High-field Accelerator Magnets

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Abstract
In this lecture an overview is given of the present technology for high field accelerator magnets. We indicate how to get high fields and what are the most important parameters. The available conductors and their limitations are presented followed by the most relevant types of coils and support structures. We conclude by showing a number of recent examples of development magnets which are either pure R&D objects or models for the LHC luminosity upgrade.

1 Introduction: magnetic field and high-field magnets

The name ‘high-field magnet’ is being used for the magnets that are at the limit of the technology at the time we speak. Before the 1980s, accelerators were practically only using resistive magnets with maximum fields of 2 T. To get higher fields one has to switch from resistive to superconducting magnets. The first superconducting accelerators were constructed at the beginning of the 1980s. If we look at the high-field magnets that were constructed during this early period, we will recognise the technological advancement with respect to today: the field level for accelerator magnets has moved up from around 4 T to close to 12 T implying also the move from Nb-Ti to Nb₃Sn conductors. We should look at the orders of magnitude of the flux density B we can achieve to appreciate the task of building high-field magnets.

1.1 Iron-dominated magnets

Let us consider an iron-dominated resistive magnet with a C-shaped yoke as shown in Fig. 1 with the integration path of equation (1) indicated as a dotted line.

\[
\oint_c \vec{H} \cdot d\vec{l} = N \cdot I. \tag{1}
\]

When we take average of the fields in the iron and in the pole gap, it follows that

\[
N \cdot I = H_{\text{iron}} \cdot l_{\text{iron}} + H_{\text{air gap}} \cdot l_{\text{air gap}} \tag{2}
\]

and

\[
N \cdot I = \frac{B}{\mu_0 \mu_r} \cdot l_{\text{iron}} + \frac{B}{\mu_0} \cdot l_{\text{air gap}}. \tag{3}
\]
As $\mu_r \gg \mu_0$ in the iron, we get

$$N \cdot I = \frac{B}{\mu_0} \cdot l_{\text{air gap}}.$$  \hspace{1cm} (4)

For a magnet with a flux density of 1.8 T in a 50 mm pole gap we will need $NI = 71619$ A. This can be done with a coil of $2 \times 36$ turns, with $I = 1000$ A. This implies a current density of $5$ A/mm$^2$ in a Cu conductor with a surface of $14 \times 14$ mm$^2$. Copper coils with air cooling can run with current densities of a few A/mm$^2$, while hollow water cooled copper conductors can be used up to a few tens of A/mm$^2$.

The permeability of the iron depends on the flux density and the best types of magnetic steel will be fully saturated close to 2 T. In Fig. 2 the relative permeability $\mu_r$ of a standard steel type used for laminated magnet yokes is shown. When the value of $\mu_r$ approaches unity the approximation to derive Eq. (4) is not valid any more and we can see that the required current to reach a field $B > 2$ T will steeply increase. Iron-dominated magnets with $B > 2$ T very quickly become unpractical or impossible to build as the required current density in the coil exceeds the cooling possibilities.

![Fig. 2: Permeability as function of flux density for a standard steel for laminated yokes](image)

In Fig. 3 one can see as an example the SPS dipole magnet. The magnet generates a flux density $B_{\text{max}} = 2.05$ T using a 16-turn coil with $I_{\text{max}} = 4900$ A in a 52 mm high and 92 mm wide aperture.

![Fig. 3: The $B_{\text{max}} = 2.05$ T SPS dipole magnet: left, the cross-section, right, a photograph taken during assembly in the early 1970s.](image)
1.2 Magnetic fields in magnets without steel amplification
From the Ampere law with no time dependences (in the integral form) we get the expression from which we can calculate the flux density caused by a line current at a distance $r$:

$$\oint_c \vec{B} \cdot d\vec{l} = \mu_0 I.$$  \hspace{1cm} (5)

From Eq. (5) we can derive the law of Biot and Savart:

$$\vec{B} = \frac{\mu_0 I}{2\pi r} \hat{\phi}.$$  \hspace{1cm} (6)

One can now use this to see how to generate an 8 T flux density, as for the LHC main dipole magnets, with just two infinitely thin wires placed at 50 mm distance (see Fig. 4). We need a current in each wire of $I = 5 \times 10^5$ A. In an LHC dipole the coil has 80 turns with a current in each conductor of 11850 A, generating a flux density $B = 8.3$ T. In Fig. 4 we can see a cross-section of one-quarter of the LHC dipole. The total current in an LHC dipole coil is $9.48 \times 10^5$ A, which means that in the circular coil area the current density is $\sim 300$ A/mm$^2$. We can see that in order to get high fields ($B > 10$ T) one needs very large currents in small coil volumes.

