High Field Accelerator Magnets

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CAS

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• Introduction: magnetic field and high field magnets

• How to get high fields in accelerator dipole and quadrupole magnets?

• Superconductors for magnets

• Practical accelerator magnet design

• High field magnets for future accelerators

• Literature on High Field Magnets
Magnetic fields

From Ampere’s law with no time dependencies

\[ \oint_C \mathbf{B} \cdot d\mathbf{l} = \mu_0 I_{\text{encl}}. \]

We can derive the law of Biot and Savart

If you wanted to make a \( B = 8 \) T magnet with just two infinitely thin wires placed at 50 mm distance one needs: \( I = 5 \times 10^5 \) A

LHC dipole coil 80 turns of 11850 A at 8.3 T = 9.48 \times 10^5 A

To get high fields (\( B > 10 \) T) one needs very large currents in small volumes

For LHC dipole@8.3 T \( \sim 1 \) MA in 3300 mm\(^2\) : \( \sim 300 \) A/mm\(^2\)

(overall current density in the coil area)
Iron magnets

“resistive” or “classical” magnets

\[ \oint H \cdot dl = N \cdot I \]

\[ N \cdot I = H_{\text{iron}} \cdot l_{\text{iron}} + H_{\text{airgap}} \cdot l_{\text{airgap}} \Rightarrow \]

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

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

This is valid as \( \mu_r \gg \mu_0 \) in the iron: limited to \( B < 2 \text{T} \)

Example: C shaped dipole for accelerators

Yoke

\( B = 1.8 \text{T} \)

Gap = 50 mm

\( N \cdot I = 71619 \text{ A} \)

2 x 36 turn coil

\( I = 1000 \text{ A} \)

@5 A/mm\(^2\), 200 mm\(^2\)

14 x 14 mm Cu

\( \mu_r \) as function of B for low carbon magnet steel (Magnetit BC)
Resistive accelerator magnet example: SPS dipole

- **H magnet** type MBB
- **B** = 2.05 T
- **Coil**: 16 turns
- **I_{\text{max}}** = 4900 A
- **Aperture** = 52 × 92 mm²
- **L** = 6.26 m
- **Weight** = 17 t
Superconductors

Below a the critical surface the material is “superconducting” . Above the surface it is “normal conducting”

- $\theta_c$ Critical Temperature (at zero field and current density)
- $B_{c2}$ Critical Field (at zero temperature and current density)
- $J_c$ Critical Current Density (at zero temperature and field)

The Critical surface depends on the material type (Nb-Ti, Nb$_3$Sn, etc) and the processing.

Superconducting means: $R = 0$

$J$: few x $10^3$ A/mm$^2$ inside the superconductor.
High field magnets example: resistive solenoids

High field resistive solenoids
- Onion shells of coils
- High power consumption

Institutes:
- NHFML, National High Magnetic Field Laboratory, Tallahassee, Florida (US)
  45 T Hybrid magnet, Ø 32mm, Power: 33 MW
- HFML, High Field Magnet Laboratory, Nijmegen (NL)
  33.0 T Bitter magnet, Ø 32mm
  Power: 17 MW
- LNCMI, Laboratoire National des Champs Magnétiques Intenses, Grenoble (Fr)
  35 T Hybrid magnet, Ø 34mm
Superconducting Accelerator dipole magnets (1)

- Tevatron: 4.4 T
  1983

- RHIC: 3.5 T
  2000

- HERA: 5 T
  1992

- LHC: 8.34 T
  2008
Size overview

**HERA**
B = 4.7 T  
BORE : 75 mm

**RHIC**
B = 3.5 T  
Bore : 80 mm

**TEVATRON**
B = 4.5 T  
Bore : 76 mm

**LHC**
B = 8.3 T  
Bore : 56 mm
Superconducting Accelerator dipole magnets (2)

Tevatron dipoles: 4.2 T
single aperture, warm yoke

Tevatron

LHC
## Superconducting Accelerator dipole magnets (2)

