Superconducting Magnets

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High Field Accelerator Magnets

- Introduction: magnetic field and superconducting magnets
- How to get high fields in accelerator dipole and quadrupole magnets?
- Superconductors for magnets
- Practical accelerator magnet design
- High field superconducting magnets for future accelerators
- Literature on High Field Magnets
Magnet types, technological view

We can classify magnets based on their technology.

- Electromagnet
- Permanent magnet
- Iron dominated
- Coil dominated
- Normal conducting (resistive)
- Superconducting
- Static
- Cycled / ramped
- Slow pulsed
- Fast pulsed
Maxwell equations

Integral form

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

\[ \oint \mathbf{E} d\mathbf{s} = -\frac{\partial}{\partial t} \int_A \mathbf{B} d\mathbf{A} \]

\[ \int_A \mathbf{B} d\mathbf{A} = 0 \]

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

Differential form

\[ \text{Ampere’s law} \]

\[ \text{Faraday’s equation} \]

\[ \text{Gauss’s law for magnetism} \]

\[ \text{Gauss’s law} \]

With:

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

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

\[ \mathbf{J} = \kappa \mathbf{E} + \mathbf{J}_{\text{imp.}} \]
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 field quality: multipole description

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

with:

\[ z = x + iy, \]

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

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

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

\( b_n \) the normal \( n \)th multipole component,

\( a_n \) the skew \( n \)th 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:

\[ a_n, b_n \leq 1 \text{ unit } 10^{-4} \]
Magnetic Length

In 3D, the longitudinal dimension of the magnet is described by a magnetic length

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

A circular yoke around the coil can give a 10-15% field increase

The magnetic length \(L_{mag}\) for SC magnets is adjustable by varying the length of the yoke: often the coils stick outside the end of the yoke: no easy rule of thumb for \(L_{mag}\)

Courtesy A. Milanese, CERN
Magnetic fields

From Ampere’s law with no time dependencies

\[ \oint_c \vec{B} \, d\vec{l} = \mu_0 I_{encl} \]

(Integral form)

We can derive the law of Biot and Savart

\[ \vec{B} = \frac{\mu_0 I}{2\pi r} \cdot \hat{\phi} \]

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

\[ I = 5 \times 10^5 \text{ A} \]

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

⇒ To get high fields one needs very large currents in small volumes

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

(overall current density in the coil area)
Coils for generating the Perfect Dipole Field

1) Conductors: 2 solid Intercepting ellipses (or circles)
   1) A uniform, opposite polarity, current density in the area of two intersecting ellipses produces a pure dipolar field *, but:
      1) The aperture is not circular
      2) Not easy to realise with a flat or round cable

4) Thick conductor shell with a $\cos\theta$ current distribution $J = J_0 \cos\Theta$
   1) Pure dipolar field
   2) Easier to reproduce with a flat rectangular (or slightly key-stone) cable

* This very easy and elegant calculation can be found in Ref[9], slides 49-50
Magnet types and higher orders

A “pure” multipolar field can be generated by a specific coil geometry

- dipole $n=1$
- quadrupole $n=2$
- sextupole $n=3$

Courtesy P. Ferracin, CERN
Coils for generating the Perfect multipole Field

For the generation of multipolar fields similar arguments apply
e.g. for quadrupolar field: \( J = J_0 \cos 2\Theta \)

This is only one way to look at possible coil layout for coil dominated magnets. Developments are still ongoing for alternative coil layouts.

eg. see:
Uni-layer magnets: a new concept for LTS and HTS based superconducting magnets, J-L. Rudeiros Fernández and P. Ferracin
Lawrence Berkeley National Laboratory, 2023 Supercond. Sci. Technol. 36 055003
What is specific about accelerator magnets?