![Fig. 4: Left: two wires spaced by 50 mm to generate 8 T; right: one-quarter of the cross-section of the coil of the LHC dipole magnet.](image)

2 Examples of high-field magnets in accelerators, for research and for fusion
After an extensive period of development in the 1970s in the USA, the first large accelerator using high-field superconducting magnets was the Tevatron at Fermi National Accelerator Laboratory near Chicago. This machine was used in the first few years after 1983 to produce proton beams for fixed-target experiments and since 1987 as a proton–antiproton collider. A competing project, ISABELLE (the Intersecting Storage Accelerator + ‘belle’) at Brookhaven National Laboratory was cancelled in 1983 after long-lasting problems with the development of the magnets. The infrastructures and magnet development were ultimately salvaged and re-used for the Relativistic Heavy Ion Collider (RHIC), which started operation in 2000. At DESY in Hamburg an electron–proton collider was built; this unique machine was commissioned in 1992. These three machines all employed Nb-Ti conductors at 4.2 K and operated in the 3.5 T to 5 T range. Starting during the second half of the 1980s the USA worked on the SSC (Superconducting Super Collider), a proton–proton collider with 6 T magnets at 4.2 K. Due to technical problems and massive cost overruns the project was stopped in 1993. The development of the large proton–proton collider LHC (Large Hadron Collider) at CERN started in 1985 and was commissioned in 2008. The LHC employs 8.34 T dipole magnets at 1.9 K, pushing the possibilities for...
Nb-Ti to the limits. In Fig. 5 the cross-sections of the superconducting dipole magnets of four successful colliders are shown. In Table 1 the main parameters of these machines and magnets can be found. To get an impression of the size, in Fig. 6 one can find a 3D image of the dipoles in two of these projects.

The experiments at these large colliders need magnets of a different type than the accelerators. For particle track momentum measurements large volumes at high fields are required. Two types of magnet geometries have been employed in recent years, as illustrated at the LHC by the toroid magnets for ATLAS and solenoids for CMS. The ATLAS barrel toroid (see Fig. 7, right) has an inner diameter of 6.3 m, a length of 12.5 m and a cold mass of 220 t. The central field is 4 T at a current of 19 kA, with a stored energy of 2.65 GJ. The CMS solenoid (see Fig. 7, left) has a outer diameter of 21 m and a length of 26 m. It generates 4.1 T and a stored energy of 1.5 GJ. Both magnets used Nb-Ti conductors and ran at 4.2 K.

High-temperature plasma experiments for fusion research also demand high fields in large volumes. An example of a system of large high-field magnets for fusion research is the ITER (International Thermonuclear Experimental Reactor) tokamak, which is shown in Fig. 8. The tokamak has several magnet systems: a toroid field (TF) to confine the plasma in a 11.8 T field, a poloidal field (PF) of 6 T to shape the plasma and the central solenoid (CS) of 13 T to heat it up. For this large machine big amounts of conductor are needed: 376 t of Nb$_3$Sn for the 18 TF coils, 132 t of Nb$_3$Sn for the CS coil and 244 t of Nb-Ti for the PF coils. ITER is under construction at Cadarache in the south of France and is planned to be operational in 2020.

Small high-field solenoids with a bore diameter of around 50 mm and a field of up to 21 T using Nb$_3$Sn are commercially available. A number of high magnetic field laboratories are working on solenoid development to reach 40 T in small volumes. Examples of these laboratories are the National High Magnetic Field Laboratory in Tallahassee, Florida (USA), the High Field Magnet Laboratory in Nijmegen (The Netherlands) and the Laboratoire National des Champs Magnétique Intenses in Grenoble (France). For these applications the fields build up in layered coils starting from the outside with Nb-Ti to reach 9 T followed by a layer of Nb$_3$Sn for 21 T. The innermost layer consisted up to recently of Cu coils in the shape of Bitter or helicoidal coils, but more recently coils employing high-temperature superconductors (HTSs), which at 4 K have been shown to have appreciable current densities up to 40 T, are being developed for this.

3 What is specific about accelerator magnets?

The beam in a particle accelerator is confined in a beam pipe around which the bending and focusing magnets have to be arranged. This has as a consequence that the shape of the field area in the magnets is a cylindrical volume with a perpendicular field, as depicted in Fig. 9. From beam dynamics calculations one can derive that the field quality is very demanding: for the dipole magnets that provide the bending of the beam, the typical required field homogeneity is

$$\frac{\Delta B_z}{|B|} \leq 10^{-4}.$$  

(7)

The field quality in accelerator magnets is expressed and measured in a multipole expansion:

$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left( \frac{x + iy}{R_{ref}} \right)^{n-1} \text{ with } b_n, a_n \leq \text{few units.}$$  

(8)

In order to get to these demanding small field errors the coils of superconducting magnets are mostly made with a so-called cos-theta layout. This layout approximates a current density in an angular element that decreases with the cosine of the angle with respect to the horizontal axis. Such a layout provides a perfectly homogeneous field (see [2] and also [7]). Examples of coil segments of such coils for a dipole and a quadruple can be found in Fig. 10.
<table>
<thead>
<tr>
<th>Machine</th>
<th>Place</th>
<th>Type</th>
<th>Peak dipole (GeV)</th>
<th>Number of dipoles</th>
<th>Dipole length (m)</th>
<th>Ring circumference (km)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA</td>
<td>DESY (D)</td>
<td>e+–e– collider</td>
<td>40 × 920</td>
<td>5</td>
<td>416</td>
<td>8.82</td>
<td>1992</td>
</tr>
<tr>
<td>RHIC</td>
<td>BNL (USA)</td>
<td>p–Pb, Au–Au, Cu–Cu, d–Au</td>
<td>1000 × 1000n</td>
<td>3.5</td>
<td>2 × 192 + 12</td>
<td>9.45</td>
<td>2000</td>
</tr>
<tr>
<td>LHC</td>
<td>CERN (EU)</td>
<td>p–Pb, Pb–Pb</td>
<td>7000 × 7000</td>
<td>8.34</td>
<td>1232</td>
<td>14.3</td>
<td>2008</td>
</tr>
</tbody>
</table>
Fig. 5: Examples of superconducting Nb-Ti dipole magnets; left top: Tevatron, right top: RHIC, left bottom: HERA, right bottom: LHC.

