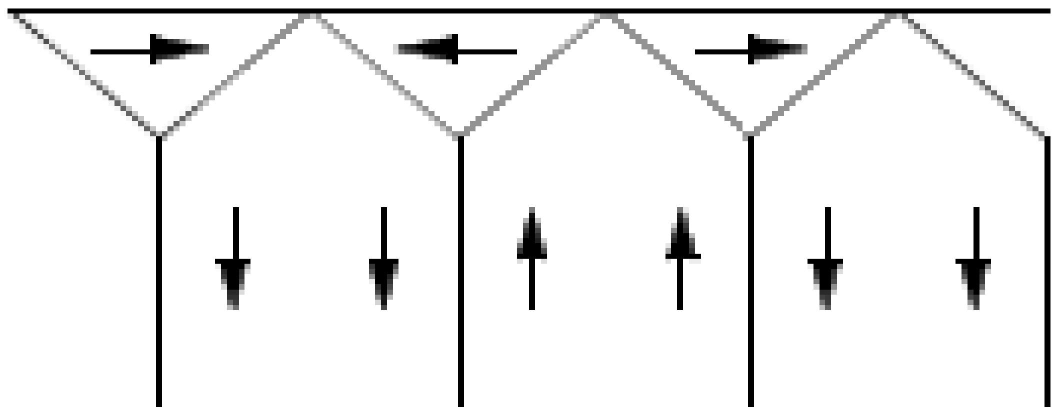
The Domain Idea

Magnetic domain theory was developed by Weiss who suggested existence of magnetic domains in ferromagnets. He suggested that large number of atomic magnetic moments (typically 1012-1018) were aligned parallel. The direction of alignment varies from domain to domain
in a more or less random manner although certain crystallographic axis may be preferred by the magnetic moments, called easy axes.
Weiss still had to explain the reason for the spontaneous alignment of atomic moments within a ferromagnetic material, he assumed that a given magnetic moment in a material experienced a very high effective magnetic field due to the magnetization of its neighbours. In the original Weiss theory the mean field was proportional to the bulk magnetization M.

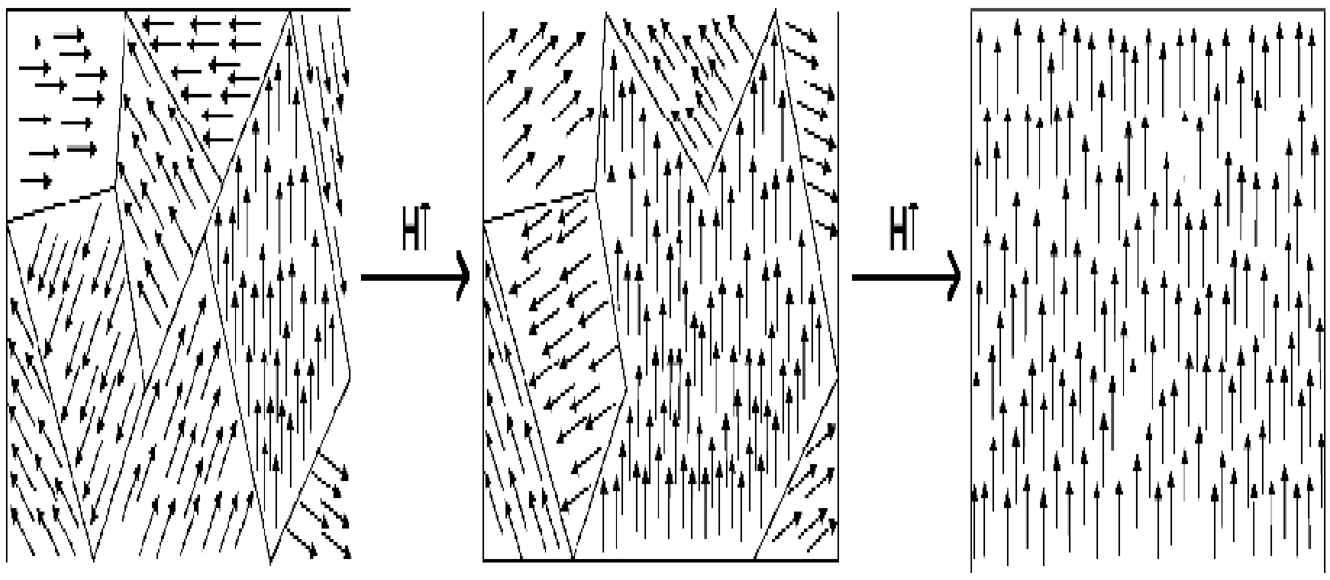
The Domain Idea



The first realistic model of magnetic domains by *Landau* and *Lifshitz*



Energy Consideration



Energy Consideration

- The primary reason for the existence of domains within a crystal is that their formation reduces the magnetic free energy. In the simplest case for such a crystal, the energy, *E*, is the sum of several free energy terms:

$$E = E_{ex} + E_k + E_\lambda + E_D + E_H$$

Magnetocrystalline anisotropy energy

- The crystal lattice is 'easy' to magnetize in some directions and 'hard' to magnetize in others. Magnetization in the easy directions lowers this energy.

Magnetoelastic anisotropy energy

- This energy is due to the effect of magnetostriction, a slight change in the dimensions of the crystal when magnetized. This causes elastic strains in the lattice, and the direction of magnetization that minimizes these strain energies will be favoured.

