CERN Accelerator School @ ESI

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Normal-conducting & Permanent Magnets

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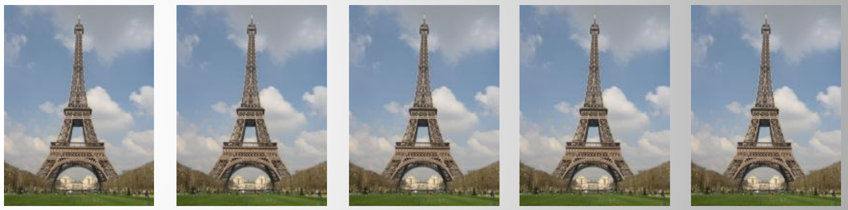
CERN

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

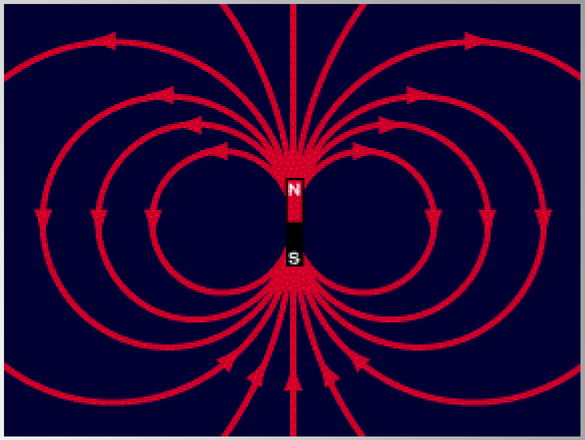
More than 4800 ‘room temperature’ magnets (50 000 tonnes) are installed in the CERN accelerator complex



Outline

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

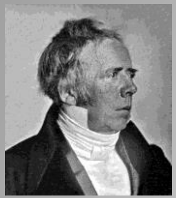
Magnetic units

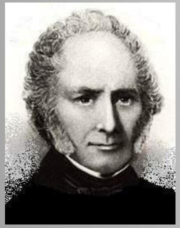


IEEE defines the following units:

- 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
  - <u>Note:</u> 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)

A bit of history...



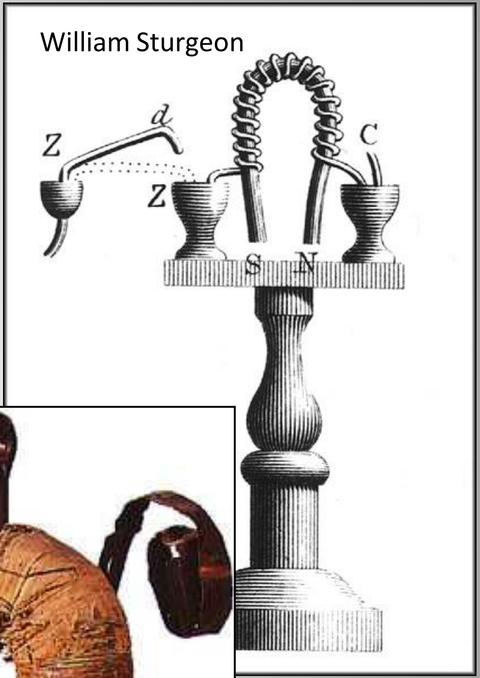

1820: Hans Christian Oersted (1777-1851) finds that electric current affects a compass needle

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

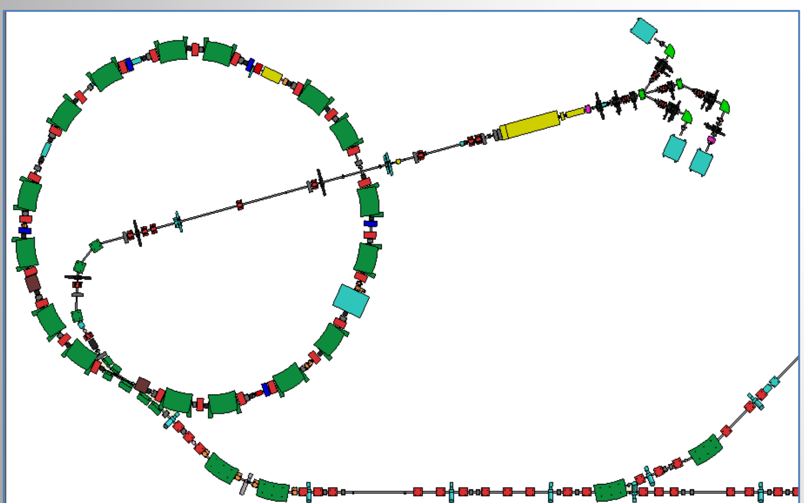


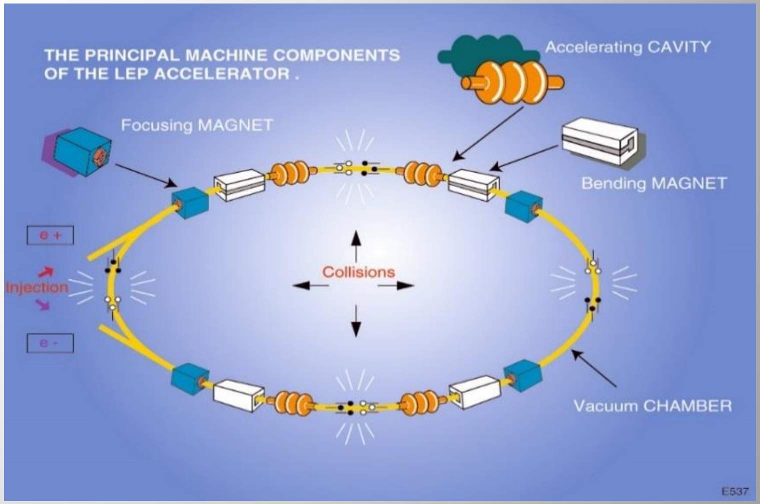
William Sturgeon


Joseph Henry

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(!)



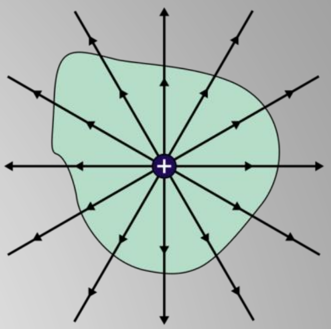


  - Permanent magnets provide only constant magnetic fields
  - Electro-magnets can provide adjustable magnetic fields

Maxwell‘s equations

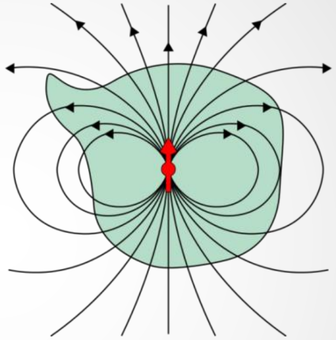
Gauss‘ law for electricity:

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



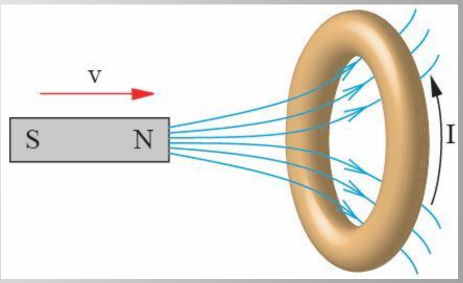
Gauss‘ law of flux conservation:

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



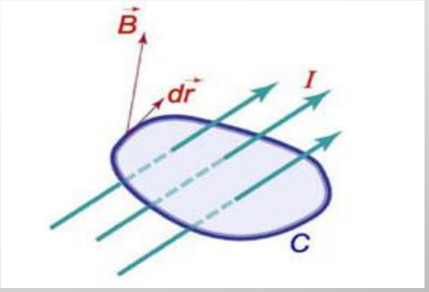
Faraday‘s law of induction:

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

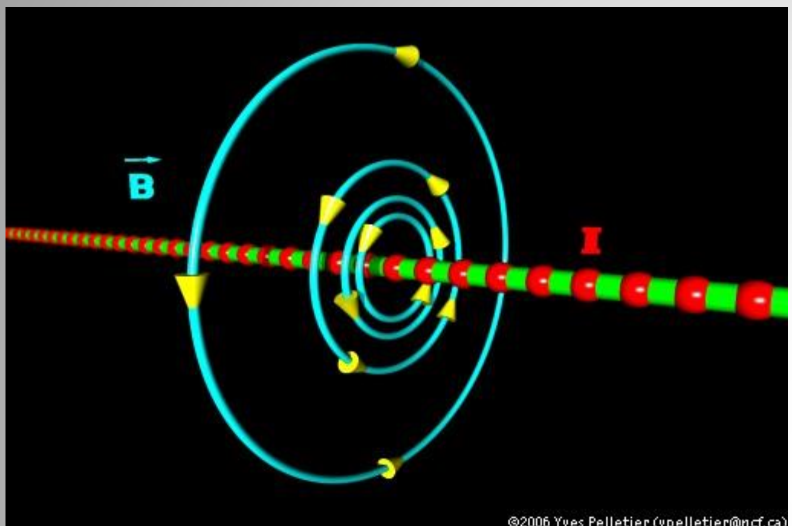


Ampere‘s law:

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



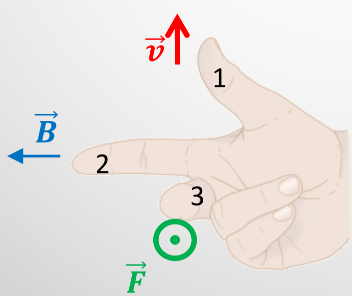
Producing the field



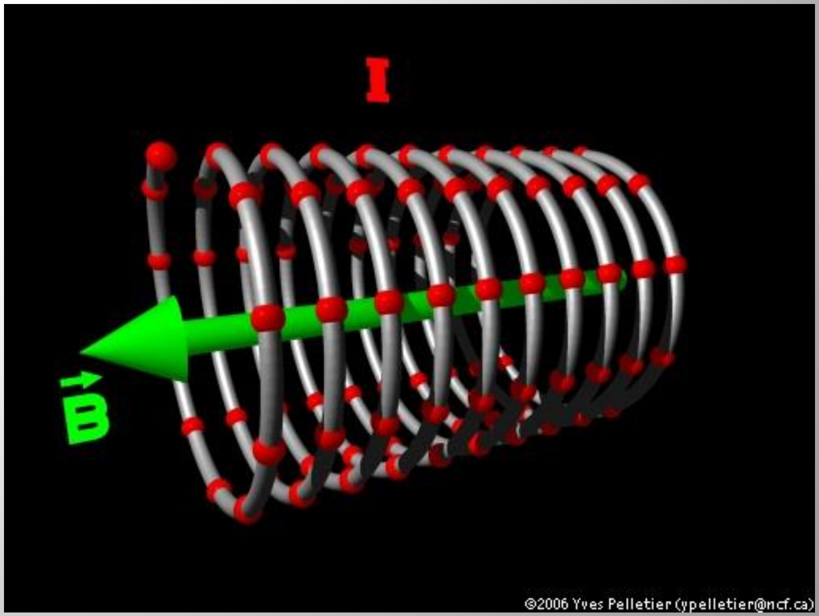
Maxwell & Ampere:

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

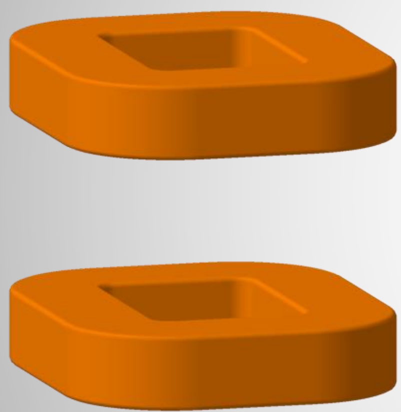
„An electrical current is surrounded by a magnetic field“

