Warm Magnets

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Contents

• Introduction: magnetic field and warm magnet principles
• Field description and magnet types
• Practical magnet design & manufacturing
• Permanent magnets
• Examples of accelerator magnets from the early times until the present
• Literature on warm Magnets
Magnet types, technological view

We can also classify magnets based on their technology.

- Electromagnet
- Permanent magnet
- Iron dominated
- Coil dominated
- Normal conducting (resistive)
- Superconducting
- Static
- Cycled / ramped slow pulsed
- Fast pulsed
In Geneva, on 7/07/2023, the (estimated) flux density is

\[ |B| = 47753 \text{ nT} = 0.047753 \text{ mT} = 4.7753 \times 10^{-5} \text{ T} \approx 0.5 \text{ Gauss.} \]

\[ B_{\text{horizontal}} = 22291 \text{ nT} \]

For comparison: \(1.6 \times 10^9 \text{ T}\) in the ultraluminous pulsar in the Milky Way J0243.6+6124. see: https://www.universetoday.com/ 17th July 2022
Maxwell equations

Integral form

\[ \oint \vec{H} \, d\vec{s} = \oint_A \left( \vec{J} + \frac{\partial \vec{D}}{\partial t} \right) \, d\vec{A} \]

Ampere’s law

\[ \oint \vec{E} \, d\vec{s} = - \frac{\partial}{\partial t} \oint_A \vec{B} \, d\vec{A} \]

Faraday’s equation

\[ \int_A \vec{B} \, d\vec{A} = 0 \]

Gauss’s law for magnetism

\[ \int_A \vec{D} \, d\vec{A} = \int_V \rho \, dV \]

Gauss’s law

Differential form

\[ \text{rot} \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \]

\[ \text{rot} \vec{E} = - \frac{\partial \vec{B}}{\partial t} \]

\[ \text{div} \vec{B} = 0 \]

\[ \text{div} \vec{D} = \rho \]

With:

\[ \vec{B} = \mu \vec{H} = \mu_0 \mu_r \vec{H} = \mu_0 \left( \vec{H} + \vec{M} \right) \]

\[ \vec{D} = \varepsilon \vec{E} = \varepsilon_0 \left( \vec{E} + \vec{P} \right) \]

\[ \vec{J} = \kappa \vec{E} + J_{\text{imp}}. \]
Magnetostatics

Let’s have a closer look at the 3 equations that describe magnetostatics

1. Gauss law of magnetism
   \[ \text{div} \, \vec{B} = 0 \]  always holds

2. Ampere’s law with no time dependencies
   \[ \text{rot} \, \vec{H} = \vec{J} \]  holds for magnetostatics

3. Relation between \( \vec{H} \) field and the flux density \( \vec{B} \)
   \[ \vec{B} = \mu_0 \mu_r \vec{H} \]  holds for linear materials
Magnetic fields

From Ampere’s law with no time dependencies (Integral form)
\[ \oint_c \vec{B} \cdot d\vec{l} = \mu_0 I_{encl} \]

We can derive the law of Biot and Savart

If you wanted to make a \( B = 1.5 \) T magnet with just two infinitely thin wires placed at 100 mm distance in air one needs:
\[ I = 187500 \text{ A} \]

- To get reasonable fields (\( B > 1 \) T) one needs large currents
- Moreover, the field homogeneity will be poor
Iron dominated magnets

With the help of an iron yoke we can get fields with less current.

