CERN Accelerator School @ ESI

Archamps, France, 25th June 2018

Normal-conducting & Permanent Magnets

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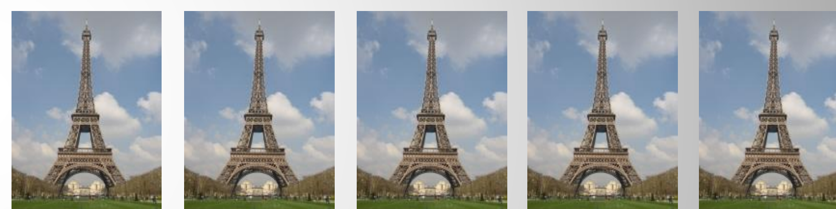
CERN

Scope of this lecture

The main goal is to provide an overview on ‘room temperature’ magnets i.e. normal-conducting, iron-dominated electro-magnets and permanent magnets

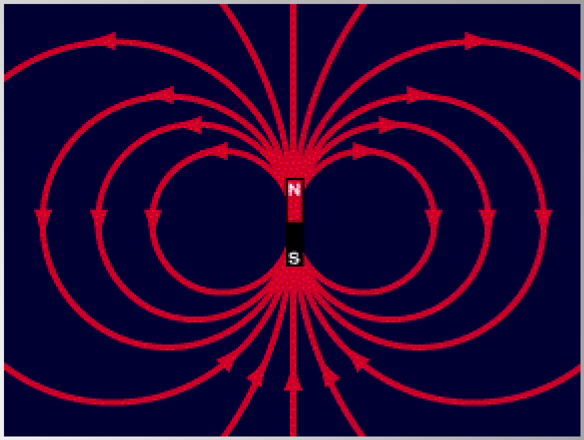
More than 4800 ‘room temperature’ magnets (50 000 tonnes) are installed in the CERN accelerator complex



Outline

- Producing magnetic fields
- Magnet technologies
- Describing magnetic fields
- Magnet types in accelerators
- Design & manufacturing
- Examples from the past
- New concepts for future accelerators

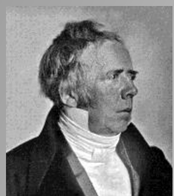
Magnetic units



IEEE defines the following units:

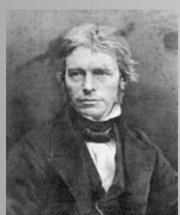
- Magnetic field:
  - H (vector) [A/m]
  - the magnetizing force produced by electric currents
- Electromotive force:
  - e.m.f. or U [V or (kg m^2)/(A s^3)]
  - here: voltage generated by a time varying magnetic field
- Magnetic flux density or magnetic induction:
  - B (vector) [T or kg/(A s^2)]
  - 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): $\mu_{\text{air}} = 1$; $\mu_{\text{iron}} > 1000$ (not saturated)

A bit of history...

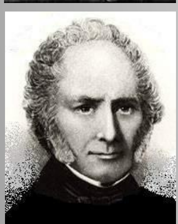


1820: Hans Christian Oersted (1777-1851) finds that electric current affects a compass needle

1820: Andre Marie Ampere (1775-1836) in Paris finds that wires carrying current produce forces on each other

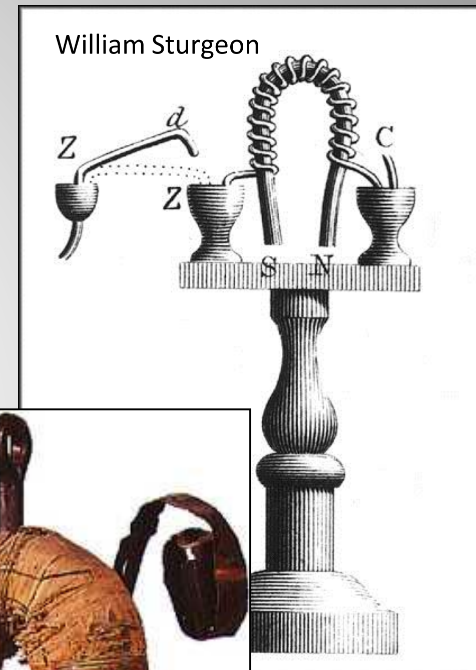


1820: Michael Faraday (1791-1867) at Royal Society in London develops the idea of electric fields and studies the effect of currents on magnets and magnets inducing electric currents



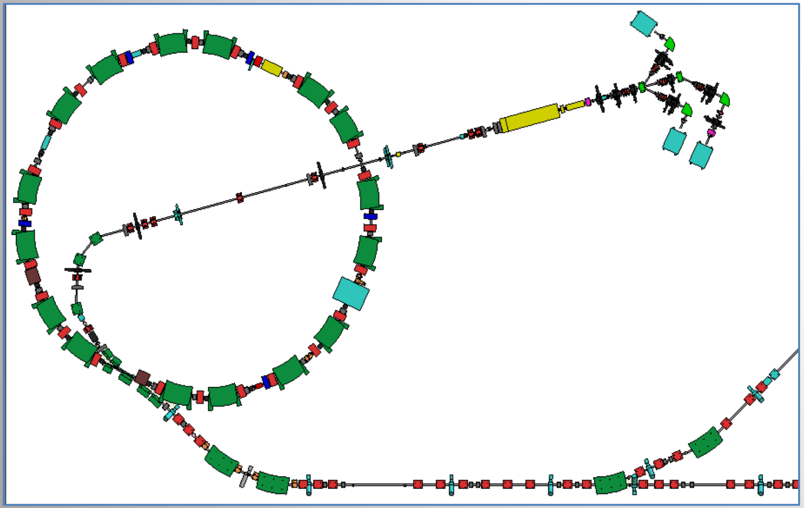
1825: British electrician, William Sturgeon (1783-1850) invented the first electromagnet

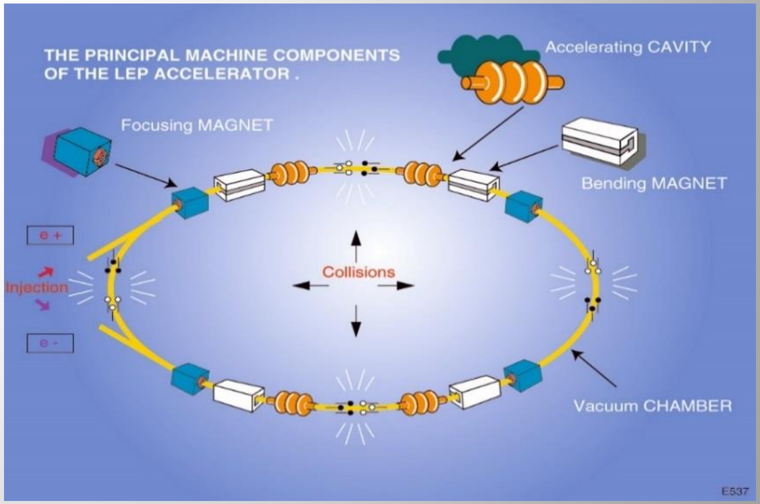
1860: James Clerk Maxwell (1831-1879), a Scottish physicist and mathematician, puts the theory of electromagnetism on mathematical basis



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(!)



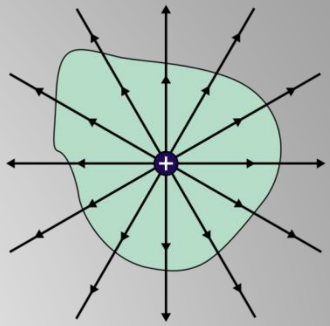


  - Permanent magnets provide only constant magnetic fields
  - Electro-magnets can provide adjustable magnetic fields

Maxwell‘s equations

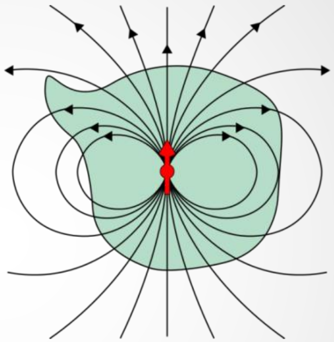
Gauss‘ law for electricity:

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$



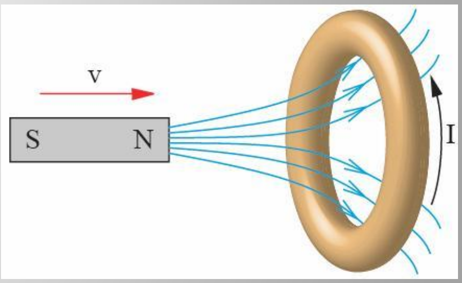
Gauss‘ law of flux conservation:

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



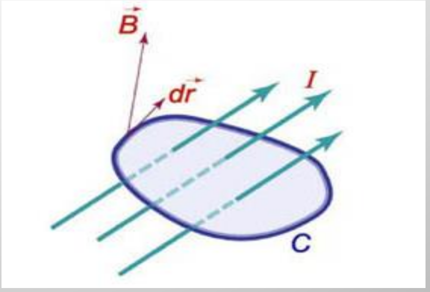
Faraday‘s law of induction:

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

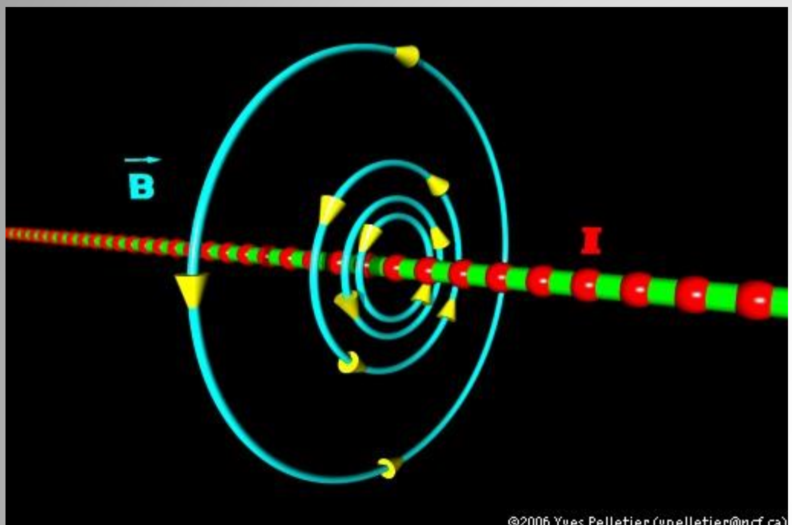


Ampere‘s law:

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$$



Producing the field

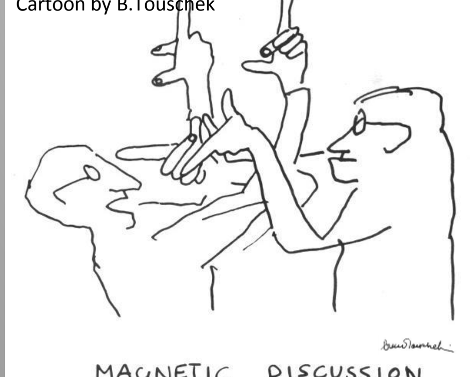


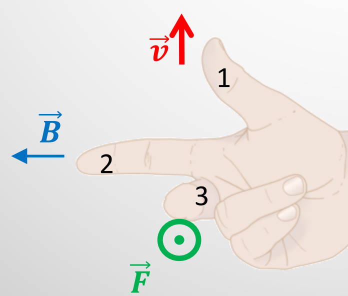
Maxwell & Ampere:

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

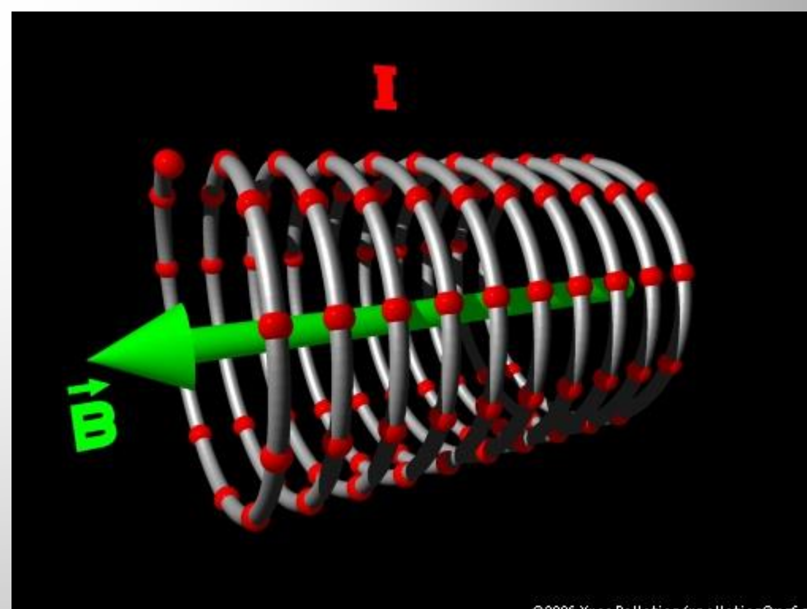
„An electrical current is surrounded by a magnetic field“