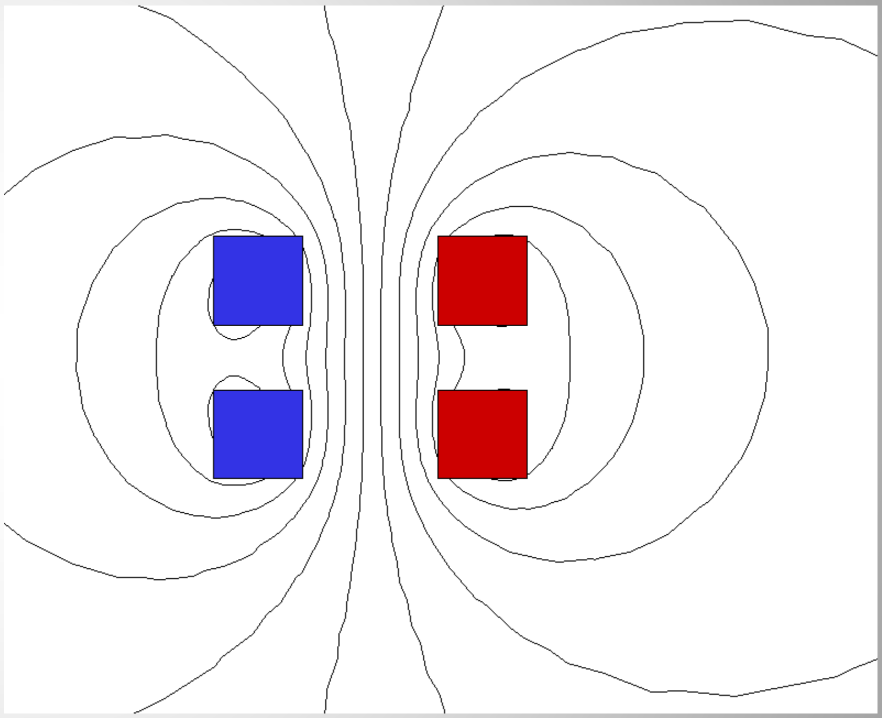


„Right hand rule“ applies



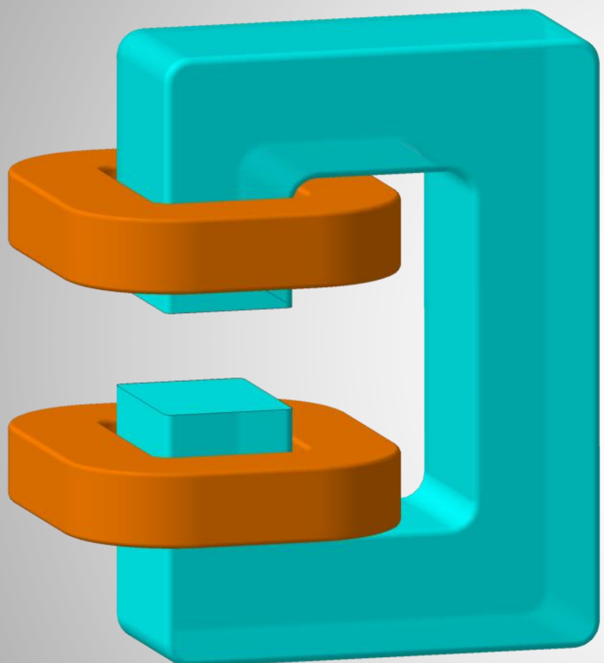
Magnetic circuit

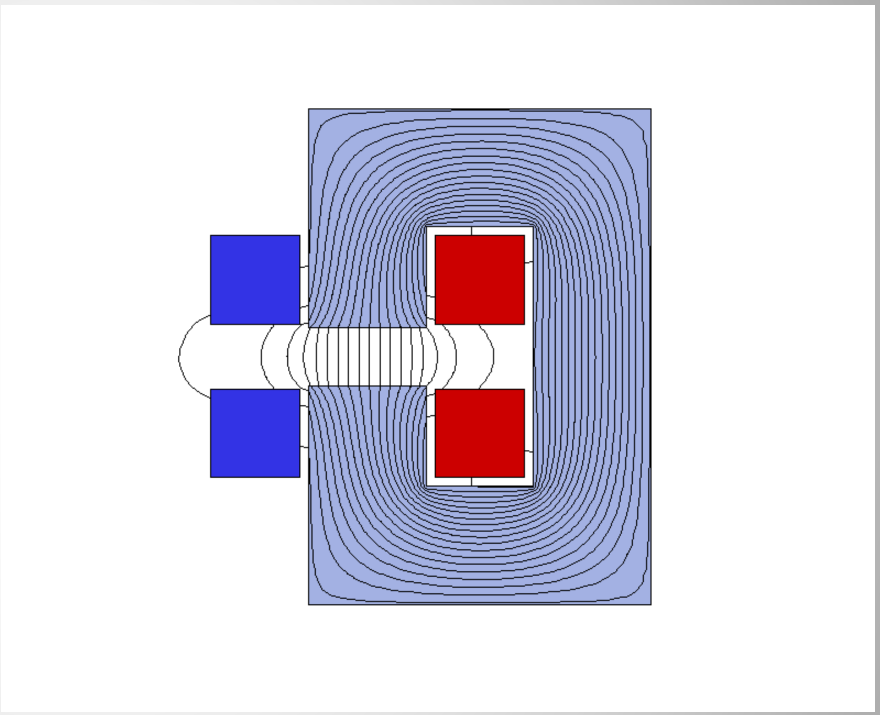




Flux lines represent the magnetic field
Coil colors indicate the current direction

Magnetic circuit





Coils hold the electrical current which induces a magnetic effect

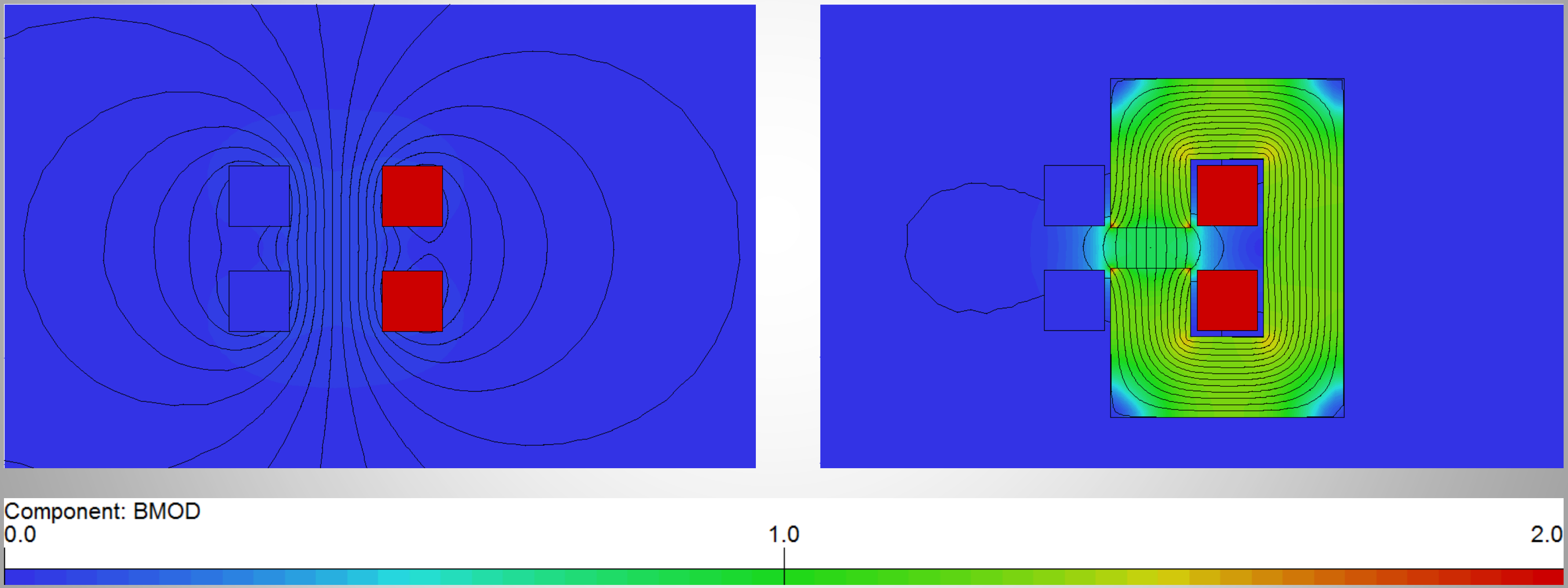
Iron enhance these effects and guides the magnetic flux

→ *"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

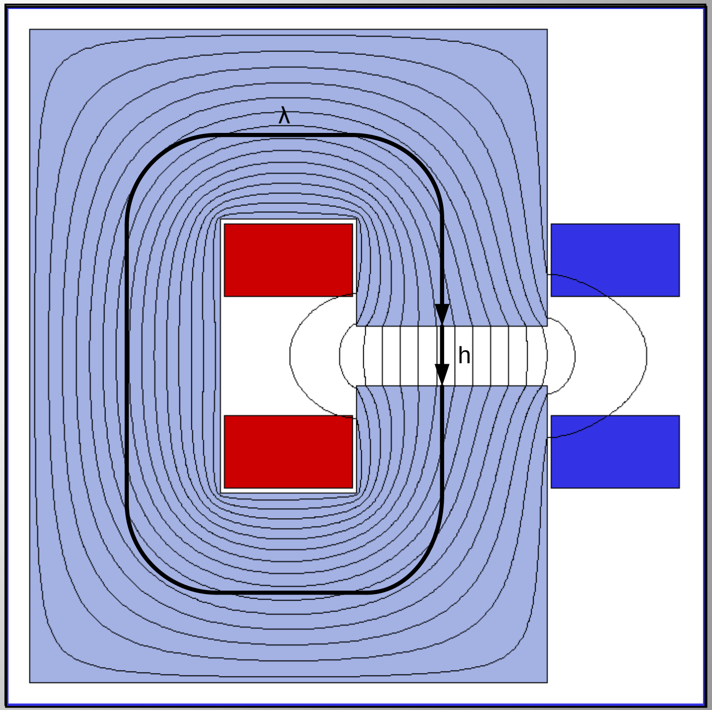
Ampere's law $\oint \vec{H} \cdot d\vec{l} = NI$ and $\vec{B} = \mu \vec{H}$

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

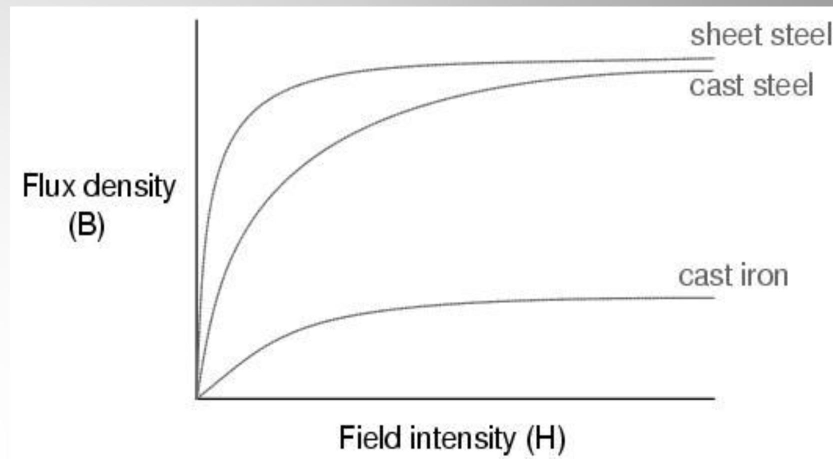
then: $$NI \approx \frac{Bh}{\mu_0}$$



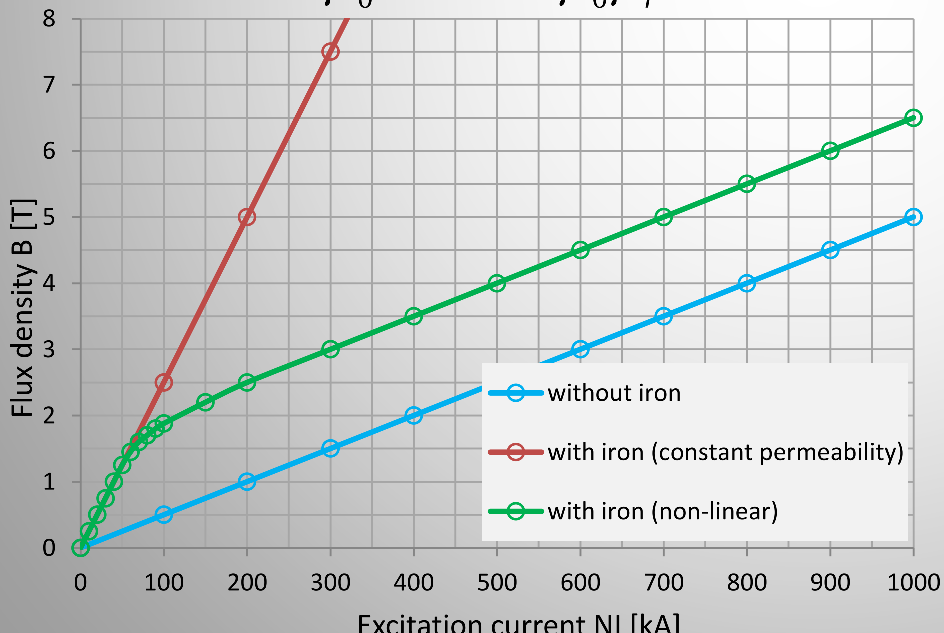
Permeability

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

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



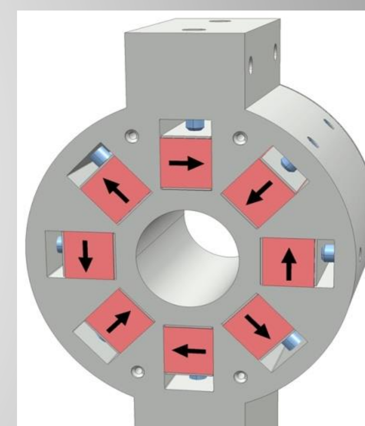
$$\vec{B} = \mu_0 \vec{H} + \vec{J} = \mu_0 \mu_r \vec{H}$$