<table>
<thead>
<tr>
<th>Machine</th>
<th>place</th>
<th>Type</th>
<th>Energy (GeV)</th>
<th>Peak Dipole field (T)</th>
<th># dipoles</th>
<th>Dipole Length (m)</th>
<th>Ring circ. (km)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron</td>
<td>FNAL (USA)</td>
<td>p-pbar FT/coll.</td>
<td>1000 x 1000</td>
<td>4.4</td>
<td>774</td>
<td>6.12</td>
<td>6.28</td>
<td>1983/1987</td>
</tr>
<tr>
<td>HERA</td>
<td>DESY (D)</td>
<td>e⁻/⁺ - p collider</td>
<td>40x920</td>
<td>5</td>
<td>416</td>
<td>8.82</td>
<td>6.34</td>
<td>1992</td>
</tr>
<tr>
<td>RHIC</td>
<td>BNL (USA)</td>
<td>p-p, Au-Au, Cu-Cu, d-Au</td>
<td>100/n</td>
<td>3.5</td>
<td>2x192+12</td>
<td>9.45</td>
<td>3.83</td>
<td>2000</td>
</tr>
<tr>
<td>LHC</td>
<td>CERN (Eu)</td>
<td>p-p, Pb-Pb</td>
<td>7000 x 7000</td>
<td>8.34</td>
<td>1232</td>
<td>14.3</td>
<td>26.66</td>
<td>2008</td>
</tr>
</tbody>
</table>

20 years were needed to go from 4 T to 8 T!
Detector magnets

CMS Solenoid
- Inner Bore 6.3 m
- Length 12.5 m
- Central field 4 T
- Nominal current 19 kA
- Stored Energy 2.65 GJ
- Cold mass 220 t

ATLAS barrel toroid
- Outer diameter 21 m
- Length 26 m
- $B_{\text{peak}}$ 4.1 T
- Stored Energy 1500 MJ
NMR and research magnets

Solenoids up to 21 T and with a bore of 50 mm (max 89 mm) are available off the shelf of many firms: Bruker, Agilent, Oxford, Cryogenic, Varian, etc.

As an example from Cryogenic:
solenoid 20 T, 2.2 K, 52 mm Ø bore, l = 285 mm, Ø 500 mm
Fusion Tokamak: ITER

The Tokamak has several magnet systems to confine

• the plasma (TF),
• control it (PF and correction coils),
• and heat it up (CS)

Large amounts of conductor are needed:

• TF system: 376 tonnes Nb$_3$Sn
• CS system: 132 tonnes Nb$_3$Sn
• PF system: 244 tonnes Nb-Ti

Courtesy J-L. Duchateau
What is specific about accelerator magnets?

- Cylindrical volume with perpendicular field
- Dipoles, quadrupoles, etc
- Field quality: \[ \frac{\Delta B_z}{|B|} \leq few \cdot 10^{-4} \]
- Field quality formulated and measured in a multipole expansion,
  \[ B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + i a_n) \left( \frac{x + iy}{R_{ref}} \right)^{n-1} \]
  \[ b_n, a_n \leq few \cdot \text{units} \]
- Long magnets: dipoles from 6 m (Tevatron) to 15 m (LHC)
- Often magnets are bend (9.14 mm sagitta for the LHC dipoles)
How to get high fields in accelerator dipole and quadrupole magnets?

From Ampere’s law one can derive the field resulting from the current in a line conductor and integrate this over the surface of a coil.

- **Dipole 60° sector coil** [see ref 10, 14]
  - The field is *proportional to the current density* \(j\)
  - The field is *proportional to coil width*
  - The field is *independent of aperture*

\[
B_1 = -4 \frac{j \mu_0}{2\pi} \int_0^{\pi/3} \int_r^{r+w} \frac{\rho d\rho d\theta}{\rho} = -\frac{\sqrt{3} \mu_0}{\pi} \frac{JW}{w} \tag{1}
\]

with: \(r\) : inner radius coil \(\rho\) : radial coordinate \(J\) : current density

- **Quadrupole 30° sector coil** [see ref 11, 14]
  - The gradient is *proportional to the current density* \(j\)
  - The gradient depends on \(w/r\)

\[
G = -8 \frac{j \mu_0}{2\pi} \int_0^{\pi/6} \int_r^{r+w} \frac{\rho d\rho d\theta}{\rho} = -\frac{\sqrt{3} \mu_0}{\pi} j \ln \left(1 + \frac{W}{r} \right) \tag{2}
\]

\(\Rightarrow\) by having very high current density close to the beam pipe.


