Magnets and Special Magnets
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CAS
Beam Injection, Extraction and Transfer
Erice
10-19 March 2017

Outline

- Basic physics
- Magnet types
- Coils
- Yokes
- Special magnets
- Magnet examples
Lorentz Equation

Charles Augustin de Coulomb (1736 – 1806)
Coulomb-Kraft
\[ \mathbf{F} = q\mathbf{E} \]

Hendrik Antoon Lorentz (1853 – 1928)
Lorentzkraft
\[ \mathbf{F} = q \mathbf{v} \times \mathbf{B} \]

\[ \mathbf{F} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B} \]
Maxwell equations

\[ \nabla \times \mathbf{H} = \mathbf{j} + \frac{\partial}{\partial t} \mathbf{D} \]
\[ \nabla \cdot \mathbf{B} = 0 \]

\[ \nabla \times \mathbf{E} = -\frac{\partial}{\partial t} \mathbf{B} \]
\[ \nabla \cdot \mathbf{D} = \rho \]

\[ \mathbf{D} = \varepsilon_0 \varepsilon \mathbf{E} \]

\[ \mathbf{B} = \mu_0 \mu \mathbf{H} \]

\[ \mathbf{j} = \sigma \mathbf{E} \]

Ampere’s law:
\[ \oint_{\partial A} \mathbf{H} \cdot d\mathbf{s} = \oint_{A} \mathbf{j} \cdot dA + \frac{\partial}{\partial t} \int_{A} \mathbf{D} \cdot dA \quad \text{from} \quad \nabla \times \mathbf{H} = \mathbf{j} + \frac{\partial}{\partial t} \mathbf{D} \]

Faraday’s law:
\[ \oint_{\partial A} \mathbf{E} \cdot d\mathbf{s} = -\frac{\partial}{\partial t} \int_{A} \mathbf{B} \cdot dA \quad \text{from} \quad \nabla \times \mathbf{E} = -\frac{\partial}{\partial t} \mathbf{B} \]

Gauss’s theorem:
\[ \int_{\partial V} \mathbf{D} \cdot d\mathbf{A} = Q \quad \text{from} \quad \nabla \cdot \mathbf{D} = \rho \]

Magnetic field has no charges:
\[ \int_{\partial V} \mathbf{B} \cdot d\mathbf{A} = 0 \quad \text{from} \quad \nabla \cdot \mathbf{B} = 0 \]
### Magnetic material properties

<table>
<thead>
<tr>
<th>Term</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu = \begin{bmatrix} \mu_{xx} &amp; \mu_{xy} &amp; \mu_{xz} \ \mu_{yx} &amp; \mu_{yy} &amp; \mu_{yz} \ \mu_{zx} &amp; \mu_{zy} &amp; \mu_{zz} \end{bmatrix} )</td>
<td>Permeability tensor</td>
</tr>
<tr>
<td>( \mu_{ij} = 0, \mu_{ik} = \mu_k \neq 0 )</td>
<td>isotropic, homogeneous</td>
</tr>
<tr>
<td>( \mu_{ij} = 0, \mu_{ik} = \mu_k(x, y, z) )</td>
<td>isotropic, inhomogeneous</td>
</tr>
<tr>
<td>( \mu_{ij} = \text{const} )</td>
<td>anisotropic, homogeneous</td>
</tr>
<tr>
<td>( \mu_{ij} = \mu_{ij}(x, y, z) )</td>
<td>anisotropic, inhomogeneous</td>
</tr>
<tr>
<td>( \mu_{ik} = \mu_k(H(x, y, z)) )</td>
<td>isotropic, homogeneous, nonlinear (massive iron)</td>
</tr>
<tr>
<td>( \mu_{ik} = \mu_k(H(x, y, z)) )</td>
<td>anisotropic, homogeneous, nonlinear (laminated iron)</td>
</tr>
</tbody>
</table>

### Magnet types
Magnets in the Accelerator

- Bending magnets => Dipole, \( B = \text{const.} \)

- Focusing magnets => Quadrupole, \( B = g^*r = B^*r \)

- Non linear magnets (corrector magnets)
  => Sextupole, \( B = B^*r^2/2 \), Octupole \( B = B^*r^3/6 \), ...