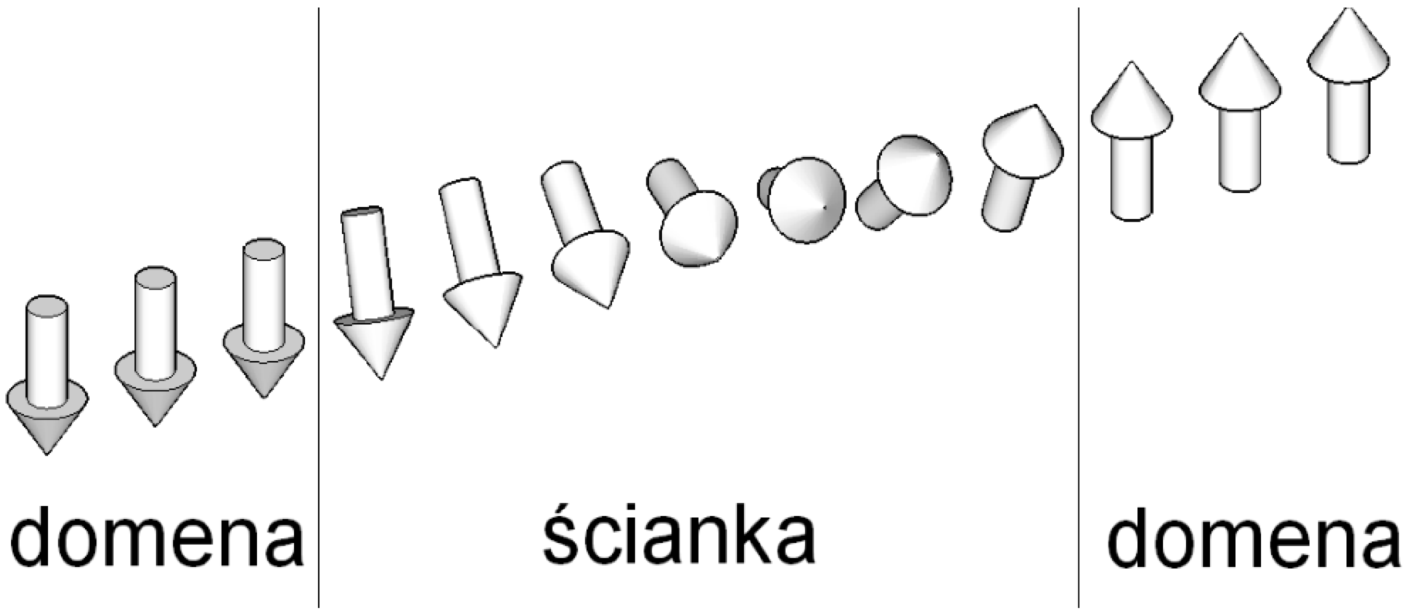
Magneto-static energy

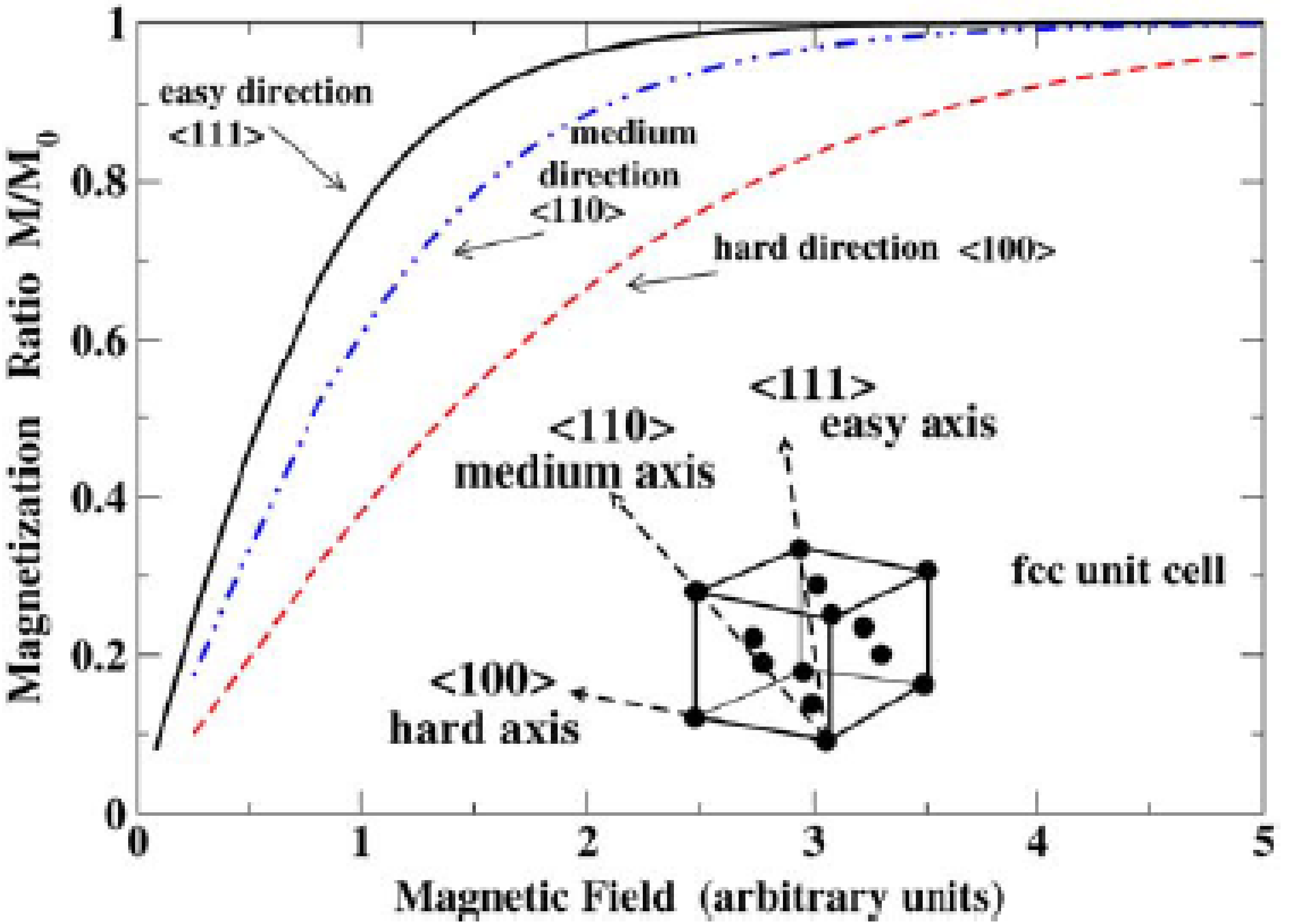
- This is a self-energy, due to the interaction of the magnetic field created by the magnetization in some part of the sample on other parts of the same sample. Intrinsically, it has exactly the same nature as the "Zeeman energy" but the interaction of the material with itself is put in the magnetostatic energy whereas the interaction with the external magnetic field is put in the "Zeeman energy". This energy term is the only one responsible for the presence of magnetic domains in magnetic materials. Minimizing its value requires that the magnetization in the material makes closed loops, with the magnetization staying parallel to the sample edges.

