Joint Universities Accelerator School

JUAS 2018

Archamps, France, 26th February – 2nd March 2017

Normal-conducting accelerator magnets
Lecture 1: Basic principles

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CERN

Scope of the lectures

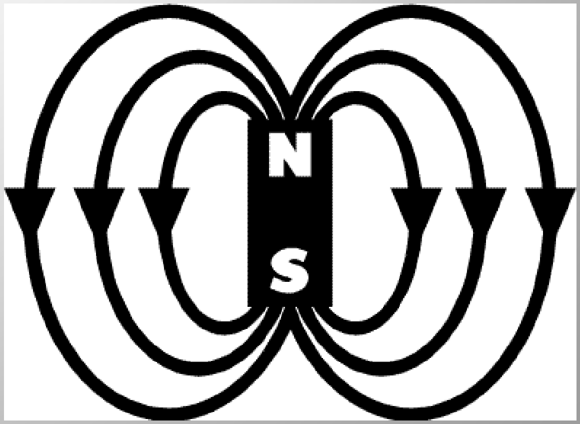
Overview of electro-magnetic technology as used in particle accelerators considering *normal-conducting, iron-dominated* electro-magnets (generally restricted to direct current situations)

Main goal is to:

- create a fundmental understanding in accelerator magnet technology
- provide a guide book with practical instructions how to start with the design of a standard accelerator magnet
- focus on applied and practical design aspects using 'real' examples
- introduce finite element codes for practical magnet design
- present an outlook into magnet manufacturing, testing and measurements

Not covered:

– permanent magnet technology
– superconducting technology



Literature

- CAS proceedings, Fifth General Accelerator Physics Course, University of Jyväskylä, Finland, September 1992, CERN Yellow Report 94-01
- International Conference on Magnet Technology, Conference proceedings
- Iron Dominated Electromagnets, J. T. Tanabe, World Scientific Publishing, 2005
- Magnetic Field for Transporting Charged Beams, G. Parzen, BNL publication, 1976
- Magnete, G. Schnell, Thiemig Verlag, 1973 (German)
- Field Computation for Accelerator Magnets: Analytical and Numerical Methods for Electromagnetic Design and Optimization, S. Russenschuck, Wiley-VCH, 2010
- Practical Definitions & Formulae for Normal Conducting Magnets, D. Tommasini, Sept. 2011
- CAS proceedings, Magnetic measurements and alignment, Montreux, Switzerland, March 1992, CERN Yellow Report 92-05
- CAS proceedings, Measurement and alignment of accelerator and detector magnets, Anacapri, Italy, April 1997, CERN Yellow Report 98-05
- Physik der Teilchenbeschleuniger und Synchrotronstrahlungsquellen, K. Wille, Teubner Verlag, 1996
- CAS proceedings, Magnets, Bruges, Belgium, June 2009, CERN Yellow Report 2010-004

Acknowledgements

Many thanks …

… to all my colleagues who contributed to this lecture, in particular L.Bottura, M.Buzio, B.Langenbeck, N.Marks, A.Milanese, S.Russenschuck, D.Schoerling, C.Siedler, S.Sgobba, D.Tommasini, A.Vorozhtsov

Program (1)

Lecture 1 — Monday 26.2. (10:45 – 12:15)

Introduction & Basic principles

Why do we need magnets?
Basic principles and concepts
Magnet types in accelerators

Lecture 2 — Monday 26.2. (14:00 – 15:00)

Analytical design

What do we need to know before starting?
Yoke design
Coil dimensioning
Cooling layout

Lecture 3 — Monday 26.2. (15:00 – 16:00)

Magnet production, tests and measurements

Magnetic materials
Manufacturing techniques
Quality assurance & tests
Cost estimation and optimization

Program (2)

Lecture 4 — Tuesday 27.2. (15:00 – 16:00)

Applied numerical design

- Building a basic 2D finite-element model
- Interpretation of results
- Typical application examples / limitation of numerical design

Tutorial — Tuesday 27.2. (16:15 – 18:15)

Case study (part 1)

- Students are invited to design and specify a ‚real‘ magnet
- Analytical magnet design on paper

Mini-workshop — Wednesday, 28.2. (9:00 – 12:00)

Case study (part 2)

- Computer work
- Numerical magnet design

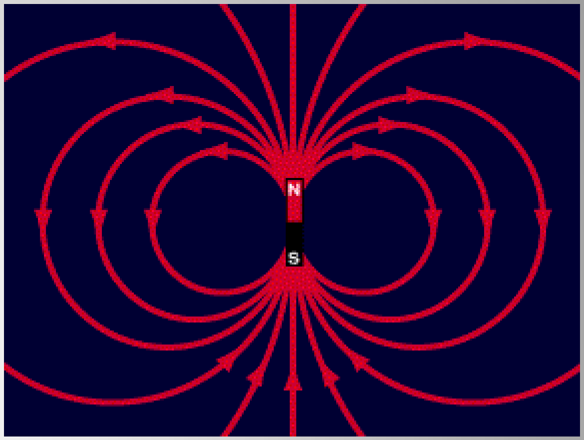
Exam — Thursday, 15.3. (9:00 – 10:30)

Lecture 1: Basic principles

- Why do we need magnets?
- Magnet technologies
- Basic principles and concepts
- Field description
- Magnet types and applications

Magnetic units

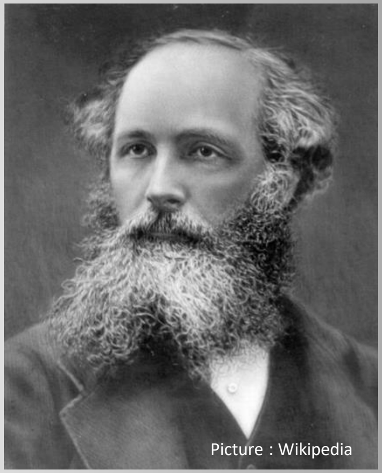
IEEE defines the following units:



- Magnetic field:
  - H (vector) [A/m]
  - the magnetizing force produced by electric currents
- Electromotive force:
  - e.m.f. or U [V or (kg m^2)/(A s^3)]
  - here: voltage generated by a time varying magnetic field
- Magnetic flux density or magnetic induction:
  - B (vector) [T or kg/(A s^2)]
  - the density of magnetic flux driven through a medium by the magnetic field
  - Note: induction is frequently referred to as "Magnetic Field“
  - H, B and μ relates by: $B = \mu H$
- Permeability:
  - $\mu = \mu_0 \mu_r$
  - permeability of free space $\mu_0 = 4 \pi 10^{-7}$ [V s/A m]
  - relative permeability μ_r (dimensionless): $\mu_{\mathrm{air}} = 1$; $\mu_{\mathrm{iron}} > 1000$ (not saturated)
- Magnetic flux:
  - ϕ [Wb or (kg m^2)/(A s^2)]
  - surface integral of the flux density component perpendicular trough a surface

Maxwell's equations

In 1873, Maxwell published "Treatise on Electricity and Magnetism" in which he summarized the discoveries of Coulomb, Oersted, Ampere, Faraday, et. al. in four mathematical equations:



Gauss' law for electricity:

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \qquad \oint_{\partial V} \vec{E} \cdot d\vec{A} = \frac{q}{\varepsilon_0}$$

Gauss' law of flux conservation:

$$\nabla \cdot \vec{B} = 0 \qquad \oint_{\partial V} \vec{B} \cdot d\vec{A} = 0$$

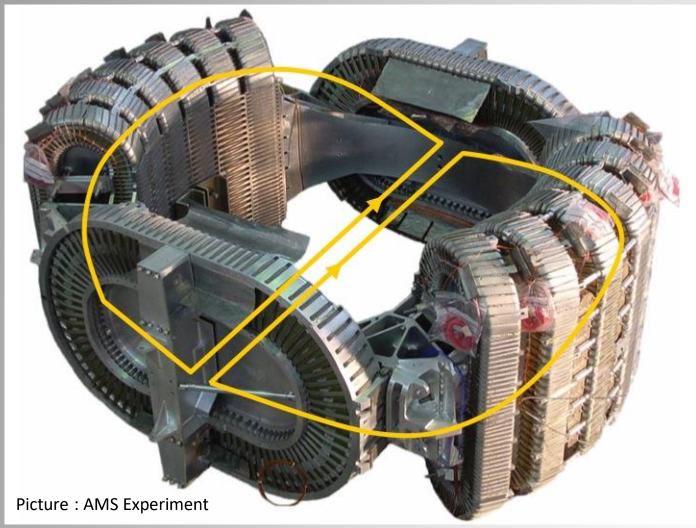
Faraday's law of induction:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \oint_{\partial A} \vec{E} \cdot d\vec{s} = -\frac{d\Phi}{dt} = -\frac{d}{dt}\int_A \vec{B} \cdot d\vec{A}$$

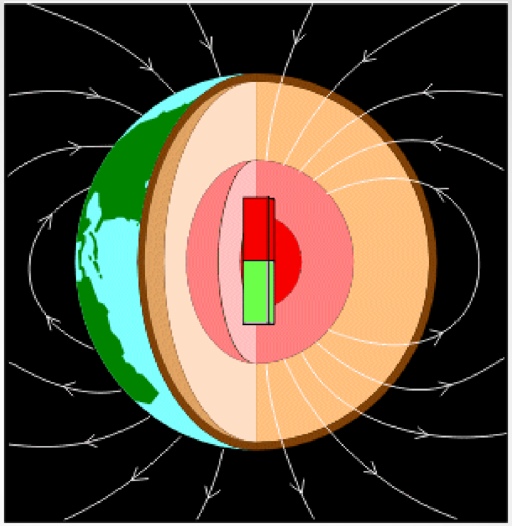
Ampere's circuital law:

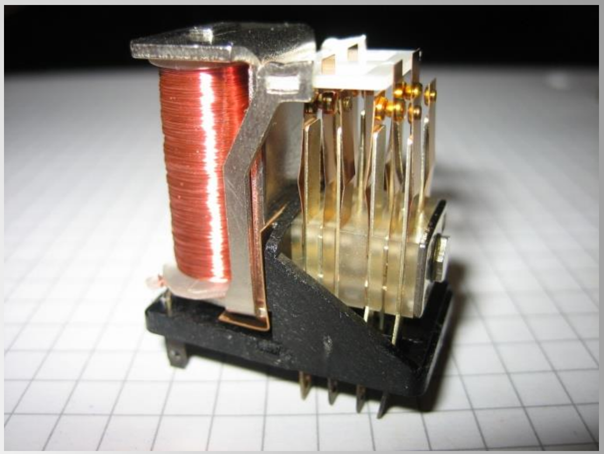
$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \qquad \oint_{\partial A} \vec{B} \cdot d\vec{s} = \int_A \mu_0 \vec{J} \cdot d\vec{A} + \frac{d}{dt}\int_A \mu_0 \varepsilon_0 \vec{E} \cdot d\vec{A}$$