For a in depth study of magnetic field calculations: S. Russenschuck ref[4]
The forces with high field dipole and quadrupole magnets

One can derive the maximum stress in the midplane for a sector dipole coil

- Dipole 60º sector coil [see ref 1, 12]

\[
\sigma \approx j^2 \frac{\mu_0 \sqrt{3}}{6\pi} \max_{\rho \in [r, r+w]} \left[ 2\rho^2 + \frac{r^3}{\rho} - 3\rho (r + w) \right]
\]

(Typically: for 8T : 40 MPa , for 13 T 130 MPa )

with:  
- \( r \): inner radius coil  
- \( \rho \): radial coordinate  
- \( w \): coil width  
- \( J \): current density

- Quadrupole 30º sector coil [see ref 1, 13 ]

\[
\sigma \approx j^2 \frac{\mu_0 \sqrt{3}}{16\pi} \max_{\rho \in [r, r+w]} \left[ 2\rho^2 + \frac{r^4}{\rho^2} + 4\rho^2 \ln \left( \frac{r + w}{\rho} \right) \right]
\]

Cross-section of a dipole based on 60º sector coils

Cross-section of a quadrupole based on 30º sector coils
Superconductors

Nb-Ti is the workhorse for 4 to 10 T
Up to ~2500 A/mm² at 6 T and 4.2 K or at 9 T and 1.9 K
Well known industrial process, good mechanical properties
Thousands of accelerator magnets have been built
10 T field in the coil is the practical limit at 1.9 K

Nb₃Sn: towards 20 T
Can reach up to ~3000 A/mm² at 12 T and 4.2 K
Complex industrial process, higher cost, brittle and strain sensitive
~25 short models for accelerator magnets have been built
~20 T field in the coil is the practical limit at 1.9 K

HTS materials: dreaming 40 T (Bi-2212, YBCO)
–Current density is low, but very little dependence on the magnetic field
–Used in solenoids, used in power lines – no accelerator magnets (only 1 model) have been built – small racetracks have been built
Superconductors

Compilation of engineering current densities (See ref 15, NHMFL)

- **Nb-Ti**: Maximal $J_C$ at 1.9 K for entire LHC Nb-Ti strand production (CERN-T, Bourbou-DT). Reducing the temperature from 4.2 K produces a “$3$ T shift in $J_C$ for Nb-Ti.


- **2223: B.1 Tape Plane**: Sumitomo Electric “Carrier Controlled” MEM’13.

- **MgB₂ 2nd Gen. Mono - MgB₂/Nb/Cu/Mo/In**: The OSU HTFL, 2012.

- **YBCO B⊥ Tape Plane**: Compiled from ASC’02 and ICME’03 papers (J. Parello OSU ST).

- **Bronze Nb₃Sn**: Compiled from ASC’02 and ICME’03 papers (J. Parello OSU ST).

- **High-Jc Nb₃Sn**: Compiled from ASC’02 and ICME’03 papers (J. Parello OSU ST).

- **18+2**: MgB₂/Nb/Cu/Mo/In (courtesy M. Tomco, HyperTech, 2007).

- **MgB₂ 19 Fil. 24% Fill**: MgB₂: 19 Fill. 24% Fill.

- **MgB₂ 1 Fill. 15% Fill**: MgB₂: 1 Fill. 15% Fill.

- **Bi2223: B⊥ Tape plane**: Bi2223: B⊥ Tape plane.

- **Bi2212: OST+NHMFL 100 bar OP**: Bi2212: OST+NHMFL 100 bar OP.

- **Nb₃Sn: Internal Sn RRP®**: Nb₃Sn: Internal Sn RRP®.

- **Nb₃Sn: High Sn Bronze**: Nb₃Sn: High Sn Bronze.

- **Nb-Ti: LHC 1.9 K**: Nb-Ti: LHC 1.9 K.
High temperature superconductor zoo

Critical Temperature and critical parameters:

2nd Oct 2009
L. Rossi
HFM @ CAS Darmstadt
Conductor stability and AC behaviour

• Pure massive superconductor is not stable as they (Nb-Ti, Nb₃Sn) are poor normal conductors
• To ‘cryogenically stabilize’ the conductor one surrounds it in Cu:
  – good electrical conductivity
  – good heat transfer to the He
• During current ramping the filaments will magnetize
  \[ \Rightarrow \text{make them thinner} \]
• Filaments will have magnetic coupling
  \[ \Rightarrow \text{twist the strand} \]
• Practical low temperature superconductors are made as thin (5 \( \mu \text{m} \) – 100 \( \mu \text{m} \)) superconducting filaments in a Cu matrix, which is twisted