Zeeman energy

- Energy resulting from the interaction between the magnetic material and an externally applied magnetic field.

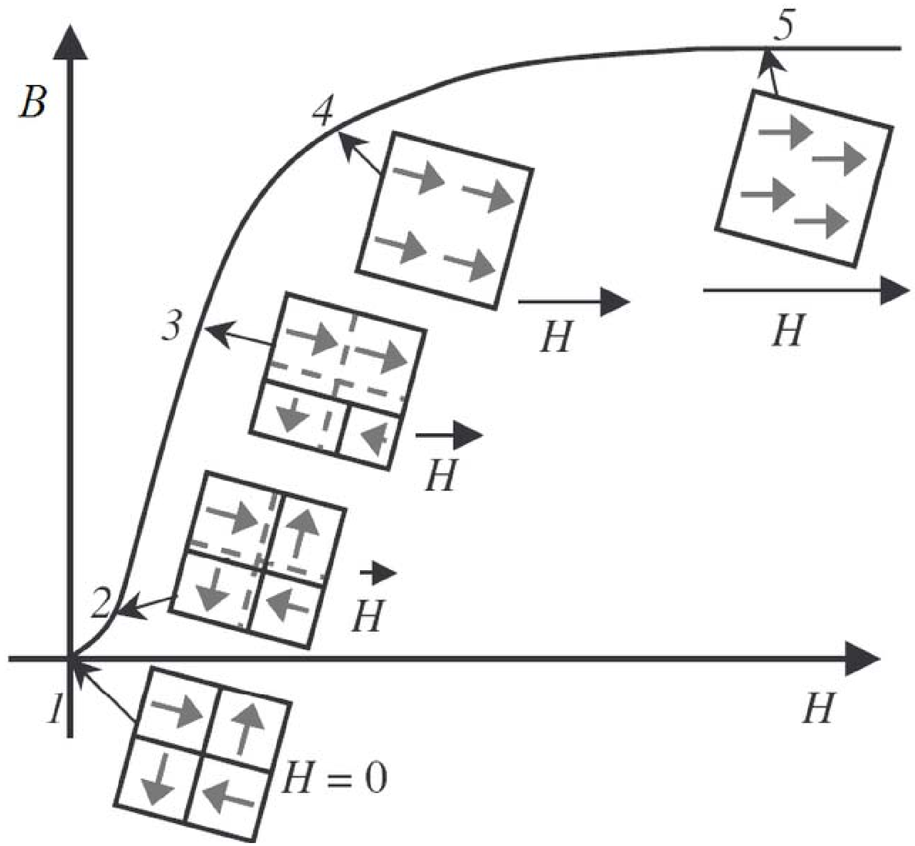
Bloch wall

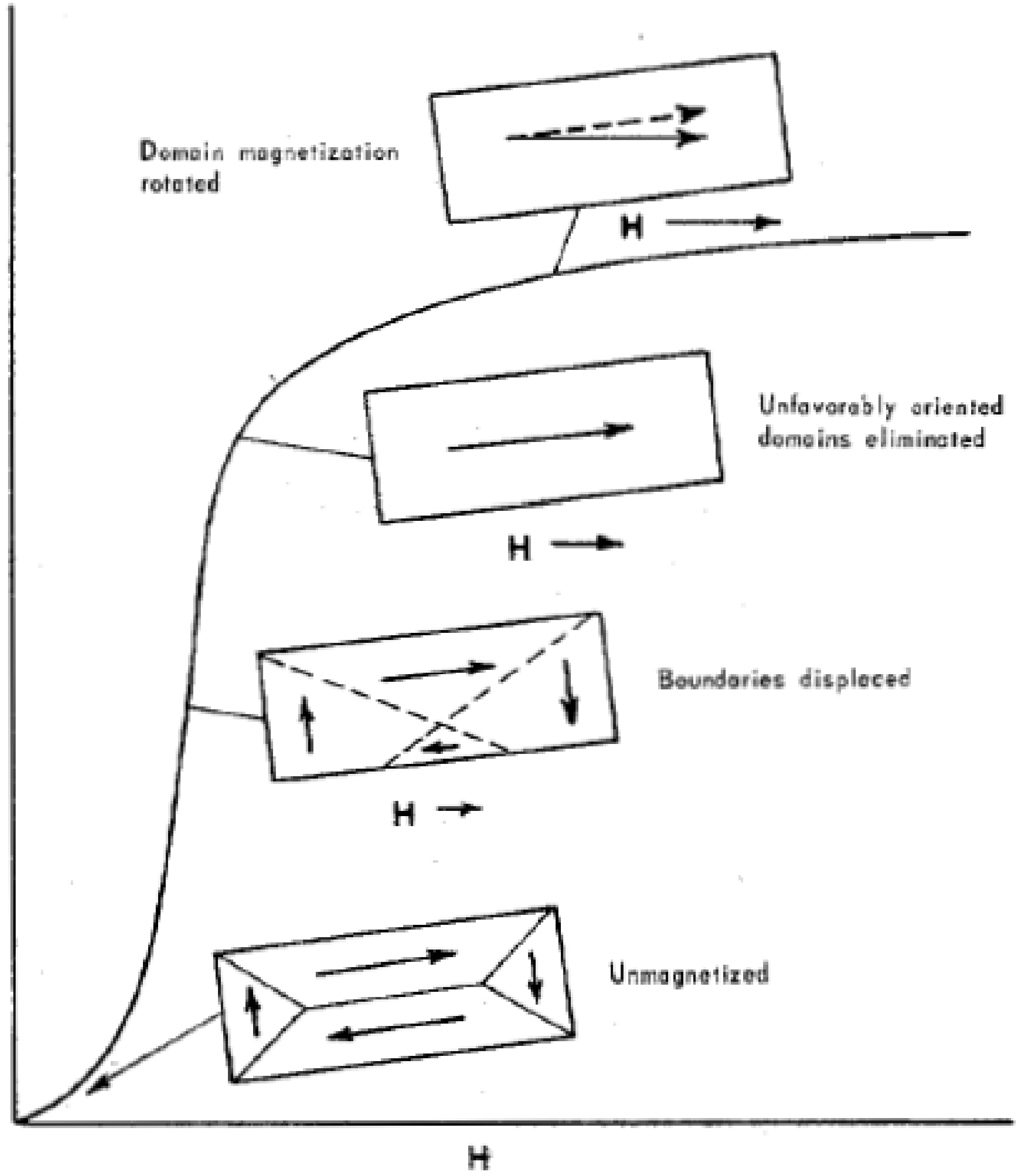




easy direction
<111>
medium
direction
<110>
hard direction <100>
<111>
easy axis
<110>
medium axis