1) Cylindrical volume with perpendicular field → Less efficient coil with more difficult forces compared to a solenoid

\[ \cos \Theta \text{ coil: } J = J_0 \cos \Theta \]

9) Dipoles, quadrupoles, etc

13) Long magnets: dipoles from 6 m (Tevatron) to 15 m (LHC)

14) Often magnets are bend (9.14 mm sagitta for the LHC dipoles)
Superconducting accelerators magnets; the state of the art

- Maximum attainable field slowly approaches 16 T
  - 20% margin needed (80% on the load line):
    for a 16 T nominal field we need to design for 20 T (or $B_n = 14.5$ T if the limit is 16T)

![Graph showing the practical upper limit for LTS dipoles](image)

Courtesy L. Bottura
Electromagnetic Forces

Scaling of electromagnetic force on a coil quadrant vs. B Field
Plot for recent production and R&D dipoles

The electromagnetic loads in a 20 T dipole would be a factor 5 to 8 larger than in the LHC dipoles
Electromagnetic Stored Energy

Scaling of the electromagnetic stored energy per unit length of magnet vs. B Field
Plot for recent production and R&D dipoles

The electromagnetic stored energy in a 20 T dipole would be close to a factor 10 larger than in the LHC dipoles
1977: Very first SC magnets at CERN in an SPS beam transfer line

1) CESAR dipole: aperture 150 mm, $B=4.5$ T, $l = 2$ m

2) CASTOR quadrupole
Both use a monolithic conductor wound into a $\cos \Theta$ coil
Early SC magnets for accelerators:
ISR Insertion quadrupole (end 1970-ies)

1) G=40 T/m in 73 mm diameter aperture
2) Nb-Ti monolithic conductor
3) fully impregnated coil
4) Prestress from yoke + shell
Existing Superconducting Accelerator dipole magnets (1)

- **Tevatron**
  - 76 mm bore
  - $B = 4.4 \, T$
  - $T = 4.2 \, K$
  - First beam 1983

- **HERA**
  - 75 mm bore
  - $B = 5.0 \, T$
  - $T = 4.5 \, K$
  - First beam 1991

- **RHIC**
  - 80 mm bore
  - $B = 3.5 \, T$
  - $T = 4.3-4.6 \, K$
  - First beam 2000

- **LHC**
  - 56 mm bore
  - $B = 8.34 \, T$
  - $T = 1.9 \, K$
  - First beam 2008

Courtesy P. Ferracin, CERN
Available Superconductors
Superconductor discovery timeline

- **TlBaCaCuO**
- **BiSrCaCuO**
- **HgBaCaCuO**
- **HgTlBaCaCuO**
- **Cs_3C_60** @ 1.4 GPa
- **LaSrCuO**
- **LaBaCuO**
- **RbCsC_60**
- **YBaCuO**
- **K_3C_60**
- **YbPd_2B_2C**
- **MgB_2**
- **SrFeAs**
- **FeSe**
- **H_2S** @ 155 GPa

**Critical temperature T_c [K]**

**Year**
- 1900
- 1940
- 1980
- 1985
- 1990
- 1995
- 2000
- 2005
- 2010
- 2015

**Liquids**
- liq. CF_4
- liq. N_2
- liq. H_2
- liq. He
Available Superconductors

2 families:

- LTS, Low Temperature Superconductor: $T = 4.5$ or lower $\rightarrow$ Liquid He
  - Well known industrial process, good mechanical properties
  - Thousands of accelerator magnets have been built

- HTS, High Temperature Superconductor: $T < 80K$ $\rightarrow$ LHe, LN2, He gas, etc.
  - LTS; Nb-Ti: the workhorse for 4 to 10 T
    - Complex industrial process, higher cost, brittle and strain sensitive
    - First usage in HL-LHC, several long magnet built and ready for installation, 25+ short development models have been built

- LTS; Nb$_3$Sn: towards 20 T
  - HTS materials: getting to 20 T and shooting to 40 T (Bi-2212, REBCO)
    - Used in solenoids (20-30 T range), used in power lines – no real accelerator magnets have been built yet (only a few models) – several small model magnets have been built
Superconducting means: \( R \equiv 0 \)

**Type I**
- \( B_c << 1 \text{T} \)
- Meissner effect

**Type II**
- \( B_{c2} > 1 \text{T} \)
- Quantized fluxoids

\[
\phi_0 = \frac{h}{2e} = 2 \times 10^{-15} \text{ Wb}
\]