\[ \text{M} = \text{wire twist pitch} \]
\[ \text{w} = \text{wire twist pitch} \]
\[ \text{d} = \text{filament diameter} \]
\[ \text{f} = \text{filament diameter} \]
\[ \text{d} = \text{filament diameter} \]

\[ \text{M} = \frac{\text{wire twist pitch}}{\text{wire twist pitch}} \]
\[ \text{w} = \frac{\text{wire twist pitch}}{\text{wire twist pitch}} \]
\[ \text{d} = \frac{\text{filament diameter}}{\text{filament diameter}} \]
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\[ \text{w} = \frac{\text{wire twist pitch}}{\text{wire twist pitch}} \]
\[ \text{d} = \frac{\text{filament diameter}}{\text{filament diameter}} \]
\[ \text{f} = \frac{\text{filament diameter}}{\text{filament diameter}} \]
Superconducting strands: Nb-Ti

- Nb-Ti is the workhorse for present accelerators, medical magnets, cyclotrons, etc

### Strands and Cables for LHC Dipole Magnets

**Performance specification**

<table>
<thead>
<tr>
<th>STRAND</th>
<th>Type 01</th>
<th>Type 02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td>1.065</td>
<td>0.825</td>
</tr>
<tr>
<td>Cu/NbTi ratio</td>
<td>1.6-1.7 ± 0.03</td>
<td>1.9-2.0 ± 0.03</td>
</tr>
<tr>
<td>Filament diameter (μm)</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Number of filaments</td>
<td>8800</td>
<td>6425</td>
</tr>
<tr>
<td>Jc (A/mm²) @1.9 K</td>
<td>1530 @ 10 T</td>
<td>2100 @ 7 T</td>
</tr>
<tr>
<td>μ0M (mT) @1.9 K, 0.5 T</td>
<td>30 ±4.5</td>
<td>23 ±4.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CABLE</th>
<th>Type 01</th>
<th>Type 02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of strands</td>
<td>28</td>
<td>36</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>15.1</td>
<td>15.1</td>
</tr>
<tr>
<td>Mid-thickness (mm)</td>
<td>1.900 ±0.006</td>
<td>1.480 ±0.006</td>
</tr>
<tr>
<td>Keystone angle (degrees)</td>
<td>1.25 ±0.05</td>
<td>0.90 ±0.05</td>
</tr>
<tr>
<td>Cable Ie (A) @ 1.9 K</td>
<td>13750 @ 10T</td>
<td>12960 @ 7T</td>
</tr>
<tr>
<td>Interstrand resistance (μΩ)</td>
<td>10-50</td>
<td>20-80</td>
</tr>
</tbody>
</table>

Cable compaction ~ 91%
Superconducting strands: Nb$_3$Sn

Nb$_3$Sn for High Field Magnets

examples

• OST (US)
  – Restacked Rod Process (RRP) for High Energy Physics (r= 0.7 mm or 0.8 mm, $J_c$ up to 3000 A/mm$^2$@12T, 4.2 K, filaments~50 µm, Cu-nonCu=0.9)

• EAS-Bruker (De)
  – Powder in Tube (PIT) for HEP and others (r=1 mm, $J_c$ up to 2400 A/mm$^2$@12T, 4.2 K, filaments ~50 µm, Cu-nonCu=1.25)

To be reacted at 650°C for ~120 hr
Superconducting strands and tapes: BSCO

BSCO: Bismuth strontium calcium copper oxide

- Available in strands (OST)
- Can reach 400 A/mm² (overall)
- Is fragile under stress and strain
- Powder in a silver tube
- Has to be reacted at 850°C with a temperature precision of 1°C in an oxygen atmosphere
- Can be cabled in high current Rutherford cables

OST wire 0.8 mm using Nexans precursor

Difficult technology but could be promising for high field magnets in >20 T region
Superconducting tapes: YBCO

YBCO: Yttrium barium copper oxide

- Available in tapes: YBCO deposited on a substrate to impose the texture (1-2 \( \mu \text{m} \))
- Can reach > 600 A/mm\(^2\) (overall)
- Is strong under axial stress and strain
- Limited cabling possibilities:
  - Difficult technology but could be promising for high field magnets in >20 T region.
Superconducting cables for magnets

We need multi-strand cables

- Superconducting accelerators are ramped up in time spans 100 s to 1000 s
- Coils are designed for voltages to ground of around 1000 V
- With the number of turns and the current the inductance is to be limited to keep the voltage below 1000 V