fcc unit cell
<100>
hard axis
Magnetization Ratio M/M0
Magnetic Field (arbitrary units)
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5

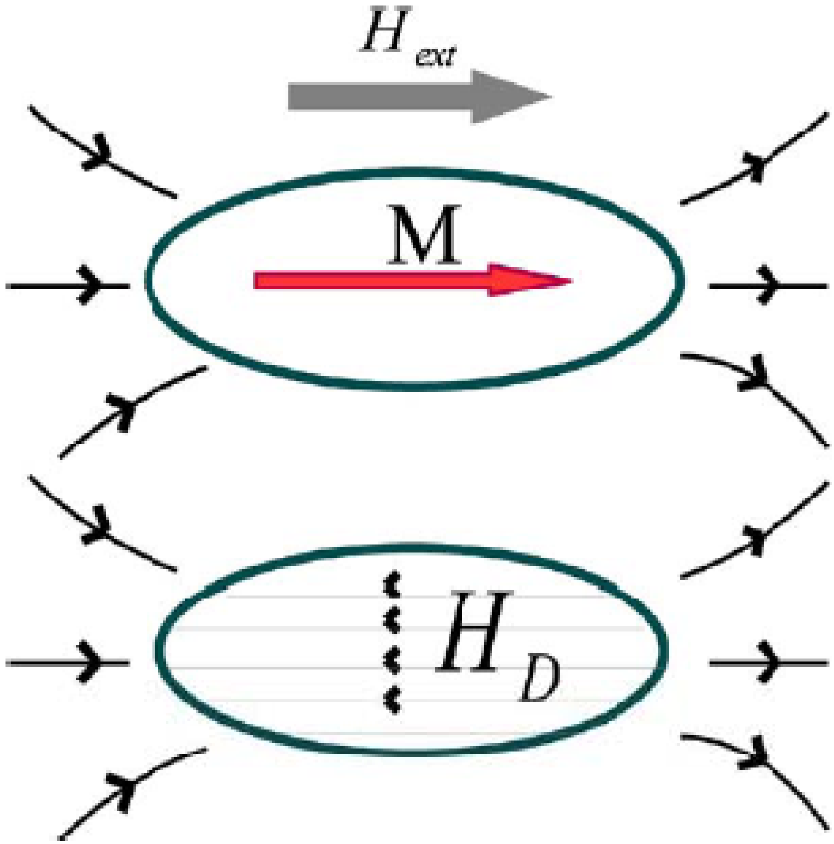
Magnetic characteristic and Domens





Domain magnetization rotated
H
Unfavorably oriented domains eliminated
H
Boundaries displaced
H
Unmagnetized
H