**Superconducting state**
- Increase of field
- Cool-down

**Normal state**

\[
B < B_{c1} < B < B_{c2}
\]

\[
J: \text{few x } 10^3 \text{ A/mm}^2 \text{ inside the superconductor}
\]
Comparing wires, LTS Superconductors vs Copper

Typical operational conditions (0.85 mm diameter strand)

<table>
<thead>
<tr>
<th>Material</th>
<th>Critical Current Density $J$</th>
<th>Current $I$</th>
<th>Magnetic Field $B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>$J \sim 5 \text{ A/mm}^2$</td>
<td>$I \sim 3 \text{ A}$</td>
<td>$B = 2 \text{ T}$</td>
</tr>
<tr>
<td>Nb-Ti</td>
<td>$J \sim 1500-2000 \text{ A/mm}^2$</td>
<td>$I \sim 400 \text{ A}$</td>
<td>$B = 8-9 \text{ T}$</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>$J \sim 1500-2000 \text{ A/mm}^2$</td>
<td>$I \sim 400 \text{ A}$</td>
<td>$B = 12-13-16 \text{ T}$</td>
</tr>
</tbody>
</table>

Courtesy P. Ferracin, CERN-LBNL
comparison critical surface Nb-Ti vs Nb$_3$Sn

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

- $T_c$ 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 materials: Nb-Ti

1) Niobium and titanium combine in a ductile alloy
   • It is easy to process by extrusion and drawing techniques.

3) When cooled down to about 9 K it becomes a type II superconductor.
   • $T_c$ is $\sim9.2$ K at 0 T.
   • $B_{C2}$ is $\sim14.5$ T at 0 K.

5) The cost is approximately 100-150 US$ per kg of wire.
Superconducting materials: Nb$_3$Sn

1) Niobium and tin form Nb$_3$Sn
   - Brittle and strain sensitive

2) When cooled down to about 18 K it becomes a type II superconductor.
   - $T_{C0m}$ is $\sim$18 K at 0 T and 0 strain.
   - $B_{C20m}$ is $\sim$28 T at 0 K and 0 strain.

3) The cost is approximately 700-1500 US$ per kg of wire.
Superconducting strands and tapes: BSCCO

BSCCO: 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

By Nazargulov - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=80940329
Photos: courtesy LBNL
Superconducting tapes: YBCO (or REBCO)

YBCO: Yttrium barium copper oxide. (RE=Rare-Earth)

• Available in tapes: YBCO deposited on a substrate to impose the texture (1-2 \( \mu \)m)
• Can reach > 600 A/mm\(^2\) (overall)
• Is strong under axial stress and strain (300 MPa)
• Limited cabling possibilities:
• Difficult technology but could be promising for high field magnets in >20 T region.

Critical current depends on the angle between the face of the tape and the B field

PhD thesis J. van Nugteren

Multifilament wires, Fabrication of Nb-Ti multifilament wires

- Monofilament rods are stacked to form a multifilament billet, which is then extruded and drawn down.
- When the number of filaments is very large, multifilament rods can be re-stacked (double stacking process).

Courtesy A. Devred, ITER; P. Ferracin, CERN
Since Nb$_3$Sn is brittle, it cannot be extruded and drawn like Nb-Ti. The process requires several steps:

1) Assembly multifilament billets from Nb$_3$Sn precursor
2) Fabrication of the wire through extrusion-drawing
3) Fabrication of the cable
4) Fabrication of the coil
5) “reaction”: the Cu, Sn and Nb are heated to 600-700 C and the Sn diffuses in Nb and reacts to form Nb$_3$Sn

**Nb$_3$Sn strand types**

- **Bronze Process**
  - Cu
  - $\alpha$-Bronze
  - Nb (or Nb alloy) Filaments
  - Diffusion Barrier (Ta or Ta/Nb)

- **Internal Sn (Single Barrier)**
  - Cu
  - Cu
  - Nb (or Nb alloy) Filaments
  - Diffusion Barrier (Ta or Ta/Nb)

- **Internal Sn (Distributed Barrier)**
  - Cu
  - Cu
  - Nb (or Nb alloy) Filaments
  - Diffusion Barrier (Nb, Ta or Nb-Ta)