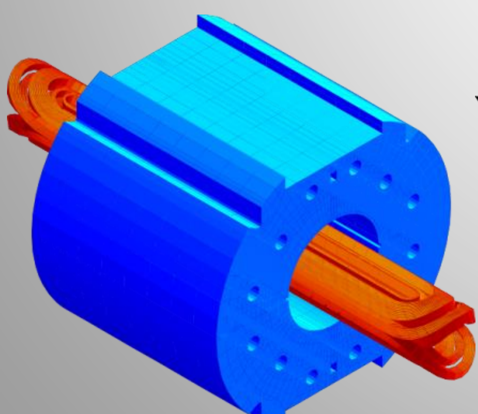


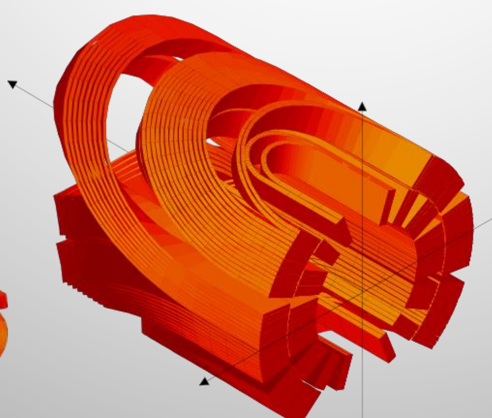
Ferro-magnetic materials: high permeability (μ_r>>1), but not constant

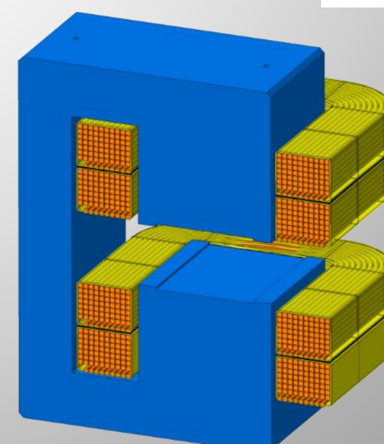
Magnet technologies

- 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**





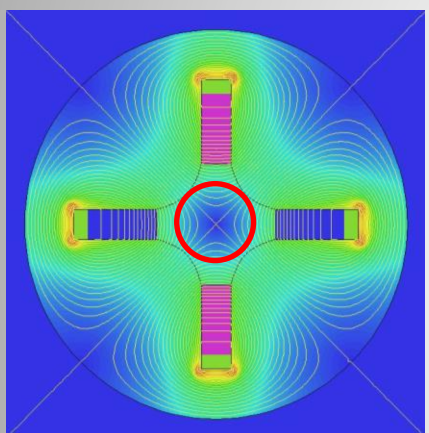


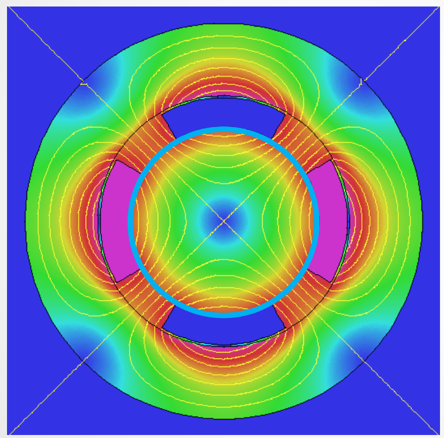


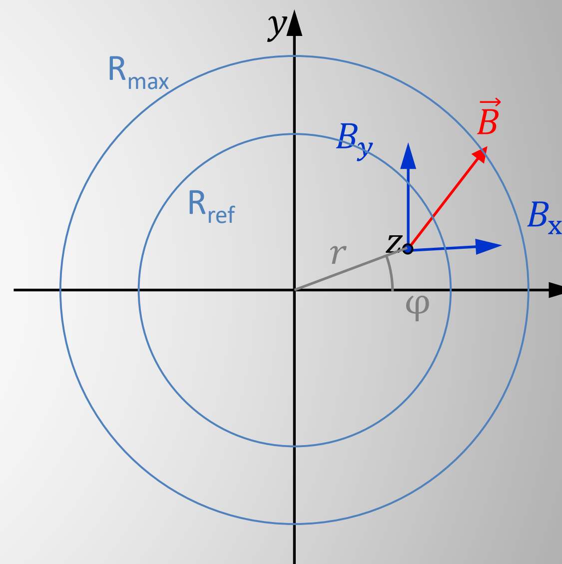
Field description

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

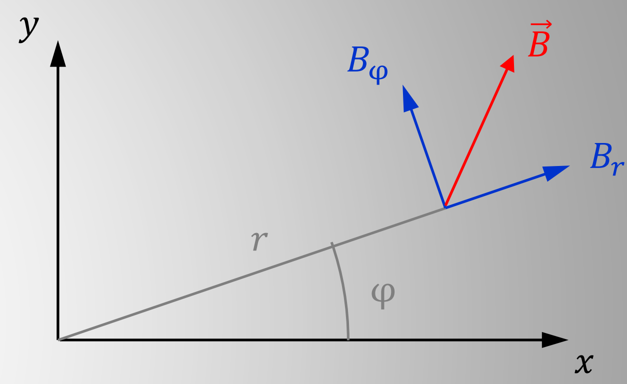
$$B_y(z) + iB_x(z) = \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{z}{R_{ref}} \right)^{n-1}$$

Field description

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

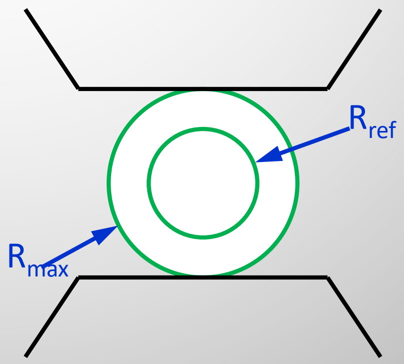
$$B_r(r,\varphi) = \sum_{n=1}^{\infty} \left(\frac{r}{R_{ref}}\right)^{n-1} [B_n \sin(n\varphi) + A_n \cos(n\varphi)]$$

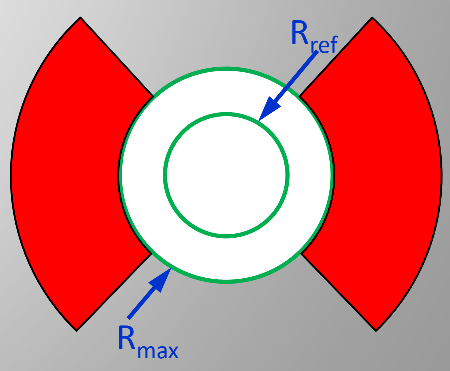
$$B_\varphi(r,\varphi) = \sum_{n=1}^{\infty} \left(\frac{r}{R_{ref}}\right)^{n-1} [B_n \cos(n\varphi) - A_n \sin(n\varphi)]$$



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

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

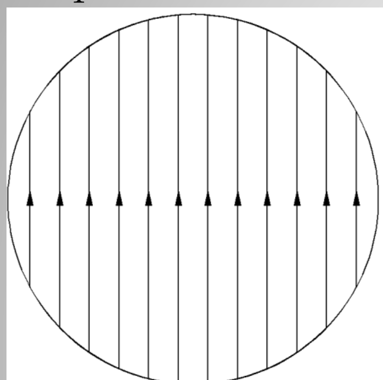




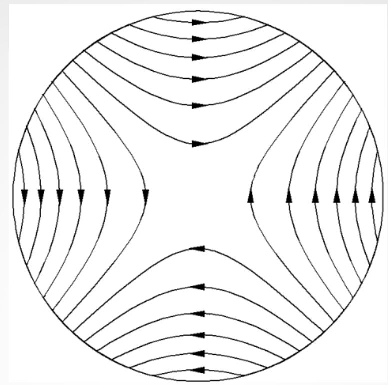
Field description

Each multipole term has a corresponding magnet type:

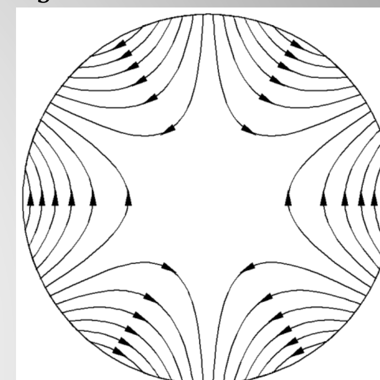
B_1: normal dipole



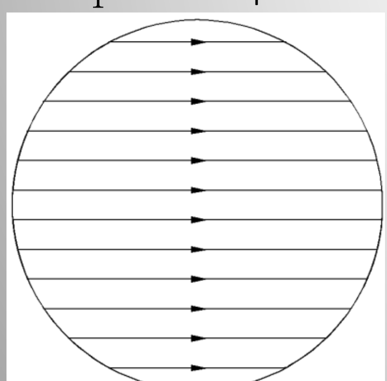
B_2: normal quadrupole



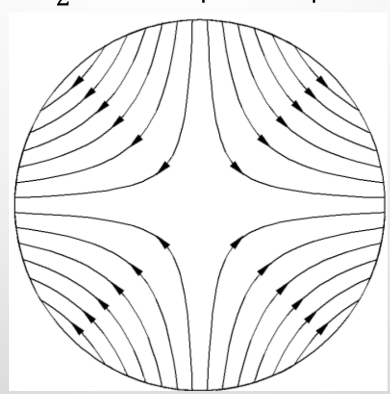
B_3: normal sextupole



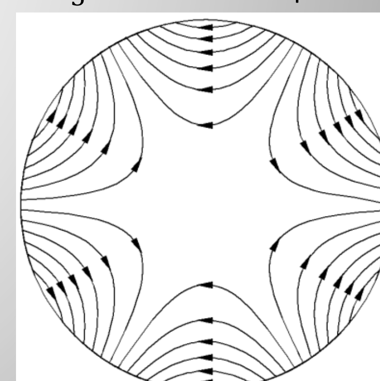
A_1: skew dipole



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

$$b_n = \frac{B_n}{B_N} 10^4 \quad \text{and} \quad a_n = \frac{A_n}{B_N} 10^4$$

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

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

$$B_y(z) + iB_x(z) = \frac{B_N}{10^4} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{z}{R_{ref}} \right)^{n-1} \qquad F_d = \sum_{n=1;n \neq N}^{K} \sqrt{b_n^2 + a_n^2}$$

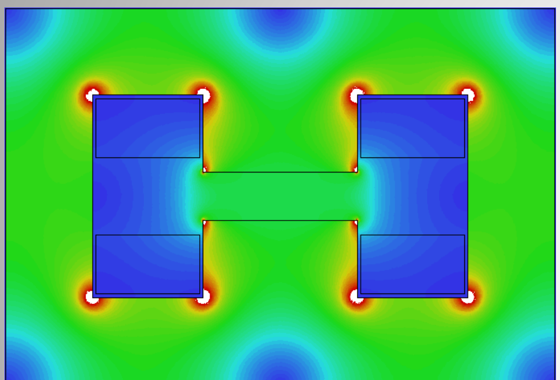
Fundamental field — $\frac{B_N}{10^4}$

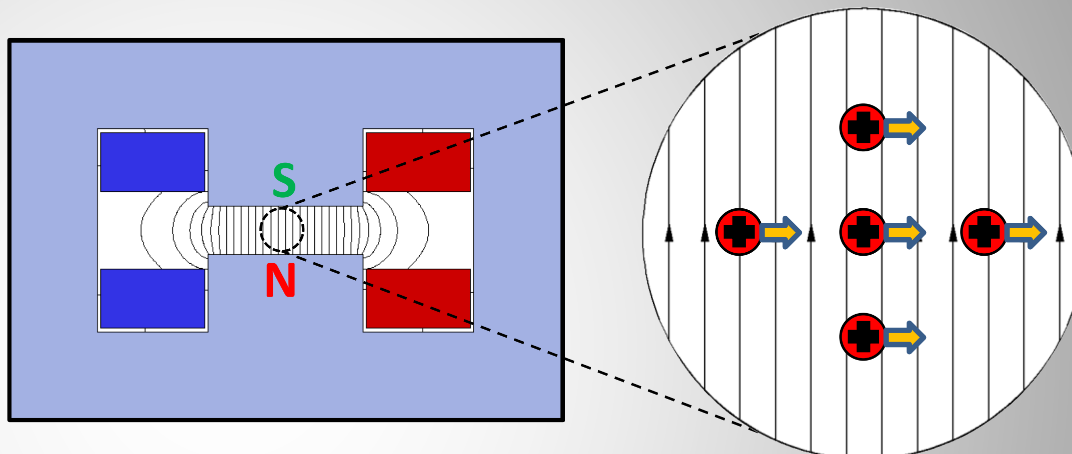
Harmonic distortions — $\sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{z}{R_{ref}} \right)^{n-1}$