Example: C shaped dipole for accelerators

\[ \int_c \vec{H} \, dl = NI \]

\[ N \cdot I = H_{\text{iron}} \cdot l_{\text{iron}} + H_{\text{air gap}} \cdot l_{\text{air gap}} \]

\[ N \cdot I = \frac{B}{\mu_0 \mu_r} \cdot l_{\text{iron}} + \frac{B}{\mu_0} \cdot l_{\text{air gap}} \]

\[ N \cdot I = \frac{B}{\mu_0} \cdot l_{\text{air gap}} \]

This is valid as \( \mu_r \gg 1 \) in the iron : limited to \( B < 2 \, \text{T} \)

**Example:**

- **B** = 1.5 T
- **Gap** = 50 mm
- **N . I** = 59683 A
- 2 x 30 turn coil
- **I** = 994 A
- @5 A/mm², 200 mm²
- 14 x 14 mm Cu

\[ \oint_c H \, dl = NI \]

\[ N \cdot I = H_{\text{iron}} \cdot l_{\text{iron}} + H_{\text{air gap}} \cdot l_{\text{air gap}} \]

\[ N \cdot I = \frac{B}{\mu_0 \mu_r} \cdot l_{\text{iron}} + \frac{B}{\mu_0} \cdot l_{\text{air gap}} \]

\[ N \cdot I = \frac{B}{\mu_0} \cdot l_{\text{air gap}} \]
Imagine a magnet with a 50 mm vertical gap (horizontal width ~100 mm)
Iron magnet wrt to an air coil:
- Up to 1.5 T we get ~6 times the field
- Between 1.5 T and 2 T the gain flattens off: the iron saturates
- Above 2 T the slope is like for an air-coil: currents become too large to use resistive coils

These two curves are the transfer functions – B field vs. current – for the two cases
Magnetic field quality: multipole description

\[ B_y(z) + iB_x(z) = 10^{-4}B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left( \frac{x + iy}{R_{\text{ref}}} \right)^{n-1} \]

with:

\[ z = x + iy, \]

\( B_x \) and \( B_y \) the flux density components in the x and y direction,

\( R_{\text{ref}} \) the radius of the reference circle,

\( B_1 \) the dipole field component at the reference circle,

\( b_n \) the normal nth multipole component,

\( a_n \) the skew nth multipole component.

The “wanted” \( b_n \) or \( a_n \) is equal to 1

In a ring-shaped accelerator, where the beam does multiple passes, one typically demands:

\[ a_n, \ b_n \leq 1 \ \text{unit} \ 10^{-4} \]
In 3D, the longitudinal dimension of the magnet is described by a magnetic length

\[ l_{\text{mag}} B_0 = \int_{-\infty}^{\infty} B(z) dz \]

magnetic length \( L_{\text{mag}} \) as a first approximation:

- For dipoles: \( L_{\text{mag}} = L_{\text{yoke}} + d \)  \[ d = \text{pole distance} \]
- For quadrupoles: \( L_{\text{mag}} = L_{\text{yoke}} + r \)  \[ r = \text{radius of the inscribed circle between the 4 poles} \]
Magnets in an accelerator: power convertor and circuit

- B field stability in time: $\sim 10^{-5} - 10^{-6}$
- Typical R of a magnet $\sim 20\,\text{m}\Omega - 60\,\text{m}\Omega$
- Typical L of a magnet $\sim 20\,\text{mH} - 200\,\text{mH}$
- Powering cable (for 500A): Cu 250 mm$^2$ (Cu: 17 n$\Omega$.m) $R = 70\,\mu\Omega$/m, for 200m: $R = 13\,\text{m}\Omega$
- Take a typical rise time 1s

Then the Power Convertor has to Supply: 0-500 A with a stability of a few ppm.
Voltage up to 40 V (resistive)
And 100 V (inductive)
Types of magnetic fields for accelerators

NORMAL: vertical field on mid-plane

Dipole: $|B| = const$

Quadrupole: $|B| = G \cdot r$

Sextupole: $|B| = \frac{1}{2} B'' \cdot r^2$

Octupole: $|B| = \frac{1}{6} B''' \cdot r^3$

SKEW: horizontal field on mid-plane

Courtesy D. Tommasini, CERN
fluxlines in magnets

Dipole

Quadrupole

sextupole
Symmetry and allowed harmonics

In a fully symmetric magnet certain field harmonics are natural.