Cartoon by B.Touschek

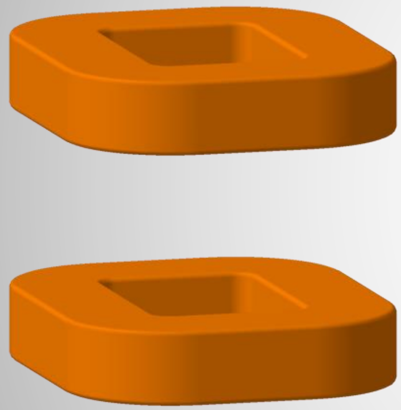


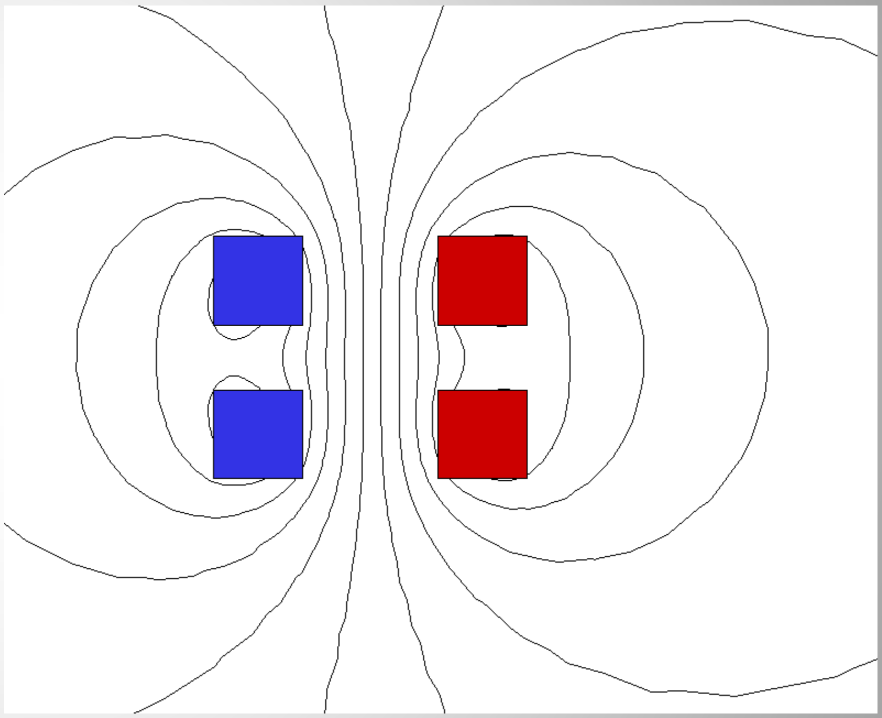


„Right hand rule“ applies



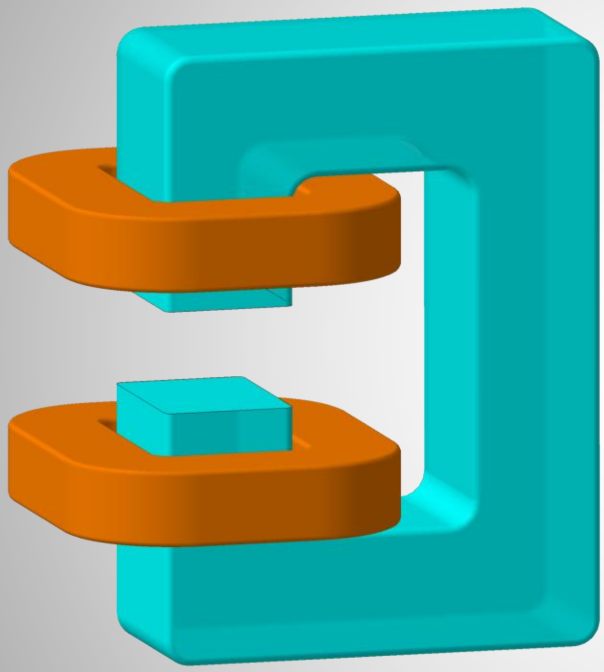
Magnetic circuit

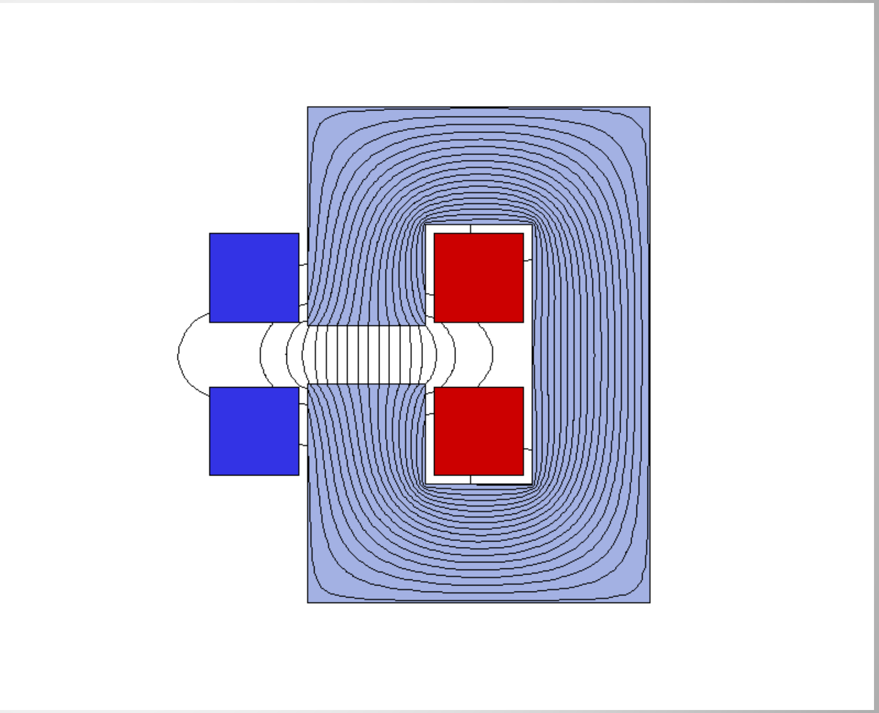




Flux lines represent the magnetic field
Coil colors indicate the current direction

Magnetic circuit





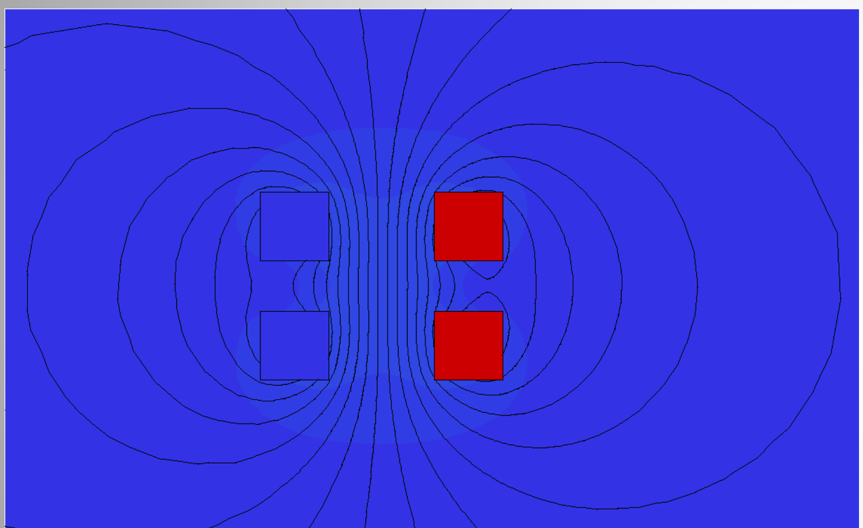
Coils hold the electrical current which induces a magnetic effect

Iron enhance these effects and guides the magnetic flux

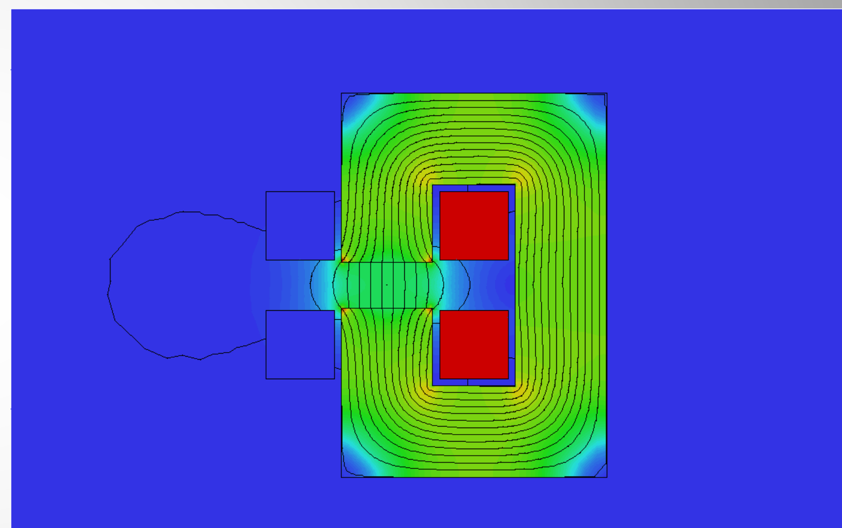
→ *"iron-dominated magnet"*

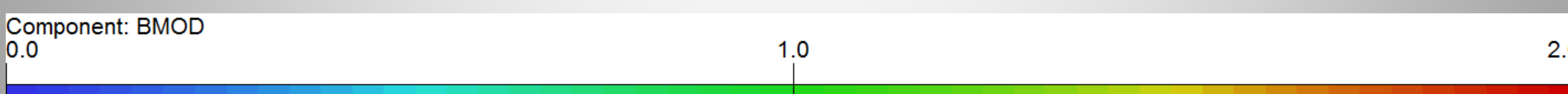
Magnetic circuit

$I = 32$ 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

Excitation current in a dipole

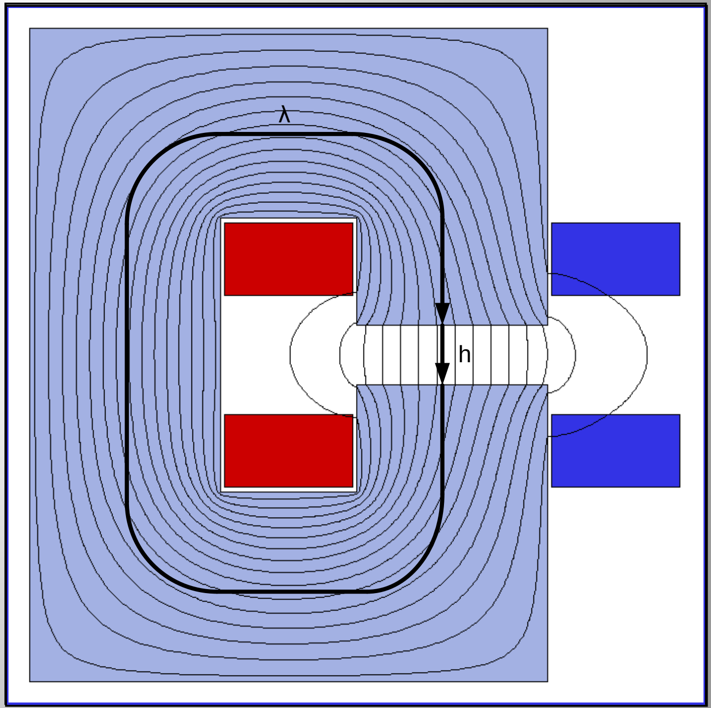
Ampere's law $\oint \vec{H} \cdot d\vec{l} = NI$ and $\vec{B} = \mu\vec{H}$

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: $$\frac{h}{\mu_{air}} >> \frac{\lambda}{\mu_{iron}}$$

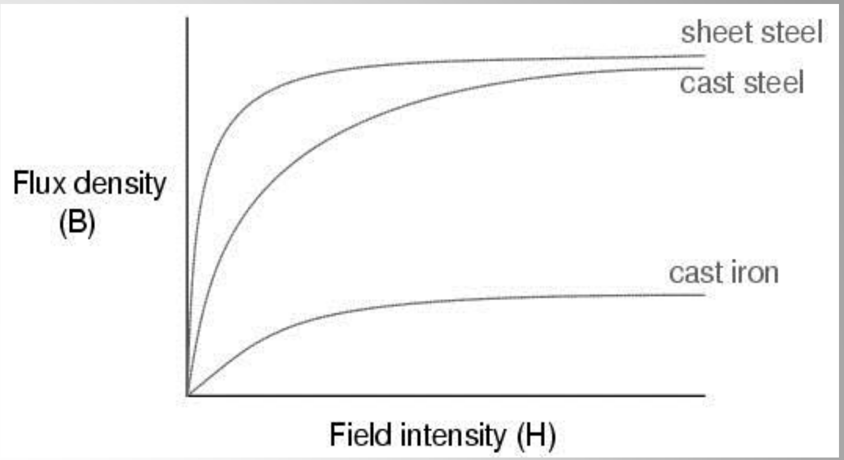
then: $$NI \approx \frac{Bh}{\mu_0}$$



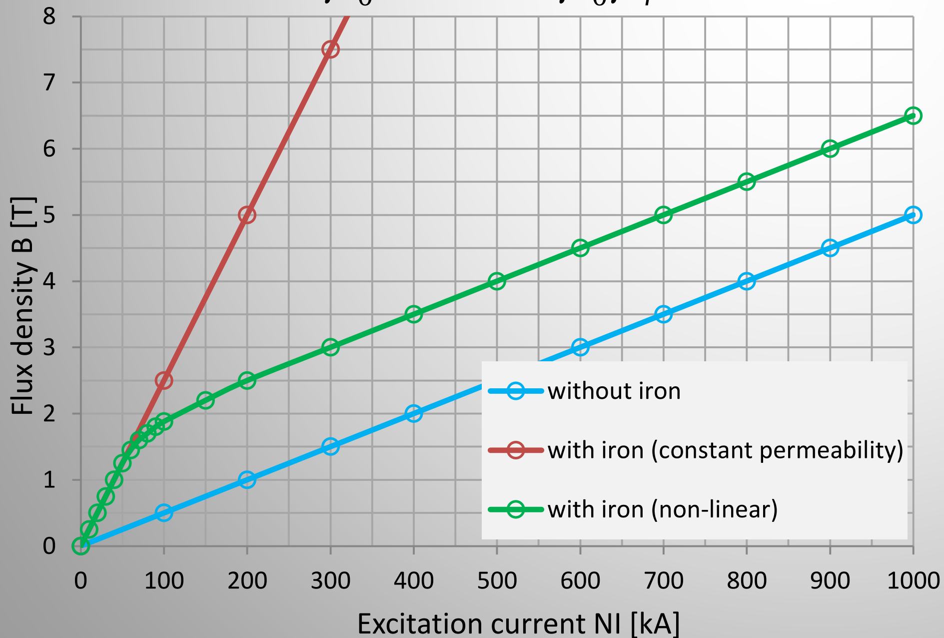
Permeability

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

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



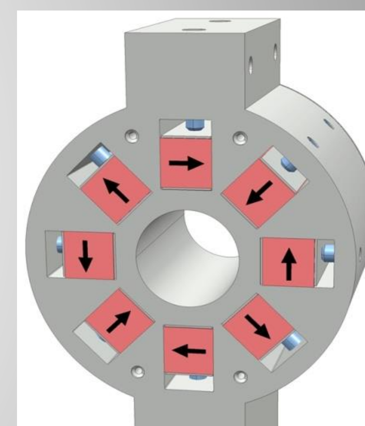
$$\vec{B} = \mu_0 \vec{H} + \vec{J} = \mu_0 \mu_r \vec{H}$$