Optical Analogies

- Prism => Dipole

- Spherical lens => Quadrupole

- Aspherical lens => Sextupole, Octupole, ...
Design Types

Current dominated

Cos nθ

Intersecting ellipses

Iron dominated

H-Magnet

C-Magnet

O-Magnet

(Window-frame m.)

Magnetic Flux Lines

South pole

North pole

Dipole

Quadrupole

Sextupole

Quadrupoles and higher orders have a radially symmetric field strength distribution but not the field direction.
**Forces on the Beam - Dipole**

- Positive ion into the plane
- Right hand rule
- Direction of a positive ion = technical definition of current
- Constant field => constant force

![Dipole Diagram](image)

**Forces on the Beam - Quadrupole**

- Field increases linearly with the distance from the center => Force increases linearly
- Ion beam
  - Horizontally defocusing
  - Vertically focusing
  - -> More than one QP for focusing in both planes
- Named according to horizontal plane => Defocusing Quadrupole

![Quadrupole Diagram](image)
**Forces on the Beam - Sextupole**

- Field increases quadratically with the distance => force increases quadratically!
- Force has same direction on both sides of the axis
- Named after the horizontal axis w.r.t. the machine center

**Polarity - Dipole**

- Field direction according to right hand rule

---

Field increases quadratically with the distance => force increases quadratically!

- Force has same direction on both sides of the axis
- Named after the horizontal axis w.r.t. the machine center

**Polarity - Dipole**

- Field direction according to right hand rule

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Polarity - Quadrupole

Fig. J. Tanabe

Polarity - Sextupole

Fig. J. Tanabe
Forces on the Particle Beam – Alternative Formulations

- Currents with equal charge and equal direction of movement attract each other.

Conclusions:
- Currents with opposite charge and equal direction of movement repel each other.
- Currents with equal charge and opposite direction of movement repel each other.
- Currents with opposite charge and opposite direction of movement attract each other.

Dipole Types

- Named by yoke shape
- Field quality dominated by iron
Orthogonal Analog Model

Recipe to judge the field quality (homogeneity)
- Draw lines from plus to minus currents
- Field is perpendicular to these

Window frame type dipole has better field quality
- Optimisation by
  - Pole overhang and/or
  - Pole profile

Dipole Types- pros and cons

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>O (Window frame)</td>
<td>Symmetrical</td>
<td>Bedstead coils or cylindrical coils with high flux leakage</td>
</tr>
<tr>
<td>C</td>
<td>Saves space at one side, Simple coil assembly</td>
<td>Asymmetrical, bedstead coil, heavy yoke</td>
</tr>
<tr>
<td>H</td>
<td>Symmetrical, Simple pancake coils</td>
<td>Bad field quality (compared to WF)</td>
</tr>
</tbody>
</table>
Quadrupole Types

a) Collins-Quadrupole
   (≈ “Figure of 8”-Quadrupole)
b) 1. Standard-Quadrupole
   (no increase of the pole basis)
c) 2. Standard-Quadrupole
   (max. increase of the pole basis)
d) Panofsky-Quadrupol

Coils
Ampère's Law

André-Marie Ampère (1775 – 1936)

The field integral along a closed path equals the enclosed current

Dipole Excitation

\[ \int \frac{\vec{B}}{\mu_0} \cdot d\vec{l} = \frac{Bh}{\mu_0} \]

Ampère's law:

\[ NI \approx \frac{Bh}{\mu_0} \]

is small, as \( \mu \) is large
Ampère’s law:
\[ \int \frac{\mathbf{B}}{\mu_0} \cdot d\mathbf{l} = \frac{ Bh }{ \mu_0 } \]
is small, as \( \mu \) is large

Similar for sextupole:
\[ NI \approx \frac{ B r_0^2 }{ 2 \mu_0 } \]