<table>
<thead>
<tr>
<th>Magnet type</th>
<th>Allowed harmonics $b_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>n=1 Dipole</td>
<td>n=3,5,7,...</td>
</tr>
<tr>
<td>n=2 Quadrupole</td>
<td>n=6,10,14</td>
</tr>
<tr>
<td>n=3 Sextupole</td>
<td>n=9,15,21</td>
</tr>
<tr>
<td>n=4 Octupole</td>
<td>n=12,20,28</td>
</tr>
</tbody>
</table>

Non-symmetric designs and fabrication errors give rise to non allowed harmonics: $b_n$ with n other than listed above and $a_n$ with any n
## Basic magnet types

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Pole shape</th>
<th>Transfer function</th>
<th>Inductance (H)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram 1" /></td>
<td>parallel</td>
<td>$B = \mu_0 NI / g$</td>
<td>$L = \mu_0 N^2 A / g$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A \approx (w+1.2 \cdot g) \cdot (l+g)$</td>
</tr>
<tr>
<td><img src="image2.png" alt="Diagram 2" /></td>
<td>parallel</td>
<td>$B = \mu_0 NI / g$</td>
<td>$L = \mu_0 N^2 A / g$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A \approx (w+1.2 \cdot g) \cdot (l+g)$</td>
</tr>
<tr>
<td><img src="image3.png" alt="Diagram 3" /></td>
<td>parallel</td>
<td>$B = \mu_0 NI / g$</td>
<td>$L = 2\mu_0 N^2 A / g$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A \approx (d+2/3t) \cdot (l+g)$</td>
</tr>
<tr>
<td><img src="image4.png" alt="Diagram 4" /></td>
<td>parallel</td>
<td>$B = \mu_0 NI / g$</td>
<td>$L = \mu_0 N^2 A / g$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A \approx (d+2/3t) \cdot (l+g)$</td>
</tr>
<tr>
<td><img src="image5.png" alt="Diagram 5" /></td>
<td>$2xy=R^2$</td>
<td>$B(r) = G \cdot r$</td>
<td>$L = 8\mu_0 N^2 A / R$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A \approx (d+1/3t) \cdot (l+2/3R)$</td>
</tr>
<tr>
<td><img src="image6.png" alt="Diagram 6" /></td>
<td>$3x^2y-y^3=R^3$</td>
<td>$B(r) = S \cdot r^2 = \frac{1}{2} B'' \cdot r^2$</td>
<td>$L = 20\mu_0 N^2 A / R$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$S = 3\mu_0 NI / R^3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A \approx (d+1/3t) \cdot (l+1/2R)$</td>
</tr>
</tbody>
</table>

Courtesy D. Tommasini, CERN
Practical magnet design & manufacturing

Steps in the process:

1. Specification
2. Conceptual design
3. Detailed design
   1. Yoke: yoke size, pole shape, FE model optimization
   2. Coils: cross-section, geometry, cooling
   3. Raw material choice
   4. Yoke ends, coil ends design
4. Yoke manufacturing, tolerances, alignment, structure
5. Coil manufacturing, insulation, impregnation type
6. Magnetic field measurements
Before you start designing you need to get from the accelerator designers:

- $B(T)$ or $G \, (T/m)$ (higher orders: $G_3(T/m^2)$, etc)
- Magnet type: C-type, H-type, DC (slow ramp) or AC (fast ramp)
- Aperture:
  - Dipole: “good field region“ → air-gap height and width
  - Quads and higher order: “good field region“ → aperture inscribed circle
- Magnetic length and estimated real length
- Current range of the power convertor (and the voltage range: watch out for the cables )
- Field quality:
  - **dipole**: $\frac{\Delta B}{B}(\text{ref volume})$, **quadrupole**: $\frac{\Delta G}{G}(\text{reference circle})$
  - or $b_n, \ a_n$ for $n = 1,2,3,4,5,…$
- Cooling type: air, water ($P_{\text{max}}$, $\Delta p_{\text{max}}$ and $Q_{\text{max}}$ (l/min))
- Jacks and Alignment features
- Vacuum chamber to be used → fixations, bake-out specifics