- Dipoles and Current:
  - Tevatron  \( B = 4.4 \, \text{T} \); \( I \sim 4000 \, \text{A} \)
  - Hera  \( B = 5 \, \text{T} \); \( I \sim 6000 \, \text{A} \)
  - LHC  \( B = 8.3 \, \text{T} \); \( I \sim 12000 \, \text{A} \)

- For magnets \( 10 \, \text{T} < B < 15 \, \text{T} \) the current has to be \( 10 \, \text{kA} < I < 15 \, \text{kA} \)
- For stability reasons strands are \( 0.6 \, \text{mm} < \text{strand diameter} < 1 \, \text{mm} \)
- With a Cu-nonCu ratio (stability) around 1 and a \( J_c \sim 1000 \, \text{A/mm}^2 \)
  - a 1 mm diameter strand can carry ~400 A
  - need a 30 strand cable to get up to 12 kA

\[
V = -L \frac{dI}{dt}
\]

\[
L \approx N^2
\]
Cable types

Superconducting Cable Types

- Rutherford
- CIC
- Detector magnets
- Rope, Braid and Rutherford cables
- ITER magnets
- Nuclotron Type (b) Pulsed SIS 100 magnets
- Accelerator magnets
  - Tevatron, HERA
  - RHIC and LHC
- Indirectly cooled

Courtesy A. Balarino
Rutherford cables

- Compact cables giving high overall current density
- Can be wound relatively easy
- Easy rectangular geometry

![Diagram of Rutherford cables and cabling machine](image-url)
Two types of coils are in use for high field magnets:

- **Cos(\(\theta\)) coil** and **Block coil**

  - **Cos(\(\theta\)) coil**
    - Allows a very good field quality (\(b_n < 1 \cdot 10^{-4}\)) in thin coils
      - all (but one) existing accelerators use this type of coil
    - Is very efficient wrt the quantity of superconductor used
    - The EM forces cause a stress buildup at the midplane where also high fields are located
    - Wedges are needed in the straight part (‘Keystoned’ cable)
    - The ends are short, special geometry for which there is a large experience but not it is easy
Practical accelerator magnet design: Dipoles

- Block coil
  - Used with thick coils the field quality is good
  - Not yet used in accelerators
  - Is less efficient (~10%) wrt to $\cos(\Theta)$ for quantity of superconductor used
  - The EM forces cause a stress buildup at the outside edge of the coil where the fields are lower
  - The straight part is very easy: rectangular cable and wedges (field quality)
  - ‘flared ends’ look easy but there is little experience exists to make them
Quadrupole coil geometries

- **Cos(θ) coil**
  - Allows a very good field quality \( b_n < 1 \times 10^{-4} \)
    - all (but one) existing accelerators use this type of coil
  - Is very efficient wrt the quantity of superconductor used
  - The EM forces cause a stress buildup at the midplane where also high fields are located, (but are limited)
  - Wedges are needed in the straight part (‘Keystoned’ cable)
  - The ends are short, special geometry for which there is a large experience but not it is easy
Quadrupole coil geometries

- Block coil
  - Used with thick coils the field quality is good
    - Not yet used in accelerators
  - Is less efficient (~10%) wrt to \( \cos(\Theta) \) for quantity of superconductor used
  - The EM forces cause a stress buildup at the outside edge of the coil where the fields are lower
  - The straight part is very easy: rectangular cable and wedges (field quality)
  - Model with racetrack coils were built but is not pursued

Subscale Quadrupole
SQ
0.3 m long
110 mm bore
Prestress

• Why prestress?
  – Field quality is determined by the cable positions (be precise to ~0.02 mm)
  – Under the MN forces the coils will move
    ➔ Apply prestress to fix the positioning
  – Very small amounts of heat can quench the coil: limit the movement (avoid stick-slip effects on ~10 µm movements)
    ➔ Apply prestress to fix the positioning

• How to put prestress?
  Three methods:
  1. Compress at room temperature: collar system
  2. Use room temperature prestress plus differential shrinkage at cooldown: Al or stainless steel shrinking cylinder and/or a (shrinking) key
  3. Compress a bit at room temperature and use differential shrinkage at cooldown: Al shrinking cylinder + bladder and key system

• Order of magnitudes: LHC 8.34 T: 70 MPa warm, 30 MPa cold
  Fresca2 13 T: 60 MPa warm, 130 MPa cold
Prestress: collars