In high-energy accelerators with a large circumference, magnets need to be long in order to be efficient. The dipole bending magnets for the Tevatron at FNAL are 6 m long while for the LHC at CERN they are 15 m long. As the beam is bent by the dipole magnets, depending on the bending curvature, the magnets will have to follow the beam path. For many accelerators the dipole magnets are thus bent: e.g., for the LHC they have a sagitta of 0.14 mm.

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

Let us consider a dipole with a sector coil of up to 60 deg as shown in Fig. 11(left). The dipolar field component $B_1$ can then be calculated to be (see [3])

$$B_1 = -\frac{4 J \mu_0}{2 \pi} \int_{r/3}^{\pi/3} \int_r^{r+w} \frac{\cos \theta \rho d \rho d \theta}{\rho} = -\frac{\sqrt{3} \mu_0 J w}{\pi}$$

(9)

with

- $r$: coil inner radius,
- $w$: coil width,
- $\rho$: radial coordinate,
- $J$: current density.

We can see that the dipole field value is proportional to the current density $J$, proportional to the coil width $w$ and independent of the aperture radius $r$. 

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The critical surface is reached first by exceeding the critical field. In a cos-theta coil the maximum field dipole and quadrupole magnets (in fact in any type of magnet) is limited by the position in the coil where the ratio \( \frac{w}{r} \) can be calculated to be (see [4])

\[
G = -8 \frac{J \mu_0}{2\pi} \int_0^{\frac{\pi}{6}} \int_r^{r+w} \frac{\cos \theta}{\rho} \rho \, d\rho \, d\theta = -\frac{\sqrt{3} \mu_0}{\pi} J \ln \left( 1 + \frac{w}{r} \right). \tag{10}
\]

We can see that the quadrupole gradient is proportional to the current density \( J \) and dependent on the ratio \( w/r \).

One can see that the field in the coil is varying with the position on the coil. The field in both dipole and quadrupole magnets (in fact in any type of magnet) is limited by the position in the coil where the critical surface is reached first by exceeding the critical field. In a cos-theta coil the maximum field in the coil decreases when going outwards in multilayered coils. To maximise the field one can adopt a technique called ‘grading’: using a conductor with a higher current density in the outer layers.

One can calculate the stress in the coil of a dipole sector coil due to the electromagnetic forces Fig. 12 (see [5]):

\[
\sigma = J^2 \mu_0 \sqrt{3} \frac{\pi}{6} \max_{\rho \in [r, r+w]} \left[ 2\rho^2 + \frac{r^3}{\rho} - 3\rho(r + w) \right] \tag{11}
\]

with

- \( r \): coil inner radius,
- \( w \): coil width,
- \( \rho \): radial coordinate,
- \( J \): current density.
For a quadrupole sector coil the stress in the coil is likewise (see [6])

\[
\sigma = J^2 \frac{\mu_0 \sqrt{3}}{6\pi} \max_{\rho \in [r, r+w]} \left[ 2\rho^2 + \frac{\rho^4}{\rho^2} + 4\rho^2 \left( \frac{r + w}{\rho} \right) \right].
\]  

(12)

5 Superconductors for magnets

5.1 Introduction to superconductors

The property of superconductors that is most important for magnets is that at low temperatures large current densities can be passed through the material at zero resistance. It has to be stressed that the
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Fig. 11: Left: cross-section of a dipole based on 60° deg sector coils, right: cross-section of a quadrupole based on 30° deg sector coils.

Fig. 12: Example of forces in a dipole sector coil

Resistance is zero, and not just very small, due to the fact that superconductivity is a macroscopic quantum effect of the electrons in the lattice of the material. The three parameters which determine whether the material is in the superconducting state are the temperature $\Theta$, the flux density $B$ and the current density $J$. The superconducting state exists when the material is maintained below the so-called ‘critical surface’. In Fig. 13 the critical surface of Nb-Ti is shown: below the surface drawn in the figure, the material is superconducting; above it, it is normal conducting. The values of $\Theta_c$ and $B_{c2}$ depend on the chemical composition of the material; $J_c$ also depends on the metallurgical treatment. At liquid-helium (LHe) temperatures there are two practical superconductors available, Nb-Ti and Nb$_3$Sn. Nb$_3$Sn was discovered to be superconducting in 1953 while for Nb-Ti the discovery year was 1962. The critical temperature $\Theta_c$ and flux density $B_{c2}$ for Nb-Ti and Nb$_3$Sn are from 9.2 K to about 15 K and from 18 T to about 30 T, respectively. Despite its earlier discovery, Nb$_3$Sn is only recently getting to be more used due to its brittle nature, which poses many technological problems to manufacture and operate magnets. Since the 1970s Nb-Ti has been the workhorse for all superconducting applications due to its ease of usage.