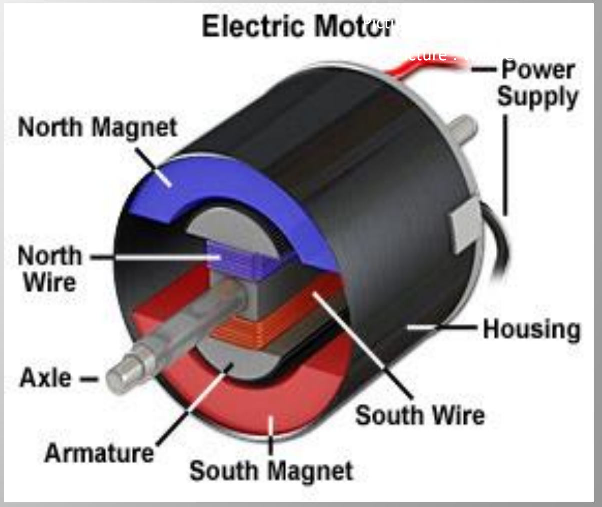
Magnets everywhere…



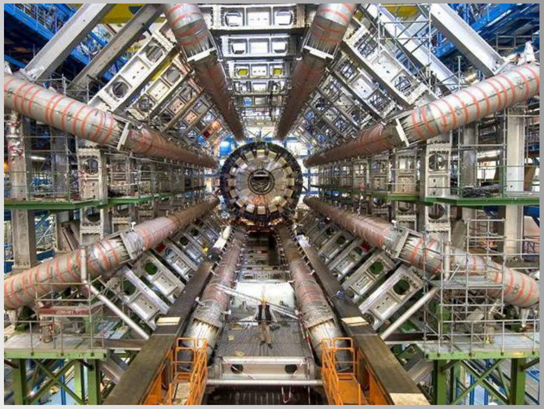
Picture : AMS Experiment

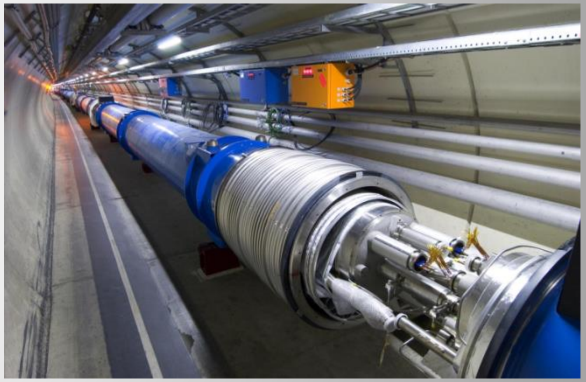


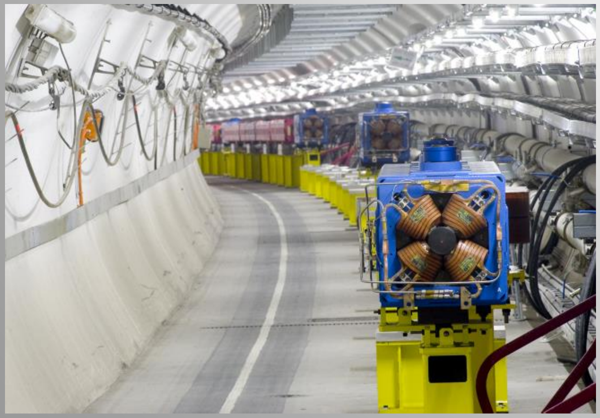




Magnets at CERN



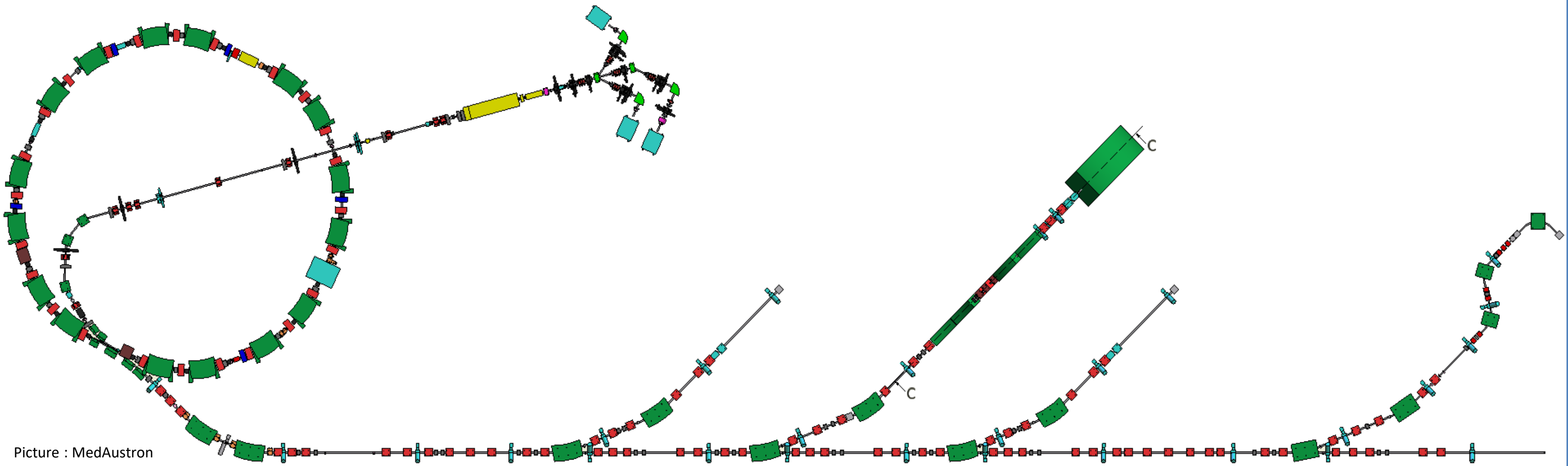




Normal-conducting magnets:
4800 magnets (50 000 tons) are installed in the CERN accelerator complex
Superconducting magnets:
10 000 magnets (50 000 tons) mainly in LHC
Permanent magnets:
150 magnets (4 tons) in Linacs & EA

Why do we need magnets?

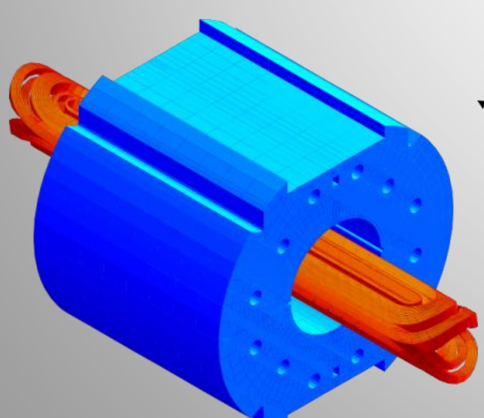
- Interaction with the beam
  - guide the beam to keep it on the orbit
  - focus and shape the beam
- Lorentz's force: $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$
  - for relativistic particles this effect is equivalent if $\vec{E} = c\vec{B}$
  - if $B = 1$ T then $E = 3 \cdot 10^8$ V/m

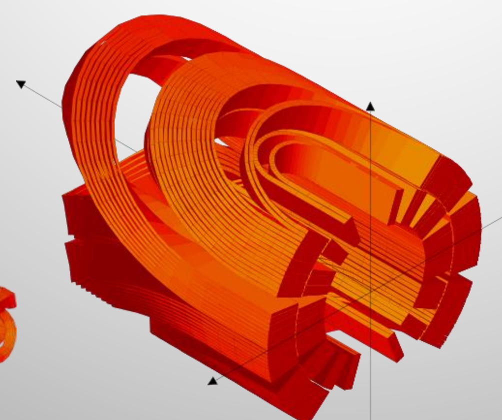


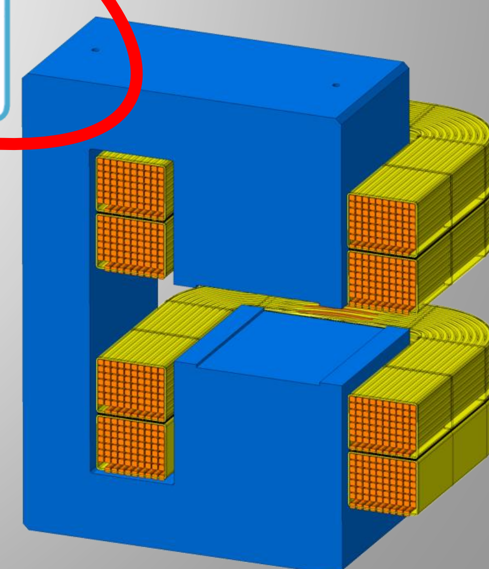
Picture : MedAustron

Magnet technologies

- Magnets
  - Electro-magnets
    - Superconducting
      - **Coil dominated** $B < 11$ T
      - Iron dominated $B < 2$ T
    - Normal-conducting
      - Coil dominated $B < 1$ T
      - **Iron dominated** $B < 2$ T
  - Permanent magnets

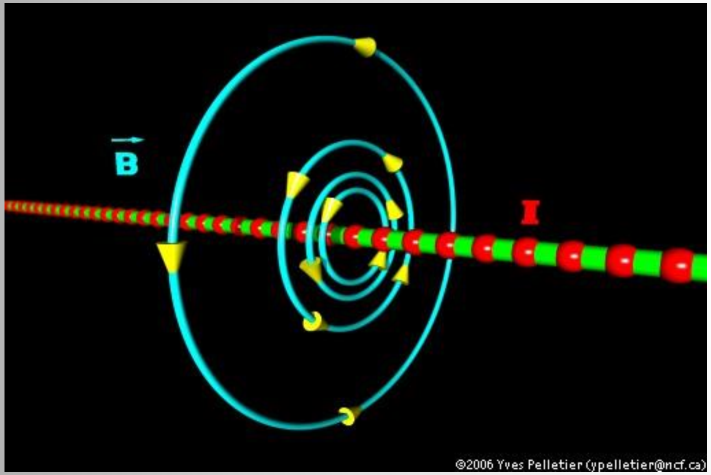






How does an electro-magnet work?

- Permanent magnets provide only constant magnetic fields
- Electro-magnets can provide adjustable magnetic fields

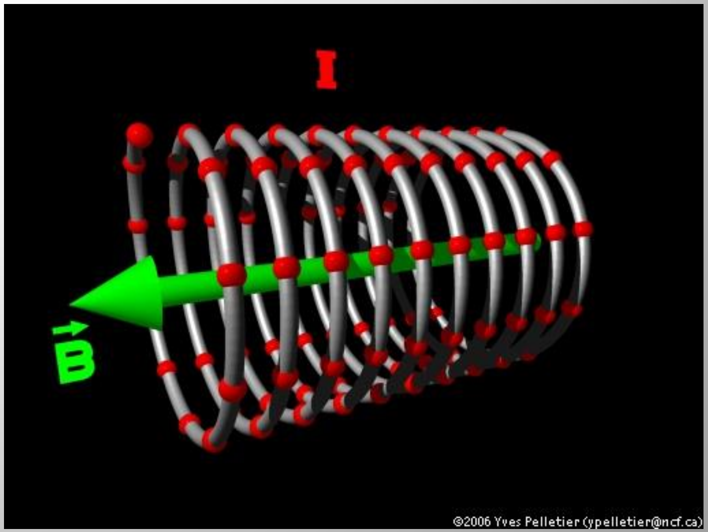


Maxwell & Ampere:

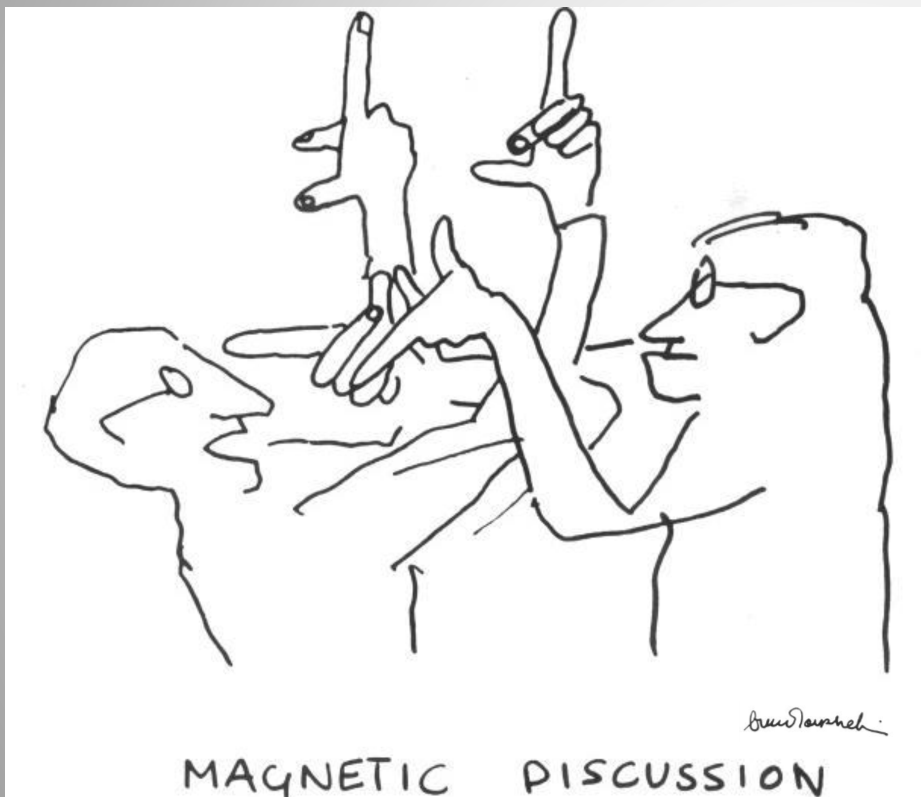
$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$