These need careful negotiations and often iterations after the conceptual (and detailed) design, and the result will probably be a compromise.
Conceptual design

- From $B$ and $l$ you get $NI$ (A)
  \[ NI = \frac{l_{\text{airgap}}B}{\mu_0} \]

- From $NI$ (A) and the power convertor $I_{\text{max}}$ you get $N$

- Then you decide on a coil X-section using:
  \[ j_{\text{coil}} = \frac{5A}{mm^2} \text{ for water cooled} \]
  \[ \text{or } j_{\text{coil}} = \frac{1A}{mm^2} \text{ for air cooled} \]

- This defines the coil cavity in the yoke (you add 0.5 mm insulation around each conductor and 1 mm ground insulation around the coil) and select the best fitting rectangular

- You can then draw the draft X-section using:
  \[ W_{\text{yoke}} = W_{\text{pole}} \frac{B}{B_{\text{sat}}} \quad \text{with} \quad 1.5 T < B_{\text{sat}} < 2 T \]

- Decide on the coil ends: racetrack, bedstead
- You now have the rough magnet cross section and envelope
Power generated

Power generated by coil
• DC: from the length of the conductor $N \cdot L_{turn}$, the cross-section $\sigma$ and the
  specific resistivity $\rho$ of the material one gets the spent Power in the coil

\[ P/l[W/m] = \frac{\rho}{\sigma} I^2 \quad \text{with:} \quad \rho_{Cu} = 1.72(1 + 0.0039(T - 20))10^{-8}\Omega m \]
\[ \rho_{Al} = 2.65(1 + 0.0039(T - 20))10^{-8}\Omega m \]

For AC: take the average $I^2$ for the duty cycle

Power losses due to hysteresis in the yoke: (Steinmetz law up to 1.5 T)
\[ P[W/kg] = \eta f B^{1.6} \quad \text{with } \eta = 0.01 \text{ to } 0.1, \quad \eta_{Si\text{ steel}} \approx 0.02 \]

Power losses due to eddy currents in the yoke
\[ P[W/kg] = 0.05 \left( d_{lam} \frac{f}{10} B_{av} \right)^2 \]

with $d_{lam}$ the lamination thickness in mm, $B_{av}$ the average flux density

Courtesy D. Tommasini, CERN
Cooling circuit parameters

Aim: to design \(d_{\text{cooling}}\), \(P_{\text{water}}[\text{bar}]\), \(\Delta P[\text{bar}]\), \(Q[\text{l/min}]\)

- Choose a desired \(\Delta T\) (20\(^\circ\)C or 30\(^\circ\)C depending on the \(T_{\text{cooling water}}\))

- with the heat capacity of water (4.186 kJ/kg\(^\circ\)C) we now know the required water flow rate: \(Q[\text{l/min}]\)

- The cooling water needs to be in moderately turbulent regime (with laminar flow the flow speed is zero on the wall !): \(Reynolds > 2000\)

\[
Re = \frac{dv}{v} \sim 140 \, d[mm] \, v[m/s] \quad \text{for} \quad T_{\text{water}} \sim 40^\circ C
\]

- A good approximation for the pressure drop in smooth pipes can be derived from the Blasius law, giving:

\[
\Delta P[\text{bar}] = 60 \, L[m] \, \frac{Q[\text{l/min}]^{1.75}}{d[mm]^{4.75}}
\]
Theoretical pole shapes

The ideal poles for dipole, quadrupole, sextupole, etc. are lines of constant scalar potential

- **Dipole** \( y = \pm \frac{h}{2} \) straight line
- **quadrupole** \( 2xy = \pm r^2 \) hyperbola
- **sextupole** \( 3x^2y - y^3 = \pm r^3 \)

