Normal-conducting & Permanent Magnets

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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 $\mu$ 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 $\mu_r$ (dimensionless): $\mu_{\text{air}} = 1$; $\mu_{\text{iron}} > 1000$ (not saturated)
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 \( B = 1 \text{T} \) then \( E = 3 \cdot 10^8 \text{V/m}(!) \)

– 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“

„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”
The presence of a magnetic circuit can increase the flux density in the magnet aperture by factors of 10.
Excitation current in a dipole

Ampere’s law \( \int \vec{H} \cdot d\vec{l} = NI \) and \( \vec{B} = \mu \vec{H} \)

leads to \( NI = \int \frac{\vec{B}}{\mu} \cdot d\vec{l} = \int \frac{\vec{B}}{\mu_{\text{air}}} \cdot d\vec{l} + \int \frac{\vec{B}}{\mu_{\text{iron}}} \cdot d\vec{l} = \frac{Bh}{\mu_{\text{air}}} + \frac{B\lambda}{\mu_{\text{iron}}} \)

assuming, that \( B \) is constant along the path.

If the iron is not saturated: \( \frac{h}{\mu_{\text{air}}} \gg \frac{\lambda}{\mu_{\text{iron}}} \)

then: \( NI \approx \frac{Bh}{\mu_0} \)
Permeability: correlation between magnetic field strength $H$ and magnetic flux density $B$

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

Ferro-magnetic materials: high permeability ($\mu_r >> 1$), but not constant
Magnet technologies

- **Magnets**
  - **Electro-magnets**
    - **Superconducting**
      - *Coil dominated*
        - $B < 11 \text{ T}$
    - **Iron dominated**
      - $B < 2 \text{ T}$
  - **Normal-conducting**
    - *Coil dominated*
      - $B < 1 \text{ T}$
    - *Iron dominated*
      - $B < 2 \text{ T}$
- **Permanent magnets**
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):

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

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

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

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

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

and introducing dimensionless normalized multipole coefficients

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

with \( B_N \) being the fundamental field of a magnet: \( B_N{\text{(dipole)}} = B_1; \ B_N{\text{(quad)}} = B_2; \ldots \)

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

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

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

Fundamental field \quad Harmonic distortions \quad Harmonic distortion factor
Dipole

Purpose: bend or steer the particle beam

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

\( \rightarrow \) 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: $2xy = \pm r^2$

$\Rightarrow$ 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: \( 3x^2 y - y^3 = \pm r^3 \)

\( \Rightarrow \) often approximated by circular arc

**Magnetic flux density:**

\[
B_x = \frac{B_3}{R_{\text{ref}}^2} xy; \quad B_y = \frac{B_3}{R_{\text{ref}}^2} (x^2 - y^2)
\]
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:

- 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: continuous, cycled
- Electrical parameters
- Mechanical dimensions
- Cooling
- Environmental aspects
1. Beam rigidity: \( (B\rho) = \frac{p}{q} = \frac{1}{qc} \sqrt{\frac{T^2}{2} + 2TE_0} \)
   Bending radius: \( r_M \)

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

3. Aperture \( h = \text{Good-field region} + \text{vacuum chamber thickness} + \text{margin} \)

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

5. Pole and iron yoke dimensioning

6. Select current density: \( j = \frac{NI}{f_cA} = \frac{I}{a_{\text{cond}}} \)
   Attention: \( P_{\text{dip}} = \rho NI j l_{\text{avg}} \)
   \( \rho: \text{conductor resistivity} \)
   \( l_{\text{avg}}: \text{avg. length of coil} \)

7. Determine number of turns \( N \) and current \( I \)
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

Investment vs running costs

- Magnet capital
- Power equipm. capital
- Total capital
- Running
- Total

Normalized costs vs Current density $j$ [A/mm$^2$]

Normalized costs
### 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

<table>
<thead>
<tr>
<th>2D</th>
<th>3D</th>
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</table>
| • 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
A simple judgment of the field quality can be done by plotting the field homogeneity:

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

The homogeneity along the x-axis is calculated as:

\[ \Delta B = B_y(x, y) - B_y(0,0) \]

Graph showing homogeneity along the GFR boundary.
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

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
  - $j < 2 \text{ A/mm}^2$ 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 $j \leq 10 \text{ A/mm}^2$
- Requires *demineralized* water (low conductivity) and hollow conductor profiles

**Indirect water cooling:**
- Current density $j \leq 3 \text{ A/mm}^2$
- Tap water can be used
Excitation coils

**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 ($j < 10 \text{ A/mm}^2$)
- (Water) cooling required for $j > 2 \text{ A/mm}^2$
- 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$_2$Co$_{17}$)
- **Non-magnetic yoke** (e.g. austenitic steel 316LN)
- **Magnetic poles** (e.g. low-carbon steel)

<table>
<thead>
<tr>
<th><strong>Nd$<em>2$Fe$</em>{14}$B</strong></th>
<th><strong>SmCo$_5$ or Sm$<em>2$Co$</em>{17}$</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical $B_r \approx 1.4$ T</td>
<td>Typical $B_r \approx 1.2$ T</td>
</tr>
<tr>
<td>Temp. coef. of $B_r = -0.11%/^\circ$C</td>
<td>Temp. coef. of $B_r = -0.03%/^\circ$C</td>
</tr>
<tr>
<td>Poor corrosion resistance</td>
<td>Good corrosion/radiation resistance</td>
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**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$_2$Co$_{17}$)
- Sensible to $\Delta T$
Magnets in the 1940s

730 MeV cyclotron with 2.34 T magnet at the University of California at Berkeley (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

Machine-Detector Interface (MDI) with the FF system
“2-Beams Modules” with 41848 DBQ and 4274 MBQ magnets
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

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

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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