- **Powder in Tube (PIT)**
  - Cu
  - Cu-rich Powder (mostly NbSn$_2$)
  - Nb (or Nb alloy) tube
Superconducting cables for magnets

We need multi-strand cables

1) Superconducting accelerators are ramped up in time spans 100 s to 1000 s
2) Coils are designed for voltages to ground of around 1000 V
3) With the number of turns and the current the inductance is to be limited to keep the voltage below 1000 V
4) Dipoles and Current:
   1) Tevatron \( B = 4.4 \, \text{T} \); \( I \sim 4000 \, \text{A} \)
   2) Hera \( B = 5 \, \text{T} \); \( I \sim 6000 \, \text{A} \)
   3) LHC \( B = 8.3 \, \text{T} \); \( I \sim 12000 \, \text{A} \)
5) For magnets \( 10 \, \text{T} < B < 15 \, \text{T} \) the current has to be \( 10 \, \text{kA} < I < 15 \, \text{kA} \)
6) For stability reasons strands are \( 0.6 \, \text{mm} < \) strand diameter < \( 1 \, \text{mm} \)
7) With a Cu-nonCu ratio (for stability reasons) around 1 and a \( J_c \sim 1000 \, \text{A/mm}^2 \)
   \( \Rightarrow \) a 1 mm diameter strand can carry \( \sim 400 \, \text{A} \)
   \( \Rightarrow \) so we need a 30 strand cable to get up to 12 kA
LTS Cable types

- CIC
- ITER magnets

- Rutherford
- Accelerator magnets
  - Tevatron, HERA
  - RHIC and LHC

- Rutherford
- Detector magnets

- Nuclotron Type (b)
  - Pulsed SIS 100 magnets

Rope, Braid and Rutherford cables

Courtesy A. Balarino
Rutherford cables

1) Compact cables giving high overall current density
2) Easy rectangular geometry for convenient winding
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

1) Dipole 60° sector coil [see ref 13]
   1) The field is proportional to the current density \(j\)
   2) The field is proportional to coil width
   3) The field is independent of aperture

   \[
   B_1 = -4 \frac{j \mu_0}{2\pi} \int_0^{\pi/3} \int_r^{r+w} \frac{\cos(\theta)}{\rho} \rho d\rho d\theta = -\frac{\sqrt{3}\mu}{\pi} j w
   \]

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

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

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

→ 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 mid-plane for a sector dipole coil

1) Dipole 60° sector coil [see ref 1, 15]

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

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

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

5) Quadrupole 30° sector coil [see ref 1, 16 ]

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

The e.m. forces in a dipole magnet tend to push the coil
- Towards the mid plane in the vertical-azimuthal direction \((F_y, F_\theta < 0)\)
- Outwards in the radial-horizontal direction \((F_x, F_r > 0)\)

The e.m. forces in a quadrupole magnet tend to push the coil
- Towards the mid plane in the vertical-azimuthal direction \((F_y, F_\theta < 0)\)
- Outwards in the radial-horizontal direction \((F_x, F_r > 0)\)

Tevatron dipole

HD2

TQ

HQ

Courtesy P. Ferracin, CERN
Conductor stability and AC behaviour

1) Pure massive superconductor is not stable as they (Nb-Ti, Nb$_3$Sn) are poor normal conductors

2) To ‘cryogenically stabilize’ the conductor one surrounds it in Cu:
   1) good electrical conductivity
   2) good heat transfer to the He

3) During current ramping the filaments will magnetize ➔ make them thinner

5) Filaments will have magnetic coupling ➔ twist the strand

9) Practical low temperature superconductors are made as thin (5 μm – 100 μm) superconducting filaments in a Cu matrix, which is twisted

Courtesy M. Wilson
Due to perturbations locally the conductor can get $T > T_c (J, B)$

A thermal runaway can then occur, called a Quench (see also ref[17])

With stored energies > MJ the coils can overheat if nothing is done ($T = 3000K$ is possible !)

What to do ?