„An electrical current is surrounded by a magnetic field“

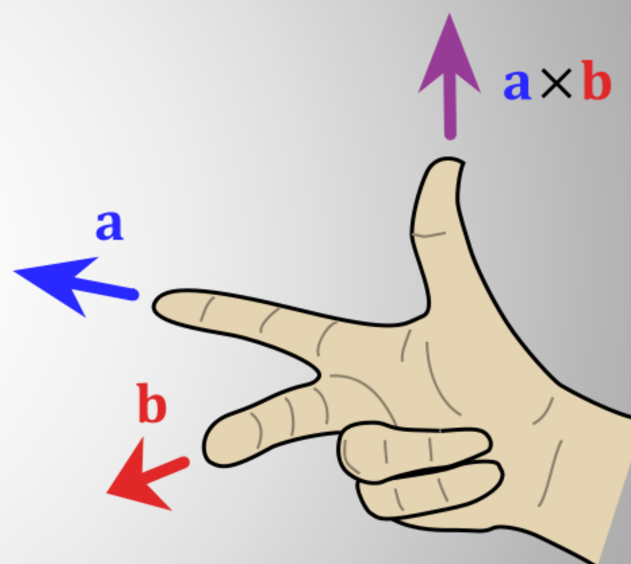
„*Right-hand rule*“ applies



Right-hand rule

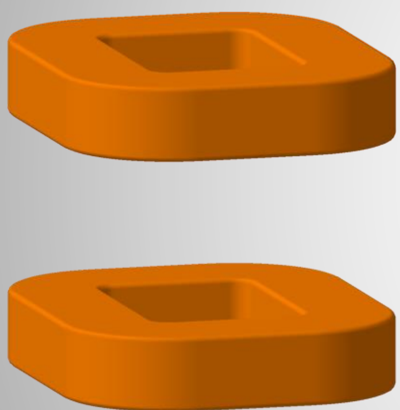


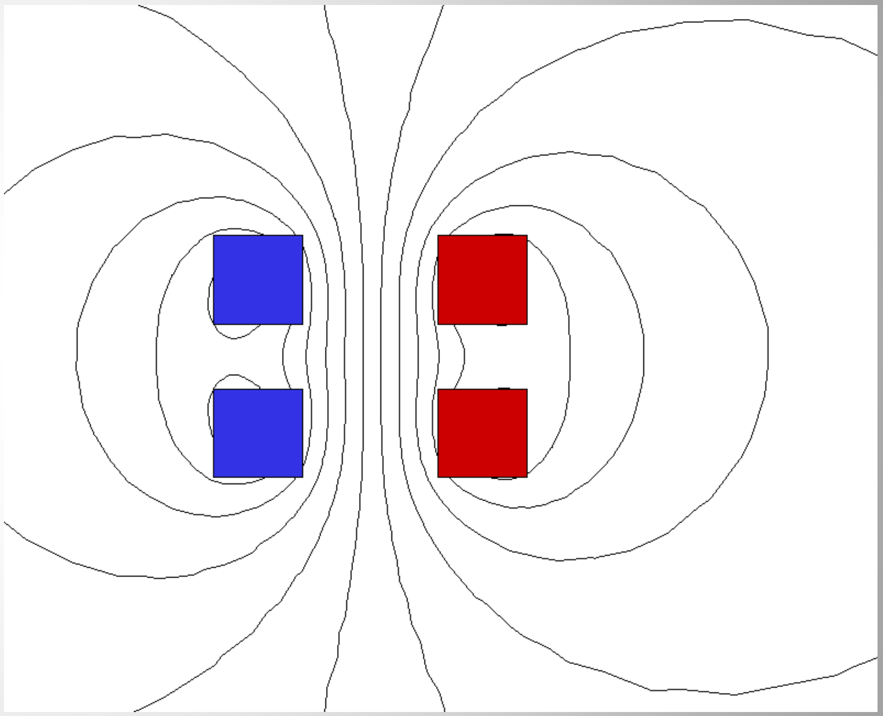
Cartoon by Bruno Touschek



$$\vec{F} = q\vec{v} \times \vec{B}$$

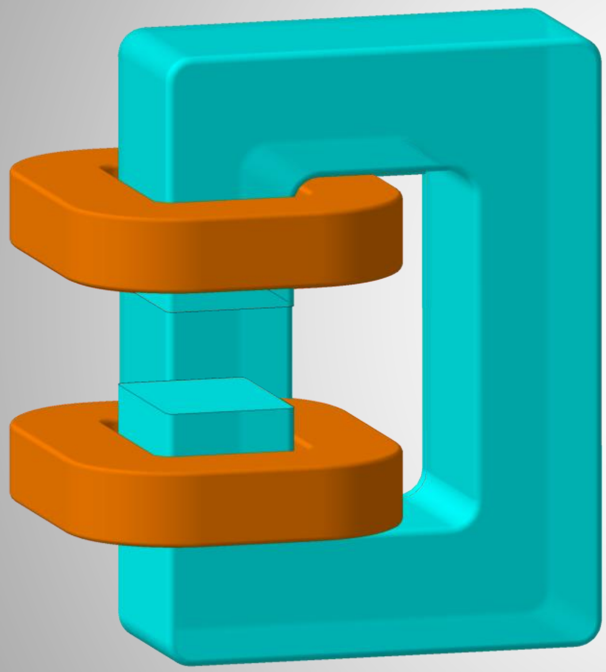
Magnetic circuit

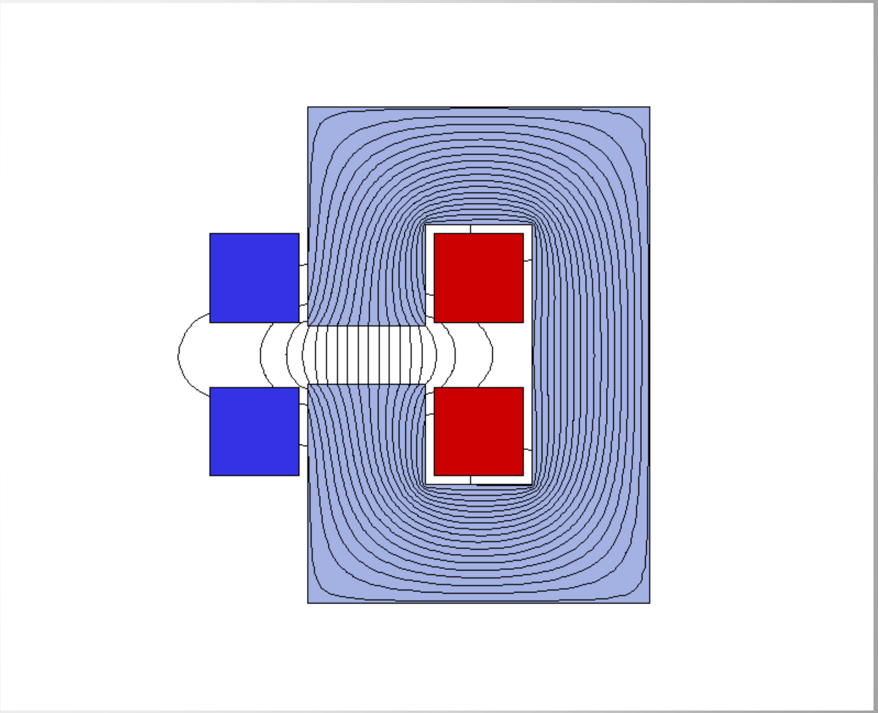




Flux lines represent the magnetic field
Coil colors indicate the current direction

Magnetic circuit





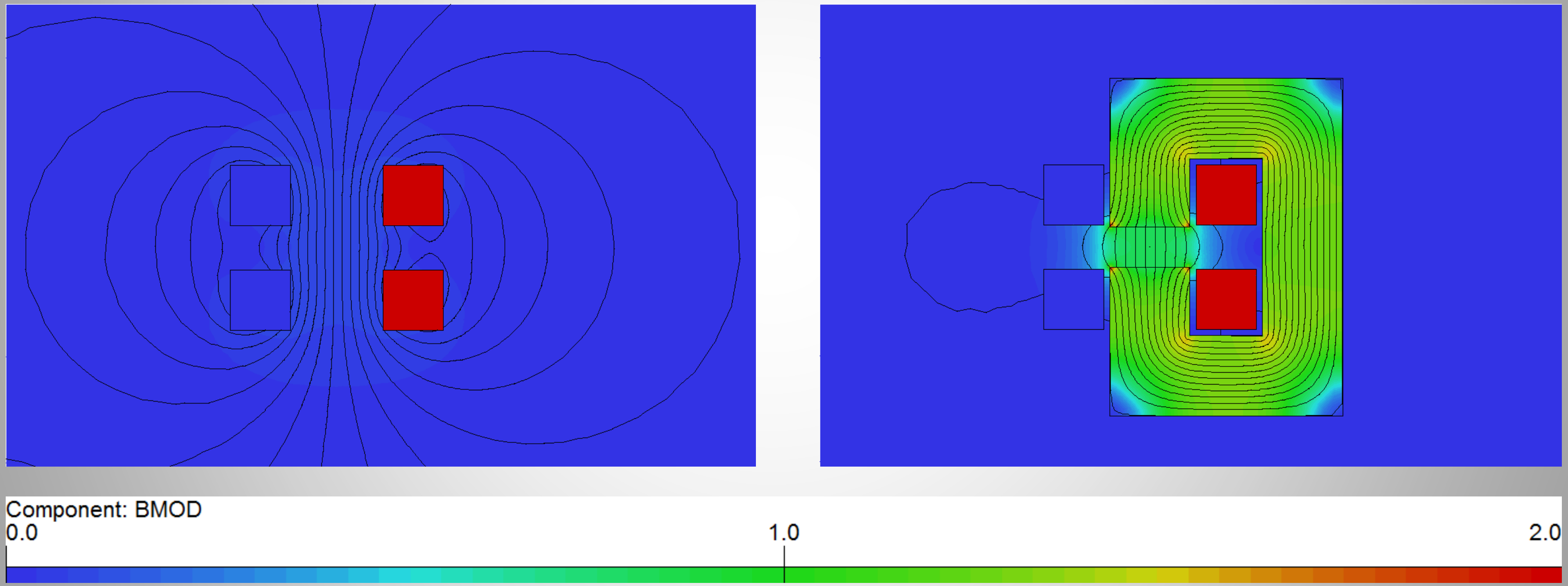
Coils hold the electrical current
Iron holds the magnetic flux

→ *"iron-dominated magnet"*

Magnetic circuit

$I = 32$ kA
$B_{centre} = 0.09$ T

$I = 32$ kA
$B_{centre} = 0.80$ T

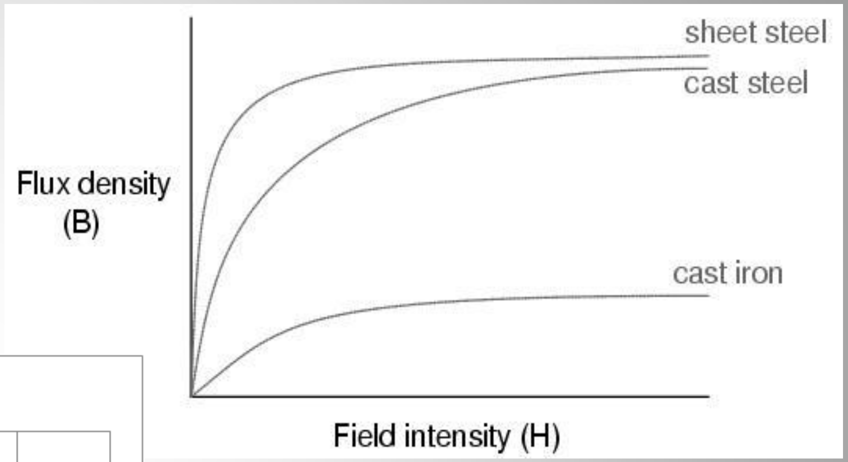


The presence of a magnetic circuit can increase the flux density in the magnet aperture by factors

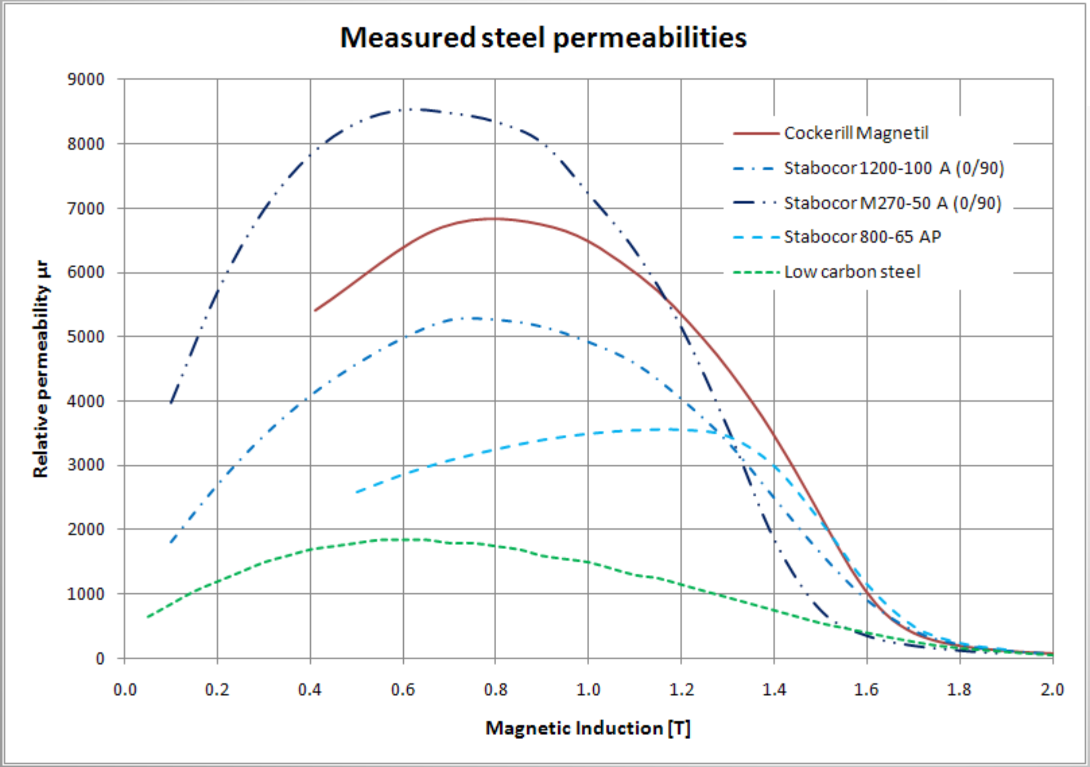
Note: the asymmetric field distribution is an artifact from the FE-mesh

Permeability

$$\vec{B} = \mu\vec{H} \qquad \mu = \mu_0\mu_r$$



Permeability: correlation between magnetic field strength H and magnetic flux density B



Ferro-magnetic materials: high permeability (μ_r>>1), but not constant

Excitation current in a dipole

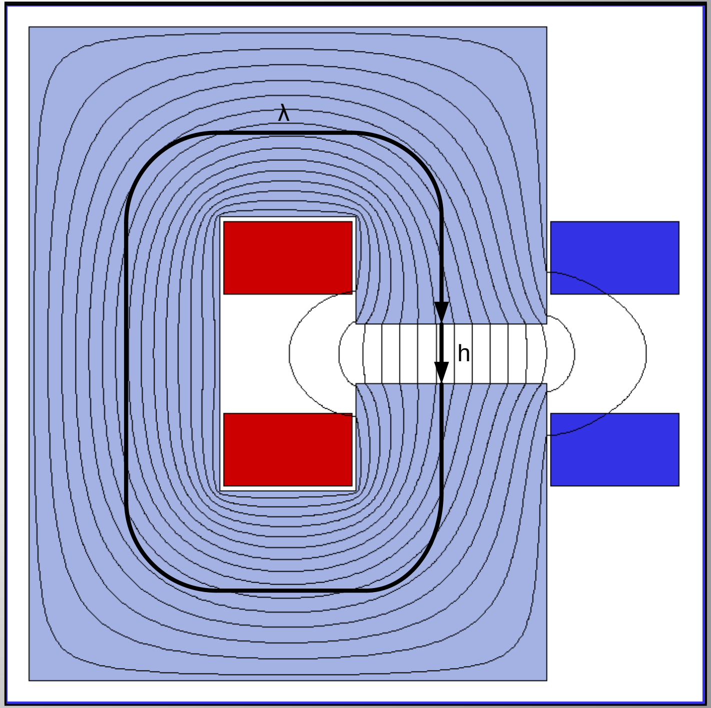
Ampere's law $\oint \vec{H} \cdot d\vec{l} = NI$ and $\vec{B} = \mu \vec{H}$

leads to $$NI = \oint \frac{\vec{B}}{\mu} \cdot d\vec{l} = \int_{gap} \frac{\vec{B}}{\mu_{air}} \cdot d\vec{l} + \int_{yoke} \frac{\vec{B}}{\mu_{iron}} \cdot d\vec{l} = \frac{Bh}{\mu_{air}} + \frac{B\lambda}{\mu_{iron}}$$