To calculate pole shapes of pure and combined function magnet poles a convenient new code exist, the note describing the method and the Python code can be found on:

A. Milanese, CERN, "Tracking magnetic equipotential curves for general combinations of multipolar fields" : https://edms.cern.ch/document/2792136/1

**Example of combined quadrupole-sextupole**

4.7 Quadrupole \( B' = 2 \) T/m + Sextupole \( B'' = 150 \) T/m², tangent poles

```
geom_ch = (0.050, 0.030, 2)  # hyperbola
R = 0.020  
B = np.array([0, 2*R, 0.5*150*R**2])
A = np.array([ ])  
poles_of_interest = 'tangent'
```
Practical pole shapes: shims and alignment features

- Dipole example: below a lamination of the LEP main bending magnets, with the pole shims well visible

from: LEP design report

- Quadrupoles: at the edge of the pole one can put a combination a shim and alignment feature (examples: LHC-MQW, SESAME quads, etc)

- This then also allows to measure the pole distances: special instrumentation can be made for this
Finite Element electromagnetic models

- Aim of the electromagnetic FE models:
  - The exact shape of the yoke needs to be designed
    - Optimise field quality: adjust pole shape, minimise high saturation zones
    - Minimise the total steel amount (magnet weight, raw material cost)
  - Calculate the field: needed for the optics and dynamic aperture modelling
    - Transfer function $B_{xsection}(l)$, $\int Bdl$, magnetic length
    - Multipoles (in the centre of the magnet and integrated) $b_n$ and $a_n$

- Some Electromagnetic FE software packages that are often used:
  - Opera from Cobham: 2D and 3D commercial software see: http://operafea.com/
  - “Good old” Poisson, 2D: now distributed by LANL-LAACG see: http://laacg.lanl.gov/laacg/services/download_sf.phtml
  - ROXIE (CERN) 2D and 3D, specialised for accelerator magnets; single fee license for labs & universities see: https://espace.cern.ch/roxie/default.aspx
  - ANSYS Maxwell: 2D and 3D commercial software see: http://www.ansys.com/Products/Electronics/ANSYS-Maxwell
  - RAT (Little Beast Engineering): 3D magnetic field solver for any coil geometry, see: https://www.littlebeastengineering.com/
FE models: steel curves

You can use a close ‘generic’ B(H) curve for a first cut design
You HAVE to use a measured, and smoothed, curve to properly calculate
\[ B_{xsection}(l) , \int Bdl , b_n \text{ and } a_n \]
As illustration the curves for several types of steel:
Yoke shape, pole shape: FE model optimisation

Use symmetry and the thus appropriate boundary conditions to model only $\frac{1}{4}$th (dipoles, quadrupoles) or even $\frac{1}{6}$th sextupoles. Meshing needs attention in the detailed areas like poles, slits, etc.

<table>
<thead>
<tr>
<th>Table 8.6: Main parameters of the MQW normal conducting quadrupole magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnet type</strong></td>
</tr>
<tr>
<td>Magnetic length</td>
</tr>
<tr>
<td>Beam separation</td>
</tr>
<tr>
<td>Aperture diameter</td>
</tr>
<tr>
<td>Operating temperature</td>
</tr>
<tr>
<td>Nominal gradient</td>
</tr>
<tr>
<td>Nominal current</td>
</tr>
<tr>
<td>Inductance</td>
</tr>
<tr>
<td>Resistance</td>
</tr>
<tr>
<td>Conductor X-section</td>
</tr>
<tr>
<td>Cooling hole diameter</td>
</tr>
<tr>
<td>Number of turns per magnet</td>
</tr>
<tr>
<td>Minimum water flow</td>
</tr>
<tr>
<td>Dissipated power at $I_{\text{nom}}$</td>
</tr>
<tr>
<td>Mass</td>
</tr>
</tbody>
</table>
Yoke manufacturing