Conductor Materials

<table>
<thead>
<tr>
<th></th>
<th>Aluminum (pure, &gt; 99.5%)</th>
<th>Copper (OFHC- Oxygen free high conductivity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price (large quantities)</td>
<td>2.7-3.4 EUR/kg</td>
<td>8-16 EUR/kg</td>
</tr>
<tr>
<td>Conductivity</td>
<td>36 S m/mm²</td>
<td>58 S m/mm²</td>
</tr>
<tr>
<td>Specific weight</td>
<td>2.70 g/cm²</td>
<td>8.96 g/cm³</td>
</tr>
<tr>
<td>Linear expansion coefficient</td>
<td>23*10^{-6} K^{-1}</td>
<td>17*10^{-6} K^{-1}</td>
</tr>
<tr>
<td>Elasticity modulus</td>
<td>72.000 N/mm²</td>
<td>123.000 N/mm²</td>
</tr>
<tr>
<td>Keystoning effect</td>
<td>Smaller</td>
<td>Higher</td>
</tr>
<tr>
<td>Oxydation</td>
<td>In air. Dissolves in mixed copper/aluminum cooling circuits</td>
<td>Small</td>
</tr>
<tr>
<td>Conclusions (for same ( N^I ))</td>
<td>Larger</td>
<td>Smaller</td>
</tr>
<tr>
<td></td>
<td>Lighter</td>
<td>Heavier</td>
</tr>
<tr>
<td></td>
<td>Higher transparency for particles</td>
<td>Reduced transparency for particles</td>
</tr>
<tr>
<td></td>
<td>Lower investment costs</td>
<td>Higher investment costs</td>
</tr>
<tr>
<td></td>
<td>Higher operating costs</td>
<td>Lower operating costs</td>
</tr>
<tr>
<td></td>
<td>=&gt; Rather for detector magnets</td>
<td>=&gt; Rather for accelerator magnets</td>
</tr>
</tbody>
</table>

=> You need more of the cheaper material!
Coil Cooling

Cooling

- Air
  - Free flow
  - Forced flow
  - No measures
  - Fan ventilation
- Water
  - Direct
  - Indirect
  - Internal cooling channel
  - Cooling disc 1
  - Cooling disc 2
  - Winding
  - Cooling channel
  - Water

C. Muehle / Magnets and Special Magnets

Copper Profiles

- Quadratic or rectangular with round bore -> best packing factors
- Round tube -> small coils with tight bends in several directions
- Exotic shapes
Coil Shapes

Dipoles:
- O-Magnets:
  - a) Saddle shaped (bedstead) coil (type 1, upper part)
  - b) Saddle shaped (bedstead) coil (type 2, upper part)
  - c) Pair of cylindrical coils
- H-Magnets:
  - c) 1 race track coil per pole

Quadrupoles:
- Analog shapes (shape a bent inside)

Yokes
Yoke Material Choice

- Material choice according to required ...
  - ... flux density
  - ... ramp rate
  - ... space requirements
  - ... costs

Flux density
- Ferrite
- Sintered iron
- Soft iron
- Cobalt iron

Ramp rate
- Ferrite
- Sintered iron
- Laminated iron
- Bulk iron
Saturation Effects

- $\mu_r = \mu_r(B)$, for $B > 1.5$ T $\mu_r$ becomes smaller

Saturation effects

- Reduced field
  - Reduced field quality
    - Loss of Ampere turns
- Increased $N^*I$
  - Adapt yoke design (thicker yoke)
- Adapt pole profile (wider pole)
  - Correction windings
  - Slits in the pole

Slits in the Pole

2 options

- Field guidance
- Artificial saturation near the center
Sagitta

- Asymmetric central trajectory in a *straight* dipole

- Consequences:
  - Wider aperture
  - Curved dipole

\[ h = r \left(1 - \cos\left(\frac{\alpha}{2}\right)\right) \propto l^2 \]

Aperture Reduction for Laminated Dipoles

- Laminations are stacked parallel on radius \( R \) => Aperture reduction
  - Use several blocks with adapted stacking direction along the magnet
Special magnets
(incl. examples)

- Magnets with special technical features or materials in their design
  - Magnetic Septa -> separate talk
  - Kicker Magnets -> separate talk
  - Radiation Resistant Magnets
  - Special Yoke Shapes
  - Integrated Magnets
  - Magnets with Cobalt iron yokes
  - ...

- Magnets which cannot be described by multipoles as shown in the beginning
  - Solenoids
  - Magnetic Horns
  - Toroids
  - ...
Radiation

Beam loss

Intended

- Targets
- Charge state separation
- Mass separation

Unavoidable

- Any beam loss process:
  - Charge exchange reaction
    (at residual gas particles, at el. septum wires)
  - Resonances

The materials for the magnet must be chosen according to the expected radiation level. Coil insulation is the most sensitive one.