“The classical solution”
- Thin collars put around the coil
- The coil is well contained in a fixed cavity
- Pressed together and locked with pins or keys
- At 300K apply a prestress 2-3 times of what is needed as part of the stress is lost during cooldown: for very high field tends to be too high (LHC:70 MPa at 300 K and 40 MPa at cold)
- Field quality is in good part determined by collar shape
- If the coils size is not so well controlled, the stress can be too high or too low
- Nb₃Sn is stress sensitive and this could be a problem

Hera dipole
DESY

LHC dipole
CERN

TQC quadrupole
LARP-FNAL
Prestress: shrinking cylinder and/or prestress key

- The differential shrinking and room temperature prestress between a (thick) shell or key and the Fe (split) yoke provides prestress.
- Pre-stress completely depends on dimensioning of the components and the materials.

Figure 1: HFDA coil and magnet cross-sections. Courtesy A. Zlobin
Prestress: Al shrinking cylinder + bladder and keys

Developed at LBNL, example: TQS a LARP model quadrupole

300K: Bladders pressurized with water (<600 bar), then insert keys → load between 10 MPa and 80 MPa

Cooldown: differential shrinkage between AL shell and Fe yoke load another ~100 MPa

Needs careful mechanical FE modeling before and strain measurements during bladder operations and cooldown
Manufacturing of Nb$_3$Sn Magnets

- Nb$_3$Sn has to be reacted after winding for ~120 hr at 650°C (react and wind)
- Cables have to be insulated with a non-organic woven insulation: glass fibre or ceramic
- After reaction the coils has to be impregnated to prevent any movements and to take care that stresses are distributed, instrumentation connections are moulded in
- Reacted Nb$_3$Sn is brittle and stress sensitive
Comparison of magnets

Nb-Ti: blue diamonds, nominal field
Nb$_3$Sn: red squares, maximum field
As a rule magnets are used with ~20% margin (nominal = 0.8 x maximum)
High Field dipole designs: 11T Dispersion Suppressor

Developed at FNAL and CERN for the LHC luminosity upgrade.

two 5.5 m 11 T dipoles should replace one 15 m 8.3 T main dipole

Has to operate in series with the main bend dipole chain: 11 T @ 11850 A

Potentially the first Nb₃Sn magnet to be used in an accelerator (2017)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Removable Pole Design</th>
<th>Integrated Pole Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal current Iₙ⁰₉₉, kA</td>
<td>11.85</td>
<td>11.85</td>
</tr>
<tr>
<td>Nominal bore field, T</td>
<td>11.23</td>
<td>11.25</td>
</tr>
<tr>
<td>Maximum coil field, T</td>
<td>11.59</td>
<td>11.60</td>
</tr>
<tr>
<td>Magnetic length, mm</td>
<td>1.537</td>
<td>1.540</td>
</tr>
<tr>
<td>Working point on the load-line at Iₙ⁰₉₉</td>
<td>81%</td>
<td>81%</td>
</tr>
<tr>
<td>Ultimate design field, T</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Inductance at Iₙ⁰₉₉, mH/m</td>
<td>11.97</td>
<td>11.98</td>
</tr>
<tr>
<td>Stored energy at Iₙ⁰₉₉, kJ/m</td>
<td>966.3</td>
<td>968.6</td>
</tr>
<tr>
<td>Fₓ per quadrant at Iₙ⁰₉₉, kN/m</td>
<td>3.15</td>
<td>3.16</td>
</tr>
<tr>
<td>Fᵧ per quadrant at Iₙ⁰₉₉, kN/m</td>
<td>-1.58</td>
<td>-1.59</td>
</tr>
<tr>
<td>Fz per aperture, kN</td>
<td>430</td>
<td>430</td>
</tr>
<tr>
<td>Overall length, mm</td>
<td>1960</td>
<td>1960</td>
</tr>
<tr>
<td>Coil overall length, mm</td>
<td>1760</td>
<td>1760</td>
</tr>
<tr>
<td>Yoke outer diameter, mm</td>
<td>550</td>
<td>550</td>
</tr>
<tr>
<td>Outer shell thickness, mm</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>~2600</td>
<td>~2600</td>
</tr>
</tbody>
</table>

Courtesy M. Karppinen, A. Zlobin, et al.
11 T model program

- Demonstrate the required performance (11.25 T at 11850 A)
- Achieve accelerator field quality
- Study in depth mechanics and manufacturing
- Address specific issues such as quench protection

NOTE: virtual reality models

Next 2 years!