Harmonic distortion factor — F_d

Dipole

Purpose: bend or steer the particle beam





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

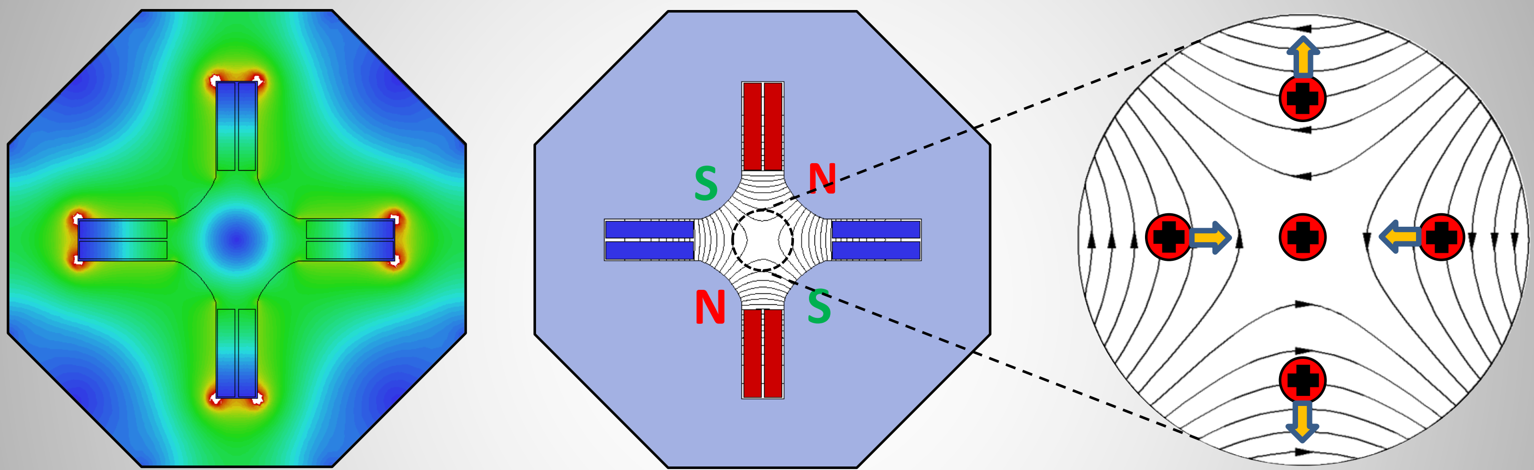
$$y = \pm h/2 \quad (\rightarrow \text{straight line with } h = \text{gap height})$$

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

Applications: synchrotrons, transfer lines, spectrometry, beam scanning

Quadrupole

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



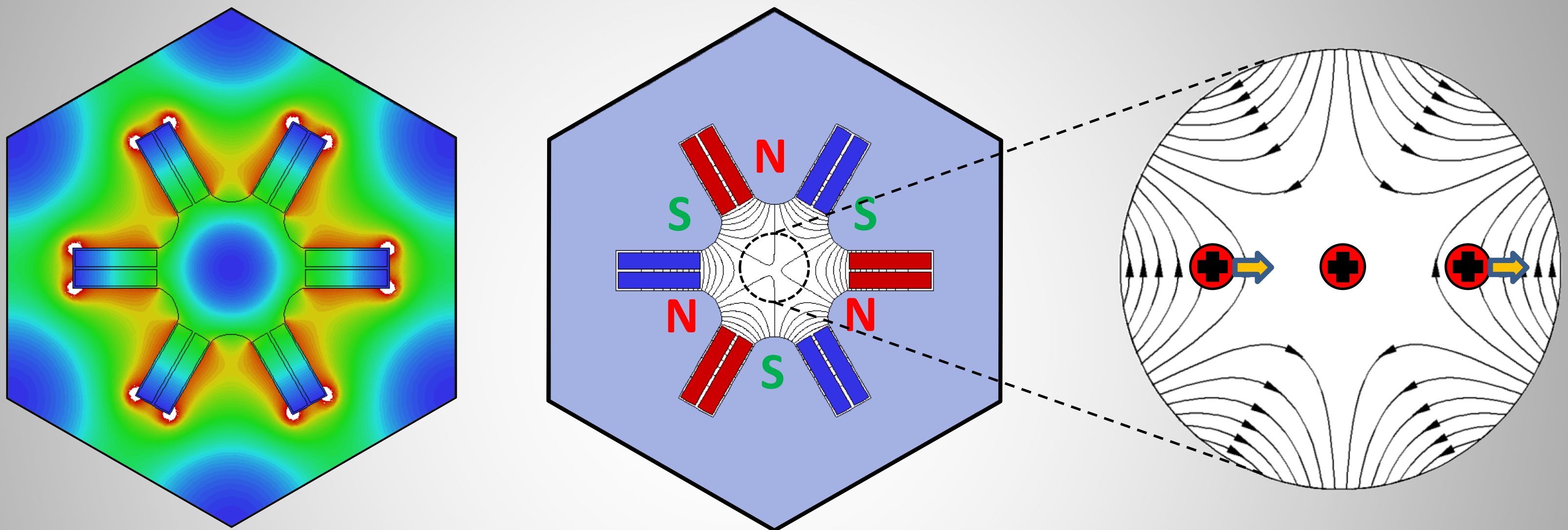
Equation for normal (non-skew) ideal (infinite) poles:

$2xy = \pm r^2$ (→ hyperbola with 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

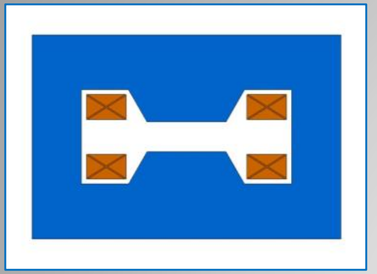


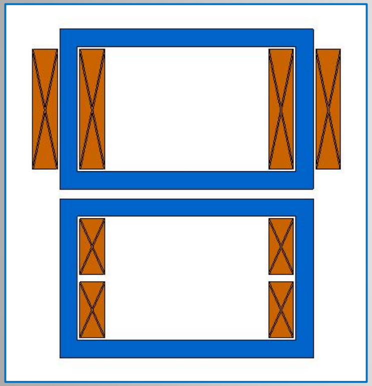
Equation for normal (non-skew) ideal (infinite) poles:

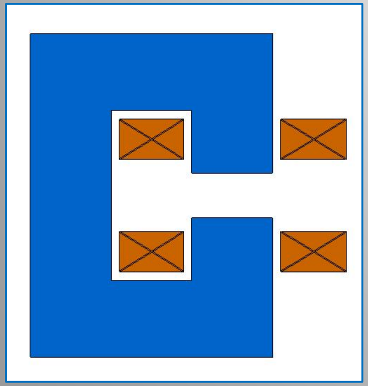
$$3x^2y - y^3 = \pm r^3 \text{ (with } r = \text{aperture radius)}$$

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





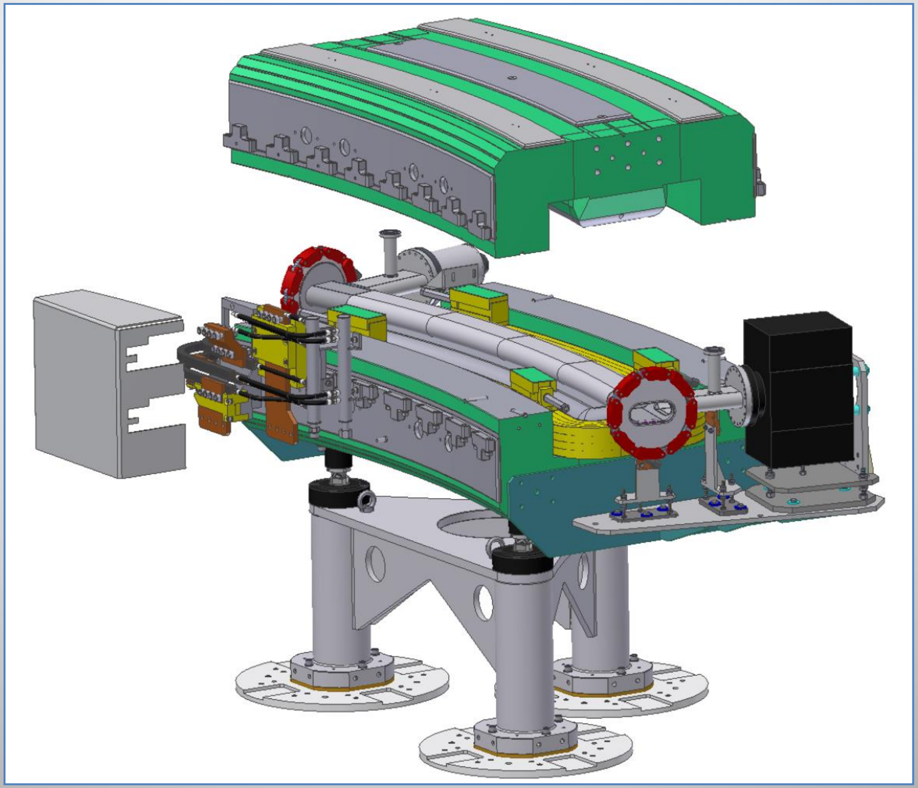


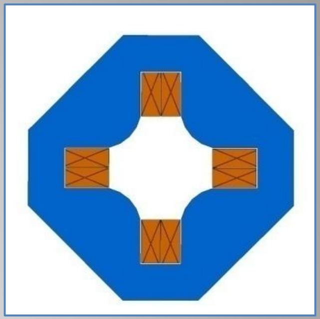
Excitation coils carry the electrical current creating H

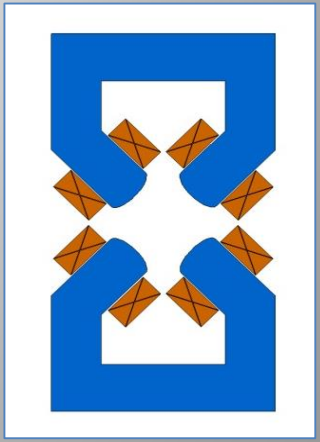
Iron yokes guide and enhance the magnetic flux

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

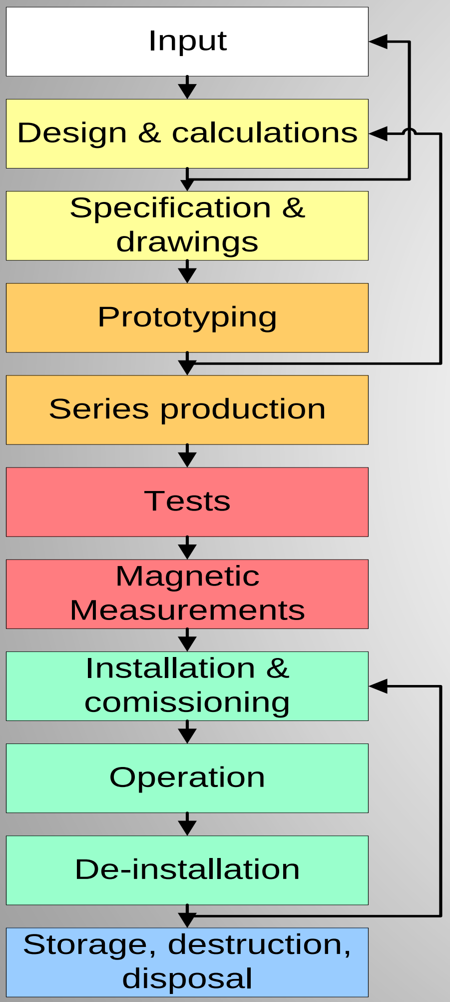
Auxiliaries for cooling, interlock, safety, alignment, ...