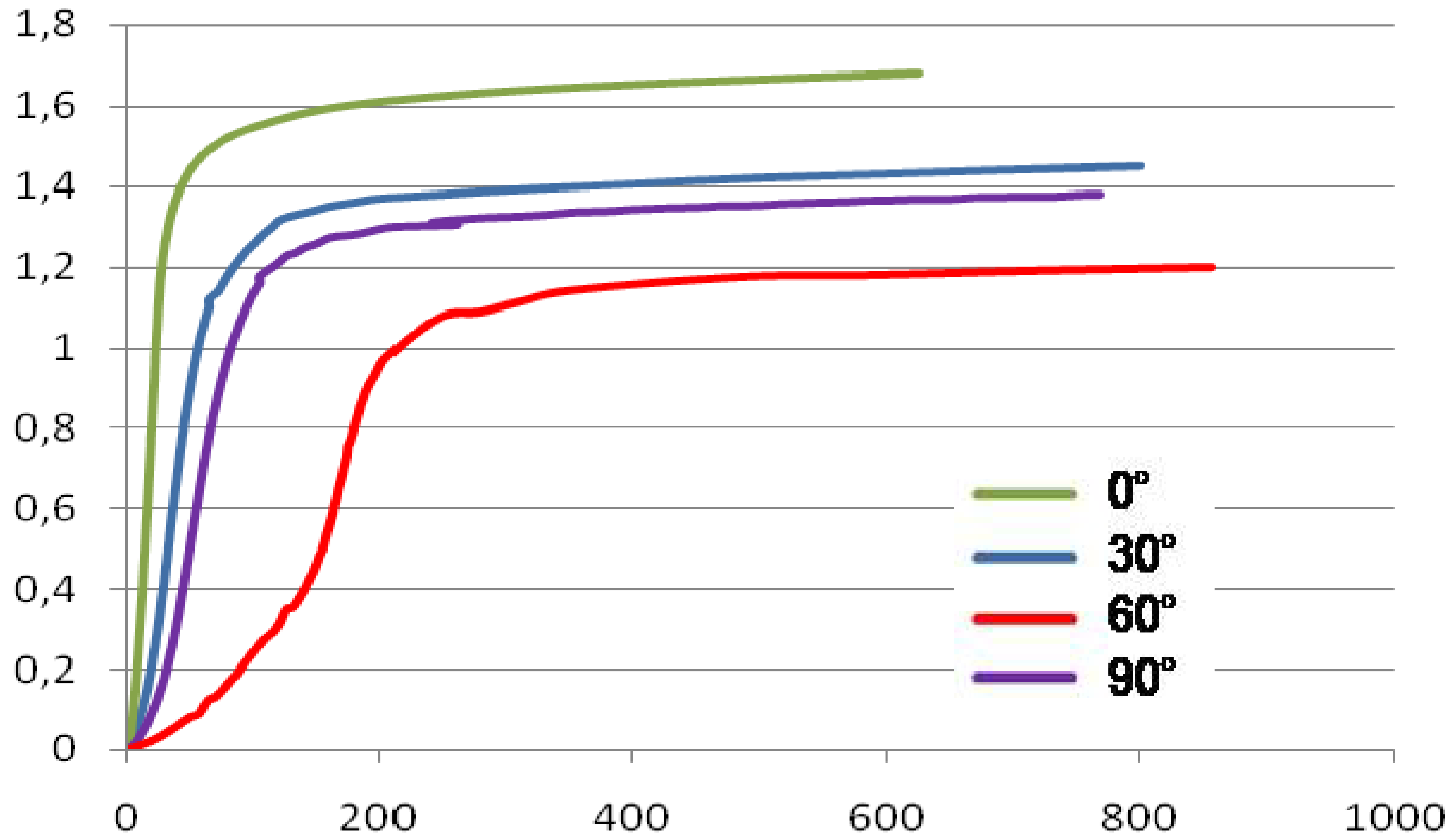
Dipole–dipole interaction and related anisotropy



Basics of magnetic anisotropy

- Magnetic anisotropy is due to the electronic exchange forces, which
- can be quite significant in magnetic materials. Even in the absence of external magnetic fields, these forces are strong enough to align magnetic moments present in a given material. Usually an external field is necessary to get these moments to align along, even in materials that are likely to be strongly ferromagnetic. The reason for such behavior is the presence of magnetic domains or subvolumes. Each one of these domains could possess a saturated (i.e., maximum possible) moment, but different domains may not be aligned with each other. This non-alignment is the cause of unsaturation in typically ferromagnetic materials. An applied (magnetic) field of sufficient strength is necessary to bring such domains to align themselves.