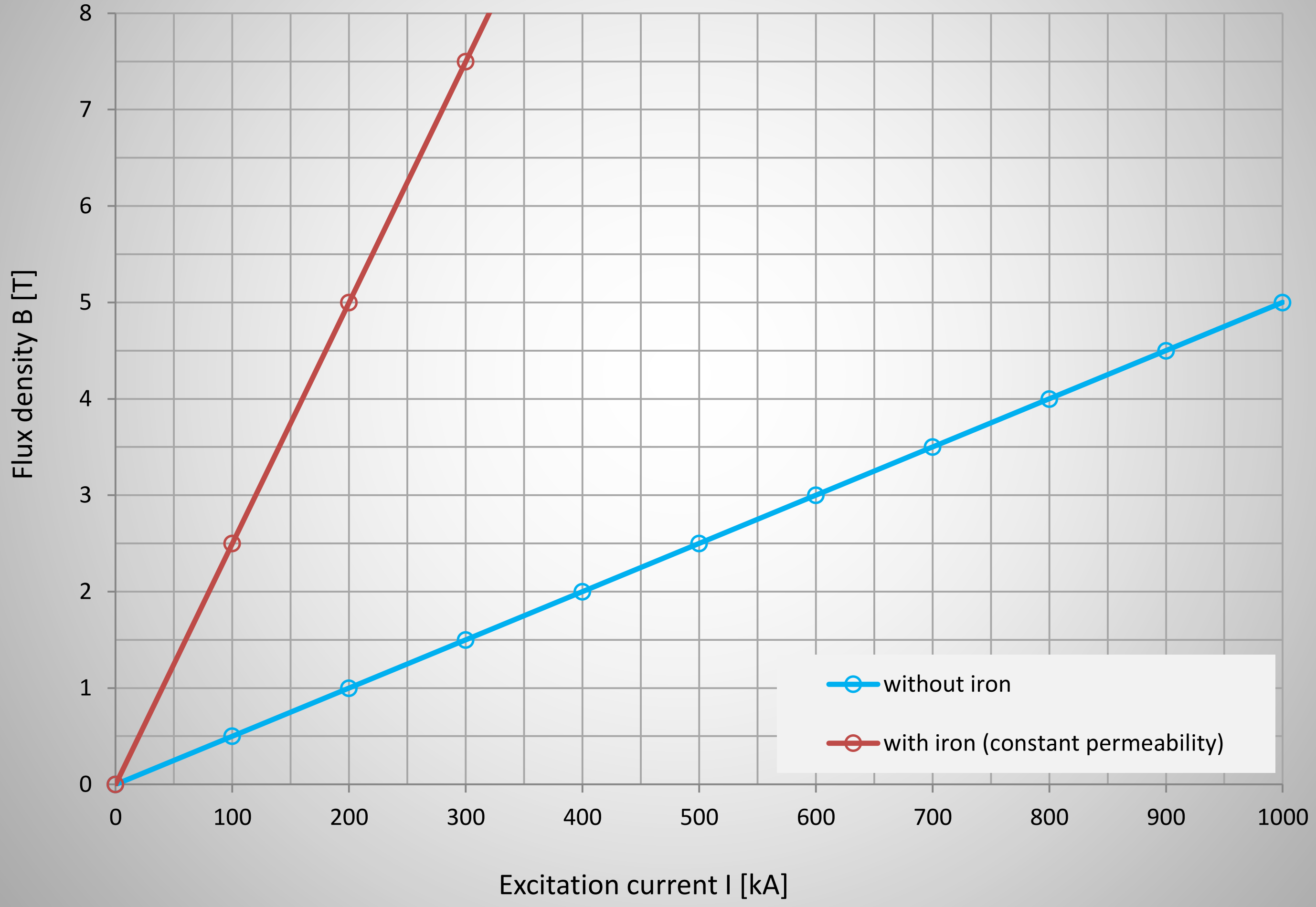
assuming, that B is constant along the path.

If the iron is not saturated: $$\frac{h}{\mu_{air}} >> \frac{\lambda}{\mu_{iron}}$$

then: $$NI_{(per\ pole)} \approx \frac{Bh}{2\mu_0}$$



Transfer function



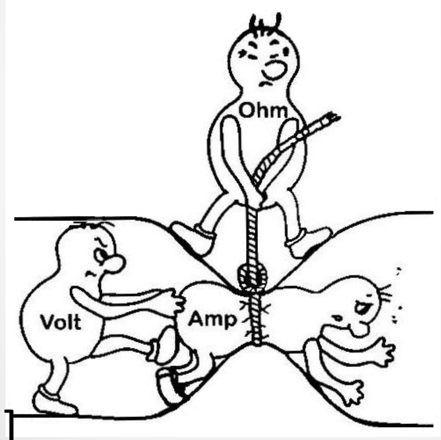
Reluctance and saturation

Similar to electrical circuits, one can define the 'resistance' of a magnetic circuit, called 'reluctance':

Ohm's law:

$$R_E = \frac{U}{I} = \frac{l_E}{A_E \sigma}$$

- Voltage drop U [V]
- Resistance R_E [Ω]
- Current I [A]
- El. conductivity σ [S/m]
- Conductor length l_E [m]
- Conductor cross section A_E [m^2]



Hopkinson's law:

$$R_M = \frac{NI}{\Phi} = \frac{l_M}{A_M \mu_r \mu_0}$$

- Magneto-motive force NI [A]
- Reluctance R_M [A/Vs]
- Magnetic flux Φ [Wb]
- Permeability μ [Vs/Am]
- Flux path length in iron l_M [m]
- Iron cross section A_M [m^2] (perpendicular to flux)

…but: μ_{iron} is in general <u>not</u> constant!