- Yokes are nearly always laminated to reduce eddy currents during ramping
- Laminations can be coated with an inorganic (oxidation, phosphating, Carlite) or organic (epoxy) layer to increase the resistance
- Magnetic properties: depend on chemical composition + temperature and mechanical history
- Important parameters: coercive field $H_c$ and the saturation induction.
  - $H_c$ has an impact on the remnant field at low current
    - $H_c < 80$ A/m typical
    - $H_c < 20$ A/m for magnets ranging down also to low field $B < 0.05$ T
  - low carbon steel (C content < 0.006%) is best for higher fields $B > 1$ T
- Yoke laminations can be glued together (small to medium size magnets), bolted or welded into stacks

### Example specification for 1.5 mm thick oxide coated steel for the LHC warm separation magnets, $B_{\text{max}} = 1.53$ T

<table>
<thead>
<tr>
<th>Field Strength [A/m]</th>
<th>Minimum Induction [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.20</td>
</tr>
<tr>
<td>60</td>
<td>0.50</td>
</tr>
<tr>
<td>120</td>
<td>0.95</td>
</tr>
<tr>
<td>500</td>
<td>1.4</td>
</tr>
<tr>
<td>1 200</td>
<td>1.5</td>
</tr>
<tr>
<td>2 500</td>
<td>1.62</td>
</tr>
<tr>
<td>5 000</td>
<td>1.71</td>
</tr>
<tr>
<td>10 000</td>
<td>1.81</td>
</tr>
<tr>
<td>24 000</td>
<td>2.00</td>
</tr>
</tbody>
</table>

### Example specification for 0.5 mm thick epoxy coated steel for LHC transfer line corrector magnet $B_{\text{max}} = 0.3$ T

<table>
<thead>
<tr>
<th>Field Strength $H$ [A/m]</th>
<th>Minimum Induction $B$ [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.07</td>
</tr>
<tr>
<td>300</td>
<td>1.05</td>
</tr>
<tr>
<td>500</td>
<td>1.35</td>
</tr>
<tr>
<td>1000</td>
<td>1.50</td>
</tr>
<tr>
<td>2500</td>
<td>1.62</td>
</tr>
<tr>
<td>5000</td>
<td>1.72</td>
</tr>
<tr>
<td>10000</td>
<td>1.82</td>
</tr>
</tbody>
</table>
Yoke manufacturing

Stacking an MBW dipole yoke stack

Stacking an MQW quadrupole yoke stack

MQW yoke assembly
Yoke stack manufacturing

Double aperture LHC quadrupole MQW
Stacking on a precision table

Welding the structural plates

Finished stack
Yokes: holding a laminated stack together

- Yokes are either
  - Glued, using epoxy coated laminations
  - Welded, full length plates are welded on the outside
  - Compressed by tie rods in holes
  or a combination of all these
- To be able to keep the yoke (or yoke stack) stable you probably need end plates (can range from ± 1 cm to 5 cm depending on the size)
- The end plates have pole chamfers and often carry end shims
Coil manufacturing, insulation, impregnation type

- Winding Cu conductors is an well established technique
- When the Cu conductor is thick it is best to use “dead soft” Cu (T treatment)
- Insulation of the coil
  - Glass fibre – epoxy impregnated
    - Individual conductor 0.5 mm glass fibre, 0.25 mm tape wound half lapped
    - Impregnated with radiation resistant epoxy, total glass volume ratio >50%
  - For thin conductors: Cu enamel coated, possibly epoxy impregnated afterwards
Coil ends

For dipoles some main types are racetrack of bedstead

Quadrupoles
Coil manufacturing

MQW Glass fibre tape wrapping.

Winding the hollow Cu conductor
Coil manufacturing

Mounted coil

coil electrical test (under water !)

