Normal-Conducting Accelerator Magnets

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

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

Outline

• Producing magnetic fields
• Magnet technologies
• Magnet types in accelerators
• Design & construction
• Milestones from the past
• New concepts for future accelerators
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

"Right hand rule" applies
A bit of history...

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

“Electricity and magnetism are somehow related...”

1825: William Sturgeon (1783-1850), a British electrician, invented the first electromagnet.
Maxwell’s equations

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

- **Gauss’ law for electricity:** \( \nabla \cdot \vec{D} = \rho \)
  \[ \vec{D} = \varepsilon \vec{E} \]

- **Gauss’ law of flux conservation:** \( \nabla \cdot \vec{B} = 0 \)

- **Faraday’s law of induction:** \( \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \)
  \[ \vec{B} = \mu \vec{H} \]

- **Ampere’s law:** \( \nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \)
IEEE defines the following terms and units:

- **Magnetic field:**
  - $\mathbf{H}$ (vector) [A/m]
  - magnetizing force produced by electric currents

- **Electro-motive force:**
  - $U$ [V or (kg·m²)/(A·s³)]
  - voltage generated by a time varying magnetic field

- **Magnetic flux density or magnetic induction:**
  - $\mathbf{B}$ (vector) [T or kg/(A·s²)]
  - density of magnetic flux driven through a medium by the magnetic field
  - **Note:** flux or induction is frequently referred to as "Magnetic Field"
  - $H$, $B$ and $\mu$ relates by the constitutive law for materials: $\mathbf{B} = \mu \mathbf{H}$

- **Permeability:**
  - $\mu = \mu_0 \mu_r$
  - permeability of free space $\mu_0 = 4\pi \cdot 10^{-7}$ [(V·s)/(A·m) or (kg·m)/(A·s³)]
  - relative permeability $\mu_r$ (dimensionless): $\mu_{\text{air}} = 1$; $\mu_{\text{iron}} > 1000$ (not saturated)
Producing the magnetic field

Maxwell & Ampere:

\[ \nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \]
\[ \vec{B} = \mu \vec{H} \]
\[ \nabla \times \vec{B} = \mu_0 \vec{J} \]

„An electrical current is surrounded by a magnetic field“
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**
Coil dominated – Iron dominated

In coil-dominated magnets, the magnetic field in the aperture is shaped by the position of the conductors respectively the current distribution around the aperture.

In iron-dominated magnets, the magnetic field is shaped by the geometry of the poles, which are surfaces of constant scalar potential.

$B_1$: normal dipole

$B_2$: normal quadrupole

$B_1$: normal dipole

$B_2$: normal quadrupole
The magnetic (iron) circuit serves several purposes:

- **confine** the magnetic flux in the circuit to avoid stray flux
- **shape** the magnetic field distribution in the region of interest
- **enhance** the magnetic effect induced by currents in the coils
Producing the magnetic field

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

Coils hold the electrical current
Iron holds the magnetic flux
Shaping the magnetic field

To understand how the poles can shape the magnetic field, we need to have a closer look at the magnetic flux lines: we note that the flux lines in free space meet a material with infinite permeability perpendicular to the surface.
Enhancing the magnetic field

\[ I = 32 \text{ kA} \quad B_{\text{centre}} = 0.09 \text{ T} \]

\[ I = 32 \text{ kA} \quad B_{\text{centre}} = 0.80 \text{ T} \]

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

leads to \( NI = \int_{\text{gap}} \frac{\vec{B}}{\mu} \cdot d\vec{l} + \int_{\text{yoke}} \frac{\vec{B}}{\mu_{\text{iron}}} \cdot d\vec{l} = \frac{B h}{\mu_{\text{air}}} + \frac{B \lambda}{\mu_{\text{iron}}} \)

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: \( NI \approx \frac{B h}{\mu_0} \)
\[ \vec{B} = \mu \vec{H} \]
\[ \mu = \mu_0 \mu_r \]

**Permeability**: correlation between magnetic field strength \( H \) and magnetic flux density \( B \)

**Ferro-magnetic** materials: high permeability \( (\mu_r \gg 1) \), but not constant

\[ \vec{B} = \mu_0 \vec{H} + \vec{J} = \mu_0 \mu_r \vec{H} \]
Dipole

Purpose: bend or steer the particle beam

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

\[ y = \pm \frac{h}{2} \]  \( \rightarrow \) straight line with \( h = \) gap height

Magnetic flux density: \( B_x = 0; B_y = B_1 = \) const.