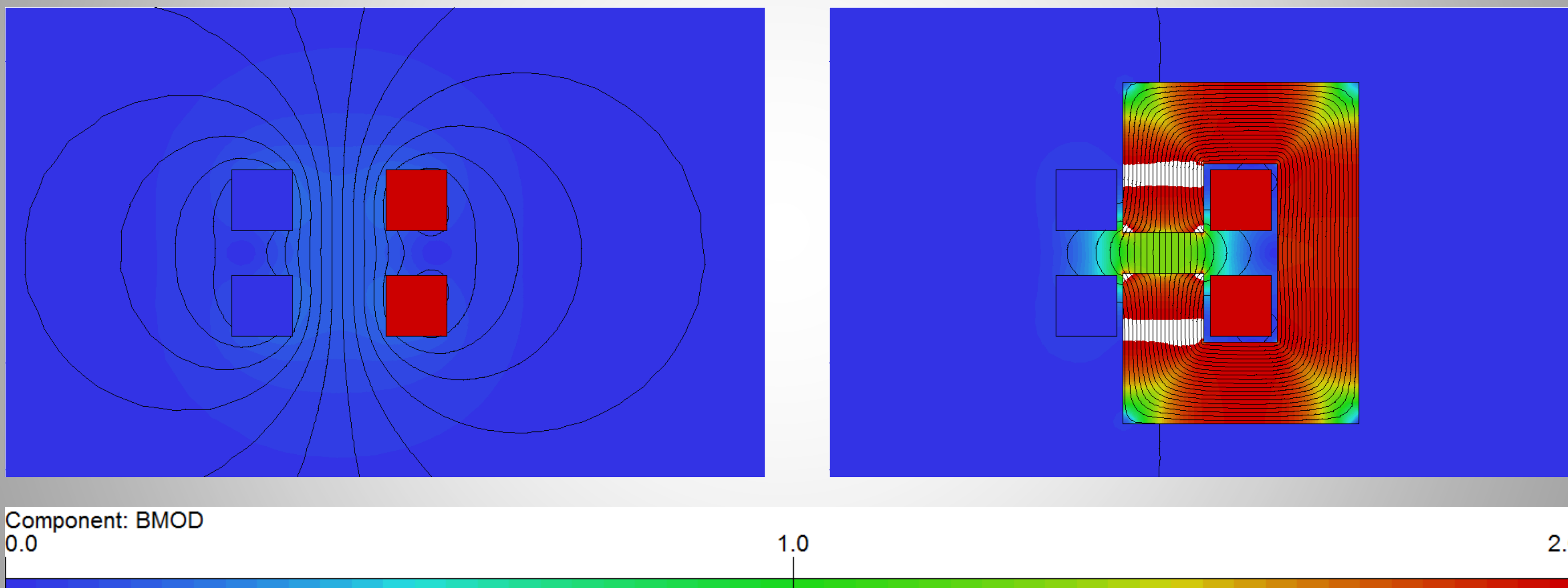
Reluctance and saturation

$I = 32$ kA
$B_{centre} = 0.09$ T

$I = 64$ kA
$B_{centre} = 0.18$ T

$I = 32$ kA
$B_{centre} = 0.80$ T

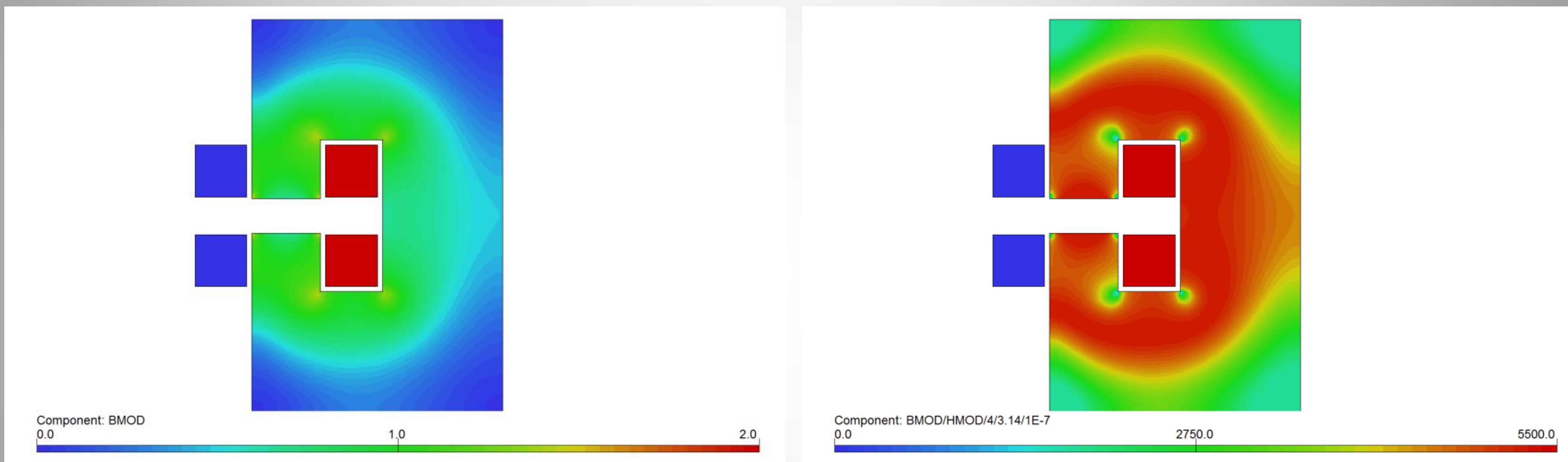
$I = 64$ kA
$B_{centre} = 1.30$ T



Increase of B above 1.5 T in iron requires non-proportional increase of H

Iron saturation (small μ_{iron}) leads to inefficiencies

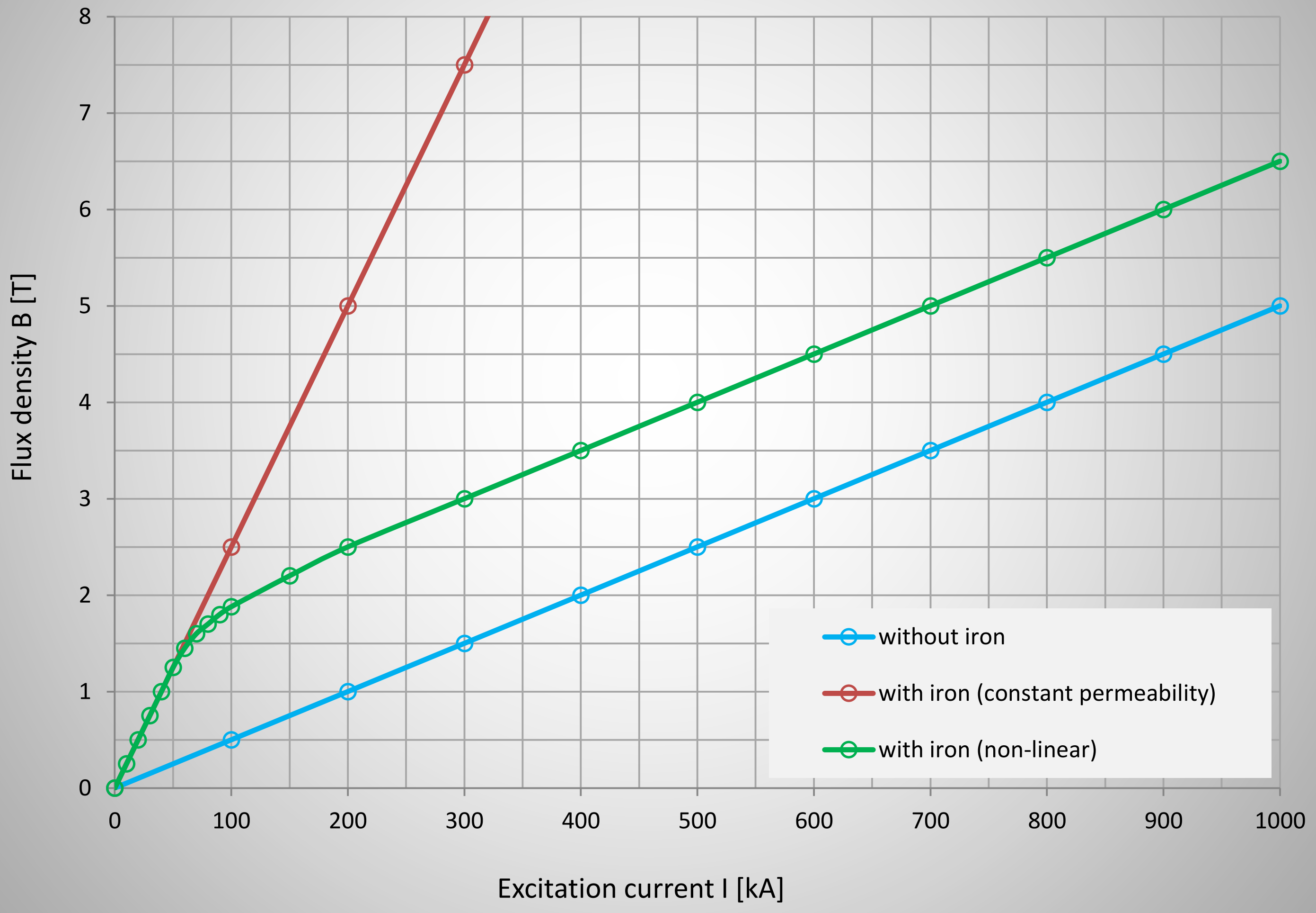
Reluctance and saturation



Keep yoke reluctance small by providing sufficient iron cross-section!

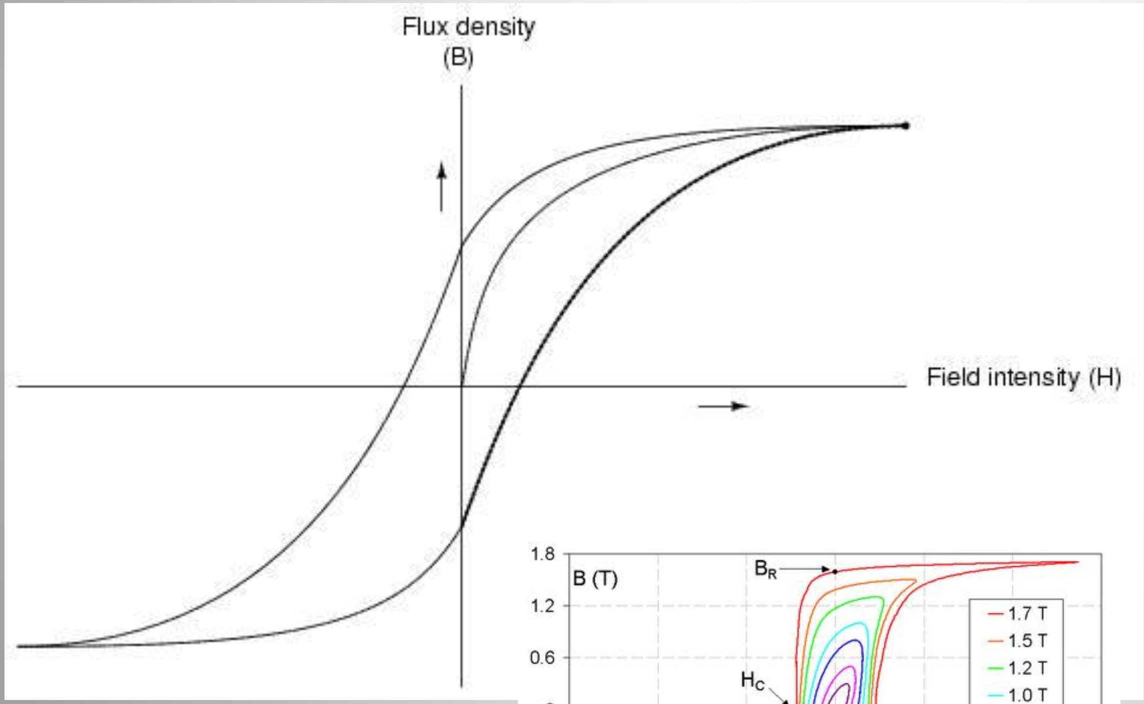
Reluctance and saturation

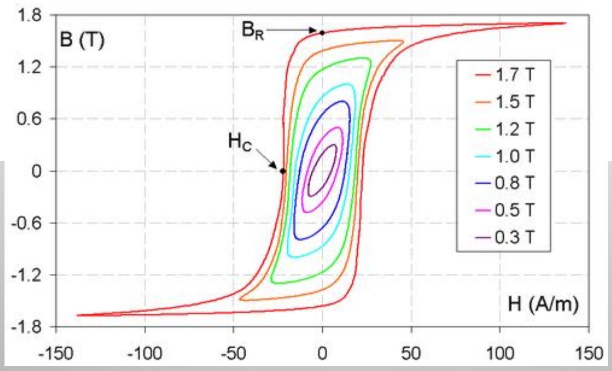
$$\vec{B} = \mu_0 \vec{H} + \vec{J} = \mu_0 \mu_r \vec{H}$$



Steel hysteresis

Flux density $B(H)$ as a function of the field strength is different, when increasing and decreasing excitation



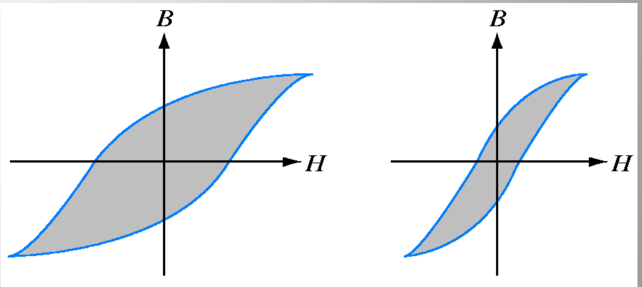


Remanent field (Retentivity):

$$H = 0 \rightarrow B = B_r > 0$$

Coercivity or coercive force:

$$B = 0 \rightarrow H = H_c < 0$$



(a) Hard material (b) Soft material

Residual field in a magnet

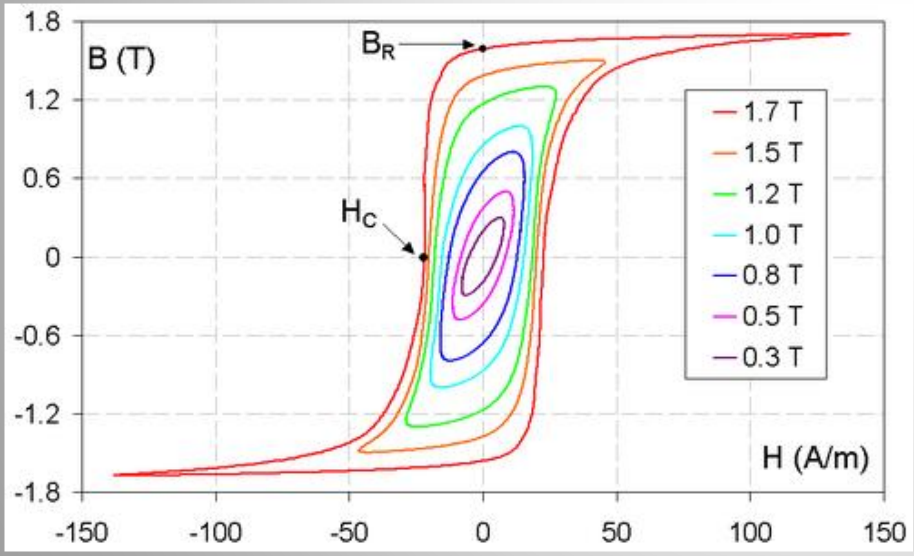
In a continuous ferro-magnetic core (transformer) the residual field is determined by the remanent field B_r

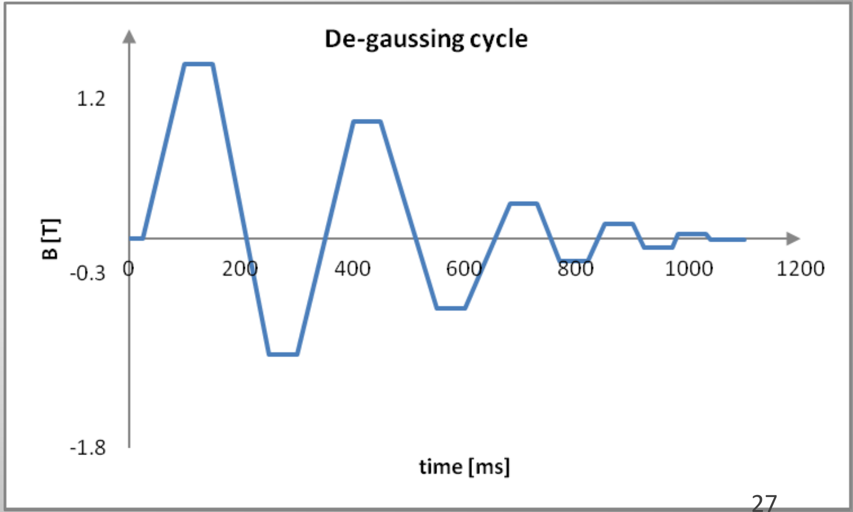
In a magnet core (gap), the residual field is determined by the coercivity H_c

Assuming the coil current $I = 0$:

$$\oint \vec{H} \cdot \vec{dl} = \int_{gap} \vec{H}_{gap} \cdot \vec{dl} + \int_{yoke} \vec{H}_c \cdot \vec{dl} = 0$$

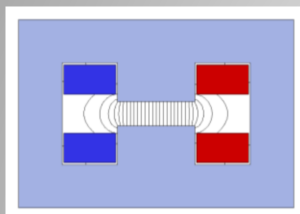
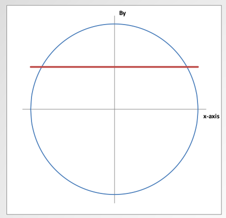
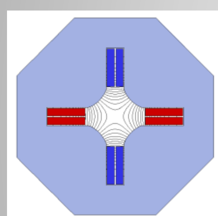
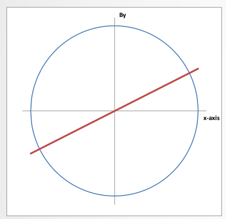
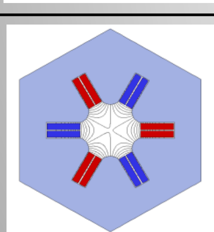
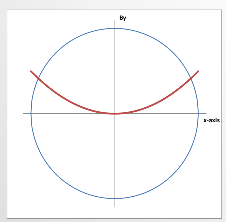
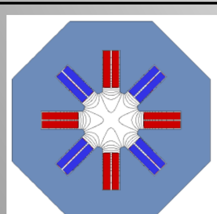
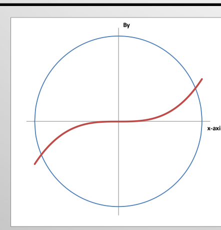
$$B_{residual} = -\mu_0 H_C \frac{l}{g}$$





Demagnetization cycle!