High-temperature superconductors are ceramic materials that display superconductivity at much higher temperatures than thought possible a few decades ago. The first one that was discovered in 1986 was a barium-doped compound of lanthanum and copper oxide with a zero-field critical temperature of 35 K. Since that date many more ceramic compounds have been discovered to be superconducting with at the moment a record at 133 K. In Fig. 14 one can see a summary plot with many HTS materials. Presently only YBCO (yttrium barium copper oxide), BSCCO (bismuth strontium calcium copper oxide) and MgB$_2$ (magnesium diboride) are used in practical applications.

For reasons of stability, all superconductor wires are made as thin filaments (with a diameter of a few microns up to 0.1 mm) inside a copper, aluminium or silver matrix. The wires can vary in diameter between roughly 0.5 mm up to 2 mm. The superconducting currents will only flow through the filaments that in a coil will have to be endless in order not to create any voltages. The engineering current density is defined as the current density in the conductor averaged over its total surface including the stabiliser.
The critical surface of niobium titanium

- Niobium titanium (NbTi) is the standard 'work horse' of the superconducting magnet business.

- It is a ductile alloy.

- It has a critical surface, which is the boundary between superconductivity and normal resistivity in 3-dimensional space.

- Superconductivity prevails everywhere below the surface, resistance everywhere above it.

\[ J_c \] and \[ B_{c2} \] are defined as upper critical field (at zero temperature and current) and critical temperature (at zero field and current), which are characteristic of the alloy.

- Critical current density \( J_c(B, \theta_c) \) depends on processing.

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**Fig. 13:** Critical surface for Nb-Ti (courtesy M. Wilson [2])

**Fig. 14:** High-temperature superconductors: years of discovery and critical temperatures

and other metals in the wire. The engineering current densities of presently available superconductors for practical applications are summarised in Fig. 15. For accelerator magnets, in order to reach high fields, an engineering current density of around 1000 A/mm\(^2\) will be needed.

We can see in Fig. 15 that up to 9 T Nb-Ti is the best choice, below 6 T at 4.2 K and above 6 T at 1.9 K. Up to 16 T Nb\(_3\)Sn is the best choice. Above 16 T YBCO and Bi-2212 should be usable. Nb-Ti is the workhorse conductor for existing accelerators; it is produced in a well-known industrial process. Nb-Ti has excellent mechanical properties but limits magnets to a maximum field of 10 T in the coil. Thousands of accelerator magnets have been produced with it. Nb\(_3\)Sn magnets are under development for first usage in the LHC from 2018 and model magnets have been successfully tested. It is nowadays...
produced in a complex industrial process and is rather costly. Nb$_3$Sn is brittle and strain sensitive and the field limit in the coil is about 16 T although the slope $J_c(B)$ is lower than for Nb-Ti, making this limit less sharp. For both YBCO and Bi-2212 the development of accelerator magnet models has only recently started. Good $J_c$ values at 40 T have been measured, only limited by the present possibility of generating higher background fields. The industrial production of these HTS conductors is still developing and extremely costly.

5.2 Conductor stability and alternating current behaviour

Superconductor materials are, when in the normal state at low temperature, poor conductors. This is due to the low number of free-carrier electrons in the lattice. The consequence of this is that pure, massive, wires of superconductors (e.g. Nb-Ti and Nb$_3$Sn) are rather unstable; when due to a local perturbation the superconducting state is lost, the large ohmic heating prevents the metal from returning to the superconducting state. To cure this, the wires consist of thin superconducting filaments surrounded by copper, which is an excellent electrical and thermal conductor. In case of a normal local transition the current is diverted through the good conductor until the local heat peak is cooled back down. This construction is called ‘cryogenic stabilisation’; see Fig. 16.

During the ramp up of the field, the superconducting filaments will try to exclude the field with current loops and hence magnetise, as depicted in Fig. 17, for subsequent up and down ramps of the field. To minimise this magnetisation effect the filaments are made very thin. The filaments in the Nb-Ti wires for the LHC dipole magnets have a diameter of 6 µm, while the filaments for the quadrupoles of the LHC luminosity upgrade are in the range of 30–50 µm.

To further limit the effects of the persistent currents on the field quality, the loops are segmented in small parts by twisting the wires as can be seen in Fig. 18. It is the basic nature of electromagnetism and superconductivity that a changing magnetic field is countered by electrical currents that in this case...
are persistent. These currents generate higher order field components in the magnets (e.g. a sextupole component in a dipole magnet) that can be reduced but not completely removed.