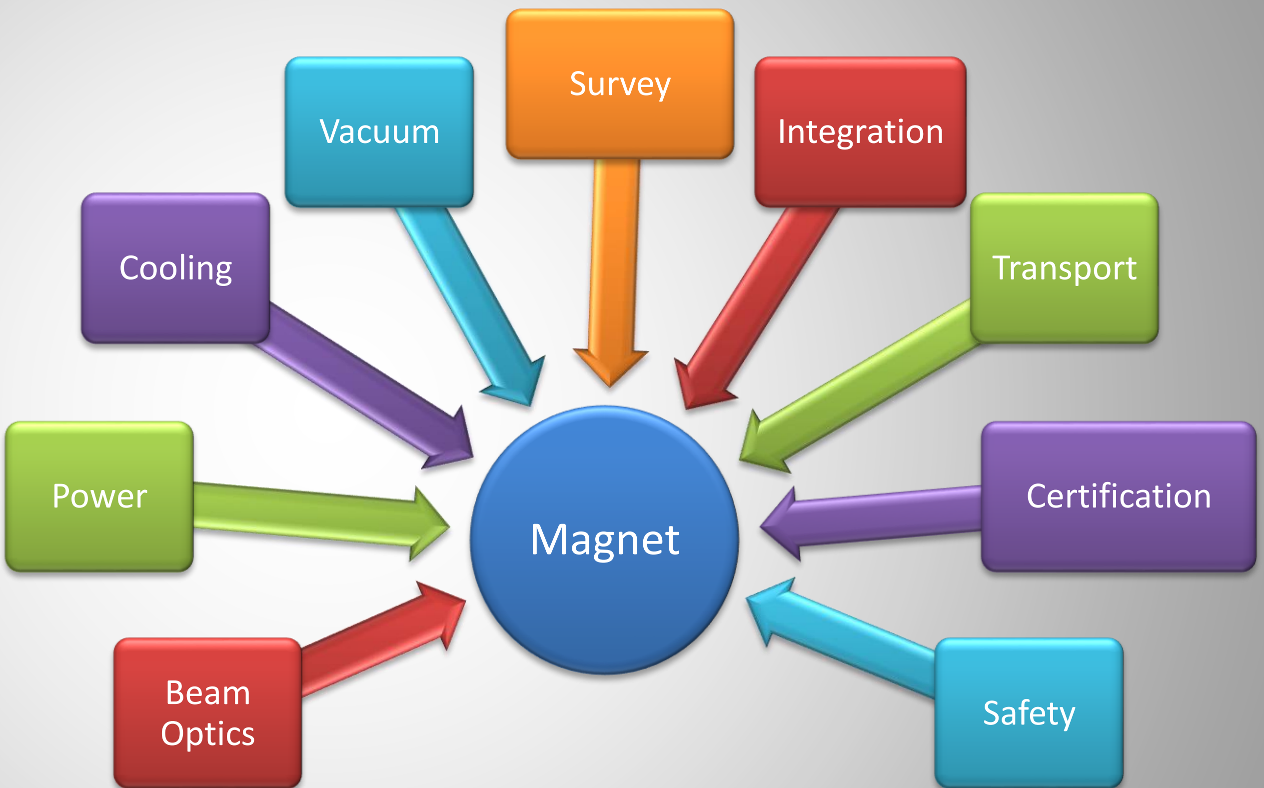






Magnet life-cycle





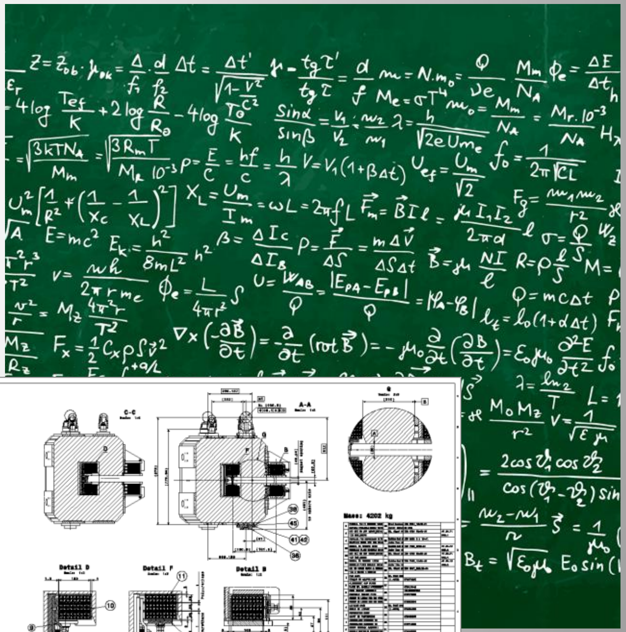
A magnet is not a stand-alone device!

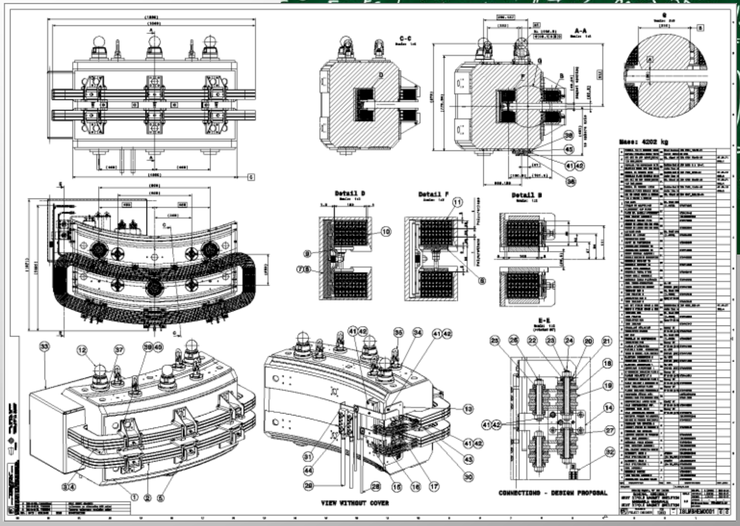
Design process

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)

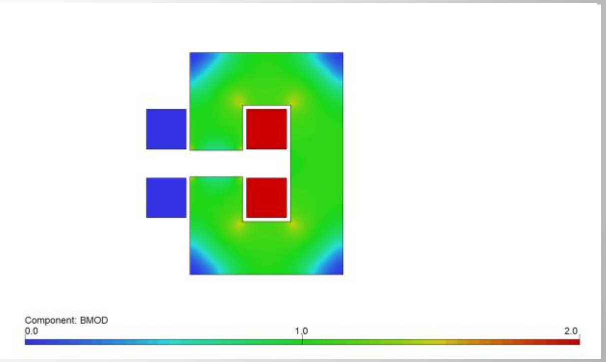
1. Beam rigidity: $(B\rho) = \frac{p}{q} = \frac{1}{qc}\sqrt{T^2 + 2T\,E_0}$ Bending radius: r_M

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

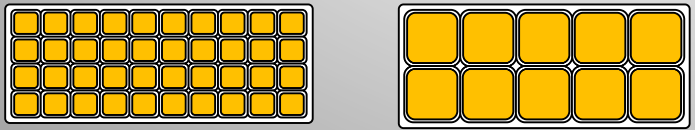


6. Select current density: $j = \frac{NI}{f_c A} = \frac{I}{a_{cond}}$

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

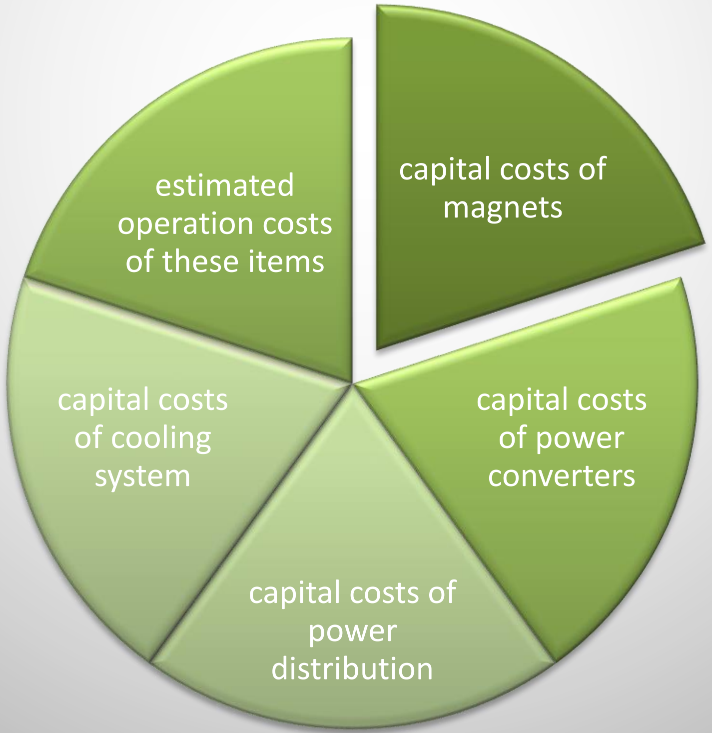


Cost optimization

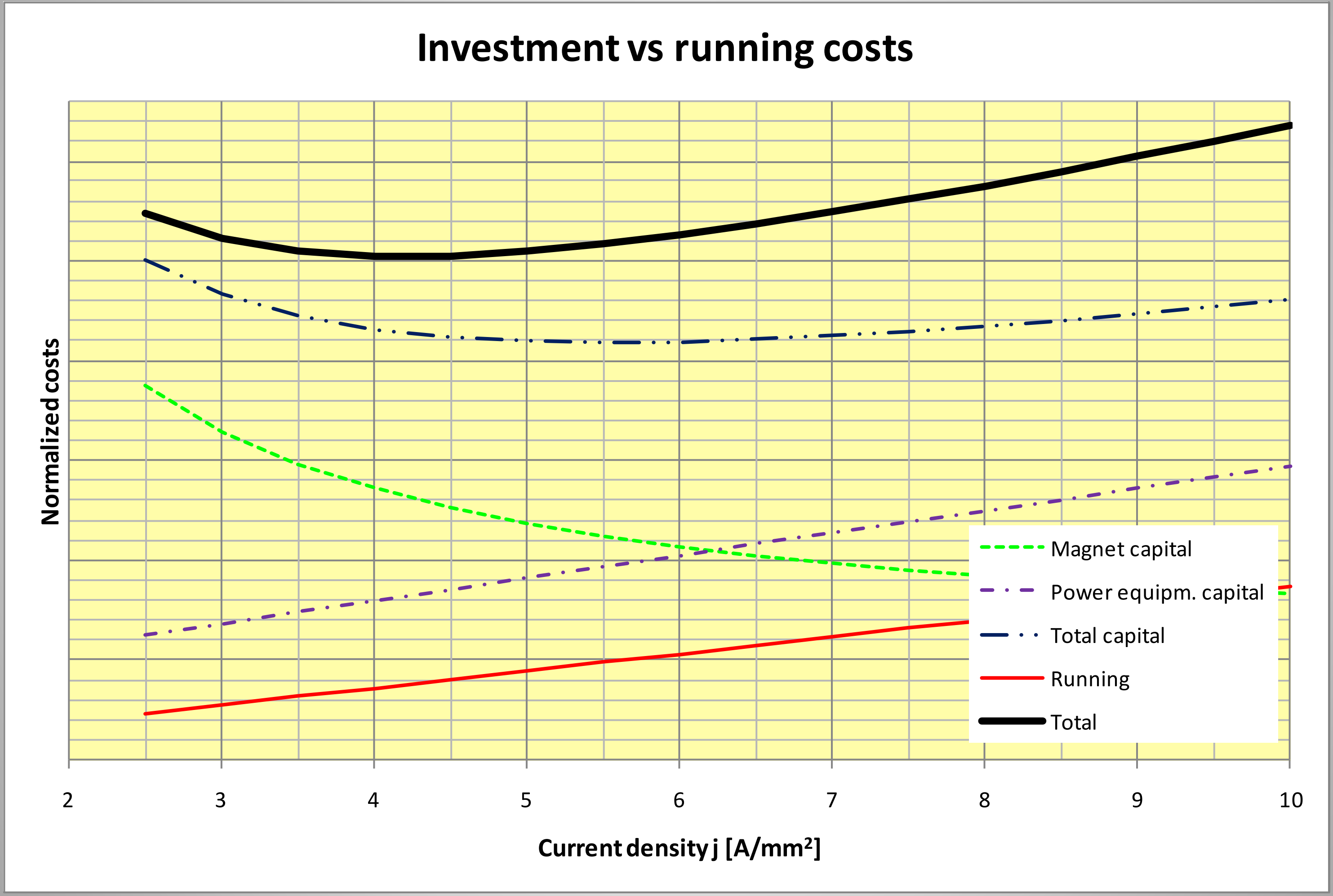
Focus on economic design!