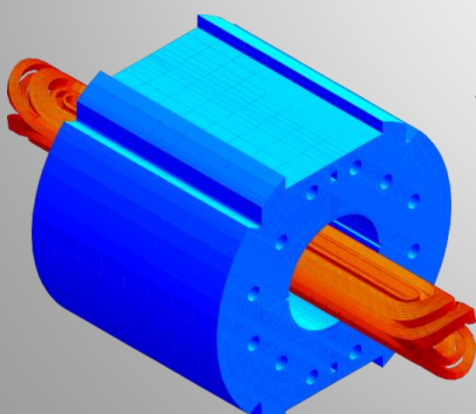


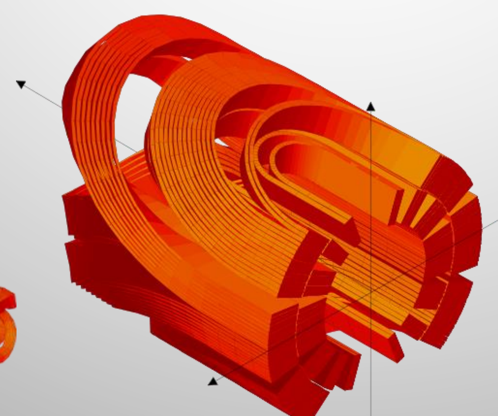
Ferro-magnetic materials: high permeability (μ_r>>1), but not constant

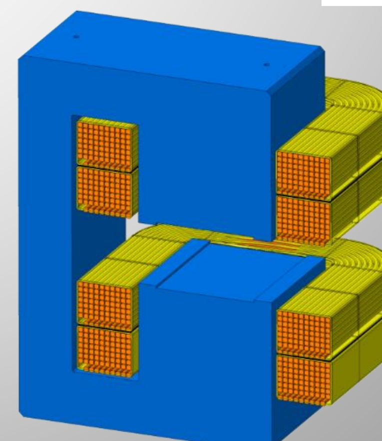
Magnet technologies

- 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**





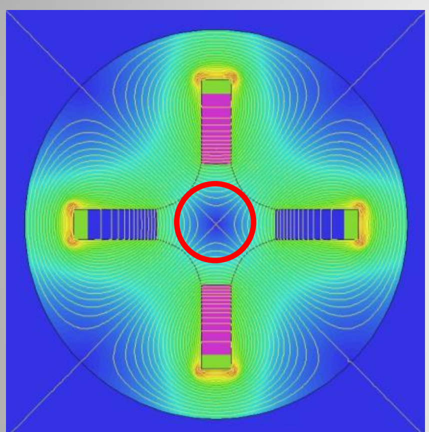
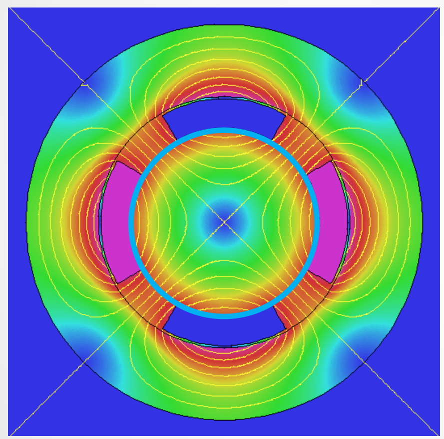
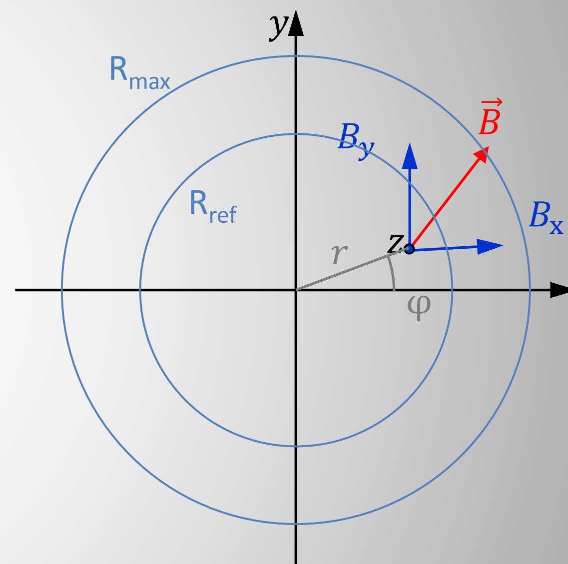




Field description

How can we conveniently describe the field in the aperture?

- at any point (in 2D) $z = x + iy = re^{i\varphi}$
- for any field configuration
- regardless of the magnet technology

Solution: multipole expansion, describing the field within a circle of validity with scalar coefficients

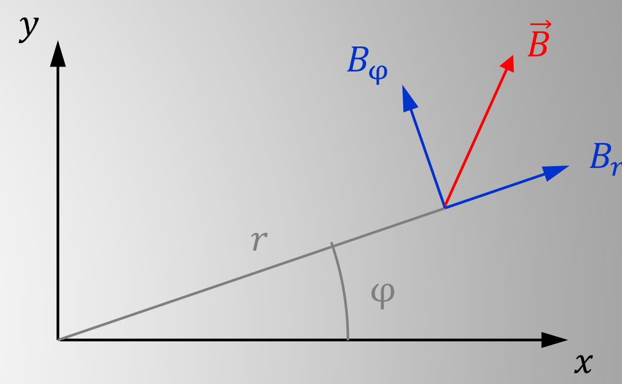
$$B_y(z) + iB_x(z) = \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{z}{R_{ref}} \right)^{n-1}$$

Field description

For radial and tangential components of the field the series contains sin and cos terms (Fourier decomposition):

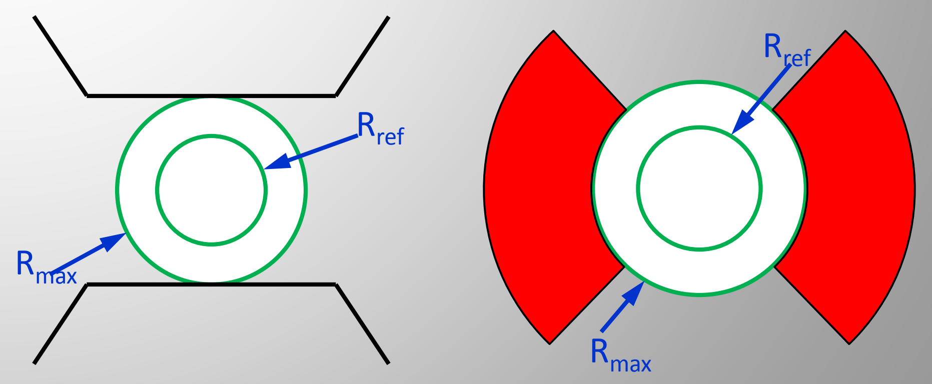
$$B_r(r,\varphi) = \sum_{n=1}^{\infty} \left(\frac{r}{R_{ref}}\right)^{n-1} [B_n \sin(n\varphi) + A_n \cos(n\varphi)]$$

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



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

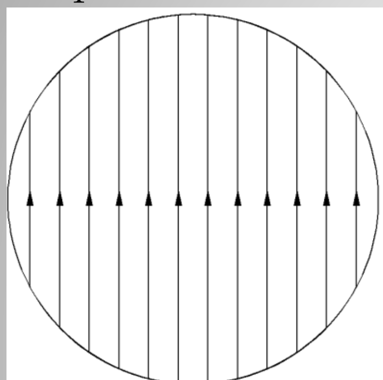
- without magnetic materials ($\mu_r = 1$)
- without currents
- when B_z is constant



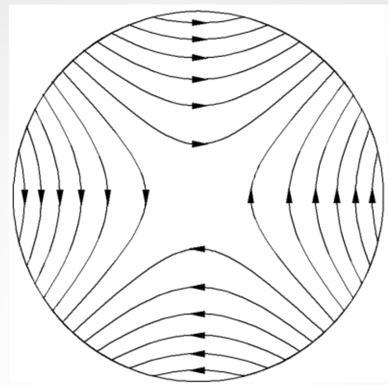
Field description

Each multipole term has a corresponding magnet type:

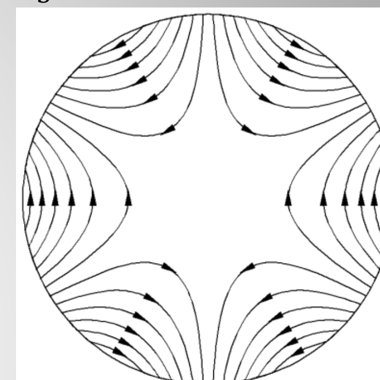
B_1: normal dipole



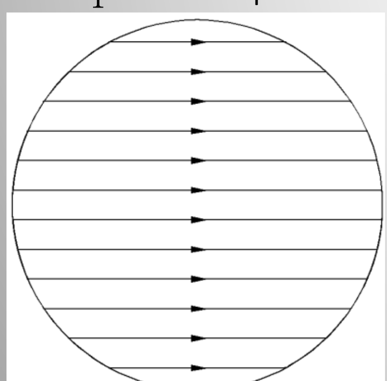
B_2: normal quadrupole



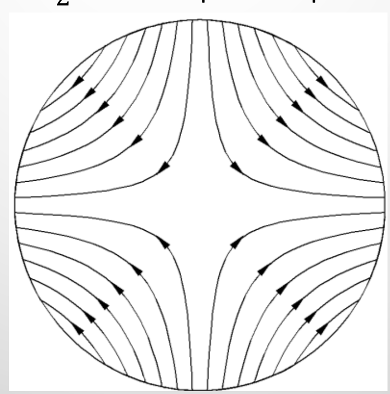
B_3: normal sextupole



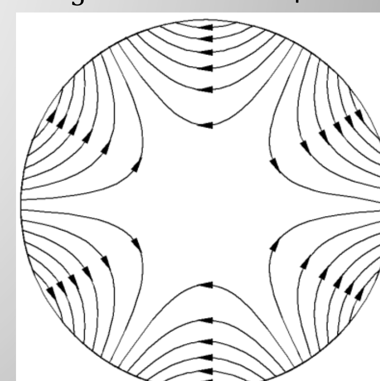
A_1: skew dipole



A_2: skew quadrupole



A_3: skew sextupole



Vector equipotential lines are flux lines. $\vec{B}$ is tangent point by point to the flux lines
Scalar equipotential lines are orthogonal to the vector equipotential lines. They define the boundary conditions for shaping the field (for iron-dominated magnets).

Field quality

Taking

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

and introducing dimensionless normalized multipole coefficients

$$b_n = \frac{B_\mathrm{n}}{B_\mathrm{N}} 10^4 \quad \text{and} \quad a_n = \frac{A_n}{B_\mathrm{N}} 10^4$$

with B_N being the fundamental field of a magnet: $B_{\mathrm{N\ (dipole)}} = B_1$; $B_{\mathrm{N\ (quad)}} = B_2$; ...

we can describe each magnet by its ideal fundamental field and higher order harmonic distortions:

$$B_y(z) + iB_x(z) = \frac{B_N}{10^4} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{z}{R_{ref}} \right)^{n-1}$$

$$F_d = \sum_{n=1; n \neq N}^{K} \sqrt{b_n^2 + a_n^2}$$

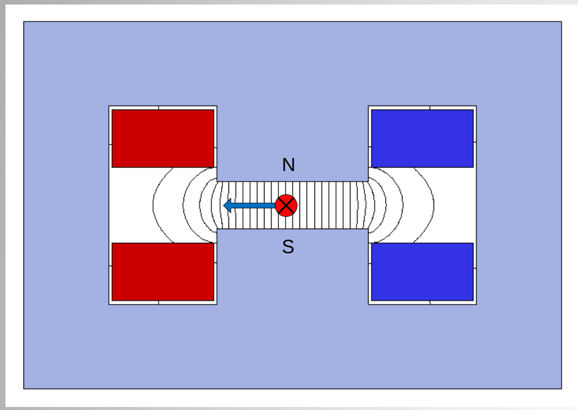
Fundamental field: $\frac{B_N}{10^4}$

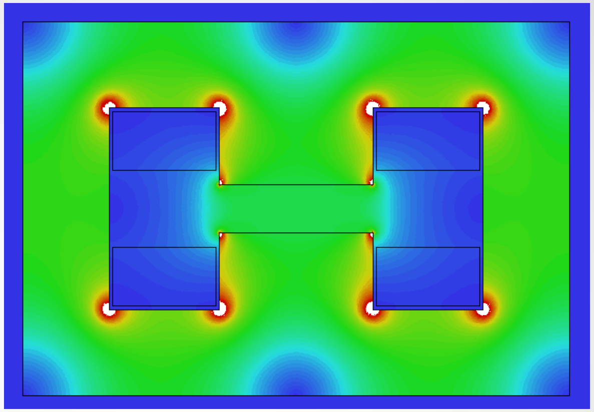
Harmonic distortions: $\sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{z}{R_{ref}} \right)^{n-1}$

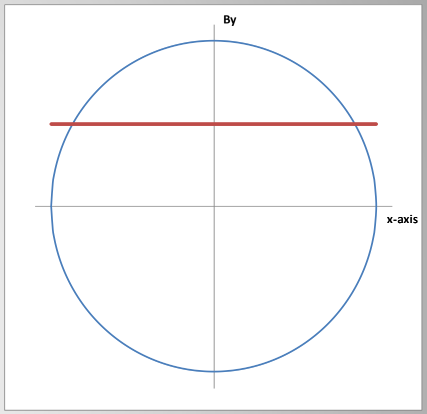
Harmonic distortion factor: F_d

Dipole

Purpose: bend or steer the particle beam







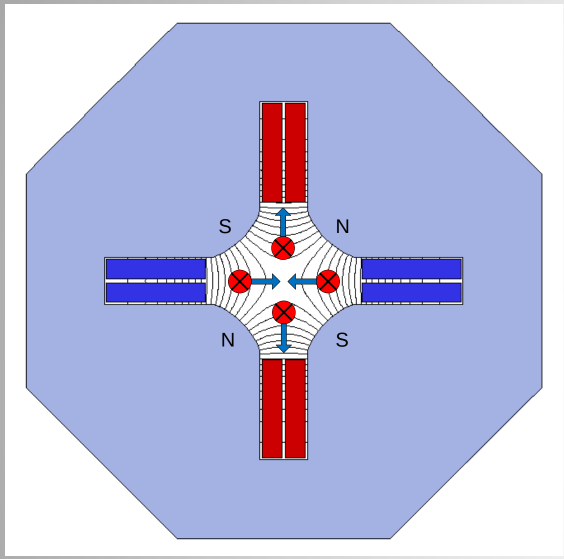
Equation for normal (non-skew) ideal (infinite) poles: $y = \pm h/2$