5.3 Superconducting wires: Nb-Ti

Nb-Ti is to date the workhorse superconductor for accelerator magnets. The Tevatron, HERA, RHIC and the LHC all employ Nb-Ti superconducting wires consisting of thin Nb-Ti filaments in a copper matrix. The wires are fabricated by extruding a hollow Cu billet loaded with Nb-Ti elements. The extrusion process takes many steps, first hot and then cold, interspersed with heat treatments. During the cold work of the wire forming and the heat treatments the required crystal structure with lattice defects for the flux pinning is formed. The exact process is specific for each provider and confidential. Historically the evolution of the wire performance was guided by the big accelerator projects, first for the Tevatron in the 1970s, then for the (aborted) SSC in the 1980s and finally for the LHC in the 1990s. In Fig. 19 one can find the critical surface and a table of parameters for the two strands used in the LHC dipoles for the inner and outer layers of the coil, where for the grading the outer layer employs a wire of a smaller diameter so as to get to a higher current density.
5.4 Superconducting wires: Nb$_3$Sn

As Nb$_3$Sn is a brittle material (an A15 intermetallic compound) the wires should not be produced with the superconducting filaments in the final state inside the wires, as is done for Nb-Ti. Due to this brittleness of the conductor one cannot wind a magnet with the final wire as the filaments would break in the process. To circumvent this problem the wires which one uses are essentially niobium tubes filled with tin inside a copper matrix. The wires are shaped into cables (see next section), insulated with a glass fibre sleeve or tape and then wound into a coil. After the winding the coil is placed in a mould, which maintains the coil in the final shape and then reacts for between 50–100 hours at 650°C. During the reaction the tin (which melts at around 200°C) will diffuse into the niobium and the two will react, forming small (<200 nm) Nb$_3$Sn crystals. This wind-and-react process poses many technological challenges in the production of the wires, which for a few decades limited the usage of Nb$_3$Sn to small-scale laboratory magnets.

In order to hoist the performance of Nb$_3$Sn wires to a level usable for accelerator magnets the DOE in the USA started an extensive development program with the US industry about 15 years ago. In Europe a similar program was started by a collaboration led by CERN and financed by the EU in 2004. The result of these programs is that both the USA and Europe have a provider for high-performance Nb$_3$Sn wires. In Fig. 20 one can find the basic layout of the four main wire types, bronze process, internal tin process and powder in tube. In the USA, OST produces Nb$_3$Sn wires with the re-stacked rod process (RRP), which is a variation of the internal tin process. In Europe Bruker offers wires of the powder in tube (PIT) process. In Fig. 21 one can find cross-sections of RRP and PIT wires. The effective filament diameters of the wires is at the moment in the order of 50 µm, while for the quadrupole and dipole magnets for the HL-LHC a diameter of 30 µm is required. To reach this target, development is continuing for which wires with more filaments of the same diameter are being made. The wires have at the moment a current density in the non-Cu part of the cross-section in the range of 2400 A/mm$^2$ to 3000 A/mm$^2$ at 12 T and 1300 A/mm$^2$ to 1500 A/mm$^2$ at 15 T. The RRR (residual resistance ratio: ratio between resistance at room temperature and at 4.2 K) is in the range of 150. The latter is needed for the Cu to be effective as stabiliser. A challenge in the production and heat treatment of the wires is that potential Sn leaking from the Nb tubes into the Cu will transfer the Cu into bronze, which has a much larger resistance than the original Cu.
5.5 Superconducting wires and tapes: BSCCO

One of the two practical high-temperature superconductors is bismuth strontium calcium copper oxide (BSCCO, pronounced as ‘bisko’). This superconductor was discovered in 1988 and comes in several variants with different relative compositions. The most common ones are Bi-2212 with $T_c \approx 95$ K and Bi-2223 with $T_c \approx 108$ K. Bi-2223 exists in the form of a multilayered tape, where one of the layers is the actual superconductor. Bi-2212 exists as both tape and wire. The wire consists of a powder in silver tubes inside a silver matrix and needs to be reacted at a temperature of $\approx 850^\circ$C with a temperature precision of 1$^\circ$C in an oxygen atmosphere. The oxygen has to penetrate into the substrate to form the BSCCO and therefore the matrix of the wire has to be permeable for oxygen; hence, the silver matrix. The current density can reach $> 400$ A/mm$^2$ (OST produced wire) at high field and remains high in fields $> 30$ T (and at low temperature: e.g. 4.2 K) as can be seen in Fig. 15. This wire can be cabled into Rutherford cables (see next section) but is unfortunately stress and strain sensitive. In Fig. 22 one can find a picture of the lattice structure of Bi-2212 and a cross-section of a Bi-2212 wire. BSCCO uses difficult technology but it could be promising for high-field magnets in the $> 20$ T region.
5.6 Superconducting tapes: YBCO

The second practical high-temperature superconductor is yttrium barium copper oxide (YBCO). It was discovered in 1987 and has a critical temperature $T_c \approx 93$ K. It is available in tapes where a few micron thick layer of YBCO is deposited on a substrate to impose the texture. The overall current density in the tape can reach $> 600$ A/mm$^2$ and the tape is strong under axial stress and strain. In Fig. 23 a picture of the lattice of YBCO and a tape layout can be seen. Due to the tape layout the cabling possibilities are however limited. The current density remains high in fields $> 30$ T (and at low temperature: e.g. 4.2 K) as can be seen in Fig. 15. Due to various issues with the tape layout YBCO uses a difficult technology but could be promising for high-field magnets in the $> 20$ T region.