<table>
<thead>
<tr>
<th>Standard epoxy resin</th>
<th>Improved plastics (e.g. Isocyanates, Polyimide)</th>
<th>Fully anorganic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^7$ Gy</td>
<td>$10^8$ Gy</td>
<td>$&gt;10^9$ Gy</td>
</tr>
</tbody>
</table>

Radiation Resistant Magnets

- Coil potting with polyimide or isocyanates
  - Conductor and coil design unchanged
  - Potting mould to be adopted for different material (e.g. cooling)
  - Coils for external beam line at KEK

- Fully anorganic
  - MIC (metall oxide insulated) conductor
  - Coil solder potted
  - Dipole for SuperFRS preseparator
Special Yoke Shapes

- Imposed by external requirements
  - Other beamlines at injection/extraction or branching points
  - ...
- Examples
  - Branching dipole (HEBT Heidelberg Ionentherapie) – opening for straight beam path including yoke reinforcement
  - Sextupole for Australian Light Source – opening for light beam line

Integrated Magnets

- Radial or longitudinal integration of several multipoles
  - Reduced space requirements
  - Reduced installation and alignment effort
  - Enlarged vibration stability
- Examples
  - Corrector magnet in SIS18 (current dominated; normal and skew quadrupoles, skew sextupole)
  - Main magnet for MAX IV (common massive yoke, dipole, quadrupoles, sextupole, steering magnets)
Special Yoke Materials: CoFe

- Enlarged saturation flux density (2.2-2.3T)
- Compact design with high field/gradient
- But
  - High material price
  - Brittle material
  - Risk of activation
- Example
  - Internal quadrupoles for IH-type LINAC
  - Maximum Pole basis
  - CoFe yoke laminations (0.35mm)
  - One layer coil
  - Up to 124T/m
- In addition an example of an integrated magnet – triplet in copper plated housing

Solenoids

- In general a long coil
- Focusing magnet (in both planes)
- Field along the beam path
- Principle of focusing
  - Stray field creates radial motion of particles
  - Radial motion is perpendicular to main field and causes therefore focusing
- Application
  - Focusing in LEBT (typically NC)
  - Focusing in LINAC (typically SC)
  - Magnet for particle tracking in experiments (NC or SC)
**Solenoids**

- **LEBT-Solenoid**
  - 0.54T
  - ~0.5t
  - Diam. ~0.6m, length ~0.3m

- **Alice central magnet**
  - 0.55T
  - ~10,000t
  - Diam. ~12m, length ~12m

**Magnetic Horn**

- Focusing magnet close to targets
- Central path field free
- Focusing of off-axis particles

*Fig. K. Knie*
**Magnetic Horn**

- Focusing after pbar production target planned at FAIR
- 400kA/15kV
- Inner conductor shaped to generate a parallel beam independently from original angle of the particles

**Toroid**

- For charged particle tracking in detectors
- Example
  - HADES (High Acceptance Dielectron Spectrometer) at GSI
  - Toroidal field generated by 6 super-conducting air coils
Examples

Magnets for HIT (Heidelberger Ionentherapie)

- Dedicated facility for cancer therapy with ions in Heidelberg
- Developed by GSI
- 2 commercial facilities were built (Siemens, Danfysik)
- More similar facilities are operational or in commissioning
- Compact accelerator
- 120 magnets
- Footprint ~70m x 70m
- Most magnets described before can be found here.
**Analysis Dipole (1.1)**

- H type magnet
- D shaped coil
- 0.2T
- Small bending radius
- 90°

**Switch Yard Dipole (1.2)**

- H type magnet
- Straight
- 0.1T
- Funneling of beams from 2 ion sources
MEBT Dipole (1.3)

- H type magnet
- Curved
- $25^\circ$
- 0.57T

Inflector Dipole (1.4)

- Window frame type magnet
- Yoke c-shaped
- Curved
- $15^\circ$
- 0.42T
Bumper (1.5)

- Window frame type magnet
- Very fast (560T/s):
  - Powder composite material
  - 2 turns
  - 0.0195T