Dipoles racetrack coil

MBXW Coil winding

Finished MBXW coil
Magnetic field measurements

Several Magnetic Measurements techniques can be applied, e.g.:

- Rotating coils: multipoles and integrated field or gradient in all magnets
- Stretched wire: magnetic centre and integrated gradient for $n > 1$ magnets
- Hall probes: field map
- Pickup coils: field on a current ramp
- Example below: MQW: double aperture quadrupole for the LHC.

Rotating radial coil
Sextupoles

- These are sextupoles (with embedded correctors) of the main ring of the SESAME light source
Permanent magnets

Remark: The field calculation of a PM follows a similar logic as for a resistive magnet (slide 9). This can be found in Ref[5]

- Permanent magnet because of space between DTL tanks
- Sm$_2$Co$_{17}$ permanent magnets
- Integrated gradient of 1.3 to 1.6 Tesla
- 15 magnets
- Magnet length 0.100 m
- Field quality/amplitude tuning blocks

Linac4 @ CERN permanent magnets, quadrupoles

Sextupole Hallback Array

Courtesy D. Tommasini, CERN
Hybrid magnets

CLIC final focus,

\[ \text{Gradient: } > \, 530 \, T/m \]
\[ \text{Aperture } \Theta: \, 8.25 \, mm \]
\[ \text{Tunability: } 10-100\% \]

Courtesy M. Modena, D. Tommasini, CERN
Examples;

Some history, some modern regular magnets and some special cases
The 184” (4.7 m) cyclotron at Berkeley (1942)

B=1.6 T

Courtesy A. Milanese, CERN
Cyclotrons

Harvard 1948

\( \text{PSI} = 590 \text{ MeV proton} \)

\( B_{\text{peak}} = 2 \text{ T} \)

picture: CERN courier
Some early magnets (early 1950-ies)

Bevatron
(Berkeley)
1954, 6.2 GeV
B=1.55T

Cosmotron
(Brookhaven)
1953, 3.3 GeV
B=1.4T
Aperture:
20 cm x 60 cm
PS combined function dipole

Magnetic field:
- at injection
- for 24.3 GeV
- maximum

Weight of one magnet unit

Gradient @ 1.2 T : 5 T/m

Equipped with pole-face windings for higher order corrections

Water cooled Al race-track coils
4 accelerator rings in a common yoke. (increase total beam intensity by 4 in presence of space charge limitation at low energy): \( B = 1.48 \ T \) @ 2 GeV
Was originally designed for 0.8 GeV!
dipole magnet : SPS dipole

H magnet     type MBB

\[ B = 2.05 \, \text{T} \]

Coil : 16 turns

\[ I_{\text{max}} = 4900 \, \text{A} \]

Aperture = 52 \times 92 \, \text{mm}^2

\[ L = 6.26 \, \text{m} \]

Weight = 17 \, \text{t}
Quadrupole magnet: SPS quadrupole

type MQ

G = 20.7 T/m

Coil: 16 turns

I_{\text{max}} = 1938 A

Aperture inscribed radius = 44 mm

L_{\text{coil}} = 3.2 m

Weight = 8.4 t
MBW LHC warm separation dipole (1)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>52 mm</td>
</tr>
<tr>
<td>Nominal field</td>
<td>1.42 T</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>3.4 m</td>
</tr>
<tr>
<td>Weight</td>
<td>18 t</td>
</tr>
<tr>
<td>Water flow</td>
<td>19 l/min</td>
</tr>
<tr>
<td>Power</td>
<td>29 kW</td>
</tr>
</tbody>
</table>
MQW: LHC warm double aperture quadrupole
Elena, antiproton decelerator

- Ring dipoles 8/8
- TL dipoles 3/3
- Skew quads 3/3
- HV correctors 3/14
Soleil, synchrotron light-source