5.7 Superconducting cables for accelerator magnets

We need multistrand cables in a high-field superconducting magnet to keep the voltage within manageable limits during the ramping up and down of the magnet. Superconducting accelerators are ramped up in time spans between 100 s and 1000 s. The coils are generally designed for voltages to ground of around 1000 V in order to keep the ground insulation thickness below about 1–2 mm and to reduce the risk of high-voltage discharges in the current leads of the magnet. Using as parameters the number of turns and the current, the inductance is to be limited to keep the voltage below 1000 V: $V = -LdI/dt$ and $L \approx N^2$. So, in order to keep the voltage down, we need to reduce the number of turns by maximising the current, as can be seen in three examples in Table 2.
Table 2: Fields and currents in superconducting accelerator magnets

<table>
<thead>
<tr>
<th>Machine</th>
<th>Field (T)</th>
<th>Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron</td>
<td>4.4</td>
<td>4000</td>
</tr>
<tr>
<td>HERA</td>
<td>5</td>
<td>6000</td>
</tr>
<tr>
<td>LHC</td>
<td>8.34</td>
<td>12000</td>
</tr>
</tbody>
</table>

For magnets in the range of $10 \, \text{T} < B < 15 \, \text{T}$ we can work out that the current has to be $10 \, \text{kA} < I < 15 \, \text{kA}$. For stability reasons we know that strand diameters are $0.6 \, \text{mm} < d < 1 \, \text{mm}$ and the Cu–non-Cu ratio is around 1. We also can take as a general parameter that $J_c \approx 1000 \, \text{A/mm}^2$ for the non-Cu part of the wires. Thus, a 1 mm diameter strand can carry $\approx 400 \, \text{A}$ and we will need a 30-strand cable to get up to 12 kA.

In Fig. 24 a number of cable types can be seen.

For high-field accelerator magnets practically only Rutherford cables (see Fig. 25) have up to now been used due to the possibility of bending them over small ($\approx 1 \, \text{cm}$) bending radii and the low loss of space in the coil resulting in high packing factors. Cable in conduit, indirectly cooled and braided, and flat cables are in use for all types of other magnets including the lower field magnets in accelerators.

For the manufacturing of the Rutherford cables, large cabling machines are needed for which a sketch can be seen in Fig. 26.

Future high-field magnets for which HTS conductors in the form of tapes are envisaged (e.g. YBCO) will also need cables for the same reasons as above. Possibilities for these are being looked at and apart from a few new proposals a promising candidate is the Roeble cable (see Fig. 27), which in the
past has been used in rotating current generators with pure Cu tapes. Many issues are still open for using Roeble cables with YBCO tapes but several laboratories are pursuing a development program to make them practical.

Fig. 26: Sketch of a cabling machine for a Rutherford cable

Fig. 27: Roeble cable used for strip conductors like YBCO

6 Practical accelerator magnet design
The design and construction of a high-field superconducting accelerator magnet is a complex multi-physics and engineering problem. A non-exhaustive list of issues is:

- wire choice;
- cable design;
- static magnetic design: select a coil layout and attain the field and field quality in the given space;
- dynamic magnetic design: field quality when ramping up or down;
- mechanical design: contain the electromagnetic forces;
- magnet protection: design the quench behaviour;
- thermal design: how to cool down and stay cold.

An additional complexity is that the items above are not independent and that an integrated design strategy has to be applied that necessitates iteration. In the sections below, I will go over some of the aspects in a separated way and, due to the limit on the time and extent of the lecture, I will limit myself to only a few items.
6.1 Dipole-coil geometries

To design a magnet a coil geometry will have to be chosen. The main candidates are, although not strictly the only ones, cos-theta and block coils, as illustrated in Fig. 28. The main feature of a cos-theta-style coil are:

- allows a very good field quality in a simple way ($b_n \leq 10^{-4}$) in thin coils;
- all (but one) existing accelerators use this type of coil; hence, a large experience exists on how to build them;
- is very efficient with respect to the quantity of superconductor used;
- the electromagnetic forces cause a stress buildup at the mid-plane where also high fields are located;
- wedges are needed in the straight part when the keystoning of the cable cannot completely compensate for the circular geometry and can be used to optimise the field quality;
- the ends are short and of a very special geometry for which there is a large experience but it remains easy to build them.

In Fig. 29 examples can be found of cos-theta coils for dipole magnets. When (see also Section 4) one can build a magnet with a single (thin) layer or with a double-layer coil (as given the current density and the required field, the coil width remains relatively small), then a cos-theta coil layout is surely the best solution. When one has to go to three (or more)-layer coils additional complications for the construction arise. In Fig. 29 a cross-sectional sketch of one example of such a four-layer model magnet is shown: the D20 from LBNL.

![Fig. 28: Possible dipole-coil geometries: left: block coil, right: cos-theta coil](image)

The main features of a block-style coil are:

- when used with thick coils the field quality is good; nowadays field optimisation software could also produce satisfactory thin-coil designs;
- block coils have not yet been used in accelerators for high-field magnets;
- they are less efficient ($\approx 10\%$) for the quantity of superconductor used, with respect to cos-theta coils;
- the electromagnetic forces cause a stress buildup at the outside edge of the coil where the fields are lower;
- the straight part is very easy to deal with: rectangular cable and wedges for the field quality;
- to make space for the beam pipe one has to use ‘flared ends’: they look easy to deal with but little experience exists to make them.
Process (RRP) 

The critical current density at strands formed by the 54/61 sub-element Restacked R LBNL using Oxford Superconducting Technology (OST) of the support structure (shell and yoke lamination persisting current effects.

final design of the coil ("as built") and on the mechanical and field quality optimizations will be performed by the iron harmonics at low field, resulting in a partial compensation. Corrective iron ring produces a significant variation of field with iron ring in Nb units, while the block magnet produces a field within 0.02 mm. During powering the coils are subjected to Lorentz forces that can be of the order of several MN/m, which

At this point, the aluminum-bronze wedges and the stainless steel side extensions are bolted on to the sides of the coil and secured during the winding process, maintain a 3-4 MPa pressure on the coil when the reaction fixture is bolted closed.