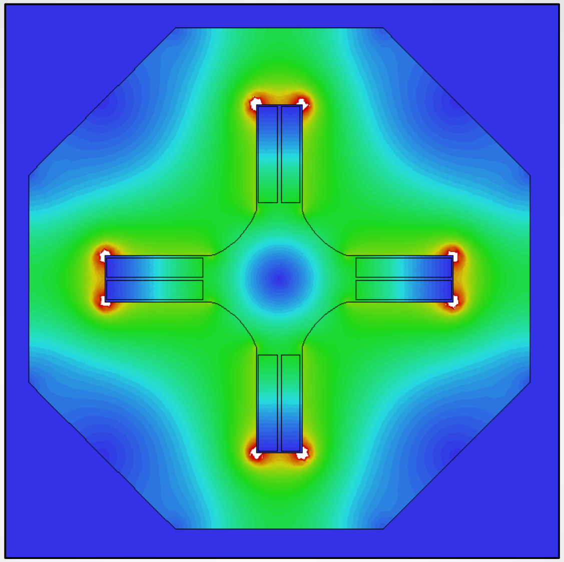
→ Straight line ($h =$ gap height)

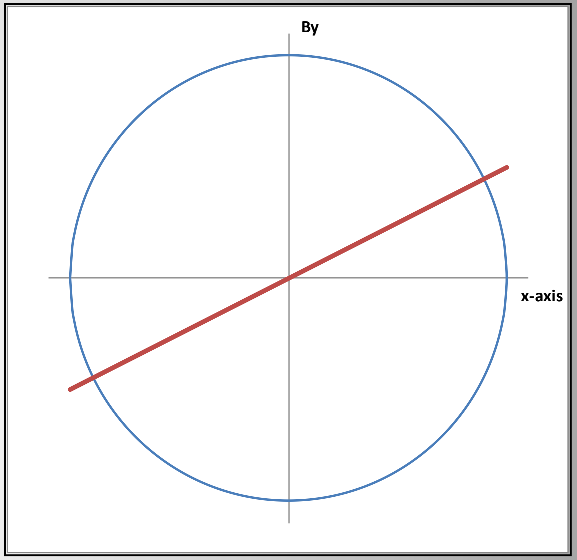
Magnetic flux density: $B_x = 0$; $B_y = B_1 = \text{const.}$

Quadrupole

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







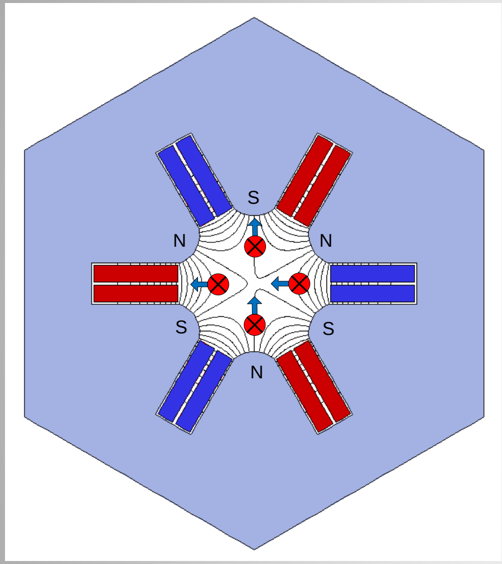
Equation for normal (non-skew) ideal (infinite) poles: $2xy = \pm r^2$

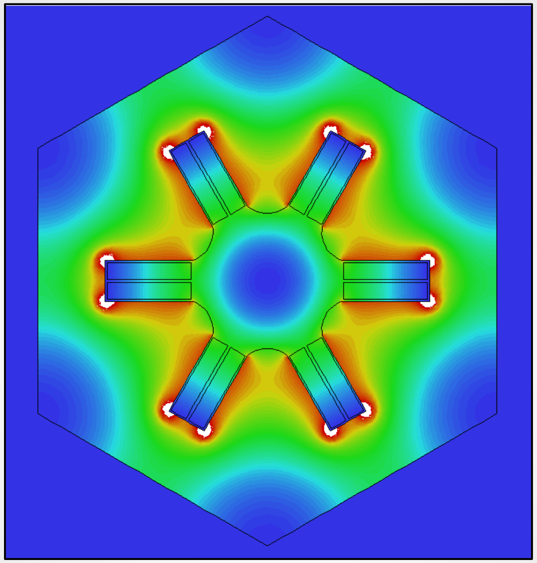
→ Hyperbola (r = aperture radius)

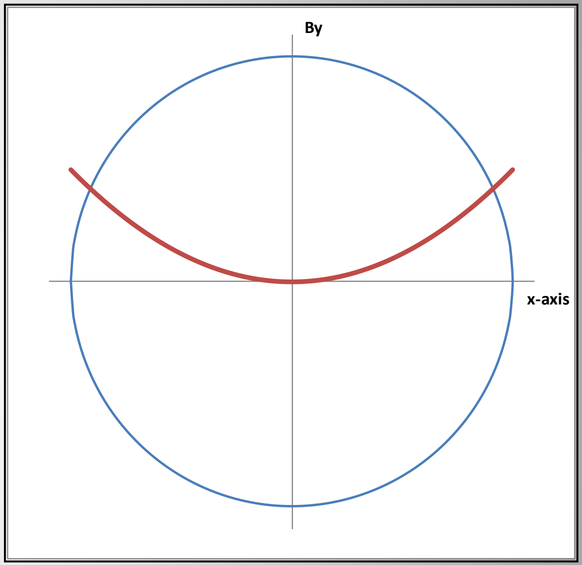
Magnetic flux density: $B_x = \frac{B_2}{R_{ref}} y \, ; B_y = \frac{B_2}{R_{ref}} x$

Sextupole

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





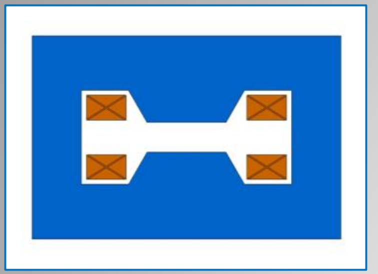


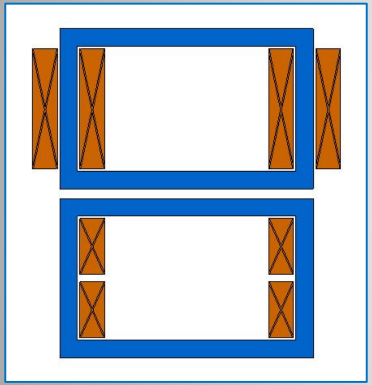
Equation for normal (non-skew) ideal (infinite) poles: $3x^2y - y^3 = \pm r^3$

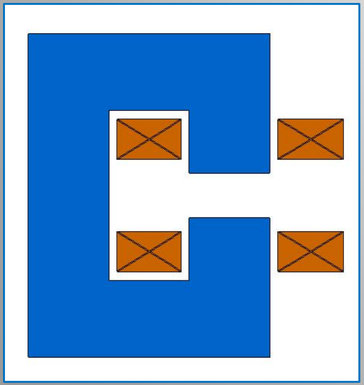
→ often approximated by circular arc

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

Conventional nc-magnet layout





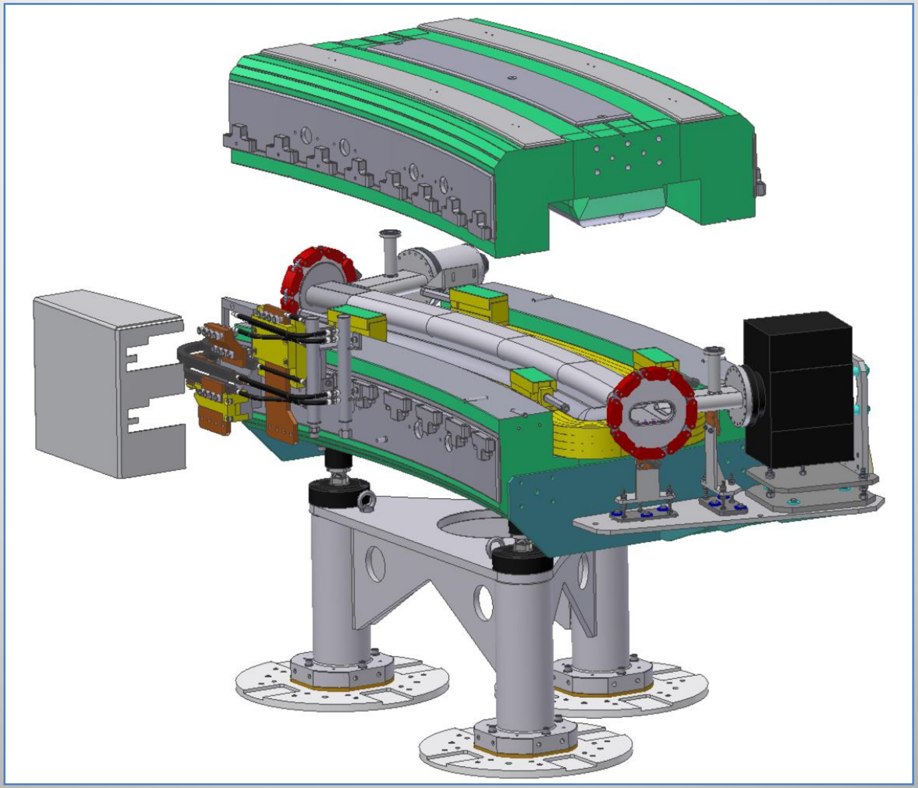


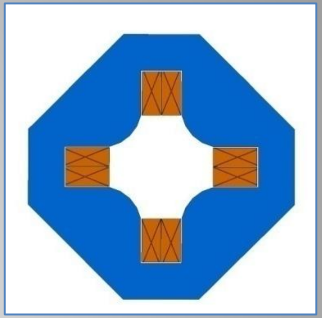
Excitation coils carry the electrical current creating H

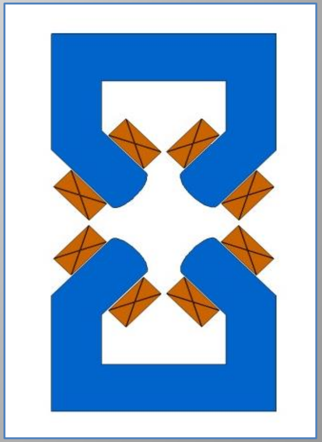
Iron yokes guide and enhance the magnetic flux

Iron poles shape the magnetic field in the aperture around the particle beam

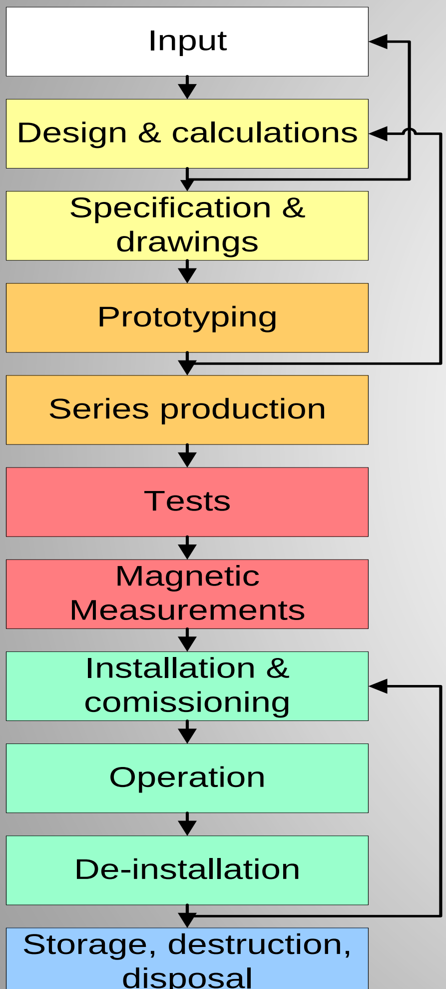
Auxiliaries for cooling, interlock, safety, alignment, ...