- Detect the quench : SC: $R=0 \rightarrow V=0$, quench $V>0$ (typically $100$mV threshold)
- Switch power convertor off
- Heat up the whole coil with quench heaters
- Dump energy of the circuit into a dump resistor

When something went wrong in an LHC dipole
Quench hot spot

In a simple approach:
assume that on the <1s time scale a volume element of the coil is not able to evacuate the heat (adiabatic case).

The heat balance of a unit volume of coil is:

\[ J^2(t) \rho(T) dt = \gamma C(T) dT \]

With:
- \( t \) time
- \( T \) temperature
- \( J(t) \) the current density
- \( \rho(T) \) the resistivity of the non-superconducting part of the cable
- \( \gamma \) the density
- \( C(T) \) the heat capacity

rearrange:

\[ J^2(t) dt = \frac{\gamma C(T)}{\rho(T)} dT \]

Integrate:

\[ \int_0^\infty J^2(t) dt = \int_{T_0}^{T_{max}} \frac{\gamma C(T)}{\rho(T)} dT \]

With this one can get a conservative estimate of the maximum temperature in the coil at the end of the quench.
Three types of coils are in use for high field magnets:

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

2) **Block coil**
3) **Canted Cos(Θ) coil**
Practical accelerator magnet design: Dipoles (2)

2) **Block coil** (used on development and test-station magnets)
   - With thick coils the field quality is good
   - Less efficient (~10%) wrt to (thin) $\cos(\theta)$ for the 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
   - ‘flared ends’ look easy but we need more experience
3) Canted $\cos(\Theta)$ : CCT (recent usage in accelerators)

- 2 layers of inclined solenoids: powered such that the axial B components compensate and the transverse B components add up.
- First proposed 40 years ago, recently further developed for accelerators: HL-LHC, HIE-Isolde, medical beam-lines, gantry magnets, …
- First in a circular machine is a 3.5 T corrector dipole MCBRD for HL-LHC
- Being designed for an ISOLDE beam line at CERN (curved, combined function magnet)
- Proposed for medical beam lines with bend dipoles and combined function magnets (H2020-HITRIplus)
1) Cos(\(\Theta\)) coil
   - Allows a very good field quality \(b_n < 1 \cdot 10^{-4}\)
     - 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 mid-plane where also high fields are located, (but are limited)
   - Wedges are needed in the straight part (‘Key-stoned’ cable)
   - The ends are short, special geometry for which there is a large experience but not it is easy

3) Canted Cos(\(\Theta\)) : CCT

Courtesy M. Wilson

Courtesy CEA
Insulation

- Cable insulation
  - requirements:
    - Good electrical properties to withstand turn-to-turn voltage after a quench
    - Good mechanical properties to withstand high pressure conditions
    - Porosity to allow penetration of helium (or epoxy)
    - Radiation hardness
  - Nb-Ti magnets: overlapped layers of polyimide (e.g. Kapton™)
  - Nb₃Sn magnets: fibre-glass braided or as tape/sleeve.
  - Typically the insulation thickness: 100 and 200 µm.

- Coil insulation: typically several layers (4-6) of polyimide between the coil and the structure.
The three manufacturing steps of Nb$_3$Sn coils:
1) winding, 2) reaction at 650degC, 3) impregnation with epoxy
Radiation hardness of the epoxy can be a strong requirement
Pre-stress

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

2) How to put pre-stress?
   Three methods:
   1. Compress at room temperature: collar system
   2. Use room temperature pre-stress 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
      cool-down: Al shrinking cylinder + bladder and key system

3) Order of magnitudes: LHC @ 8.34 T: 70 MPa warm, 30 MPa cold
    Fresca2 @ 13 T: 60 MPa warm, 130 MPa cold
Pre-stress: collars

“The classical solution”

1) Thin collars put around the coil
2) The coil is well contained in a fixed cavity
3) Pressed together and locked with pins or keys
4) At 300K apply a pre-stress 2-3 times of what is needed as part of the stress is lost during cooldown: for very high fields this tends to be too high (LHC: 70 MPa at 300 K and 40 MPa at cold)
5) Field quality is in good part determined by collar shape
6) If the coils size is not so well controlled, the stress can be too high or too low
7) \( \text{Nb}_3\text{Sn} \) is stress sensitive and this is a problem
Pre-stress:
AI shrinking cylinder + bladder and keys