In Fig. 30 examples can be found of block coils for dipole magnets. Initially at LBNL model magnets have been constructed and successfully tested. LBNL is continuing the development and for some years also a CEA-CERN collaboration and ATM (Texas) have been working on model magnets.

6.2 Quadrupole-coil geometries

The currently studied geometries for quadrupole coils are, as for the dipoles, cos-theta and block coils. Only cos-theta-type superconducting magnets have up to now been installed into circular accelerators. The list of features for both types of coils for quadrupoles is identical to the dipoles apart from that the argument on the mid-plane stress is less prominent. In Fig. 31 several examples of cos-theta quadruple coils can be seen. During the development of the Nb$_3$Sn wide-aperture quadrupoles for the upgrade of the LHC low-beta insertion by the LARP collaboration in the USA, block-coil layouts were also tried and some models were built. This line of development was abandoned as there were insufficient advantages for such a new type of magnet in the 12–15 T coil field range with Nb$_3$Sn.

6.3 Coil pre-stress

All superconducting accelerator dipole and quadrupole magnet coils are subjected to a significant pre-stress. The reason for this pre-stress is that the field quality in these coil-dominated magnets is determined by the cable positions. This positioning precision is for the LHC dipole of the order of 0.02 mm. During powering the coils are subjected to Lorentz forces that can be of the order of several MN/m, which
means that the coils will move. Hence, a retention structure is needed to meet the position precision requirements.

At the low temperatures (1.9–4.2 K) where superconducting magnets are operated the heat capacity of materials is very low, of the order of three orders of magnitude lower than at room temperature. A consequence of this low heat capacity is that any small generation of heat can result in a substantial increase of temperature raising it above the critical temperature (these movements can be of the order of 10 \( \mu \text{m} \)). Typically, stick–slip effects of the cables under pre-stress and subjected to the increasing Lorentz forces during powering of the magnet can cause this to happen. In the case where the combined heat of this effect and the resistance cannot be cooled away, a runaway effect occurs; the magnet quenches. Poorly applied pre-stress is not the only quench cause but one of the most common. It is thus important to apply the pre-stress in a well-studied and tested way to prevent any movements during powering.

The required pre-stress for the LHC dipoles at 8.34 T is 30 MPa and for a 15 T Nb\(_3\)Sn dipole magnet 130 MPa. The challenge for the mechanical design is how to put such a large pre-stress on a coil. Three main methods to put pre-stress on a coil have up to now been applied:

- compress at room temperature with a system of stainless steel collars;
- room-temperature pre-stress from the assembly plus the differential shrinkage at cool down between a stainless steel shrinking cylinder and the iron yoke;
- room-temperature pre-stress from a bladder and key system plus the differential shrinkage at cool down between an Al shrinking cylinder and the iron yoke.

### 6.3.1 Collars

This is the classical solution applied on the Tevatron, HERA and LHC magnets and on one of the LARP Nb\(_3\)Sn quadrupole models. Some examples can be seen in Fig. 32. Thin collars are put around the coil, while the collar cavity is smaller that of the non-pressed size of the coil. The collars are pressed together under a large pressure and locked with rods (in holes) or keys (in slots). The coil is then well contained in a fixed cavity. To arrive at a well-defined pre-stress a precise knowledge of the coil and collar sizes and the elastic modulus of the coil is required. Moreover, the collar shape will in good part determine the quality of the magnetic field. At 300 K one has to apply a pre-stress that is larger than what is needed at low temperature, as part of it is lost during cool down. For very high fields the values tend to be too high for the brittle Nb\(_3\)Sn coils that are moreover stress sensitive with the critical current density.


6.3.2 Shrinking cylinder

This system was applied for the RHIC magnets. After welding of the shrinking cylinder of the magnet under a pressure, or by shrinking a hot shrinking cylinder around the yoke, the differential shrinkage during cool down between a stainless steel shrinking cylinder and a split iron yoke provides the required pre-stress. The pre-stress completely depends on dimensioning of the components and the materials. Examples of this can be found in Fig. 33.

Fig. 32: Collars; left: LHC twin-aperture collars, mid-left: single-aperture dipole, mid-right: HERA dipole, right: TQC Nb$_3$Sn quadrupole from LARP.

Fig. 33: Pre-stress with stainless steel shrinking cylinders; left: HFDA Nb$_3$Sn dipole from FNAL, right: RHIC Nb-Ti dipole.