Courtesy A. Dael, CEA
Magnet designs for FCC-ee

Twin aperture dipole

Table 3.1: Parameters of the main bending magnets.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength, 45.6 GeV to 182.5 GeV</td>
<td>mT 14.1 to 36.6</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>m 21.94 / 23.94</td>
</tr>
<tr>
<td>Number of units per ring</td>
<td>mm 2900</td>
</tr>
<tr>
<td>Good field region (GFR) in horizontal plane</td>
<td>mm ± 10</td>
</tr>
<tr>
<td>Field quality in GFR (not counting quadrupole term)</td>
<td>$10^{-4}$ ≈ 1</td>
</tr>
<tr>
<td>Central field</td>
<td>mT 37</td>
</tr>
<tr>
<td>Expected $b_2$ at 10 mm</td>
<td>$10^{-4}$ ≈ 3</td>
</tr>
<tr>
<td>Expected higher order harmonics at 10 mm</td>
<td>$10^{-4}$ &lt; 1</td>
</tr>
<tr>
<td>Maximum operating current</td>
<td>kA 1.9</td>
</tr>
<tr>
<td>Maximum current density</td>
<td>A/mm$^2$ 0.79</td>
</tr>
<tr>
<td>Number of busbars per side</td>
<td>2</td>
</tr>
<tr>
<td>Resistance per unit length (twin magnet)</td>
<td>$\mu$F/m 22.7</td>
</tr>
<tr>
<td>Maximum power per unit length (twin magnet)</td>
<td>W/m 164</td>
</tr>
<tr>
<td>Maximum total power, 81.0 km (interconnections included)</td>
<td>MW 13.3</td>
</tr>
<tr>
<td>Inter-beam distance</td>
<td>mm 300</td>
</tr>
<tr>
<td>Iron mass per unit length</td>
<td>kg/m 219</td>
</tr>
<tr>
<td>Aluminium mass per unit length</td>
<td>kg/m 19.9</td>
</tr>
</tbody>
</table>

Table 3.2: Parameters of the main quadrupole magnets.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum gradient</td>
<td>T/m 10.0</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>m 3.1</td>
</tr>
<tr>
<td>Number of twin units per ring</td>
<td>mm 2900</td>
</tr>
<tr>
<td>Aperture diameter</td>
<td>mm 84</td>
</tr>
<tr>
<td>Radius for good field region</td>
<td>mm 10</td>
</tr>
<tr>
<td>Field quality in GFR (not counting dip. term)</td>
<td>$10^{-4}$ ≈ 1</td>
</tr>
<tr>
<td>Maximum operating current</td>
<td>A 474</td>
</tr>
<tr>
<td>Maximum current density</td>
<td>A/mm$^2$ 2.1</td>
</tr>
<tr>
<td>Number of turns</td>
<td>2 × 3</td>
</tr>
<tr>
<td>Resistance per twin magnet</td>
<td>$\Omega$ 33.3</td>
</tr>
<tr>
<td>Inductance per twin magnet</td>
<td>mH 81</td>
</tr>
<tr>
<td>Maximum power per twin magnet</td>
<td>kW 7.4</td>
</tr>
<tr>
<td>Maximum power, 2900 units (with 5% cable losses)</td>
<td>MW 22.6</td>
</tr>
<tr>
<td>Iron mass per magnet</td>
<td>kg 4400</td>
</tr>
<tr>
<td>Copper mass per magnet (two coils)</td>
<td>kg 820</td>
</tr>
</tbody>
</table>

Literature on warm accelerator magnets

• Books
  5. R. Appleby, et al., The Science and Technology of Particle Accelerators. 2022, Open access: https://library.oapen.org/handle/20.500.12657/53311

• Schools
  7. CAS Bruges, 2009, specialized course on magnets, 2009, CERN-2010-004
  8. CAS Frascati 2008, Magnets (Warm) by D. Einfeld
  9. CAS Varna 2010, Magnets (Warm) by D. Tommasini

• Papers and reports
  11. A. Milanese, ”Tracking magnetic equipotential curves for general combinations of multipolar fields” : EDMS 2792136, 2023
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