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

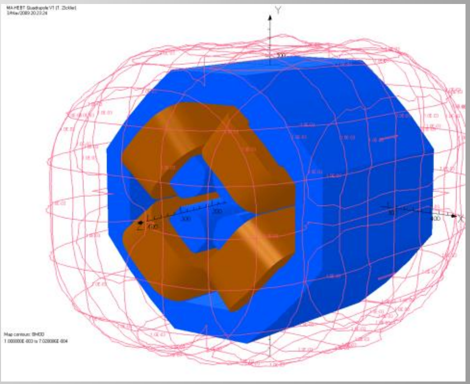
Common computer codes: Opera (2D) or Tosca (3D), Poisson, ANSYS, Roxie, Magnus, Magnet, Mermaid, Radia, FEMM, COMSOL, etc…

Technique is iterative

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

Computing time <u>increases</u> 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



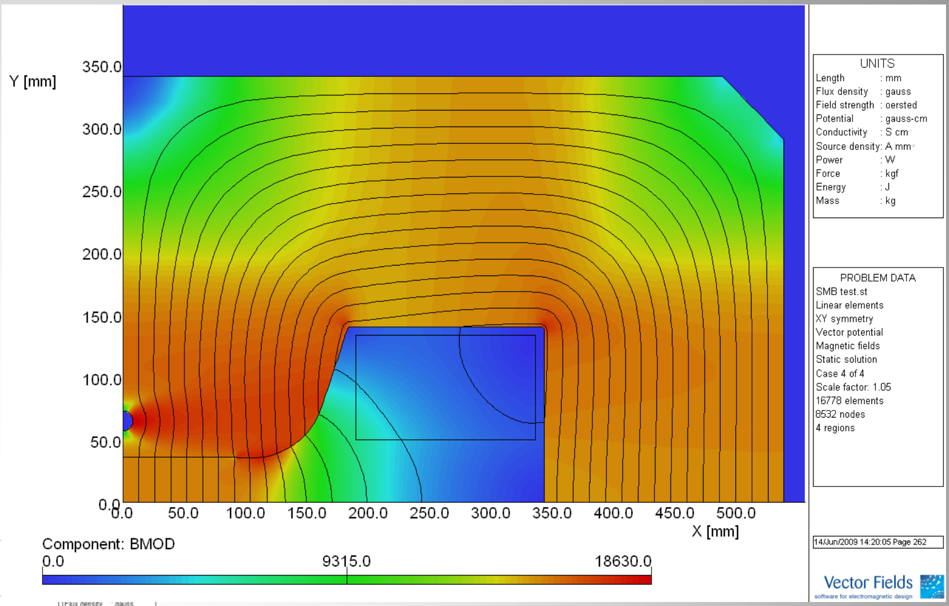
FEM codes are powerful tools, but be cautious:

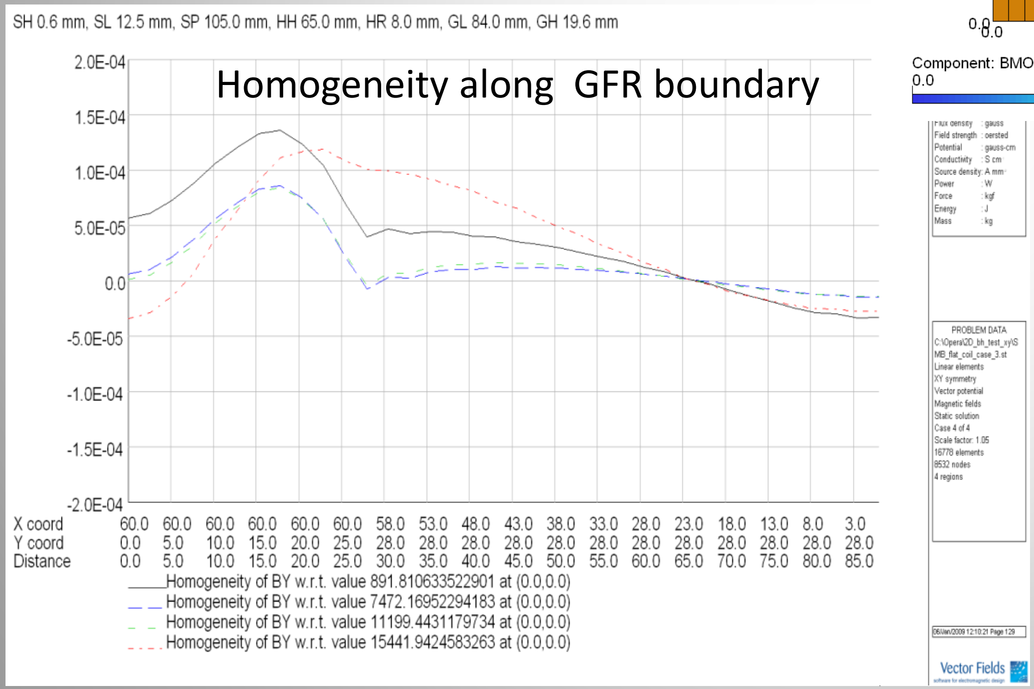
- Always check results if they are 'physical reasonable'
- Use FEM for quantifying, not to qualify

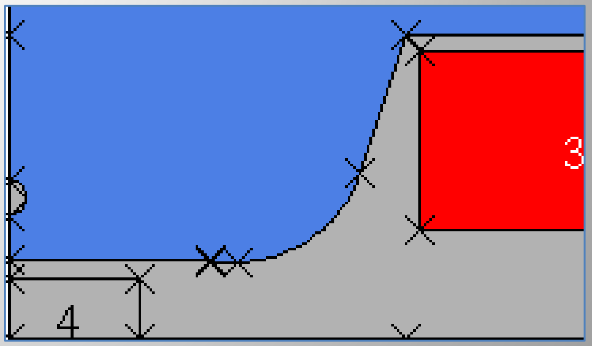
Field quality

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

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



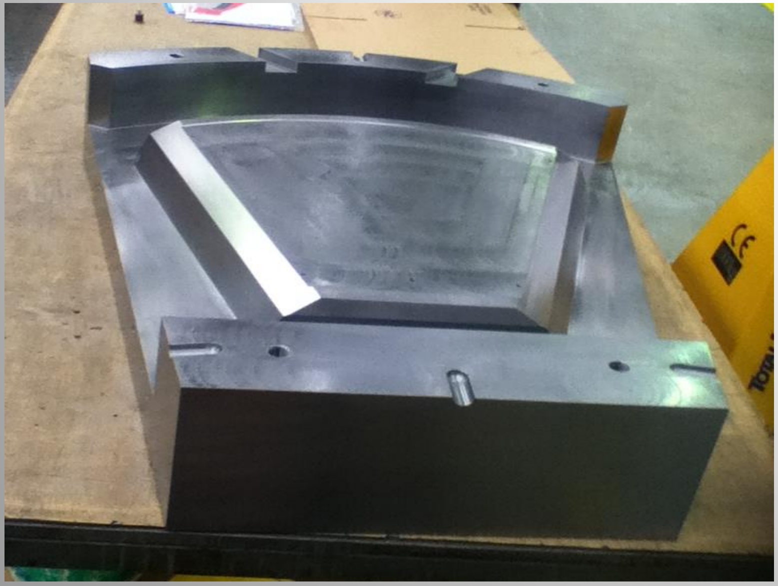




Massive vs. laminated yokes

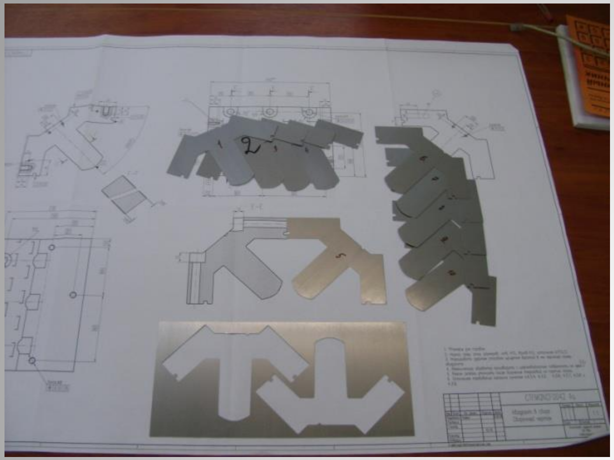
Historically, the primary choice was whether the magnet is operated in persistent mode or cycled (eddy currents)

+ 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:

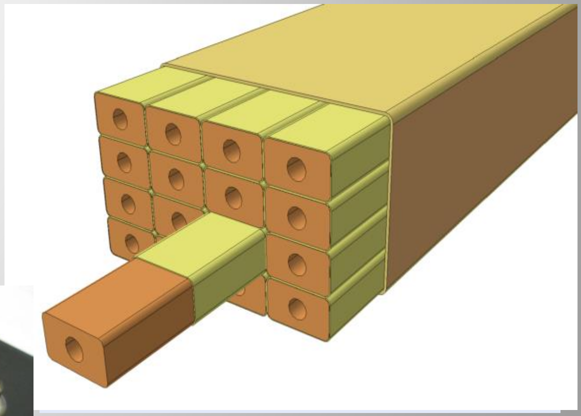
- Fields limited to 2 T (saturation)
- Field quality dependent on mechanics (machining, assembly)
- Small apertures more sensitive (small tolerances)
- dB/dt limited by eddy current effects
- Steel hysteresis requires magnetic cycling

Coil cooling

Air cooling by natural convection:

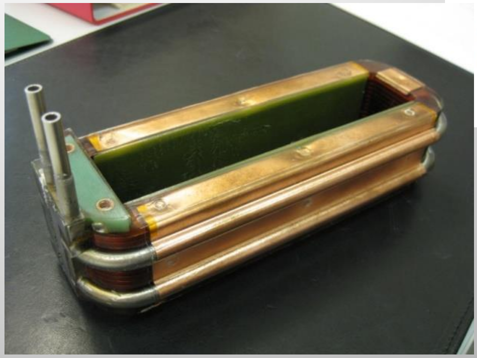
- Current density
  - $j < 2$ A/mm^2 for small, thin coils
- Cooling enhancement
  - Heat sink with enlarged radiation surface
  - Forced air flow (cooling fan)
- Only for magnets with limited strength (e.g. correctors)

Direct water cooling:



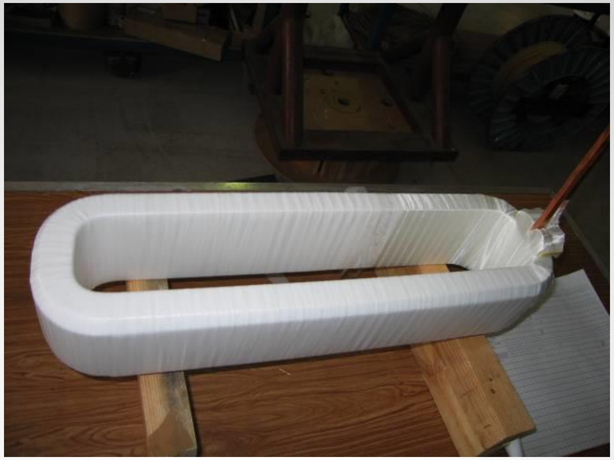
- Typical current density $j \leq 10$ A/mm^2
- Requires demineralized water (low conductivity) and hollow conductor profiles

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:

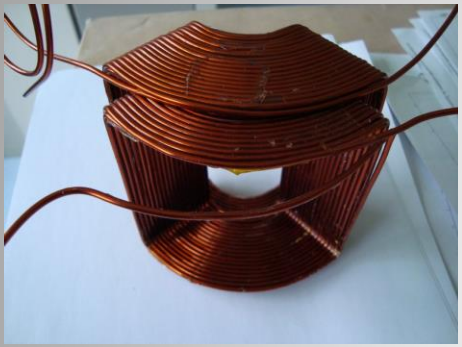
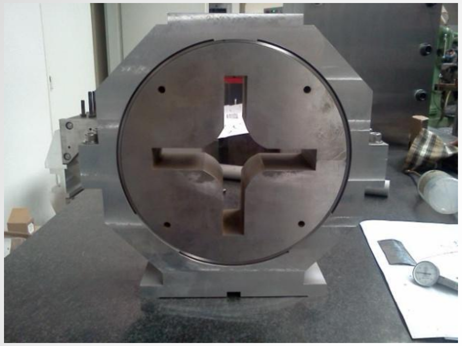
- Adjustable magnetic fields
- Well established technology
- Easy accessible and maintainable
- (Almost) no limit in dB/dt
- Conductor commercially available

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

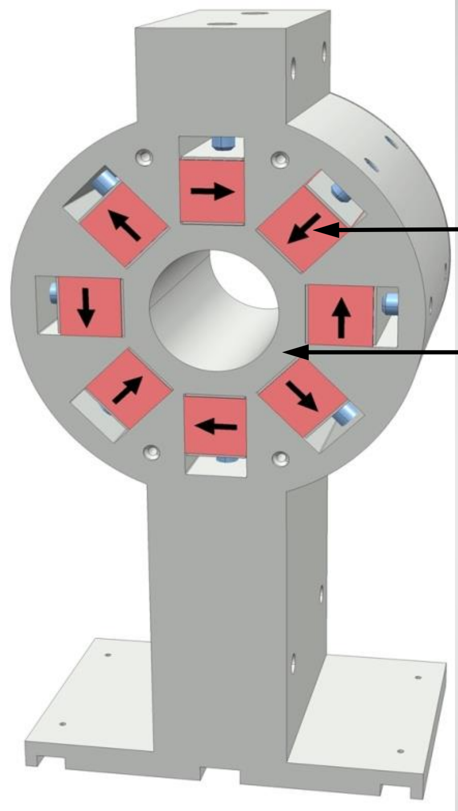
By hand....