Applications: synchrotrons, transfer lines, spectrometry, beam scanning
Purpose: focusing the beam (horizontally focused beam is vertically defocused)

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

\[ 2xy = \pm r^2 \]  \( \rightarrow \) hyperbola with \( r = \) aperture radius

Magnetic flux density:

\[ B_x = \frac{B_2}{R_{ref}} y; \quad B_y = \frac{B_2}{R_{ref}} x \]
Purpose: correct chromatic aberrations of ‘off-momentum’ particles

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

\[ 3x^2y - y^3 = \pm r^3 \]  
(with \( r = \) aperture radius)

Magnetic flux density: 

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

<table>
<thead>
<tr>
<th>Pole shape</th>
<th>Field distribution</th>
<th>Pole equation</th>
<th>$B_x$, $B_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Pole shape" /></td>
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</tr>
<tr>
<td><img src="image" alt="Pole shape" /></td>
<td><img src="image" alt="Field distribution" /></td>
<td>$4(x^3y - xy^3) = \pm r^4$</td>
<td>$B_x = \frac{B_4}{R_{ref}^3} (3x^2y - y^3)$ $B_y = \frac{B_4}{6R_{ref}^3} (x^3 - 3xy^2)$</td>
</tr>
</tbody>
</table>
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, ...
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

A magnet is not a stand-alone device!
**Focus on economic design!**

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

Total costs include:

- Estimated operation costs of these items
- Capital costs of magnets
- Capital costs of power converters
- Capital costs of power distribution
- Capital costs of cooling system

**Attention:** $\text{Power } \propto \text{ current density}$

Decreasing current density means:
- increasing coil cross section
- increasing material (coil & yoke) cost
- increasing manufacturing cost
- but decreasing operation 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>
</tr>
</thead>
<tbody>
<tr>
<td>• 2D analysis is often sufficient</td>
<td>• produces large amount of elements</td>
</tr>
<tr>
<td>• magnetic solvers allow currents only perpendicular to the plane</td>
<td>• mesh generation and computation takes significantly longer</td>
</tr>
<tr>
<td>• fast</td>
<td>• end effects included</td>
</tr>
<tr>
<td></td>
<td>• powerful modeller</td>
</tr>
</tbody>
</table>

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

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

Stamping laminations

Stacking laminations into yokes

Gluing and/or welding

Assembling the yoke parts
Excitation coils

Conductor insulation
Coil winding
Ground insulation
Epoxy impregnation
Testing
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
NC-magnets in the 1950-60s

CERN PS (1959), 25 GeV, 628 m

- Combined function magnet: dipole + quadrupole + higher order multi-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
NC-magnets in the 1970s

CERN SPS (1976), 7 km, 450 GeV

- 744 H-type bending magnets with $B = 2.05$ T
NC-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
- Max. current: 4.5 kA
NC-magnets even in the LHC ...
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
Magnet system for FCC-ee

Double collider
Counter-rotating e+ / e- beams
DC operation with top-up injection
1450 FODO cells, each 55.9 m long
Tuneability ±1%

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bending magnets</th>
<th>Quadrupole magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity (per ring)</td>
<td>2900</td>
<td>1450 + 1450</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>23.94 (21.94) m</td>
<td>3.1 m</td>
</tr>
<tr>
<td>Aperture</td>
<td>128 mm x 84 mm</td>
<td>R = 42 mm</td>
</tr>
<tr>
<td>Inter-beam distance</td>
<td>300 mm</td>
<td>300 mm</td>
</tr>
<tr>
<td>Field / max. gradient at 175 GeV</td>
<td>54.3 mT</td>
<td>9.9 T/m</td>
</tr>
<tr>
<td>Goof field region</td>
<td>±10 mm horizontal</td>
<td>R = 10 mm</td>
</tr>
<tr>
<td>Field quality</td>
<td>&lt; 10^-4</td>
<td>&lt; 10^-4</td>
</tr>
</tbody>
</table>
Recap: LEP dipoles

Using the LEP diluted dipoles for FCC-ee at 54 mT...
FCC-ee Twin dipole design

- **Energy saving**: Ampere-turns recycled $\rightarrow$ **50% less power consumption** (16 MW)
- **Cost saving**: 50% less units to manufacture, transport, install, align
- **Simple**: few components
  - Simple yoke design and coil layout $\rightarrow$ low manufacturing costs
- **Compact**: small dimensions, less material
  - Yoke: 200 kg/m $\rightarrow$ total 13500 t (low carbon) steel
  - Coil: 1-turn conductor busbar, 20 kg/m $\rightarrow$ total 1650 t hollow Al conductor
- **Reliable**: no coil inter-turn insulation needed
FCC-ee Twin dipole prototype

A. Milanese, Efficient twin aperture magnets for the future circular e+e- collider, PHYSICAL REVIEW ACCELERATORS AND BEAMS 19, 112401 (2016)
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 23 years!
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