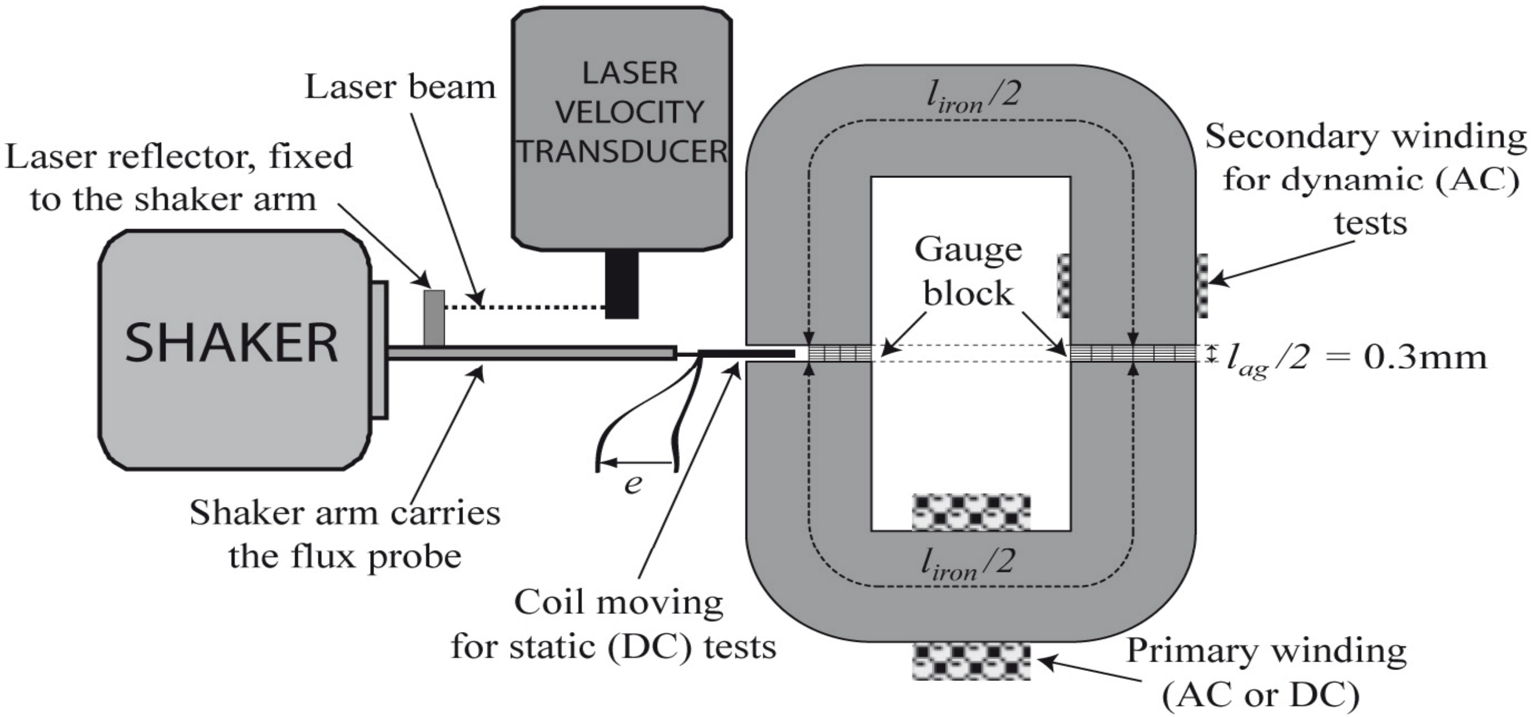
Family of characteristic B(H) for the different anisotropy directions.



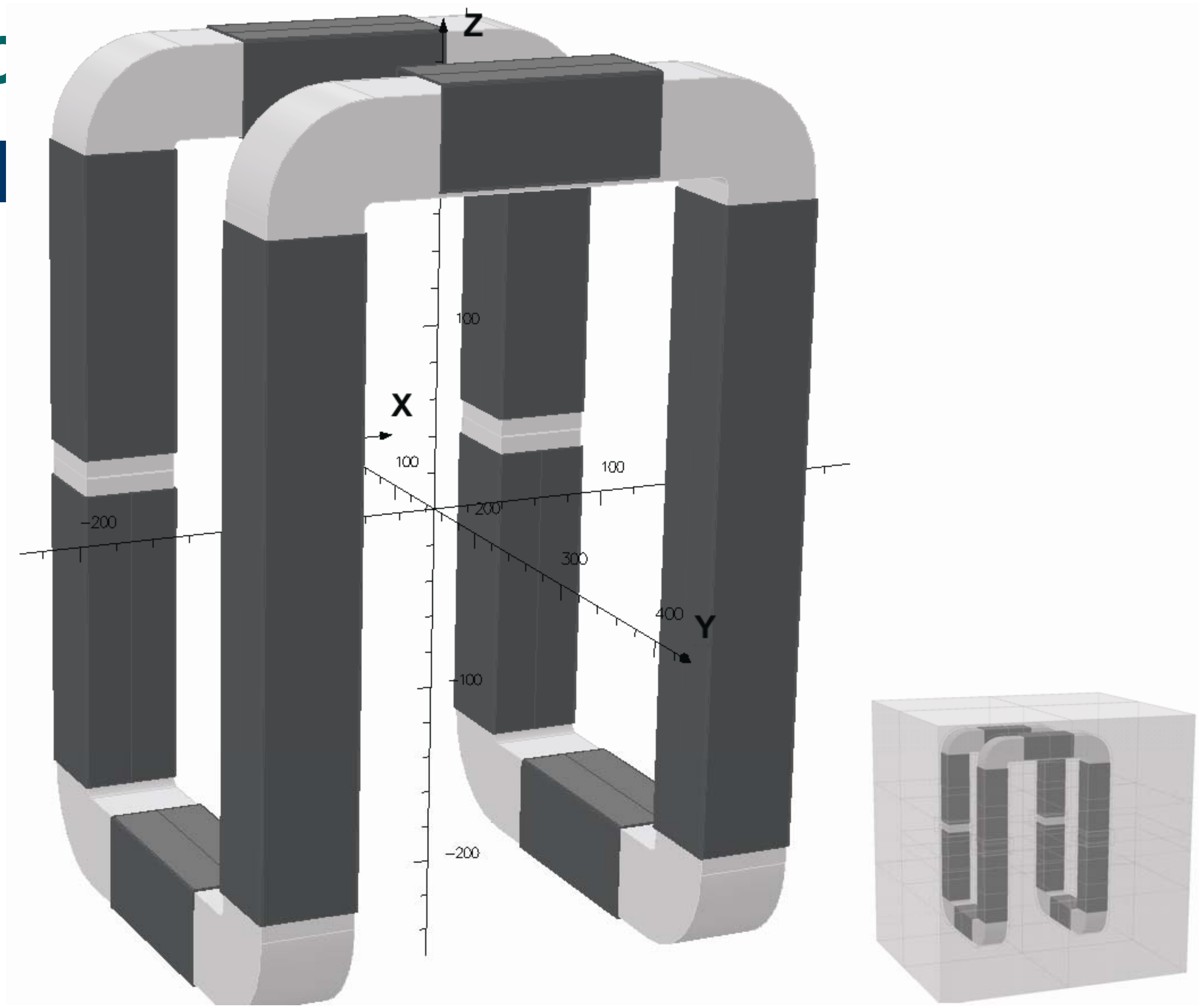
Laminated structures

- Full 3D numerical modelling of such structures is computationally very demanding, both in terms of long execution times and large memory requirements.
- The main idea of the approach is to replace the complex three-dimensional structure by a homogenized ‘equivalent’ material