... or with the help of tooling



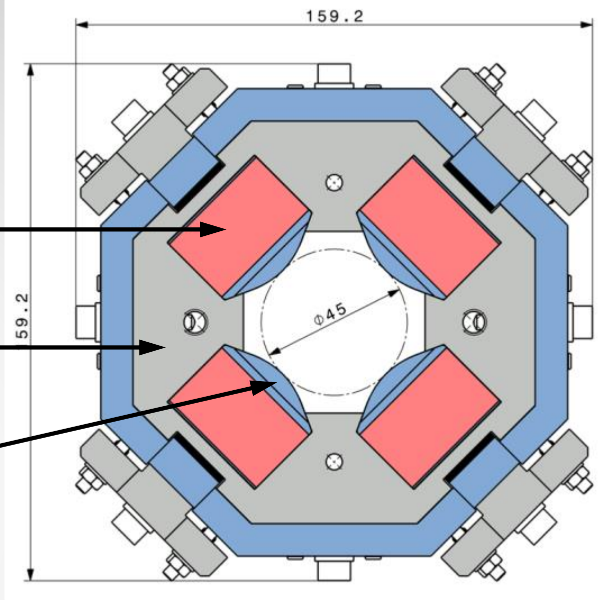

Conventional PM layout



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

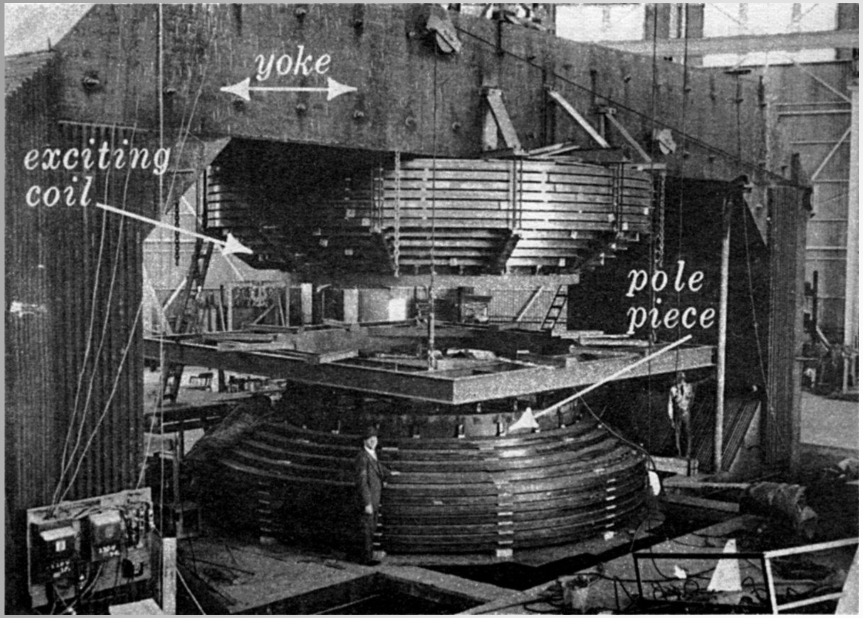
Advantages:

- 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



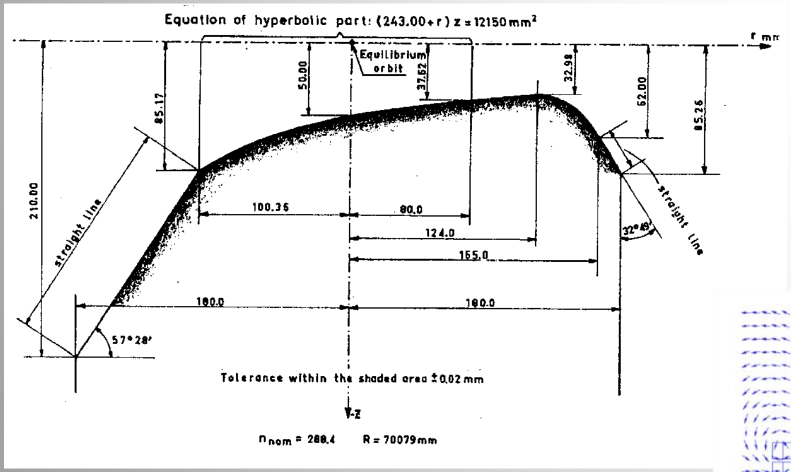
730 MeV cyclotron with 2.34 T magnet at the University of California at Berkley (1942)

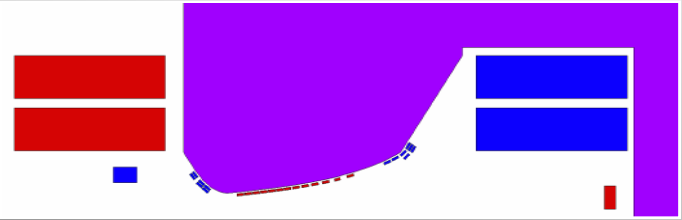
300 MeV “racetrack” electron synchrotron at University of Michigan (1949) with four 90° bending magnets

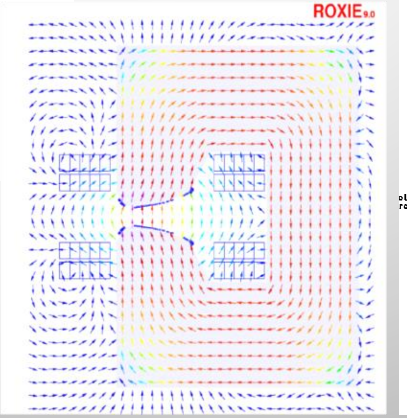
Magnets in the 1950s

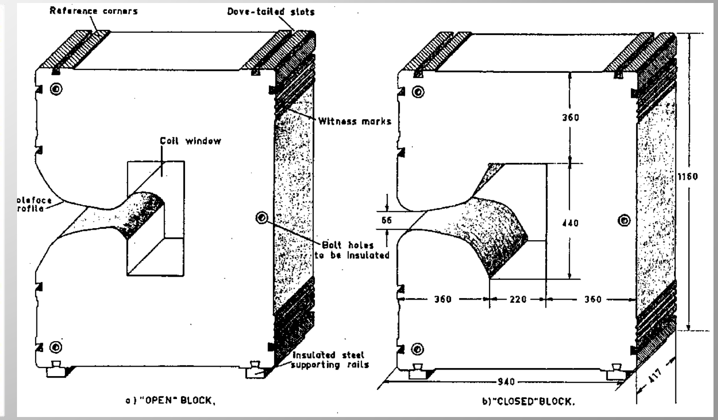
CERN PS (1959), 25 GeV, 628 m

- 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

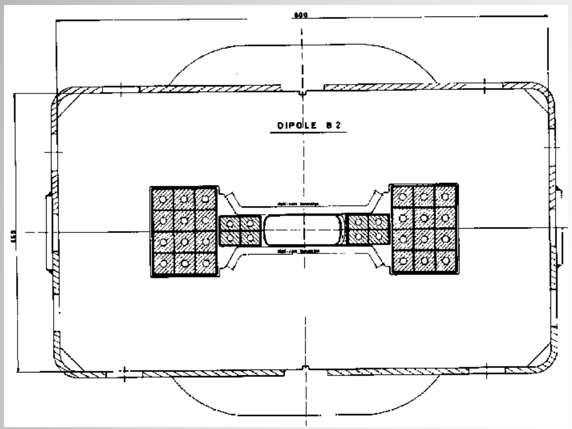
CERN PS Booster (1972), 2 GeV (originally designed for 0.8 GeV)

- 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

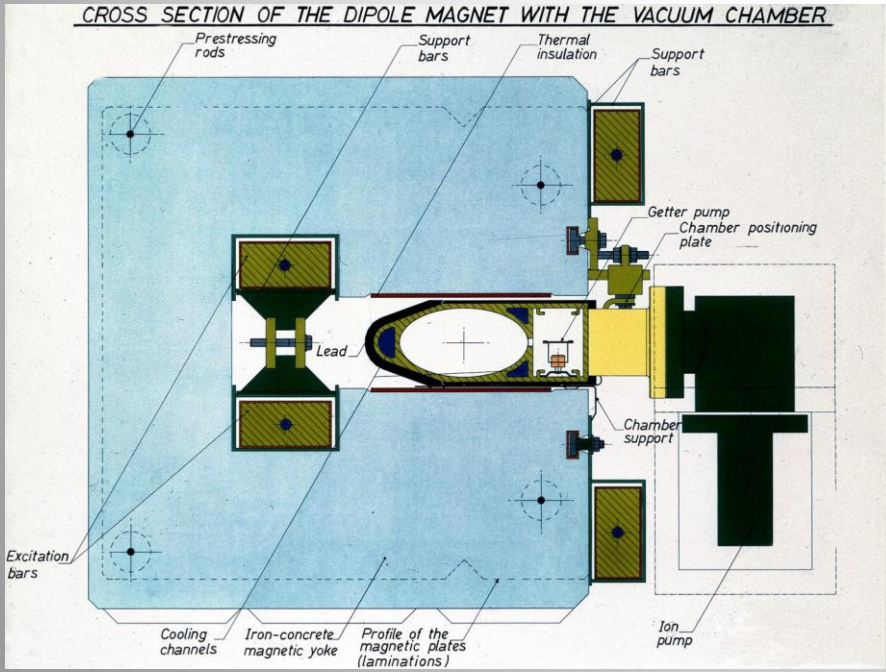
- 744 H-type bending magnets with B = 2.05 T

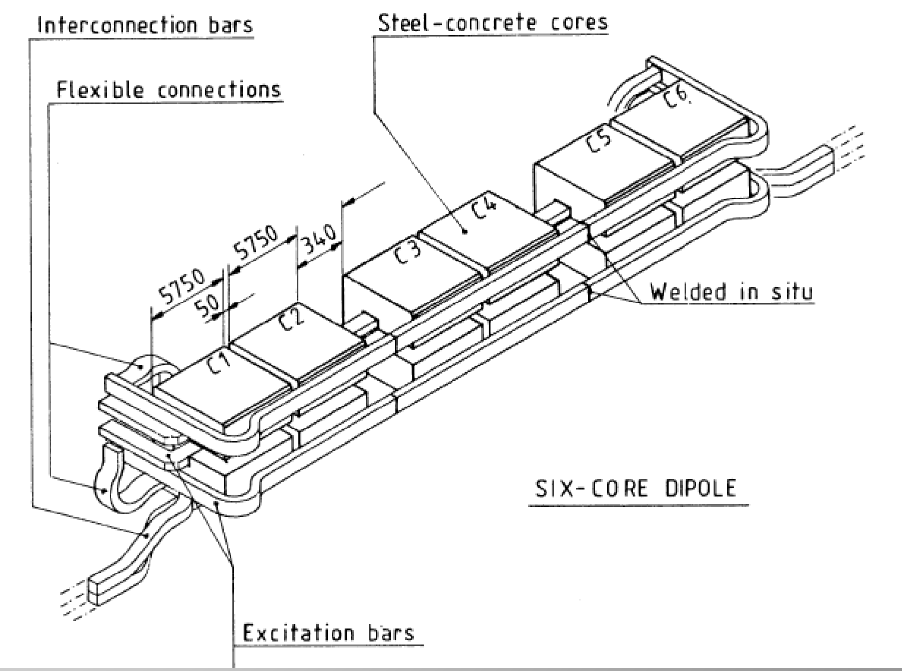


Magnets in the 1980s

LEP (1989), 27 km

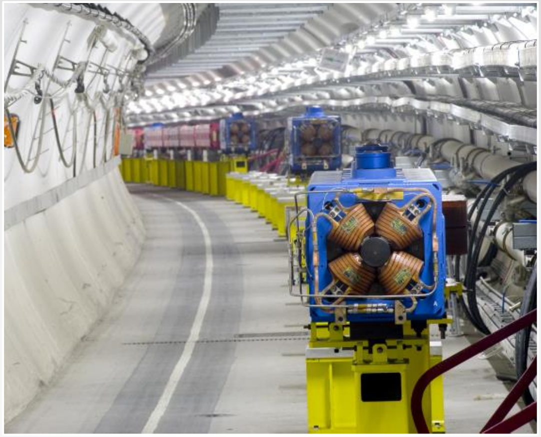
- Cycled field: 22 mT (20 GeV injection) to 108 mT (100 GeV)
- 5.75 m long ‘diluted’ magnet cores: 30% Fe / 70% concrete
- Four water cooled aluminium excitation bars