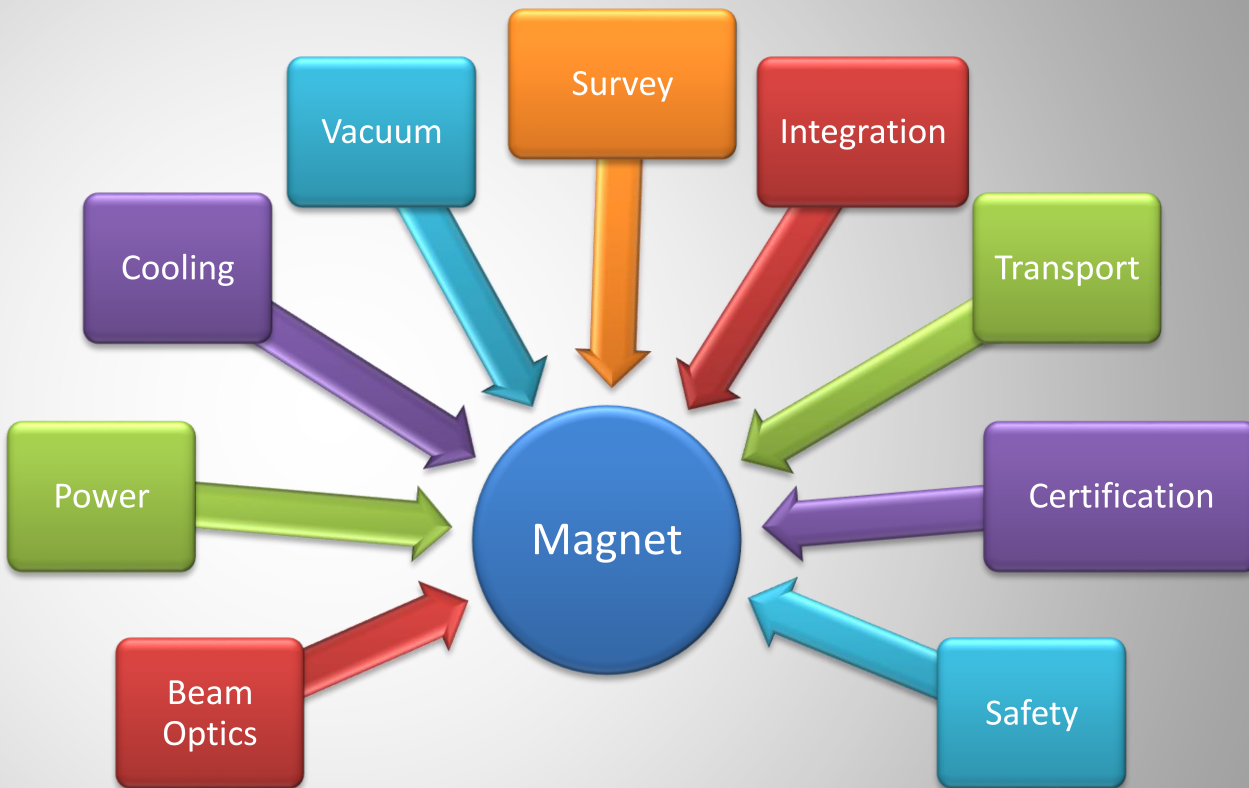






Magnet life-cycle





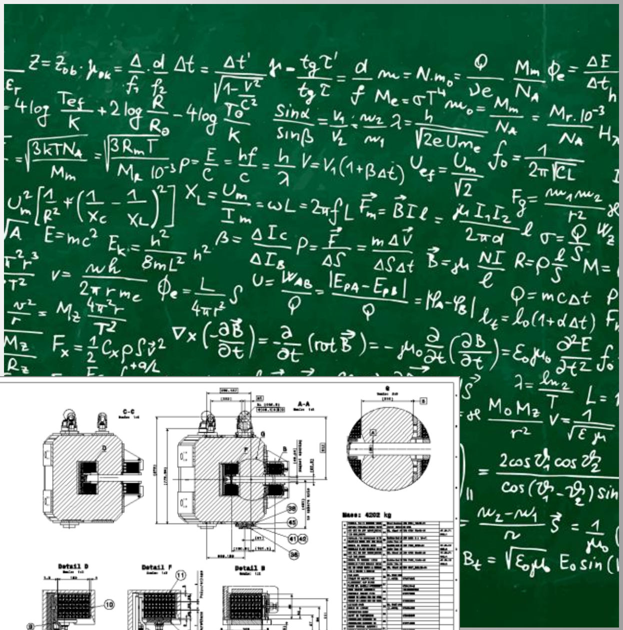
A magnet is not a stand-alone device!

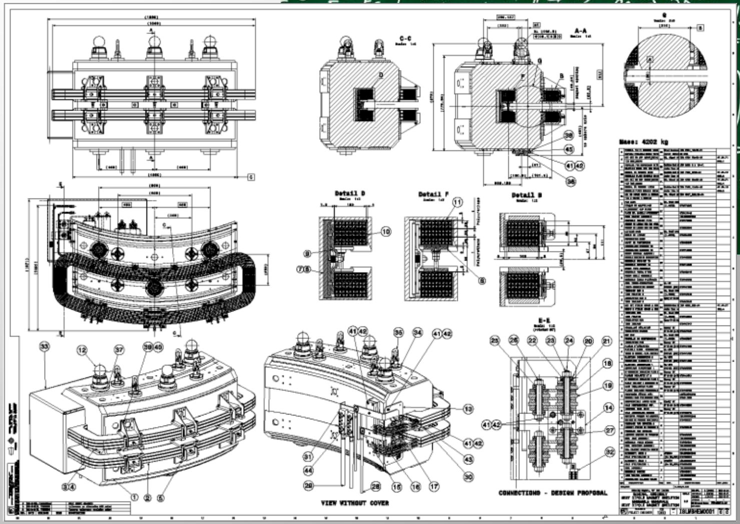
Design process

Electro-magnetic design is an iterative process:

Collect input data → Analytical design → Numerical 2D/3D simulations → Mechanical design → Drawings & specifications

- Field strength (gradient) and magnetic length
- Integrated field strength (gradient)
- Aperture and ‚good field region‘
- Field quality:
    - field homogeneity
    - maximum allowed multi-pole errors
    - settling time (time constant)
- Operation mode: continous, cycled
- Electrical parameters
- Mechanical dimensions
- Cooling
- Environmental aspects





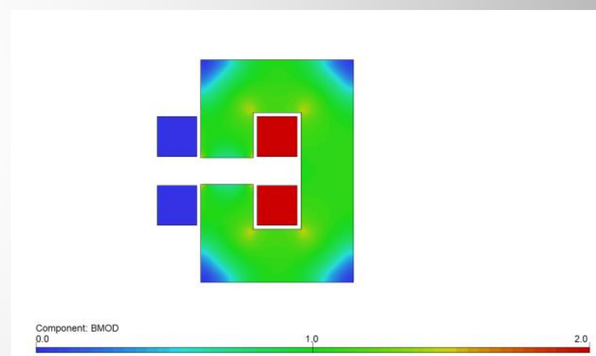
Analytical design (dipole)

1. Beam rigidity: $(B\rho) = \frac{p}{q} = \frac{1}{qc}\sqrt{T^2 + 2T\,E_0}$ Bending radius: r_M

2. Magnetic induction: $B = \frac{(B\rho)}{r_M}$

3. Aperture h = Good-field region + vacuum chamber thickness + margin

4. Excitation current: $NI \approx \frac{Bh}{\mu_0}$



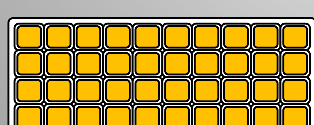
5. Pole and iron yoke dimensioning

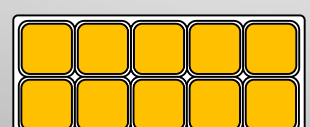
6. Select current density: $j = \frac{NI}{f_c A} = \frac{I}{a_{cond}}$

Attention: $P_{dip} = \rho\, NI\ j\, l_{avg}$

ρ: conductor resistivity
l_{avg}: avg. length of coil

7. Determine number of turns N and current I



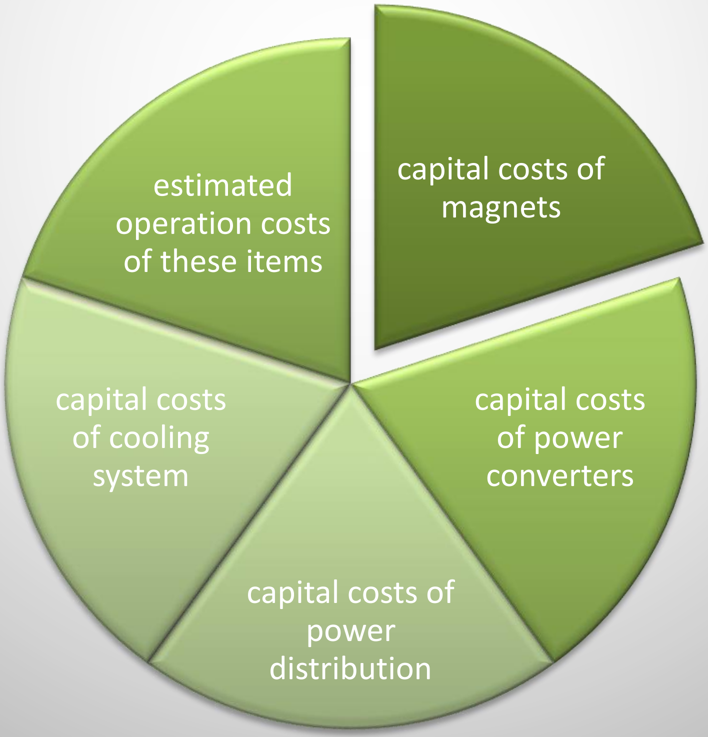


Cost optimization

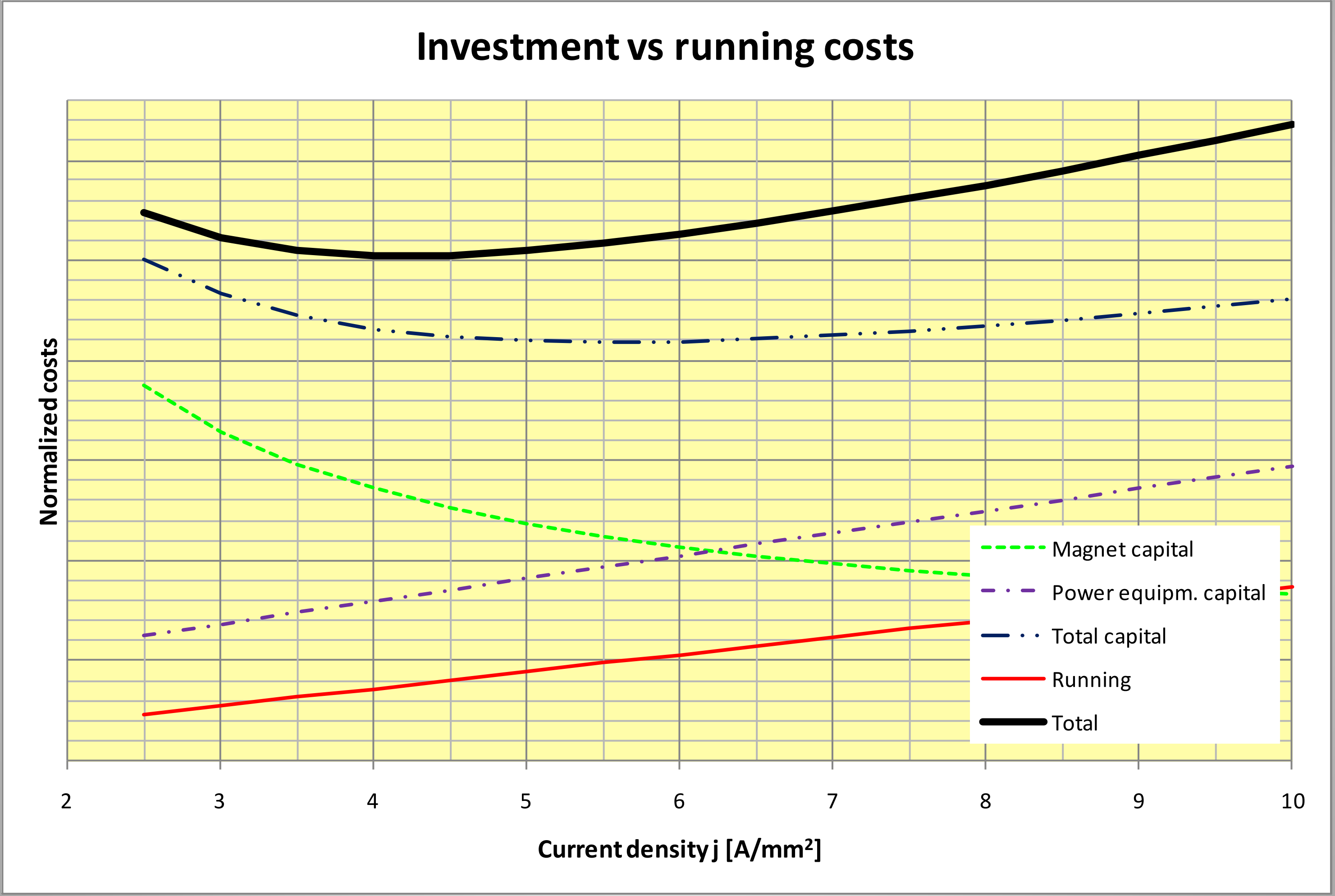
Focus on economic design!

Design goal: Minimum total costs over projected magnet life time by optimization of capital (investment) costs against running costs (power consumption)

Total costs include:



Cost optimization



Numerical design

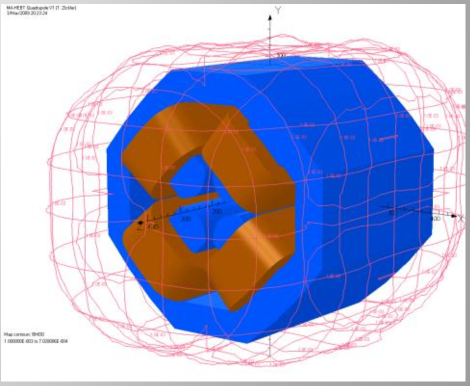
Common computer codes: Opera (2D) or Tosca (3D), Poisson, ANSYS, Roxie, Magnus, Magnet, Mermaid, Radia, FEMM, COMSOL, etc…

Technique is iterative

- calculate field generated by a defined geometry
- adjust geometry until desired distribution is achieved

Computing time increases for high accuracy solutions, non-linear problems and time dependent analysis → compromise between accuracy and computing time

2D	3D
• 2D analysis is often sufficient • magnetic solvers allow currents only perpendicular to the plane • fast	• produces large amount of elements • mesh generation and computation takes significantly longer • end effects included • powerful modeller



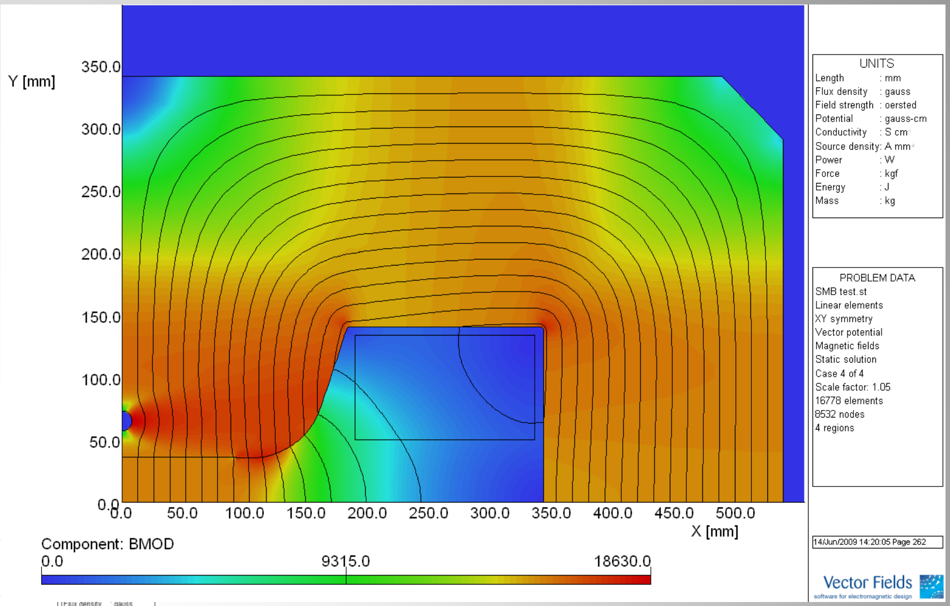
FEM codes are powerful tools, but be cautious:

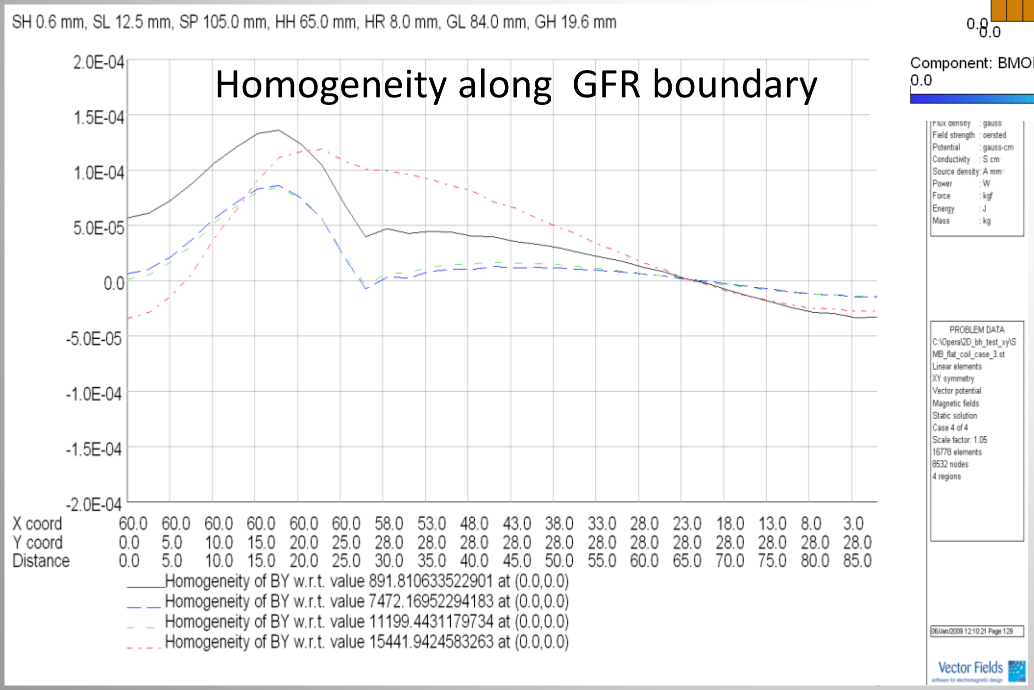
- Always check results if they are 'physical reasonable'
- Use FEM for quantifying, not to qualify

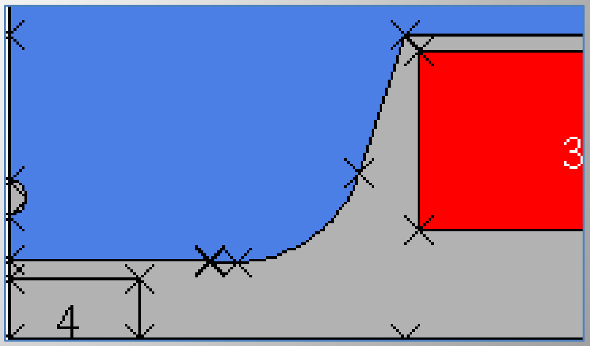
Field quality

A simple judgment of the field quality can be done by plotting the field homogeneity

$$\frac{\Delta B}{B_0} = \frac{B_y(x,y)}{B_y(0,0)} - 1 \qquad\qquad \frac{\Delta B}{B_0} \leq 0.01\%$$



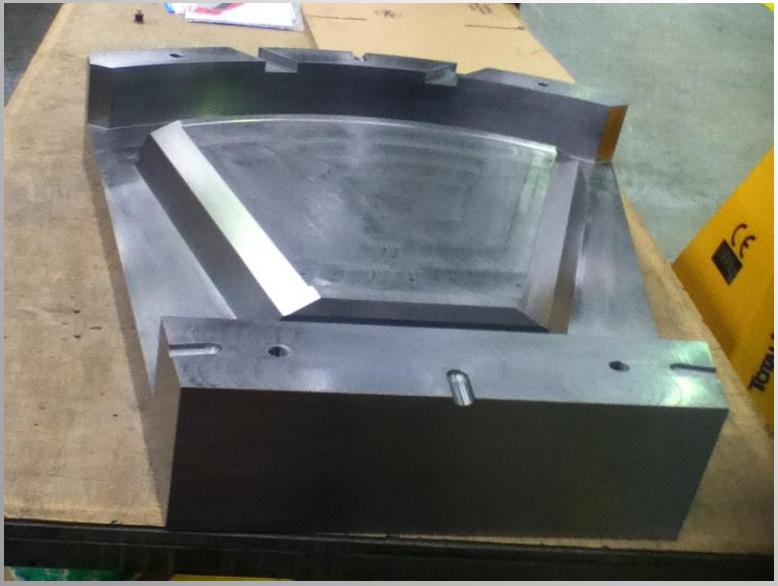




Massive vs. laminated yokes

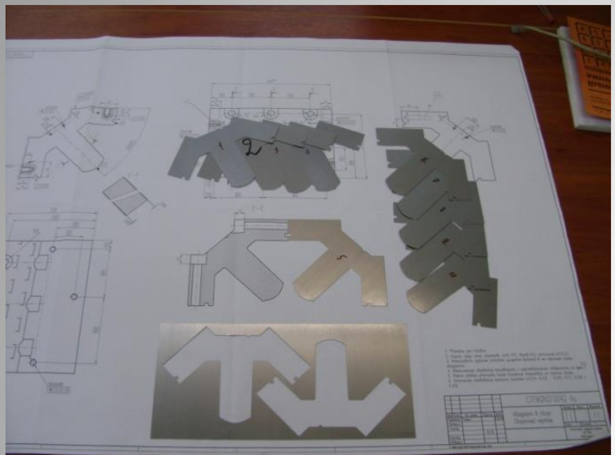
Historically, the primary choice was whether the magnet is operated in persistent mode or cycled (eddy currents)

+ no stamping, no stacking
+ less expensive for prototypes and small series
- time consuming machining, in particular for complicated pole shapes
- difficult to reach similar magnetic performance between magnets



+ steel sheets less expensive than massive blocks (cast ingot)
+ less expensive for larger series
+ steel properties can be easily tailored
+ uniform magnetic properties over large series
- expensive tooling

Iron yoke



Stamping laminations

↓

Stacking laminations into yokes

↓

Gluing and/or welding

↓

Assembling the yoke parts

Advantages:

- Well established technology with plenty of experience
- Robust design
- Industrial methods for large series
- Different magnetic materials on the market
- Steel properties are adjustable within a certain range
- Good reproducibility

Limitations:

- Fields limited to 2 T (saturation)
- Field quality dependent on mechanics (machining, assembly)
- Small apertures more sensitive (small tolerances)
- dB/dt limited by eddy current effects
- Steel hysteresis requires magnetic cycling

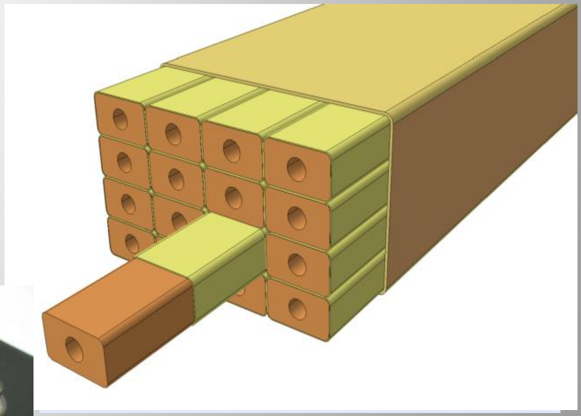
Coil cooling

Air cooling by natural convection:

- Current density
  - j < 2 A/mm^2 for small, thin coils
- Cooling enhancement
  - Heat sink with enlarged radiation surface
  - Forced air flow (cooling fan)
- Only for magnets with limited strength (e.g. correctors)

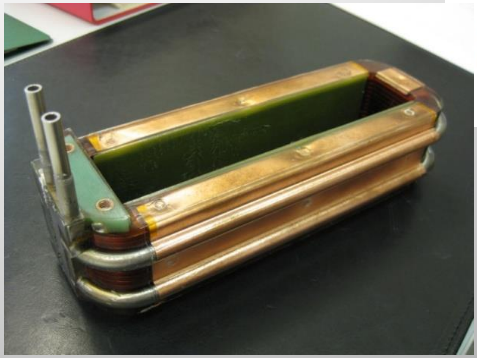
Direct water cooling:

- Typical current density $j \leq 10$ A/mm^2
- Requires demineralized water (low conductivity) and hollow conductor profiles

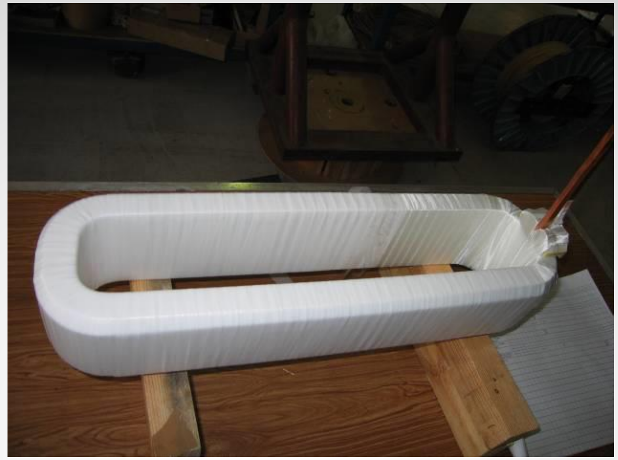


Indirect water cooling:

- Current density $j \leq 3$ A/mm^2
- Tap water can be used



Excitation coils


Conductor insulation
↓
Coil winding
↓
Ground insulation
↓
Epoxy impregnation

Advantages:

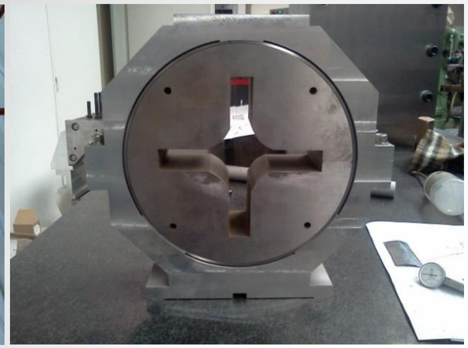
- Adjustable magnetic fields
- Well established technology
- Easy accessible and maintainable
- (Almost) no limit in dB/dt
- Conductor commercially available

Limitations:

- Power consumption (ohmic losses)
- Moderate current densities (j < 10 A/mm^2)
- (Water) cooling required for j > 2 A/mm^2
- Insulation lifetime (ionizing radiation)
- Reliability of cooling circuits (water leaks)
- Increase the magnet dimensions

Magnet assembly

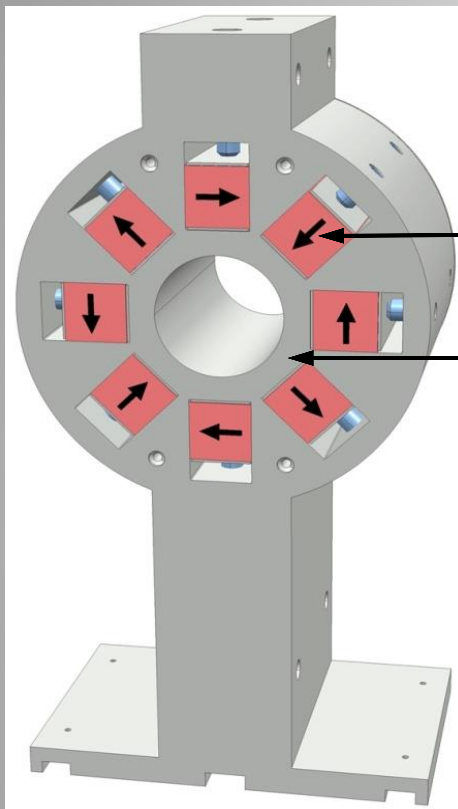
By hand....