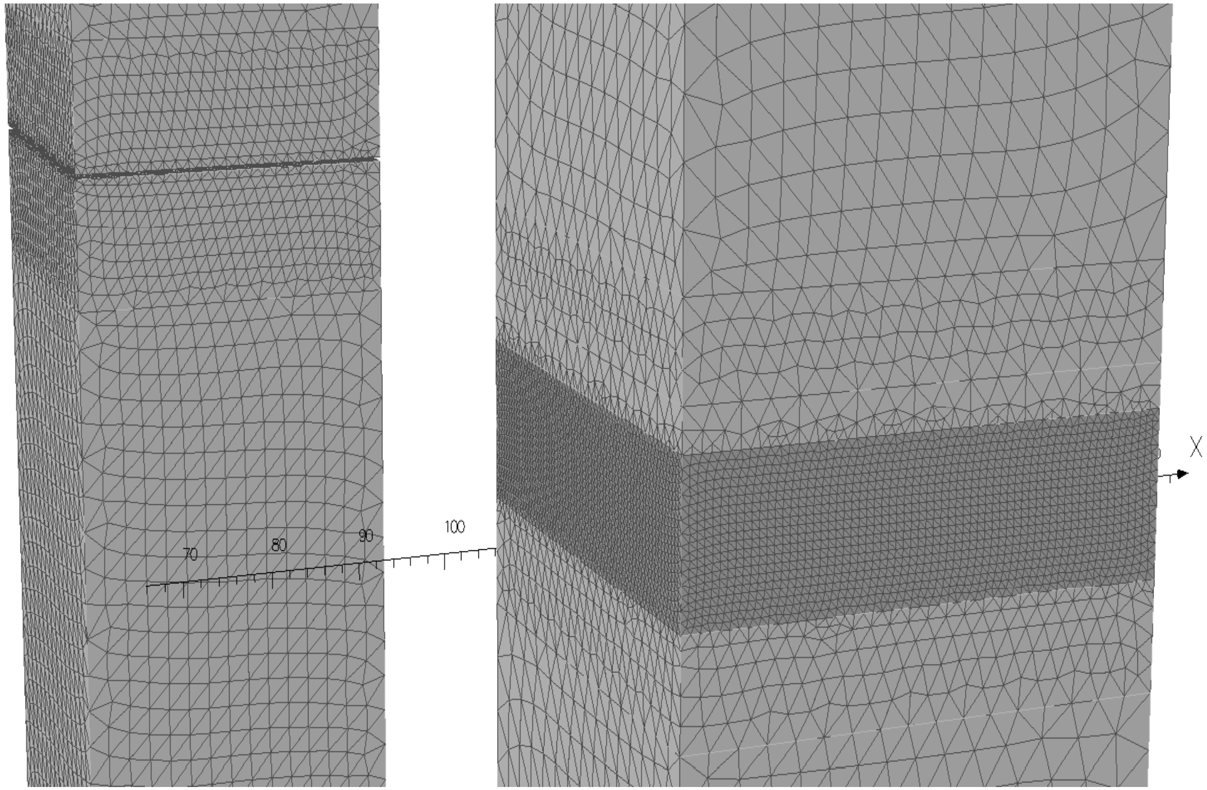
Test bench for static characterization with 2 U-shaped cores.