Magnets from 2000 till now…

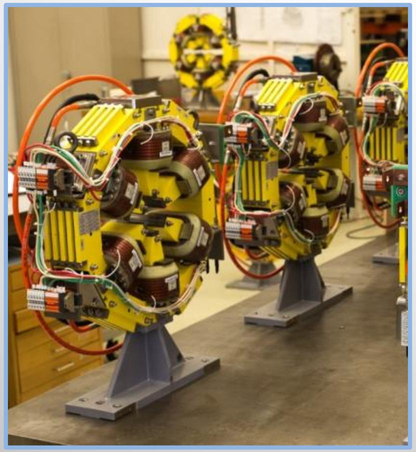
SPS – LHC transfer-line dipoles



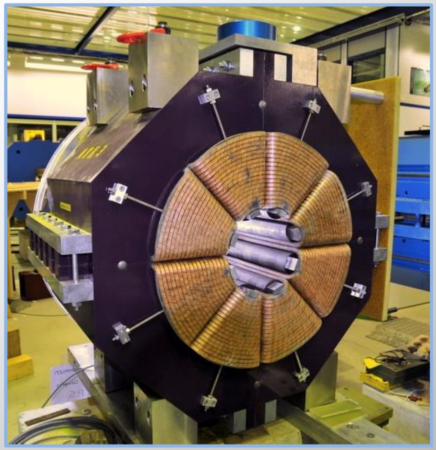
CNGS transfer-line quadrupoles

Double-aperture LHC quadrupole

Linac4 quadrupole



SESAME sextupoles

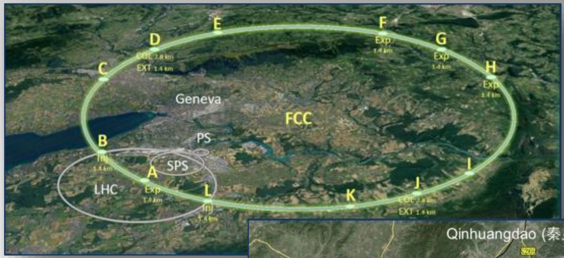


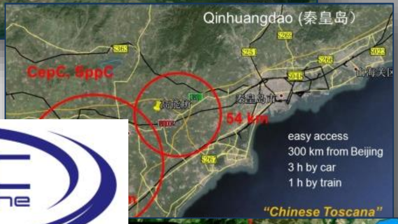
PS Multi-turn extraction octupole

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:

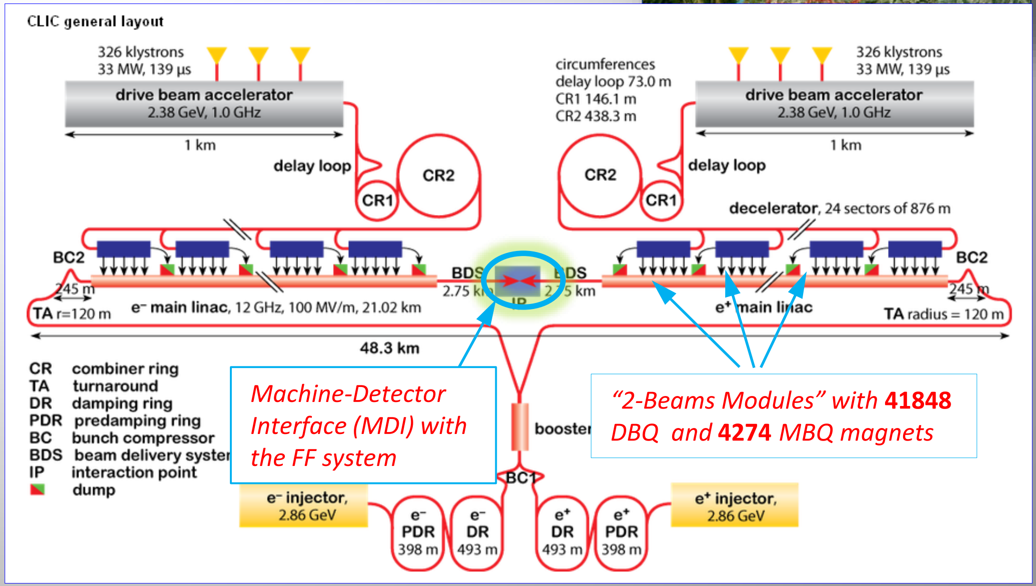
- Ionizing radiation impact on materials and electronics

Hadron colliders:

- High magnetic fields: SC magnets

Lepton colliders: (circular & linear)

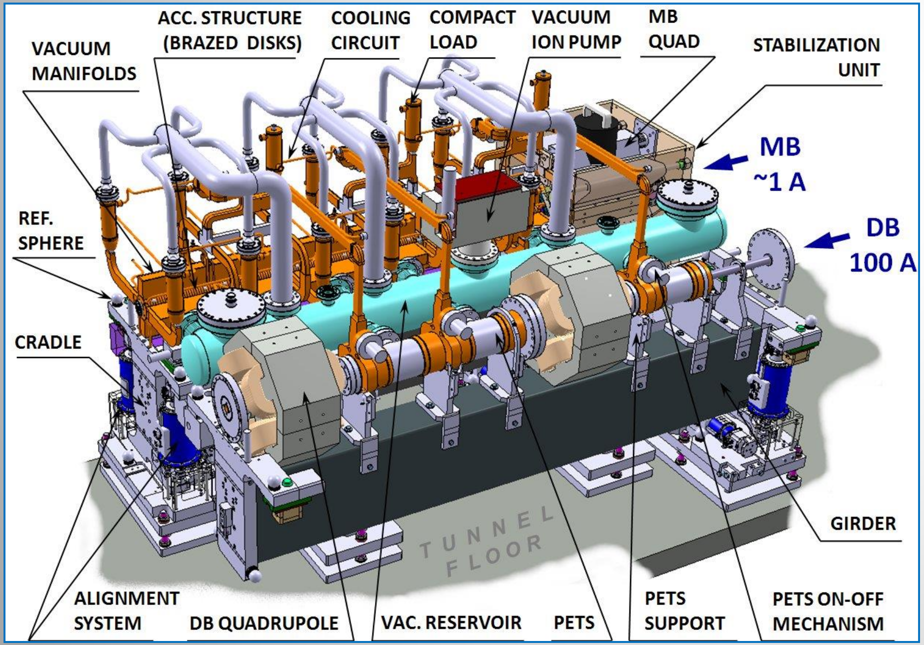
- Alignment & stabilization
- Compact design & small apertures

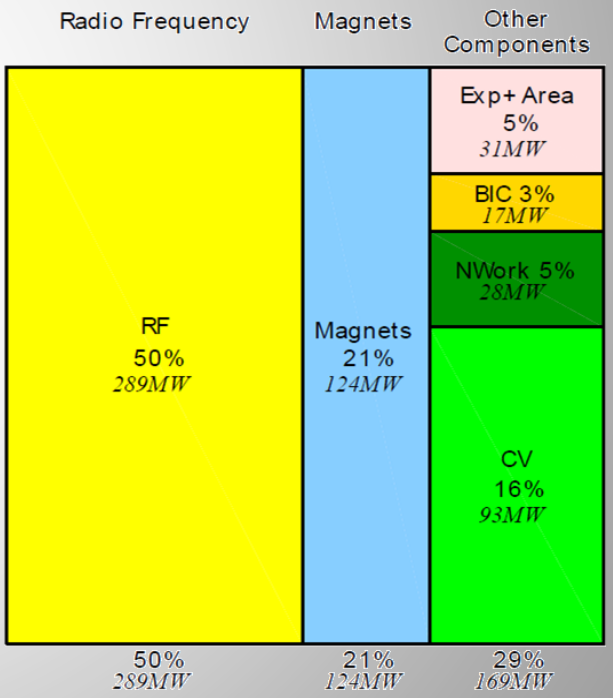


CLIC DB Quadrupole

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?

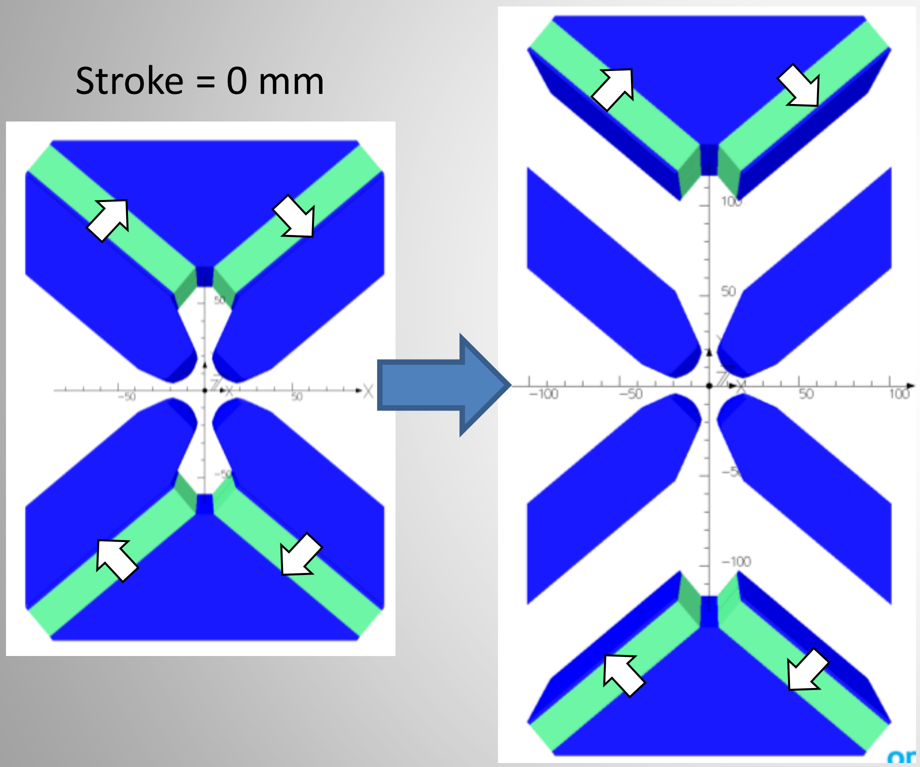
How can we deal with the wide gradient variation from 7% - 120%?

CLIC DB quadrupole

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

Stroke = 64 mm

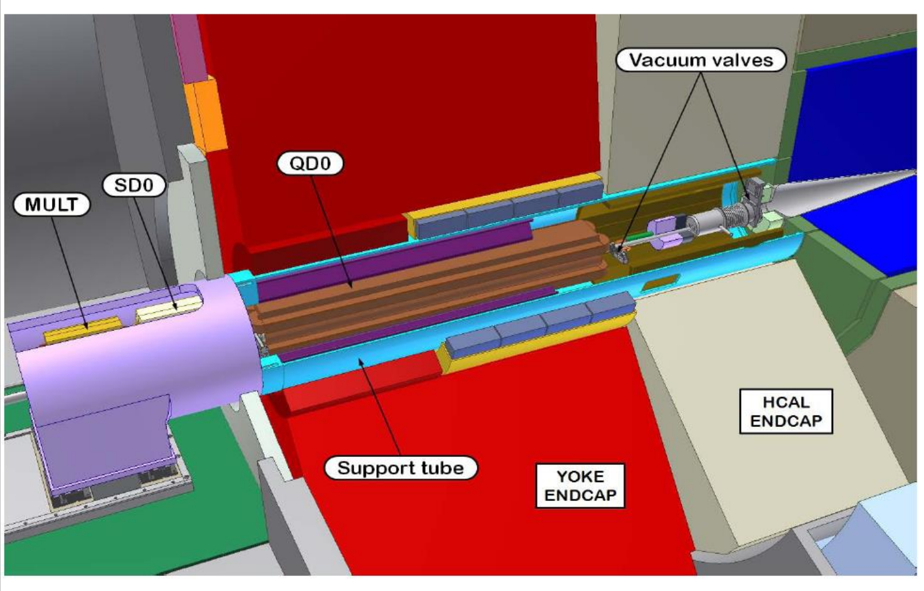
Stroke = 0 mm



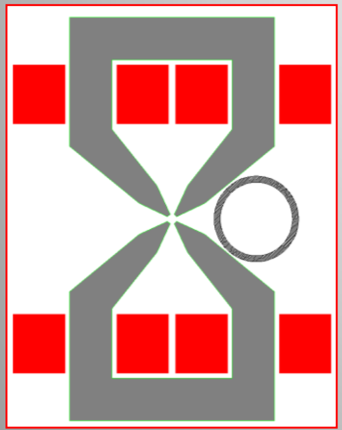
Single axis motion with one motor and two ball screws

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

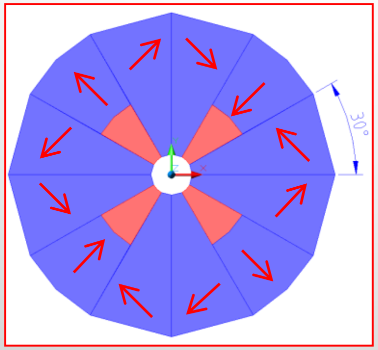


- Gradient: highest possible towards 575 T/m
- Total Length: 2.73 m
- Aperture radius: 4.125 mm
- Field Quality: better than 10^{-3}
- Tunability: -20% minimum



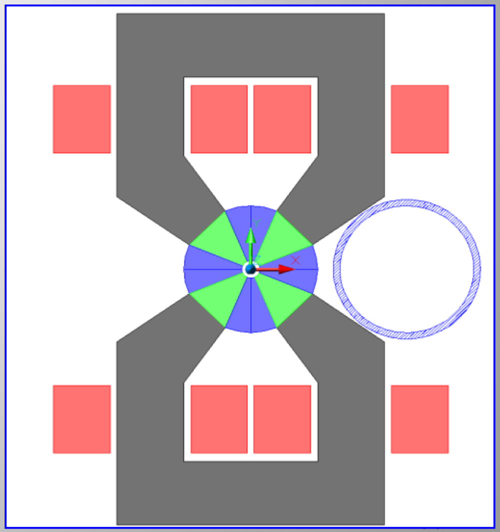
Pure EM design

+



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!

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