... or with the help of tooling



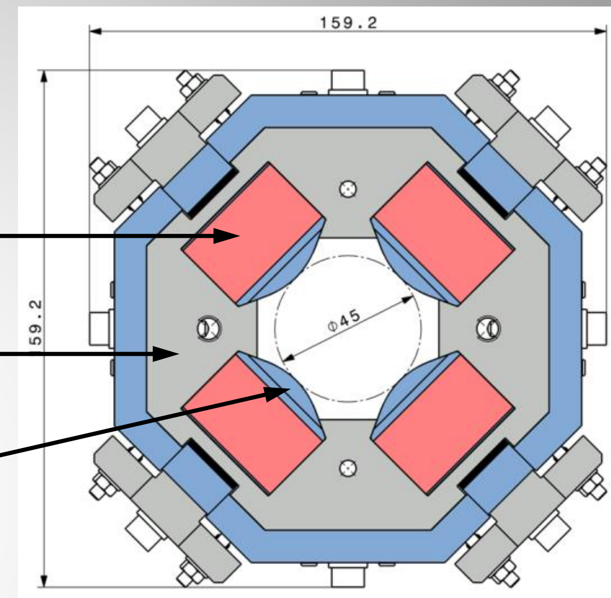

Conventional PM layout



Permanent magnets
(e.g. Sm_2Co_{17})

Non-magnetic yoke
(e.g. austenitic steel 316LN)

Magnetic poles
(e.g. low-carbon steel)



$Nd_2Fe_{14}B$	$SmCo_5$ or Sm_2Co_{17})
Typical B_r≈1.4 T	Typical B_r≈1.2 T
Temp. coef. of B_r = -0.11%/°C	Temp. coef. of B_r = -0.03%/°C
Poor corrosion resistance	Good corrosion/radiation resistance

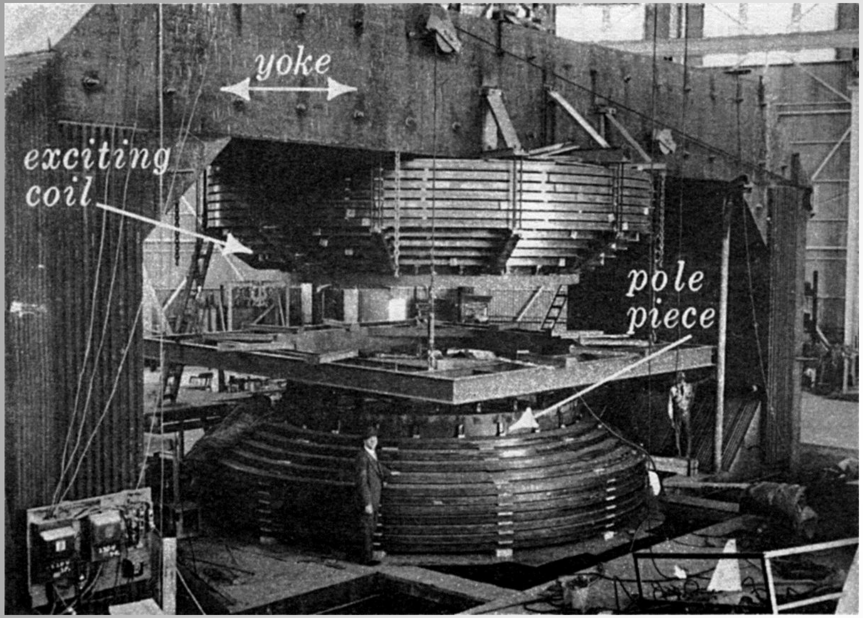
Advantages:

- No electrical power consumption
- No powering/cooling network required
- More compact for small magnets
- No coil heads / small fringe field
- Reliable: no risk of insulation failure or water leaks

Limitations:

- Produce constant fields only
- Complex mechanics when tuneability required
- Risk of radiation damage (→ use of Sm_2Co_{17})
- Sensible to ΔT

Magnets in the 1940s



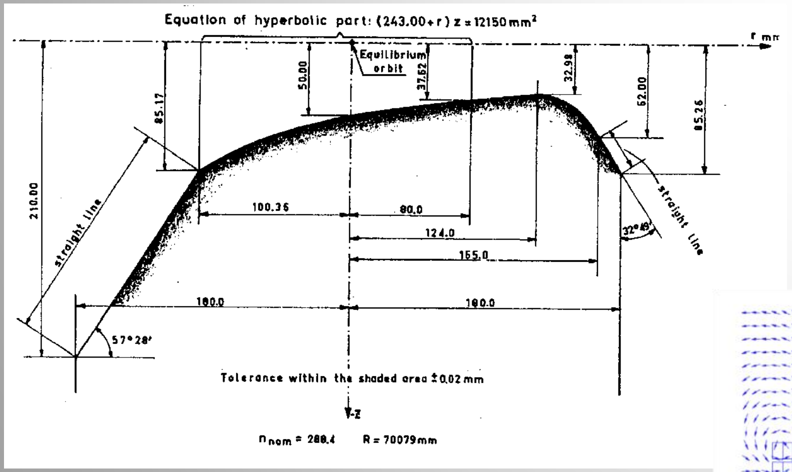
730 MeV cyclotron with 2.34 T magnet at the University of California at Berkley (1942)

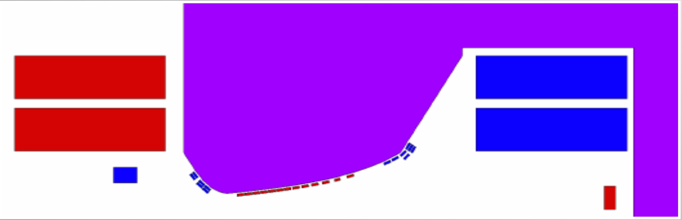
300 MeV "racetrack" electron synchrotron at University of Michigan (1949) with four 90° bending magnets

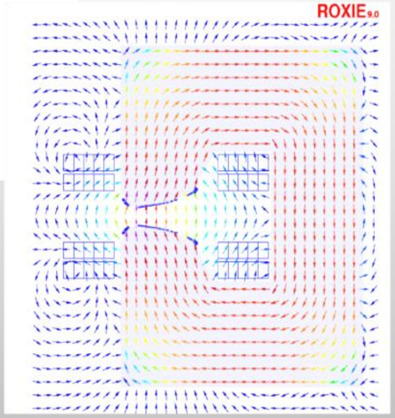
Magnets in the 1950s

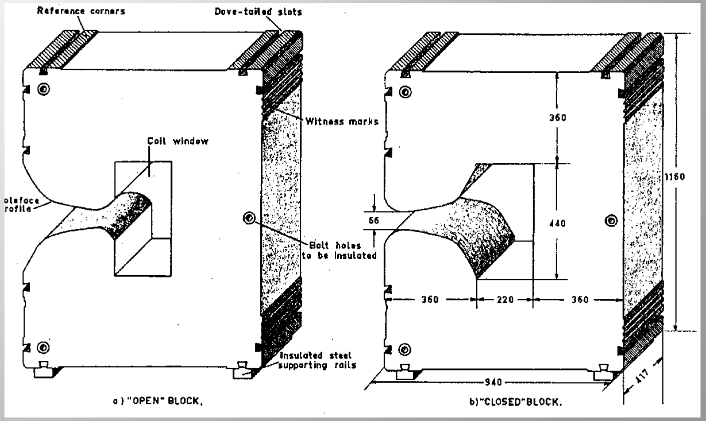
CERN PS (1959), 25 GeV, 628 m

- Combined function magnet: dipole + quadrupole + higher order poles
- Water cooled main coils + Figure-of-Eight windings + Pole-face windings
- Magnetic field B: 0.014 T – 1.4 T
- 100 + 1 magnets in series









Magnets in the 1960s

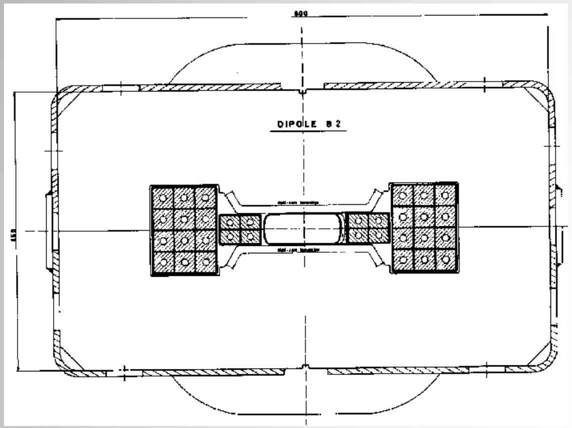
CERN PS Booster (1972), 2 GeV (originally designed for 0.8 GeV)

- 4 accelerator rings in a common yoke increase total beam intensity despite space charge effects
- Magnetic field B: 1.48 T

Magnets in the 1970s

CERN SPS (1976), 7 km, 450 GeV

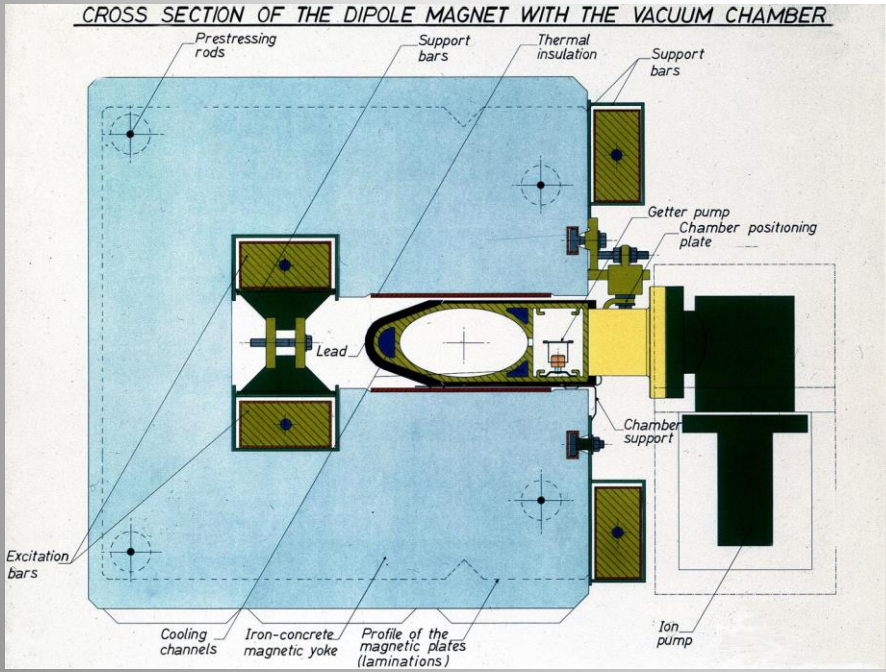
- 744 H-type bending magnets with B = 2.05 T

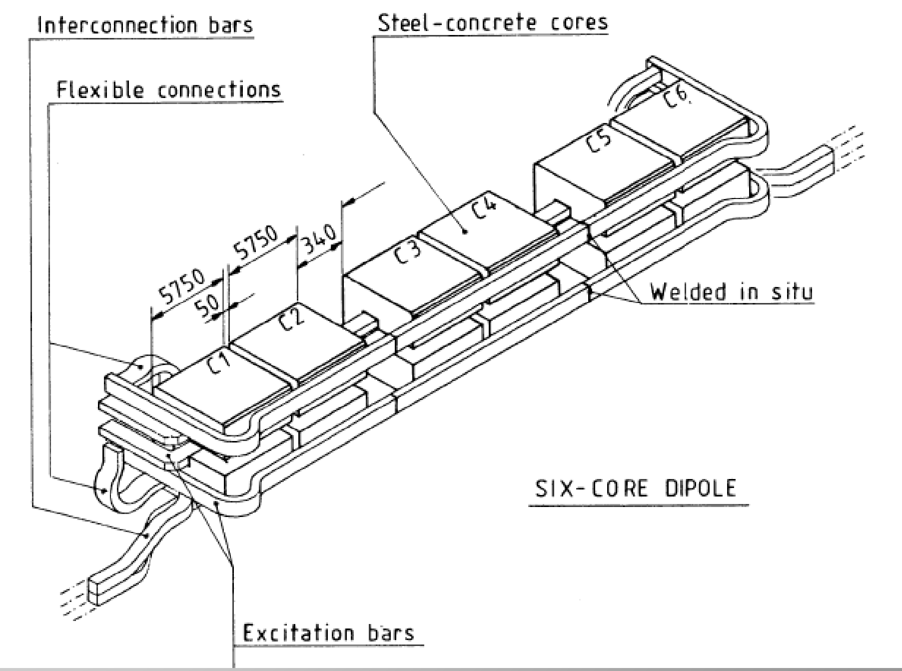


Magnets in the 1980s

LEP (1989), 27 km

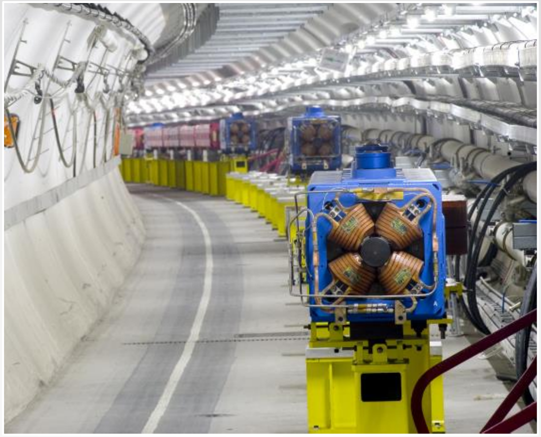
- Cycled field: 22 mT (20 GeV injection) to 108 mT (100 GeV)
- 5.75 m long ‘diluted’ magnet cores: 30% Fe / 70% concrete
- Four water cooled aluminium excitation bars

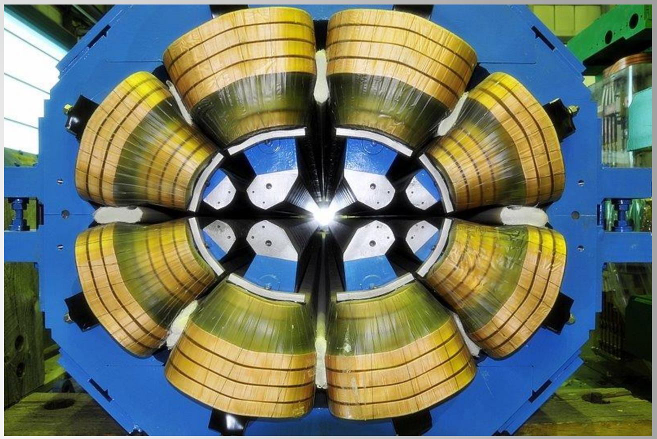




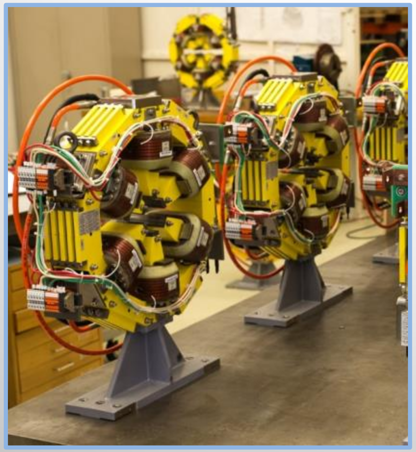
Magnets from 2000 till now…

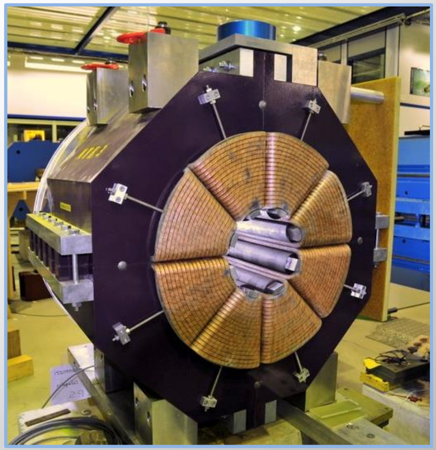

SPS – LHC transfer-line dipoles


CNGS transfer-line quadrupoles


Double-aperture LHC quadrupole


Linac4 quadrupole


SESAME sextupoles


PS Multi-turn extraction octupole


Experimental Area quadrupole

Future challenges

Future accelerator projects bear a number of financial and technological challenges in general, but also in particular for magnets …