By courtesy of D. Mitchell, F. Nobrega (FNAL) and M. Karppinen (CERN)
High Field dipole designs: HD2

- HD2: LBNL, working model
- Maximum field 13.8 T (87% x Jc)

**TABLE I CABLE PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Coil 1</th>
<th>Coil 2-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strand diameter (before reaction)</td>
<td>mm</td>
<td>0.802</td>
<td>0.801</td>
</tr>
<tr>
<td>Process</td>
<td></td>
<td>Restacked Rod Process</td>
<td></td>
</tr>
<tr>
<td>Stack</td>
<td></td>
<td>54/61</td>
<td></td>
</tr>
<tr>
<td>Non Cu %</td>
<td></td>
<td>51</td>
<td>54</td>
</tr>
<tr>
<td>RRR</td>
<td></td>
<td>16</td>
<td>287</td>
</tr>
<tr>
<td>Twist pitch</td>
<td>mm</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>No. strands</td>
<td></td>
<td>51</td>
<td></td>
</tr>
<tr>
<td>Cable width (bare)</td>
<td>mm</td>
<td>22.008</td>
<td>21.999</td>
</tr>
<tr>
<td>Cable thickness (bare)</td>
<td>mm</td>
<td>1.401</td>
<td>1.406</td>
</tr>
<tr>
<td>Insulation thickness</td>
<td>mm</td>
<td>0.095</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE II MAGNET PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>HD2a-b</th>
<th>HD2c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear aperture</td>
<td>mm</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Magnet outer diameter</td>
<td>mm</td>
<td>705</td>
<td></td>
</tr>
<tr>
<td>No. turns in layer 1 (quadrant)</td>
<td></td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>No. turns in layer 2 (quadrant)</td>
<td></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Short sample current Iₚ at 4.3/1.9 K</td>
<td>kA</td>
<td>17.3/19.2</td>
<td>18.1/20.0</td>
</tr>
<tr>
<td>Bore field at 4.3/1.9 K Iₚ</td>
<td>T</td>
<td>15.0/16.5</td>
<td>15.6/17.1</td>
</tr>
<tr>
<td>Coil peak field at 4.3/1.9 K Iₚ</td>
<td>T</td>
<td>15.9/17.4</td>
<td>16.5/18.1</td>
</tr>
<tr>
<td>Fy/Fy layer 1 (quadrant) at 17.3 kA</td>
<td>MN/m</td>
<td>+2.3/-0.4</td>
<td></td>
</tr>
<tr>
<td>Fy layer 1 (quadrant) at 17.3 kA</td>
<td>kN</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Fx/Fy layer 2 (quadrant) at 17.3 kA</td>
<td>MN/m</td>
<td>+3.3/-2.2</td>
<td></td>
</tr>
<tr>
<td>Fy layer 2 (quadrant) at 17.3 kA</td>
<td>kN</td>
<td>126</td>
<td></td>
</tr>
<tr>
<td>Stored energy at 17.3 kA</td>
<td>MJ/m</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>Inductance</td>
<td>mH/m</td>
<td>5.6</td>
<td></td>
</tr>
</tbody>
</table>
EuCARD high field dipole (Fresca2)

- Fresca2: CERN, CEA construction phase
- First tests 2014

- Diameter Aperture = 100 mm
- L coils = 1.5 m
- L straight section = 700 mm
- L yoke = 1.6 m
- Diameter magnet = 1.03 m

- 156 turns per pole
- Iron post
- $B_{\text{center}} = 13.0$ T
- $I_{13T} = 10.7$ kA
- $B_{\text{peak}} = 13.2$ T
- $E_{\text{mag}} = 3.6$ MJ/m
- $L = 47$ mH/m

Courtesy Attilio Milanese, Pierre Manil
High Field quadrupole designs: HQ

HQ: model quadrupole for LHC insertion upgrade,
Developed by LARP: LBNL, FNAL and BNL

- 0.8 mm strand
- 15 mm wide cable
- 120 mm bore
- 4.4 K/1.9 K - 195/214 T/m
- 4.4 K/1.9 K – 13.7/14.9 T

 Courtesy S. Caspi, H. Felice, P. Ferracin
High field magnets for future accelerators: HL-LHC

For the Luminosity upgrade of the LHC (High Luminosity LHC) several scenarios are under study which mainly involve the following high field magnets:

1. Make space for a collimator in the Dispersion Suppressor regions: replace a 15 m long 8.34 T dipole (MB) with two 5.5 m long 11 T dipoles with a collimator in between (11 T DS magnets, FNAL-CERN project)
2. Replace the low-\(\beta\) insertion quadrupoles (MQXA/B, 6.4/5.5 m, 70 mm, 215 T/m), with new wide aperture quadrupoles: MQXD, 8 m, 120-140 mm, 195 T/m (HQ, LARP project)
3. Replace the warm single aperture D1 separation dipoles (6 x 3.4 m, 1.28 T) with a single 8 T 150 mm dipole (D1, KEK project)
4. Replace the SC D2 double aperture separation dipoles with new larger aperture magnets (7 m, 100 mm, 5 T)
5. Replace the Q4 double aperture quadrupole with large aperture ones (4.2 m, 90 mm, 120 T/m)
6. + various corrector magnets
LHC IP Quadrupole design and technology evolution

KEK MQXA
Nb-Ti, 6.6 m
70 mm apert.
205 T/m

FNAL MQXB
Nb-Ti, 5.7 m
70 mm apert.
205 T/m

LARP TQS-TQC
Nb-Sn, 1 m
90 mm apert.
200 T/m

CERN-CEA MQXC
Nb-Ti, 2 m
120 mm apert.
118 T/m

LARP HQ
Nb-Sn, 1 m
120 mm apert.
170 T/m

LARP-CERN QXF
Nb-Sn, 1.5 m
150 mm apert.
140 T/m

Aperture (optics)

70
90
120
150

 Courtesy L. Bottura
Ten years of intense R&D

Subscale Quadrupole
SQ
0.3 m long
110 mm bore
2004-2006

Technology Quadrupole
TQS - TQC
1 m long
90 mm bore
2006-2010

Long Quadrupole LQS
3.7 m long
90 mm bore
2007-2012

High Field Quadrupole HQ
1 m long
120 mm bore
2008-2014

Long Racetrack LRS
3.6 m long
No bore
2006-2008

Courtesy G. Sabbi & H. Felice
HQ performance (120 mm, 170 T/m)

May 2010

Jun 2010

Oct 2010

Apr 2011

Jul 2011

Jul 2012

Apr 2013

4.2 K

1.9 K

Normal

Skew

HQ30 μm positioning tolerance

Harmonic order

Courtesy G. Chlachidze, J. Di Marco (FNAL), X. Wang (LBNL)
Magnets for HE-LHC

- For a 17 + 17 TeV collider
  - Need 20 T dipoles
- study to start soon
  - HTS-Nb$_3$Sn-Nb-Ti nested coil
- EuCARD2 HFM proposal being discussed
  - 20 T conductor development
  - Construct demonstrator
- CERN + others 20 T design study

Material

<table>
<thead>
<tr>
<th>Material</th>
<th>N. turns</th>
<th>Coil fraction</th>
<th>Peak field</th>
<th>$J_{\text{overall}}$ (A/mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb-Ti</td>
<td>41</td>
<td>27%</td>
<td>8</td>
<td>380</td>
</tr>
<tr>
<td>Nb$_3$Sn (high Jc)</td>
<td>55</td>
<td>37%</td>
<td>13</td>
<td>380</td>
</tr>
<tr>
<td>Nb$_3$Sn (Low Jc)</td>
<td>30</td>
<td>20%</td>
<td>15</td>
<td>190</td>
</tr>
<tr>
<td>HTS</td>
<td>24</td>
<td>16%</td>
<td>20.5</td>
<td>380</td>
</tr>
</tbody>
</table>

Courtesy: E. Todesco
Inserts for a 20 T dipole – present...

6 T HTS (YBCO) insert for test in FReSCa2 (no bore)

BSCCO-2212 sub-scale coil program

5 T HTS magnet with accelerator features (40 mm bore)

Roebel cable (YBCO)

Rutherford (BSCCO-2212)
Literature on High Field Magnets

- **Books**

- **Conference proceedings and reports**
Literature on High Field Magnets (2)

• Papers and reports
  11) E. Todesco, L. Rossi, AN ESTIMATE OF THE MAXIMUM GRADIENTS IN SUPERCONDUCTING QUADRUPOLES, CERN/AT 2007-11(MCS),
  13) P. Fessia, et al., Parametric analysis of forces and stresses in superconducting quadrupole sector windings, sLHC Project Report 0003

• Websites
  15) http://www.magnet.fsu.edu/magnettechnology/research/asc/plots.html
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