Magnet types

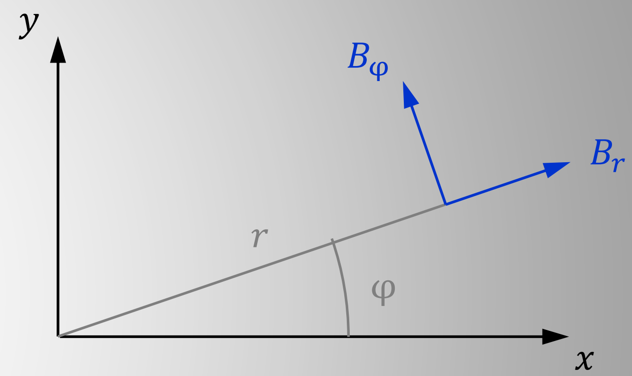
Pole shape	Field distribution	Pole equation	B_x, B_y
		$y = \pm r$	$B_x = 0$ $B_y = B_1(r_0) = \text{const.}$
		$2xy = \pm r^2$	$B_x = \frac{B_2(r_0)}{r_0} y$ $B_y = \frac{B_2(r_0)}{r_0} x$
		$3x^2y - y^3 = \pm r^3$	$B_x = \frac{B_3(r_0)}{r_0^2} xy$ $B_y = \frac{B_3(r_0)}{r_0^2}(x^2 - y^2)$
		$4(x^3y - xy^3) = \pm r^4$	$B_x = \frac{B_4(r_0)}{6r_0^3}(3x^2y - y^3)$ $B_y = \frac{B_4(r_0)}{6r_0^3}(x^3 - 3xy^2)$

Field description

The 2D vector field of B can be expressed as a series of multipole coefficients $B_n(r_0)$, $A_n(r_0)$ with r_0 being the reference radius:

$$B_r(r,\varphi) = \sum_{n=1}^{\infty} \left(\frac{r}{r_0}\right)^{n-1} [B_n \sin(n\varphi) + A_n \cos(n\varphi)]$$

$$B_\varphi(r,\varphi) = \sum_{n=1}^{\infty} \left(\frac{r}{r_0}\right)^{n-1} [B_n \cos(n\varphi) - A_n \sin(n\varphi)]$$



$$B_y(z) + iB_x(z) = \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{z}{r_0}\right)^{n-1}$$

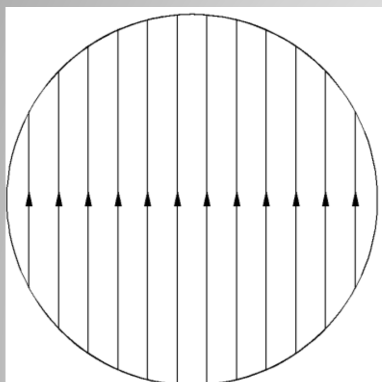
$$z = x + iy = re^{i\varphi}$$

This 2D decomposition holds only in a region of space:

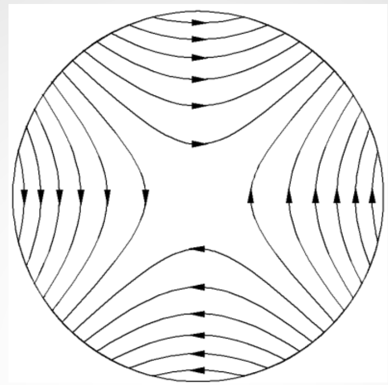
- without currents
- without magnetic materials ($\mu_r = 1$)
- when B_z on the integration boundaries is constant ($dB_z/dz = 0$)

Field description

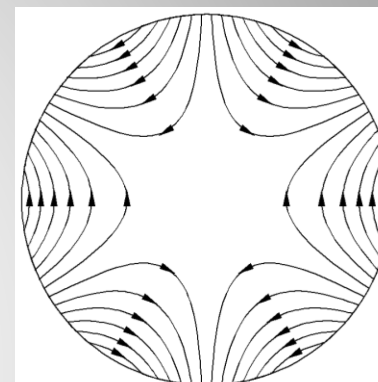
B_1: normal dipole



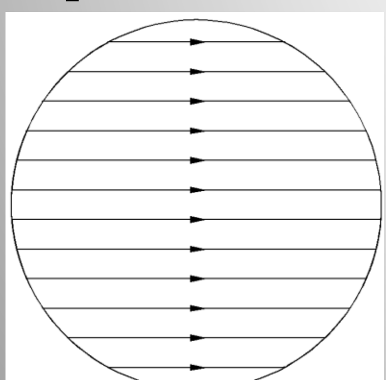
B_2: normal quadrupole



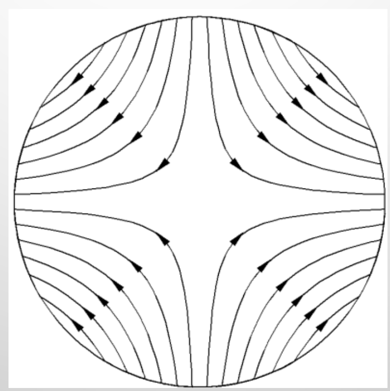
B_3: normal sextupole



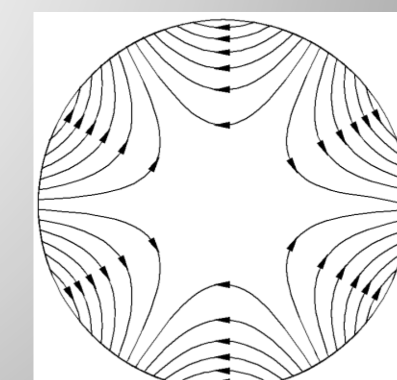
A_1: skew dipole



A_2: skew quadrupole



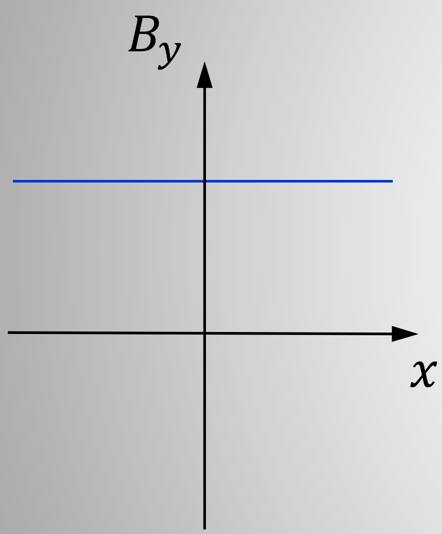
A_3: skew sextupole



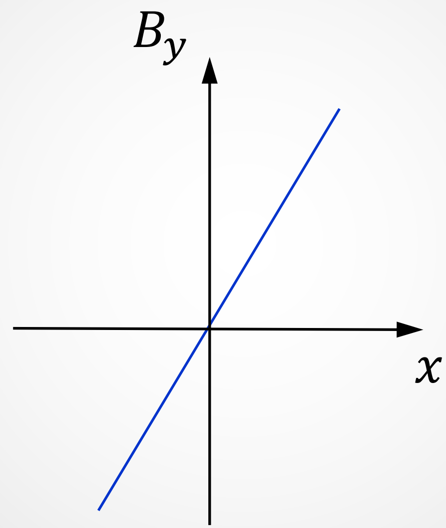
Each multipole term has a corresponding magnet type

Field description

Field expansion along x: $B_y(x) = \sum_{n=1}^{\infty} B_n \left(\frac{x}{r_0}\right)^{n-1} = B_1 + B_2 \frac{x}{r_0} + B_3 \frac{x^2}{r_0^2} + \cdots$

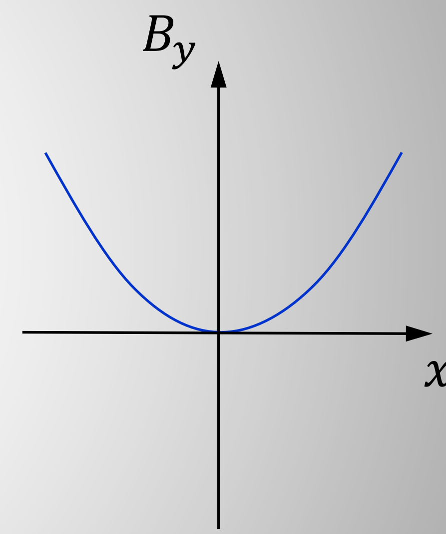


B_1: dipole



B_2: quadrupole

$$G = \frac{B_2}{r_0} = \frac{\partial B_y}{\partial x}$$



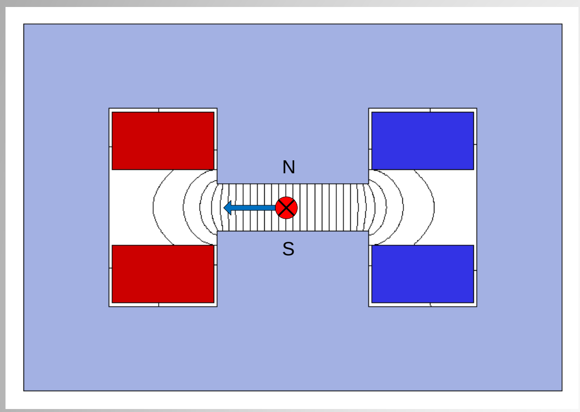
B_3: sextupole

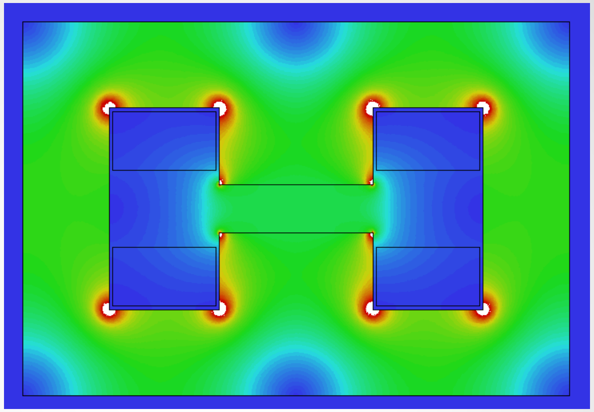
The field profile in the horizontal plane follows a polynomial expansion

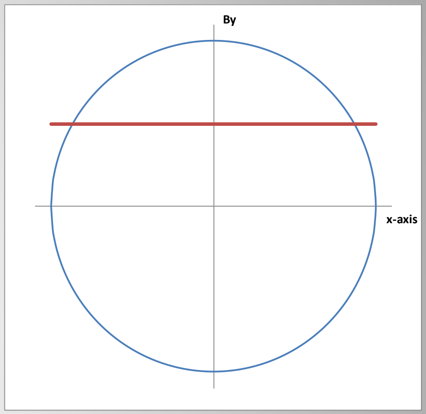
The ideal poles for each magnet type are lines of constant scalar potential

Dipoles

Purpose: bend or steer the particle beam







Equation for normal (non-skew) ideal (infinite) poles:

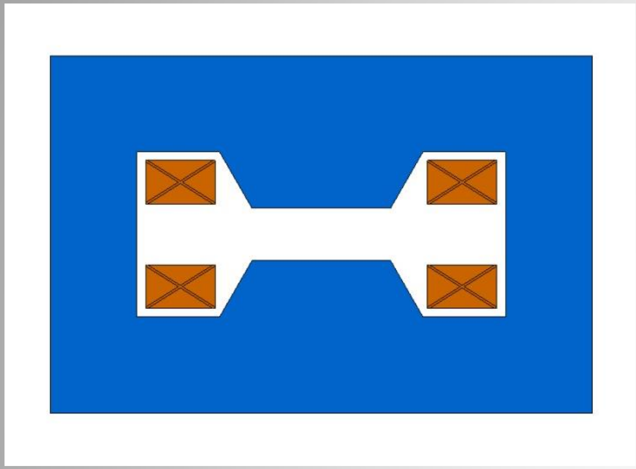
- Polar coordinates: $\rho \sin(\varphi) = \pm h/2$
- Cartesian coordinates: $y = \pm h/2$
- Straight line ($h =$ gap height)

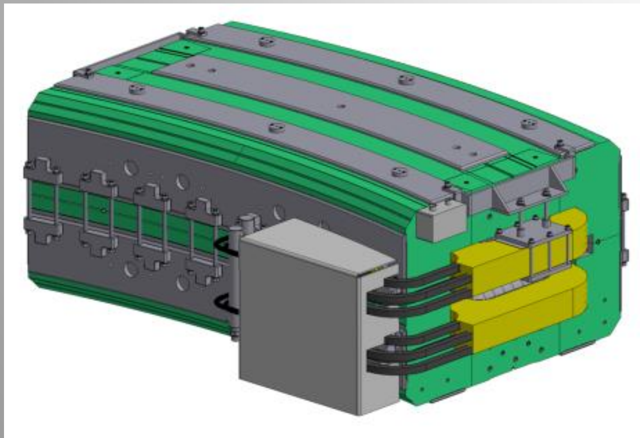
Magnetic flux density: $B_x = 0$; $B_y = B_1(r_0) = \text{const.}$