Septum I (1.6)

- Window frame type magnet
- Yoke c-shaped
- Straight (2x)
- Septum coil (soldered out of different parts)
- 6.5°
- 0.75T
Septum II (1.7)

- Window frame type magnet
- Yoke c-shaped
- Curved
- Septum (soldered)
- Operated in series with synchrotron dipoles
- 13.5°
- 0.9T

Synchrotron Dipole (1.8)

- H type magnet
- Curved – stacked in 3 blocks along the magnet to avoid aperture reduction
- Removable endplates for length adjustment
- Integrated correction windings for horizontal steering
- 1.53T, 1.53T/s
- 60°
### Spill Abortion Bumper (1.9)

- Window frame type magnet
- Safety function
- Fast Magnet (1000T/s ramp down)
  - Yoke: Powder composite material
  - Few turns
- 0.69°
- 0.2T

### 15° HEBT Dipole (1.10)

- H type magnet
- Curved
- Same cross section as 1.11
- 'Zero-field' correction coil integrated for straight beamline
- 1.5T
### 45° HEBT Dipole (1.11)

- H type magnet
- Curved – 3 blocks along the magnet
- ‘Zero-field’-coil integrated
- Return yoke width enlarged cross section for compensation of straight beam line channel
- 1.51T

### 45° Gantry Dipole (1.12)

- Hybrid type magnet
  - Inner coil – window frame type
  - Outer coil – H type (around poles), but bedstead shape
- Curved – 2 blocks along the magnet
- 1.81T
90° Gantry Dipole

- Window frame type magnet
- Extremely large Aperture – must accommodate scanned beam
- Curved – 3 blocks along the magnet
- 1.81T

Scanning dipole (1.13)

- Window frame type magnet
- Lamination thickness 0.35 mm
- Thin-walled vacuum chamber
- 0.31T, 62T/s
LEBT Steerer (2.1)

- Double steering magnet (horiz./vert.)
- Window-Frame-Magnet (x,y)
- Cylindrical coils
- No active cooling
- 0.0252T

Matching Steerer (2.2)

- Double steering magnet (x,y)
- Window-Frame-Magnet (x,y)
- 0.085T
Rohrsteerer (2.3)

- (Beam) Pipe Steering Magnet
- Coil-dominated $\Rightarrow$ cos$\theta$-Design
- Double steering $(x,y)$
- Low-Cost-Steering magnet
  - Yoke: stator of standard electrical motor
  - Indirect cooling
  - 0.05T

Synchrotron (Vertical) Steerer (2.4)

- Simple vertical steering magnet
- Window frame type magnet
- Cylindrical coils
- 0.134T
HEBT Steerer (2.5)

- Simple steering magnet (x or y)
- Window frame type magnet
- Cylindrical coils
- 0.1T

LEBT Quadrupole (3.1 and 3.2)

- Quadrupole without increased pole basis
- Singulett and tripllett
- 3.2T/m
**IH Quadrupole (3.3, 3.4)**

- Compact design with highest gradient
  - Maximum Pole basis
  - CoFe yoke laminations (0.35mm)
  - One layer coil
  - Up to 124T/m

**MEBT Quadrupole (3.5) / Gantry Quadrupole (3.6)**

- Maximum pole basis
- 18.8T/m
- 1 skew quadrupole
HEBT Quadrupole (3.7)

- Cross section as 3.5 und 3.6, but longer yoke
- 19.3 T/m

Synchrotron Quadrupole (3.8)

- "Figure of 8" type quadrupole
- Removable pole end pieces for field optimization and length adjustment
- 7.0 T/m
Solenoid (4.1)

- 0.54T
- ~0.5t
- Diameter ~0.6m
- Length ~0.3m

Sextupol (4.2)

- Yoke 3 parts
- $d^2B/dx^2 = 26.7T/m^2$
Literature

- CERN Accelerator School (CAS) Magnets in Bruges  
  https://cds.cern.ch/record/1158462
- CAS - Measurement and alignment of accelerator and detector magnets  
  https://cds.cern.ch/record/318977
- US Particle Accelerator School, Iron Dominated Electromagnet Design, Jack Tanabe, June 2005  
- ...

Questions?