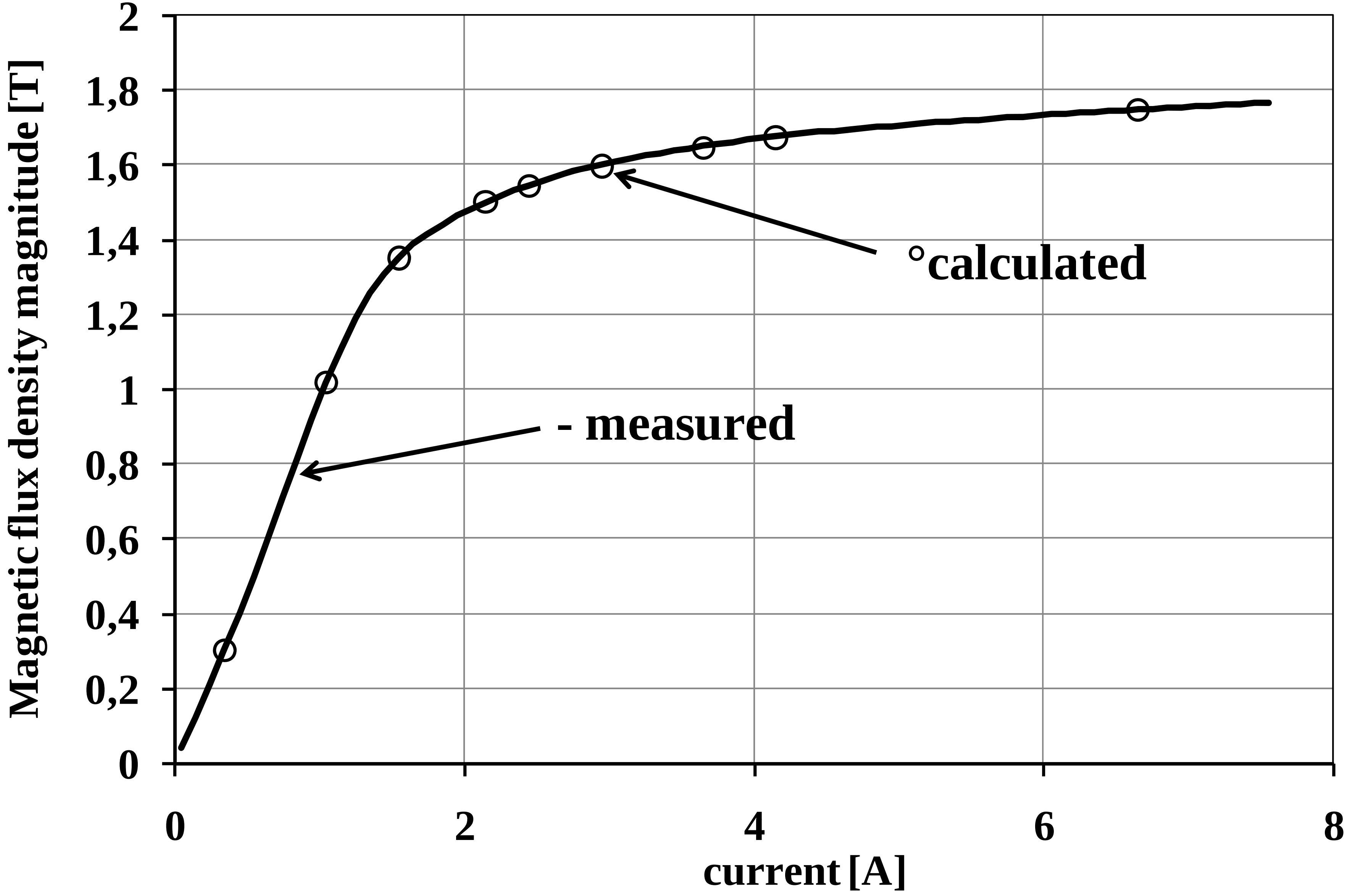


Mc

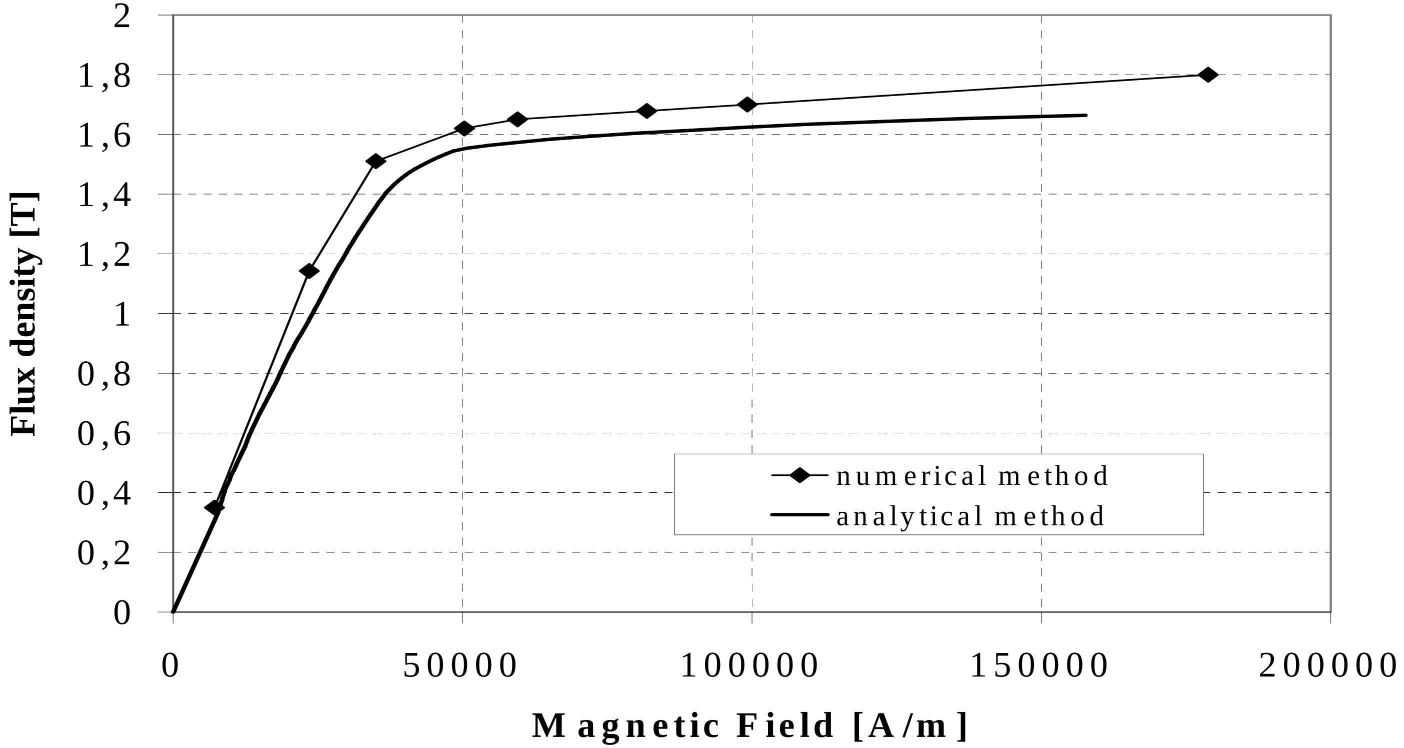


Mesh distribution in the air-gap




Magnetic flux density magnitude [T]
2
1,8
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
0
2
4
6
8
current [A]
°calculated
- measured

Characteristics of the lamination in the normal direction.



The normal characteristics measured, calculated with the evolutionary and genetic method