6.3.3 Shell, bladder and keys

The shell, bladder and keys system was developed at LBNL for the case of high-field Nb$_3$Sn dipoles and quadrupoles. It has not yet been applied in an accelerator but is the baseline solution for the upgrade of the low-beta quadrupoles of the LHC. At LBNL and in the LARP collaboration several models have been built and successfully tested at high field for both dipoles and quadrupoles using this system. An Al shell is used to hold all the forces generated by the coils. Via a split iron yoke and a set of pads the stress is transferred to the coils. At room temperature the system can be stressed up with inflatable bladders (with water pressurised to 200–600 bar) in slits between the yoke and the pads to a pre-stress between 10 MPa and 80 MPa. This room-temperature stress is consolidated by inserting keys next to the bladders. After deflating and removing the bladders, the magnet can be cooled down. During cool down the pre-stress on the coils increases to up to 160 MPa due to the differential shrinkage between the shell and the split iron yoke. In Fig. 34 this type of structure is illustrated. This type of system needs careful mechanical finite-element modelling beforehand and strain measurements during bladder operations and cool down.
6.4 Manufacturing of Nb$_3$Sn magnets

The manufacturing process of Nb$_3$Sn magnets is more delicate and complex than for Nb-Ti due to the heat treatment of the conductor and the brittleness of the conductor in the final coil. After cable manufacturing the Rutherford cable is insulated with a glass fibre sleeve with a typical thickness of 0.1–0.2 mm. The insulated cable is wound into a coil, where all the poles and spacers are metallic (stainless steel or a Ti alloy). The wound coil is put in a mould that has the final dimensions of the coil and then reacted at 650°C for about 100 hours. During the reaction the molten tin will penetrate into the niobium and react to form Nb$_3$Sn crystals. During the reaction the is a slight (few %) increase in the volume of the strands. After the reaction the coil terminations, that have to be situated in low-field zones, are soldered to Nb-Ti cables such that outside the coil there are no delicate, breakable cables. The coil is then instrumented and transferred to another mould with non-adhesive coating and impregnated with an epoxy resin. After impregnation the coil is robust and can be manipulated. The strands in the cables are completely surrounded by the epoxy and thus any stress is equally distributed over the volume preventing any shear or local peak stress effects.

Once all the coils have been made they can be assembled in the magnet and pre-stressed. The cool down has to be well controlled in order to avoid any additional stresses due to temperature gradients in the magnet.

7 State of the art high-field magnets

7.1 Comparison of magnets

In Fig. 35 a comparison can be found of high-field accelerator magnets showing their apertures and their field values. In order to reliably operate magnets in a machine the top field used (called nominal field) is typically 80% of the maximum attainable field. The development has passed via Nb-Ti with 4–5 T at 4.2 K to 8 T at 1.9 K in running accelerators. The development of Nb$_3$Sn magnets started with 10 T in the 1990s and is now moving to 15 T with a record 16 T achieved for the HD1 from LBNL. Running construction projects like Fresca2 by CEA and CERN aim at similar fields but in a much larger aperture.

7.2 Design examples

Presently, several development projects of Nb$_3$Sn magnets are running in the USA and Europe and some examples can be found in Fig. 36. CERN-FNAL is developing a 5.5 m long 11 T dipole magnet with a 60 mm aperture for a special application for the luminosity upgrade of the LHC (HL-LHC). A LARP-CERN collaboration is developing a 150 mm aperture quadrupole with a gradient of 140 T/m for the low-beta insertion in HL-LHC. At LBNL the 35 mm aperture dipole magnet HD2 achieved 13.8 T. In order to upgrade the CERN cable test facility, a CEA-CERN collaboration is building a 100 mm aperture magnet with an aim to produce 15 T.
Fig. 35: Comparison between high-field magnets. Nb-Ti: blue diamonds, \( B_{\text{nominal}} \). Nb\(_3\)Sn: red squares, \( B_{\text{maximum}} \). As a rule, magnets are used with \( \approx 20\% \) margin \((B_{\text{nominal}} = 0.8B_{\text{maximum}})\).

8 High-field magnets for future accelerators

In Europe, CERN is starting to plan for a future proton–proton accelerator in the range of 100 TeV using magnets up to 20 T. Such a very high-field magnet will need a new design with new conductor types in the centre of the coil and will probably necessitate two decades to develop. In Fig. 37 one can find a figure that illustrates this development and a possible layout of such a coil. From Eq. (9) in Section 4 one can understand the coil-width requirement shown in the figure. The coil of the magnet is thought to need all three conductor types mentioned before: Nb-Ti in the field region below 8 T, Nb\(_3\)Sn of two grades in the region between 8 T and 16 T and HTSs in the highest-field region. At the moment the commercial prices of HTS conductors would make such a machine difficult to build but other HTS applications in the power sector are expected to lower this such that the usage for a high-energy collider will become feasible.

9 References for further study

References works for a more detailed study can be found in [2], [7], [8], [9], [10], [11], [12], [13], and [14].

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References

Fig. 36: Design examples of state of the art high-field magnets: top left: 11 T (FNAL and CERN), top right: HD2 (LBNL), bottom left: Fresca2 (CERN and CEA), bottom right: HQ (LARP).

Fig. 37: The road towards 20 T magnets; left: achieved field as function of the coil width for existing machines, development magnets as as needed for HE-LHC, right: a possible coil layout with grading with four conductor types (Malta workshop).

HIGH–FIELD ACCELERATOR MAGNETS