Applications: synchrotrons, transfer lines, spectrometry, beam scanning

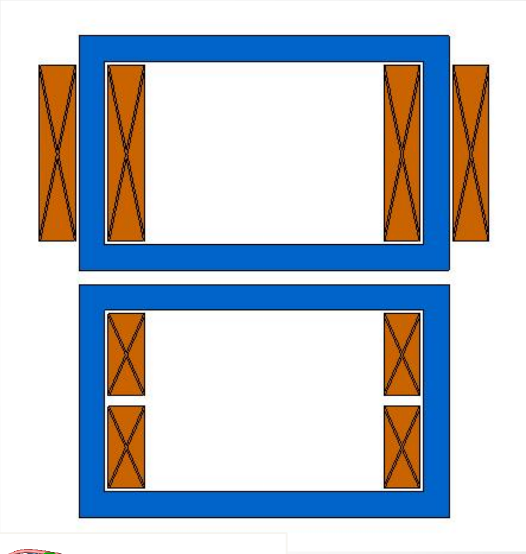
Dipole types

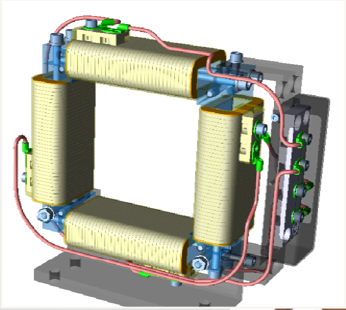
H-Shape

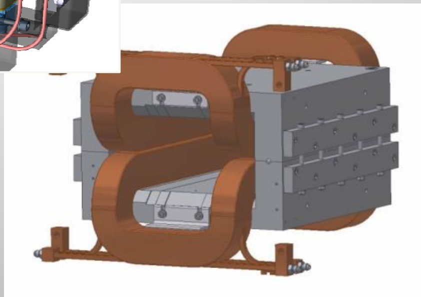




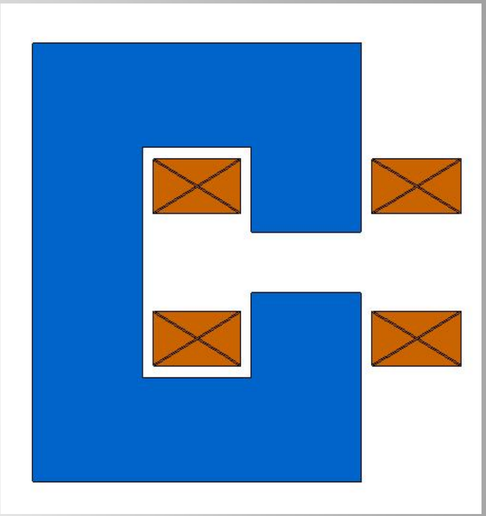
O-Shape

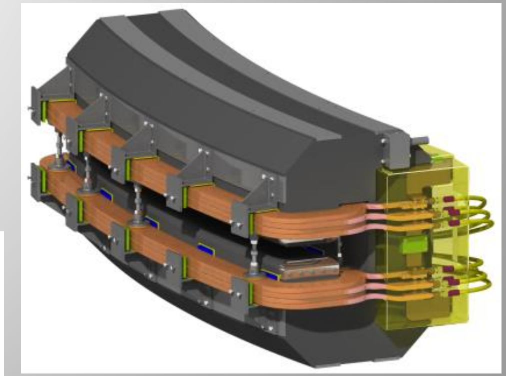






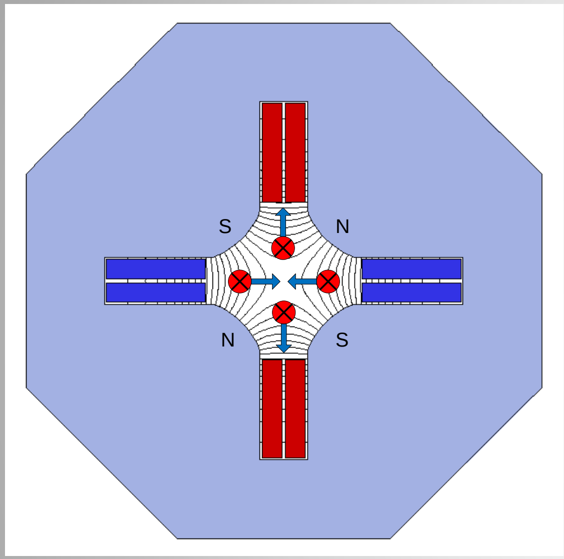
C-Shape

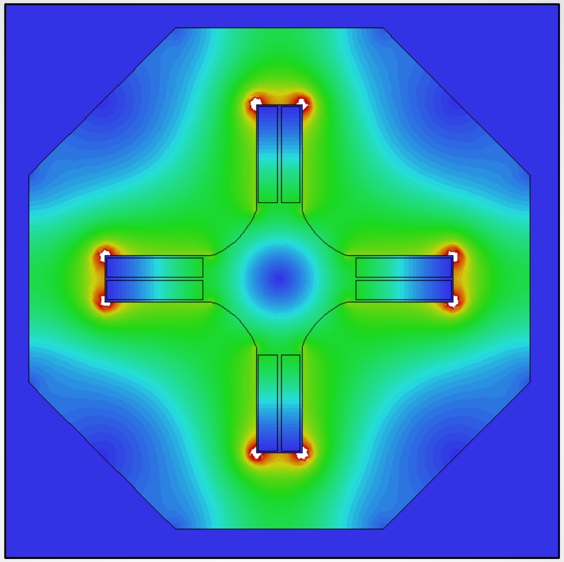


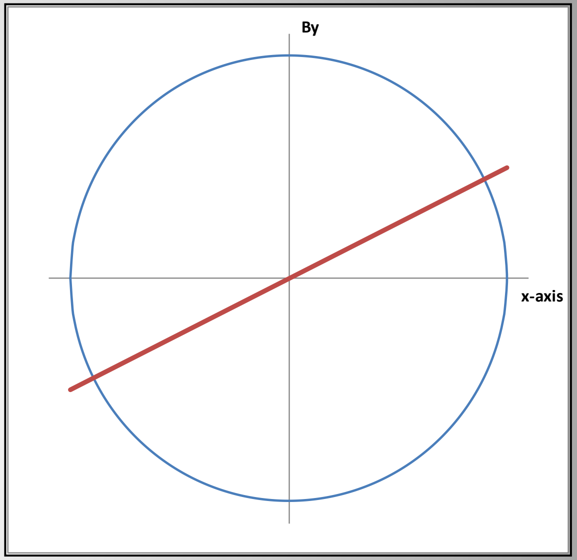


Quadrupoles

Purpose: focusing the beam (horizontally focused beam is vertically defocused)







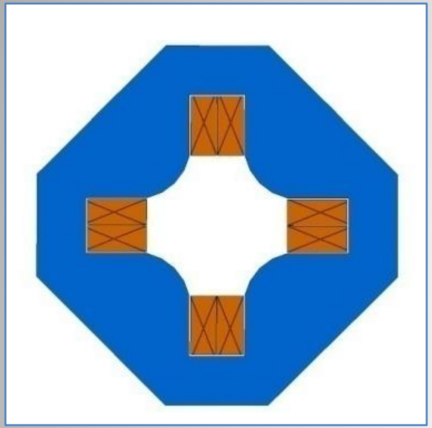
Equation for normal (non-skew) ideal (infinite) poles:

- Polar coordinates: $\rho^2 \sin(2\varphi) = \pm r^2$
- Cartesian coordinates: $2xy = \pm r^2$
- Hyperbola ($r =$ aperture radius)

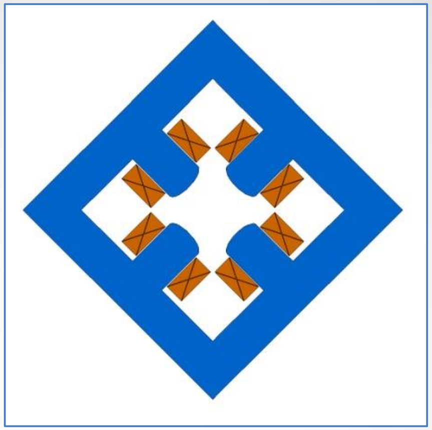
Magnetic flux density: $B_x = \frac{B_2(r_0)}{r_0} y\,; B_y = \frac{B_2(r_0)}{r_0} x$

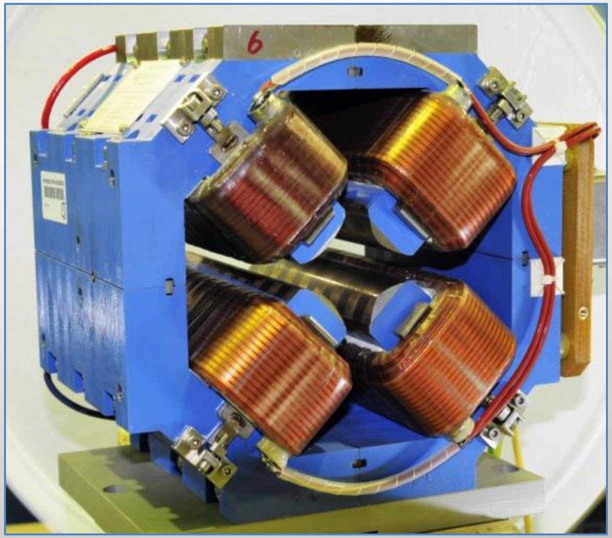
Quadrupole types

Standard quadrupole I

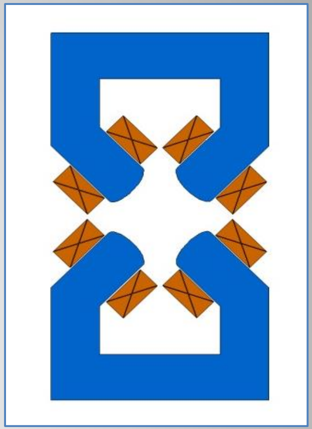


Standard quadrupole II



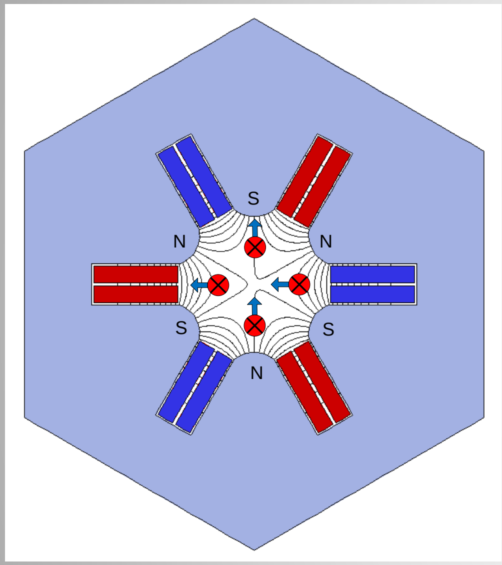


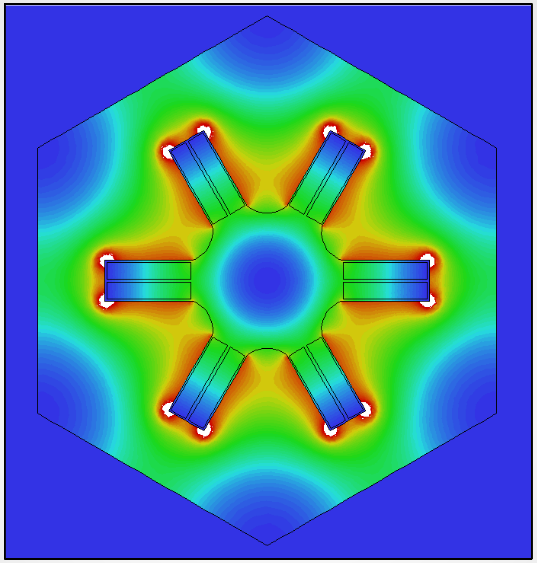
Collins or Figure-of-Eight

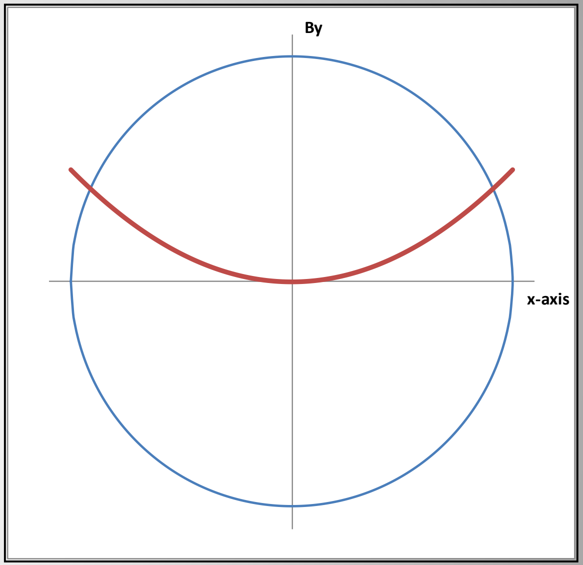


Sextupoles

Purpose: correct chromatic aberrations of ‘off-momentum’ particles







Equation for normal (non-skew) ideal (infinite) poles:

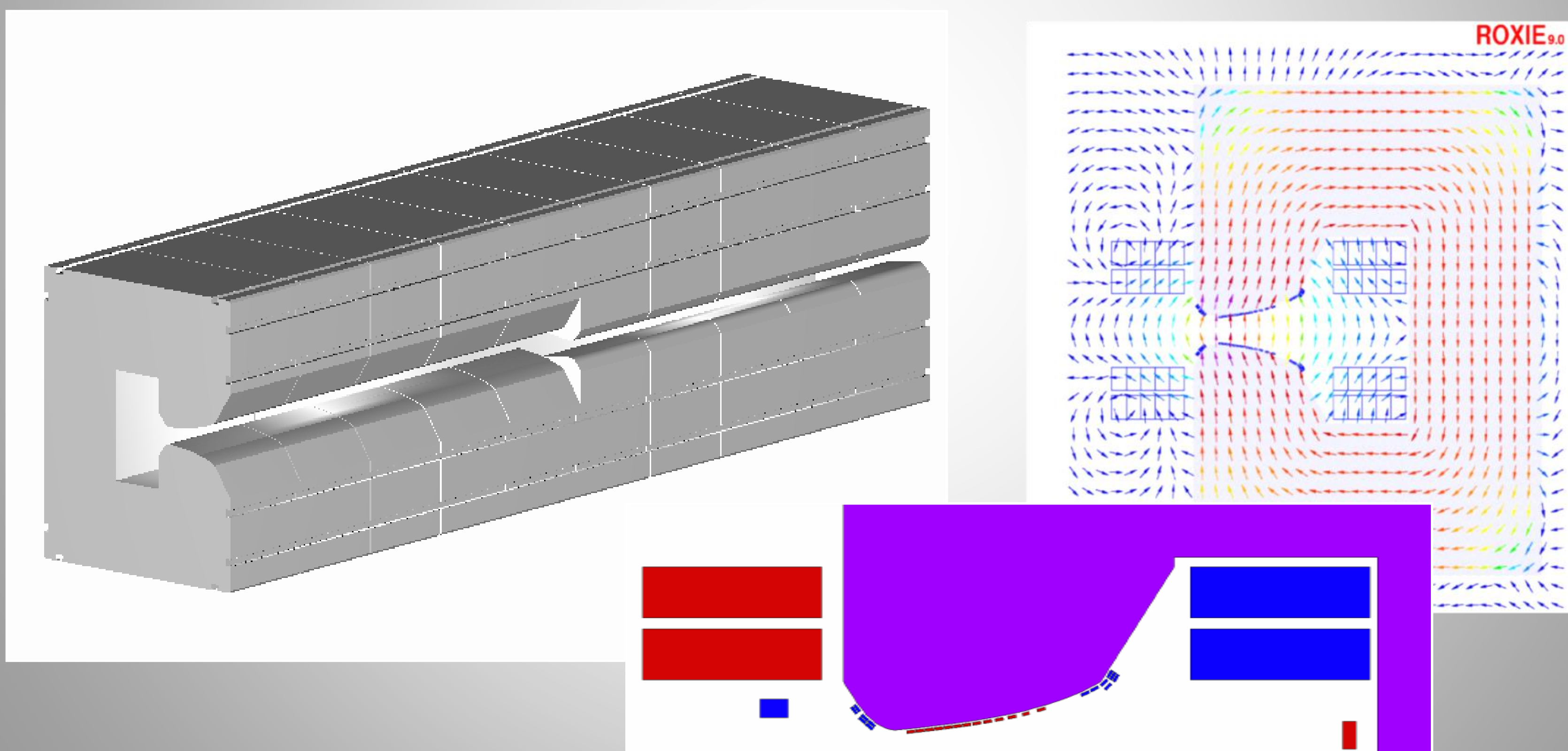
- Polar coordinates: $\rho^3 \sin(3\varphi) = \pm r^3$
- Cartesian coordinates: $3x^2y - y^3 = \pm r^3$