Developed at LBNL, example: TQS,  HL-LHC quadrupole MQXF

1) 300 K: Bladders pressurized with water (<600 bar) , then insert keys →load between 10 MPa and 80 MPa
2) 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 cool-down

Coil assembly within yoke and aluminum shell
tooling for magnet fabrication

winding

impregnation

reaction

collaring
Operating SC magnets in Accelerators

1) In synchrotrons with many, or with the majority superconducting magnets special care must be taken to cope with the specific properties of these magnets:
   1) ramp rate,
   2) excitation curves and calibration,
   3) persistent current decay and snapback,
   4) machine parameter tuning and hysteresis effects,
   5) cryogenic system operation,
   6) continuous cryostats.

2) For keeping dynamic field effects under control, we need thin filaments in the wires.

3) Magnet strings that are situated inside long cryostats with long warm-up and cool-down times, which render any repair very tedious: the entire system must be engineered to very high reliability standards.

4) The relatively slow ramp-up and ramp-down of superconducting accelerators imply that it is not evident to do quick trials with the beam settings. To get to a good efficiency, careful preparation with appropriate computer simulations are needed before trying new setting parameters out on the beam.
What is happening after the 8T magnets for LHC?

At CERN and in the US:

1) Upgrade the LHC luminosity: HL-LHC (HILUMI)
   1) Use large aperture Nb$_3$Sn triplet quadrupoles MQXF (12T class)

2. Go to higher energies
   1) 16 T Nb$_3$Sn dipoles in the LHC ring for $E_{\text{com}}=26$ TeV: HE-LHC
   2) 16 T Nb$_3$Sn dipoles in a 100 km new ring for $E_{\text{com}}=100$ TeV: FCC Future Circular Collider

   But even!
   3) 20 T HTS dipoles in the LHC ring: for $E_{\text{com}}=33$ TeV: HE-LHC
   4) 20 T HTS dipoles in a 80 km new ring for $E_{\text{com}}=100$ TeV: FCC

3. Muon collider (@CERN or elsewhere)

For the CERN High Field Magnet program see: https://indico.cern.ch/event/1279349/

In China:
A similar completely project is being studied in China: SPPC (C=100 km, 12-20 T)

For these, basic High Field Magnet development programs are since many years running in the US and Europe and recently in China.
HL-LHC Inner Triplet magnet zoo

Triplet [G. Ambrosio, P. Ferracin et al.]

MCBXFB [F. Toral, et al.]

D1 [T. Nakamoto et al.]

MCBXFA [F. Toral, et al.]

Skew quad [G. Volpini, et al.]

D2 [P. Fabbricatore, S. Farinon]

D2 Q4 correctors [G. Kirby]

Basic HFM development (HL-LHC technology): EuCARD high field dipole (Fresca2):

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

1) Diameter Aperture = 100 mm
2) L coils = 1.5 m
3) L straight section = 700 mm
4) L yoke = 1.6 m
5) 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
- $L = 47\text{mH/m}$

Courtesy Attilio Milanese, Pierre Manil
Fabrication of Fresca2 coils, test results

Straightforward technology to wind blo coils with flared ends:
This is a lesson for FCC magnets!
Models had good performance, long prototypes are being fabricated in the US and at CERN.

A CERN LARP collaboration.

Nominal Gradient 132.6 T/m
Aperture diameter 150 mm
Peak Field 12.1 T
Current 17.5 A
Load-line Margin 20% @ 1.9 K
Stored Energy 1.32 MJ/m

Courtesy P. Ferracin, S. Izquierdo
FCC: 16T dipole options

Block coil

C. Lorin, M. Durante (CEA)

Cos-theta coil

S. Farinon, P. Fabbricatore (INFN)

Common coils

F. Toral (CIEMAT)

Canted Cos-theta

B. Auchmann (CERN/PSI)
16 T, CERN approach, go in steps

1 Extended Racetrack Model Coil, ERMC
2 Racetrack Model Magnet, RMM
3 Demonstrator, DEMO

First with one conductor, then with 2 different ones to optimise the coil: Grading