Large scale machines:

- Investment cost: material, production, transport, installation
- Operation costs: low power consumption & cooling
- Reliability & availability

High energy beams and intensities:

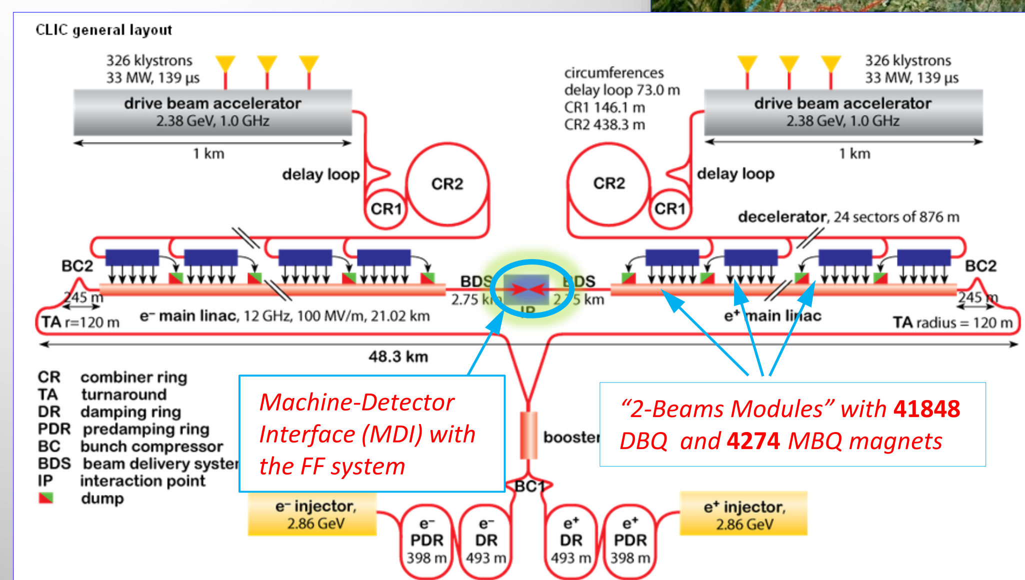
- Ionizing radiation impact on materials and electronics

Hadron colliders:

- High magnetic fields: SC magnets

Lepton colliders: (circular & linear)

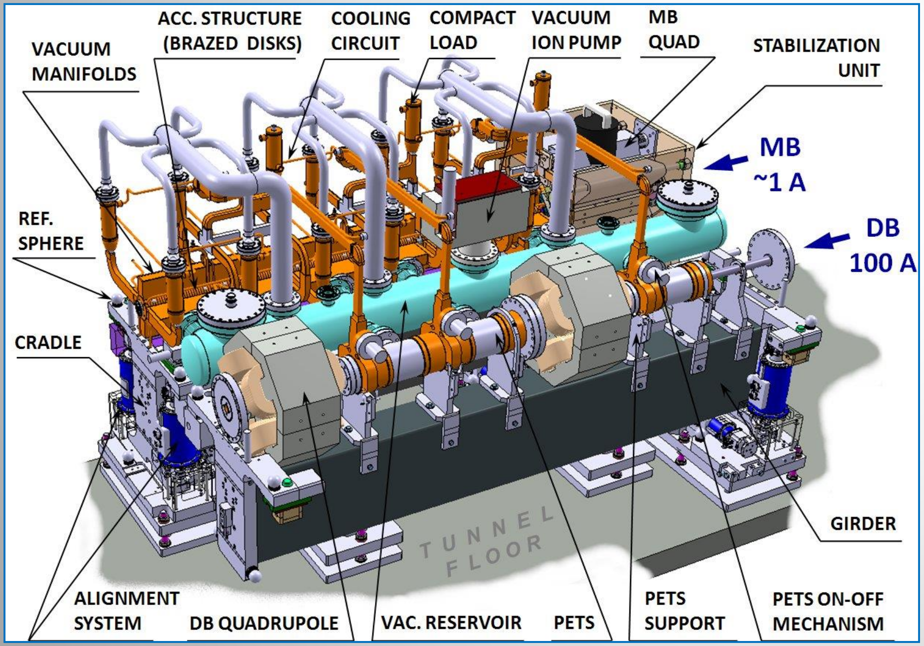
- Alignment & stabilization
- Compact design & small apertures

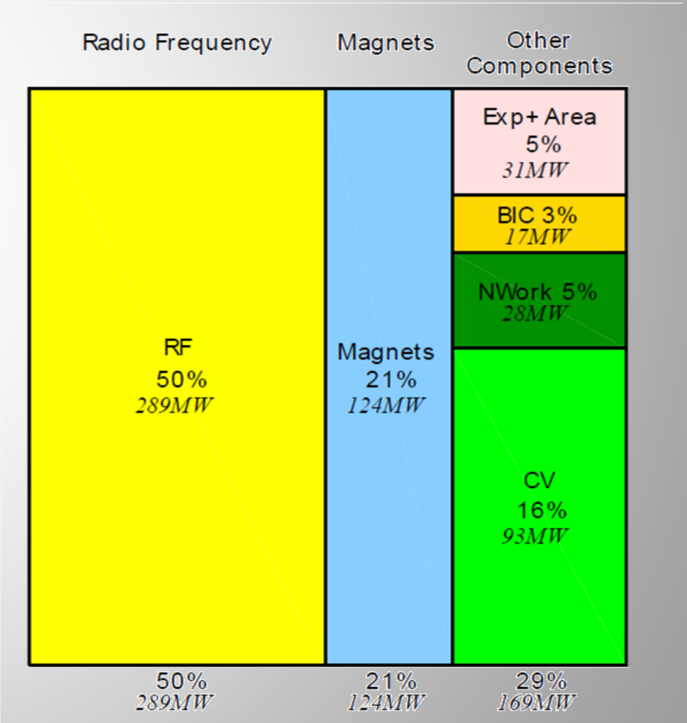


CLIC DB Quadrupole

Normal conducting systems on CLIC will result in high electrical power consumption and running costs:

- CLIC estimated to draw >580 MW (compared to 90 MW for LHC)
- 124 MW projected for nc electro-magnets
- 20 MW for DB quadrupoles





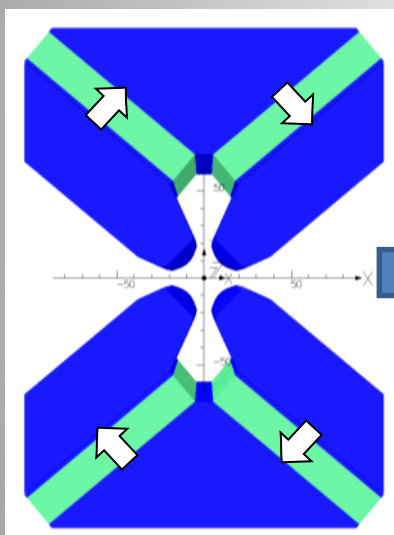
Can we use permanent magnets to save power?

How can we deal with the wide gradient variation from 7% - 120%?

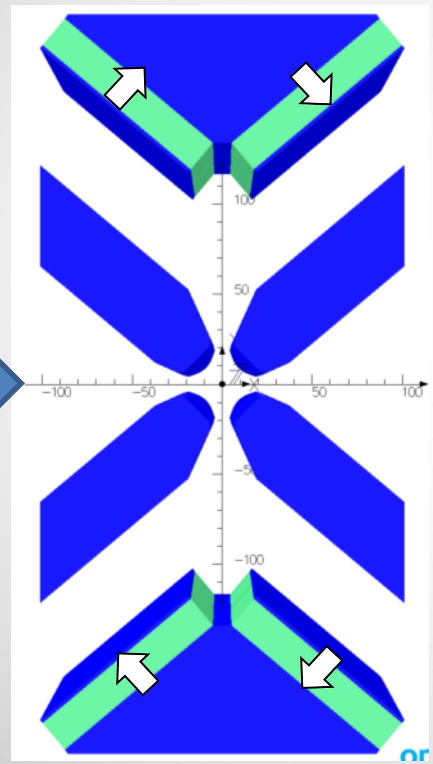
CLIC DB quadrupole

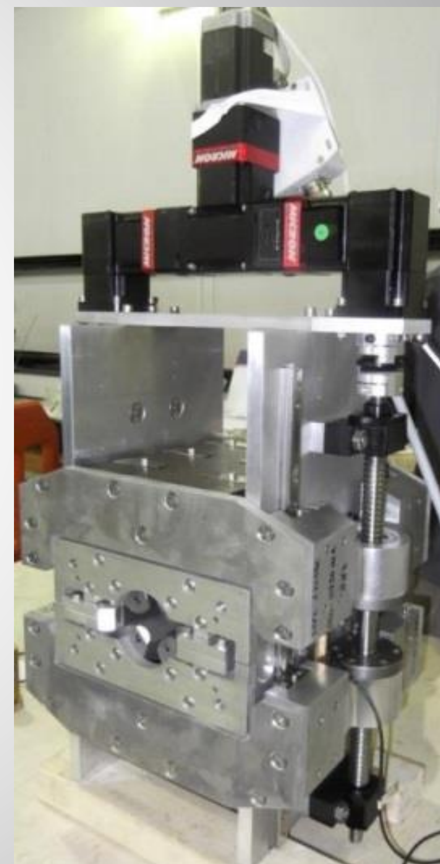
NdFeB magnets (VACODYM 764 TP), Gradient: 15 - 60 T/m, Field quality = ±0.1%

Stroke = 0 mm



Stroke = 64 mm

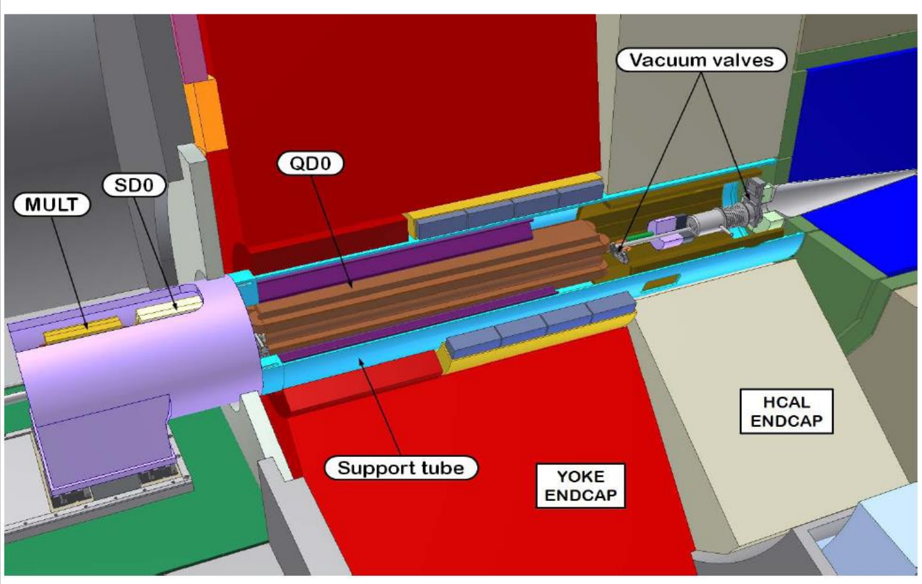




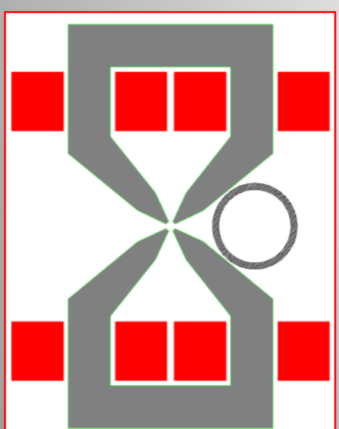
Single axis motion with one motor and two ball screws

J.A. Clarke *et al.*, "Novel Tunable Permanent Magnet Quadrupoles For The CLIC Drive Beam", MT23, Boston July 2013, IEEE Transactions on Applied Superconductivity, Vol. 24, NO. 3, JUNE 2014

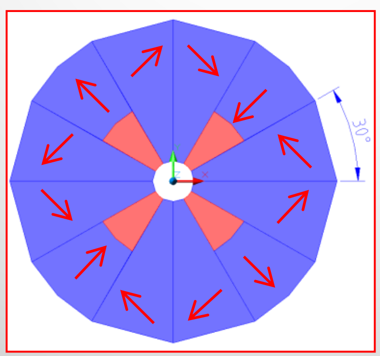
CLIC Final Focusing



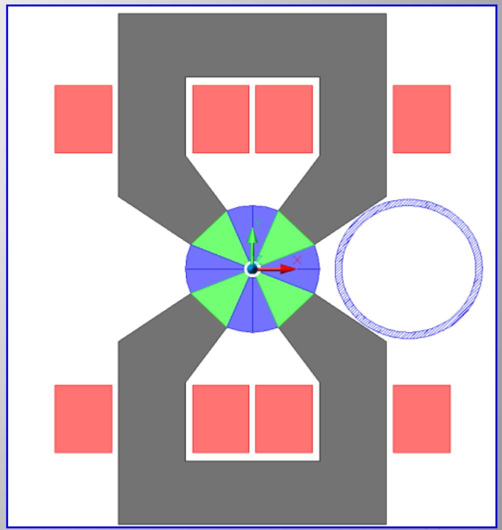
- Gradient: highest possible towards 575 T/m
- Total Length: 2.73 m
- Aperture radius: 4.125 mm
- Field Quality: better than 10^{-3}
- Tunability: -20% minimum



Pure EM design



Pure PM design



Hybrid design

M. Modena *et al.*, "Design, Assembly and First Measurements of a short Model for CLIC Final Focus Hybrid Quadrupole QD0", IPAC12, New Orleans, May 2012, Conf. Proc. C1205201 (2012)
A. Vorozhtsov, M. Modena, D. Tommasini, "Design and Manufacture of a Hybrid Final Focus Quadrupole Model for CLIC" , presented at MT22

Many thanks …

… for your attention …

… and to all my colleagues who contributed to this lecture and who supported me in questions related to magnet design and measurements in the past 20 years!

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
- The Physics of Particle Accelerators: An Introduction, K. Wille, Oxford University Press, 2000
- CAS proceedings, Magnets, Bruges, Belgium, June 2009, CERN Yellow Report 2010-004