Magnetic flux density: $B_x = \frac{B_3(r_0)}{r_0^2}\, xy\, ; B_y = \frac{B_3(r_0)}{r_0^2}(x^2 - y^2)$

Combined function magnets

Functions generated by pole shape (sum a scalar potentials):

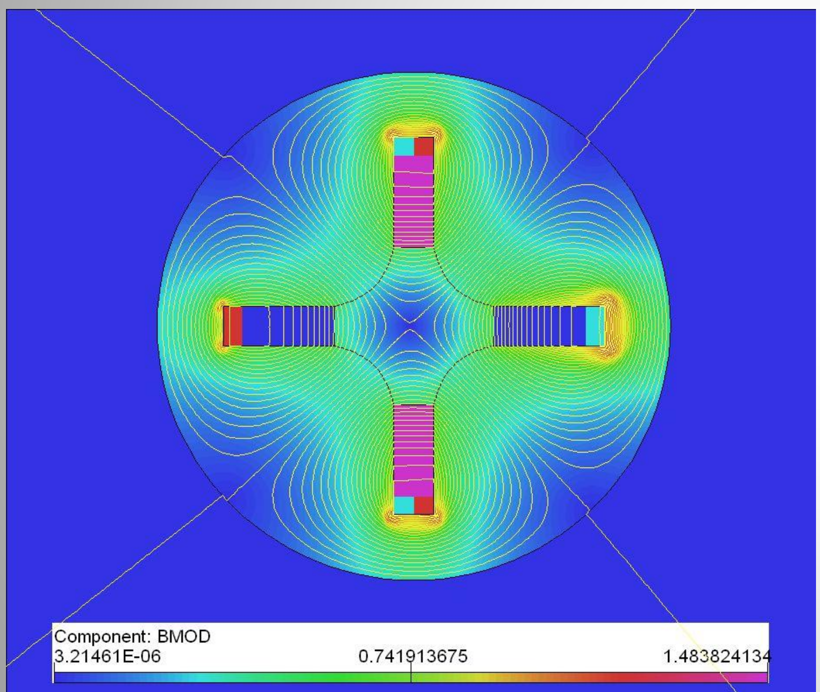
- Amplitudes cannot be varied independently
- Dipole and quadrupole: PS main magnet (PFW, Fo8…)

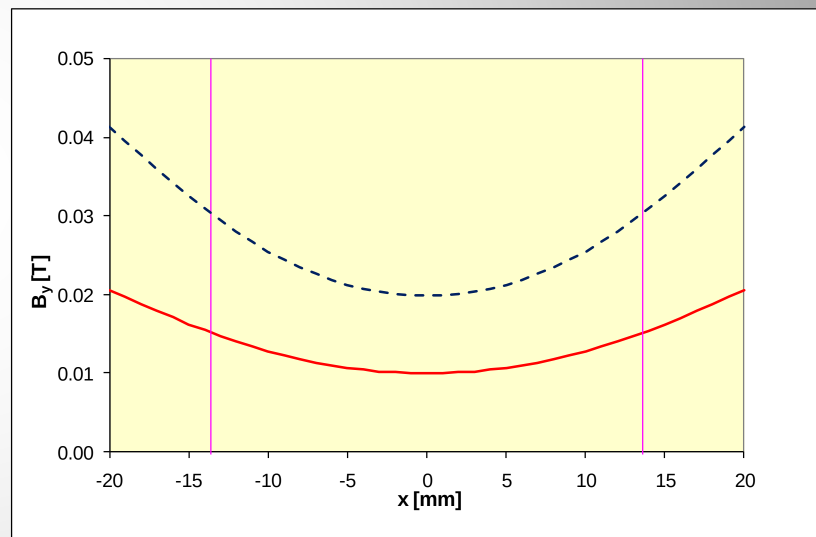


Combined function magnets

Functions generated by individual coils:

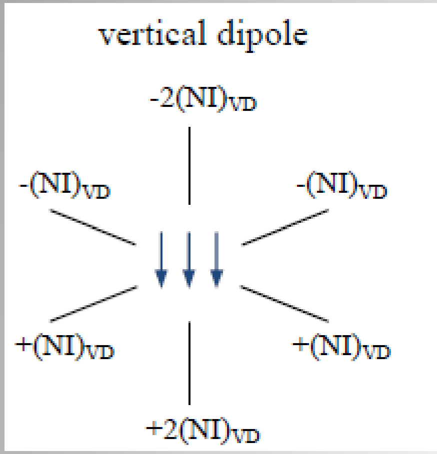
Amplitudes can be varied independently

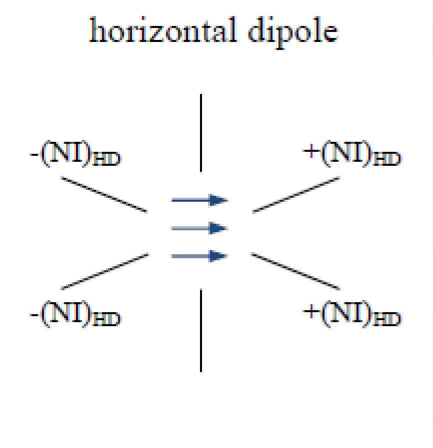


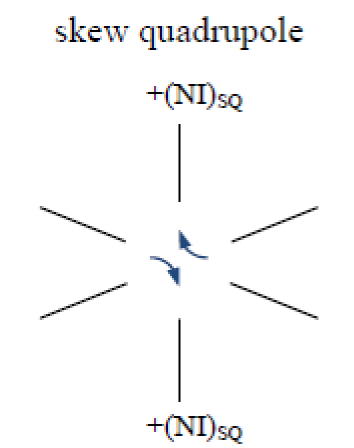


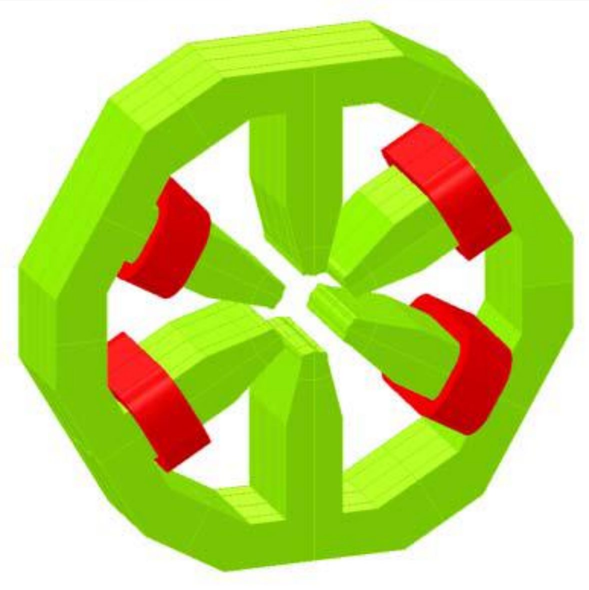
Quadrupole and corrector dipole (strong sextupole component in dipole field)

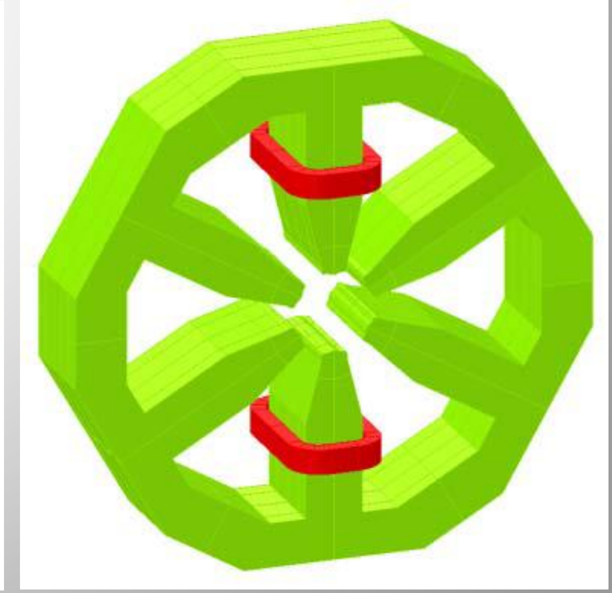
Combined function magnets







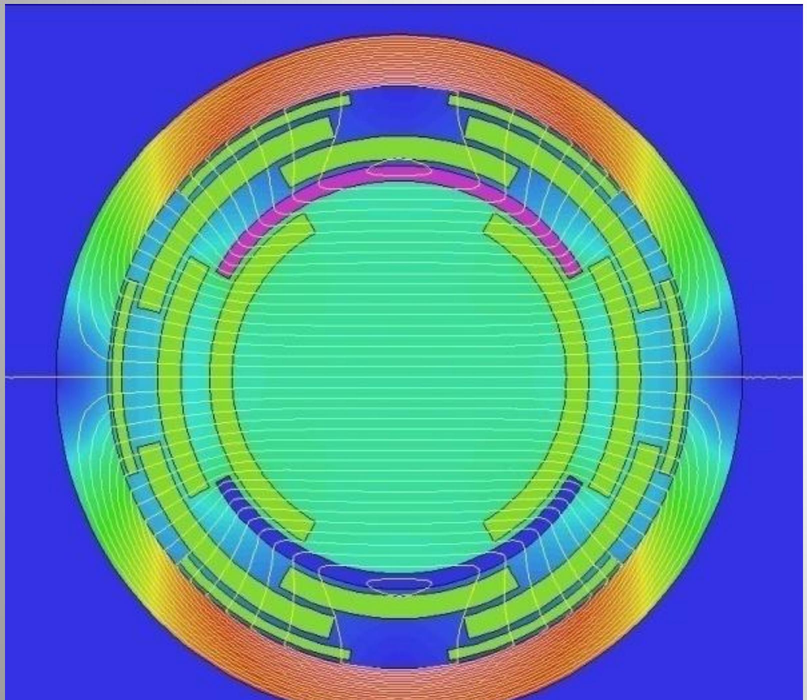


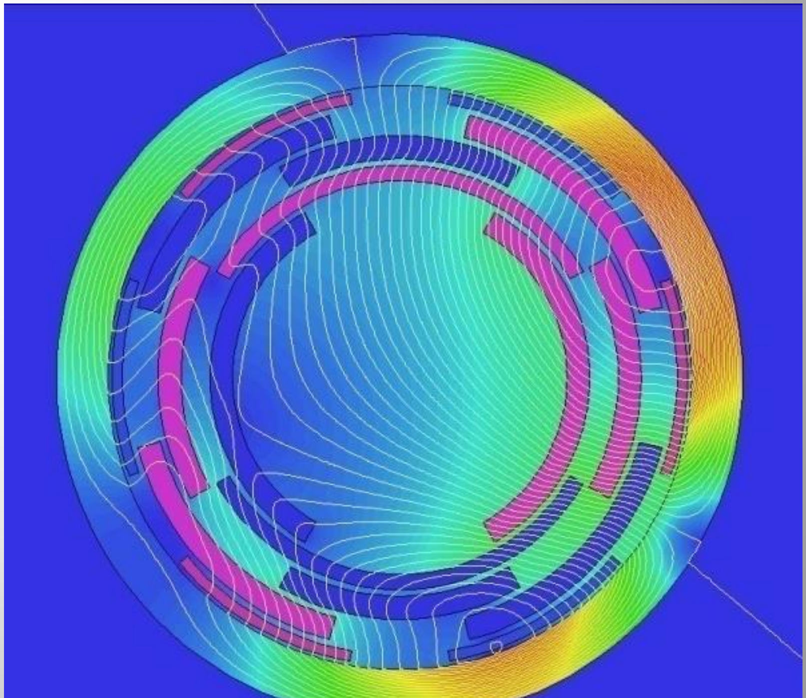


Courtesy of A. Milanese

Coil dominated magnets

- Nested multi-pole corrector (moderate field levels)
- Iron for shielding only
- Field determined by current distribution


Vertical dipole configuration


Multi-pole configuration

Summary

- Magnets are needed to guide and shape particle beams
- Coils carry the electrical current, the iron yoke carries the magnetic flux
- Magnetic steel is characterized by its relative permeability μ_r and its coercivity H_c
- Iron saturation influences the efficiency of the magnetic circuit and has to be taken into account in the design
- The 2D (magnetic) vector field can be expressed as a series of multipole coefficients
- Different magnet types for different functions