RMM test Sept 2022: reached conductor peak field Bp of 16.7T and 16.5 T in aperture cavity

courtesy: S. Izquierdo, J-C. Perez
Extensive magnet development is needed for a muon collider. This development has started in the institutes of the muon collaboration

**Muon Collider magnet “specs”**

<table>
<thead>
<tr>
<th>Type</th>
<th>Field</th>
<th>Bore</th>
<th>Length</th>
<th>Radiation Heat</th>
<th>Radiation Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target solenoids</td>
<td>20 T... 2 T</td>
<td>1200 mm</td>
<td>18 m</td>
<td>≈ 4.1 kW</td>
<td>80 MGy</td>
</tr>
<tr>
<td>6D Cooling solenoids</td>
<td>4 T ... 19 T</td>
<td>90 mm ... 600 mm</td>
<td>500 mm (x 17)</td>
<td>Radiation heat: TBD</td>
<td>Radiation dose: TBD</td>
</tr>
<tr>
<td>Accelerator magnets</td>
<td>±1.8 T (NC), &lt; 10 T (SC)</td>
<td>100 mm(H) x 30 mm(V)</td>
<td>3 m ... 5 m (x 1500)</td>
<td>Radiation heat: ≈ 3 W/m</td>
<td>Radiation dose: TBD</td>
</tr>
<tr>
<td>6D Cooling solenoids</td>
<td>20 T</td>
<td>50 mm</td>
<td>500 mm</td>
<td>Radiation heat: TBD</td>
<td>Radiation dose: TBD</td>
</tr>
<tr>
<td>6D Cooling solenoids</td>
<td>16 T peak (IR 20 T)</td>
<td>150 mm</td>
<td>10 m ... 15 m (x 700)</td>
<td>Radiation heat load: ≈ 5 W/m</td>
<td>Radiation dose: ≈ 20...40 MGy</td>
</tr>
</tbody>
</table>

See: https://muoncollider.web.cern.ch/
HTS is the only path beyond 16 Tesla

- So far, many small experimental solenoid magnets have been built, but only a few coils for accelerator dipole magnets made either of ReBCO tapes or Bi-2212 cables, and only the first HTS inserts for hybrid dipole demonstrators, such as 5 T inserts at CERN and CEA and 3 T at BNL.

- In practice, all insert coils built for hybrid LTS/HTS magnets had significant performance limitations.
Feather-M2.0: HTS has special dynamics

HTS magnets work differently than LTS magnets due to a larger enthalpy margin
HTS possibilities, an example at PSI

PSI built and tested a stack of 4 ReBCO flat non-insulated disk coils. The disks were powered in series. The coils were produced under a license- and collaboration agreement with Tokamak Energy Ltd.

Cooling: two cryo-coolers
Current: 2 kA (maximum of power supply)
Coil temperature: 12 K on plateau (higher during ramp)
Resistive-lead bottom temperature: 72 K
Central field: 18.2 T (measured)
Coil field: 20.3 T (simulated)

Courtesy B. Auchmann, PSI
Final remarks

Superconducting accelerator magnets in the 4 T – 8 T range are “state of the art” using Nb-Ti conductor.

Magnets in the 12 T range using Nb$_3$Sn are in the production phase for HL-LHC.

Development models have been shown to work up to 16 T.

For future collider 12 -16 T magnets are being designed.

Development for HTS magnets for the 20 T range has started.

Magnet development for the muon collider has recently started in the very high field range.

Lots of fun ahead!
Literature on High Field Magnets

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

• Courses
  7) F Ferracin, EUCAS 2017 short courses, https://indico.cern.ch/event/626645/

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

- Papers and reports
  16) P. Fessia, et al., Parametric analysis of forces and stresses in superconducting quadrupole sector windings, *sLHC Project Report 0003*

- Websites
  17) [https://nationalmaglab.org/magnet-development/applied-superconductivity-center](https://nationalmaglab.org/magnet-development/applied-superconductivity-center)
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