Technology challenges: Superconducting accelerator magnets
PART I/II

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Thanks to many colleagues, in particular Paolo Ferracin for the material they have given to me
Why colliders?

Accelerators are the finest microscopes: *atto-scope or zepto-scope*

\[ \lambda = \frac{h}{p} ; \quad \text{@LHC: } p = 1 \text{ TeV} \implies \lambda \approx 10^{-18} \text{ m} \]

\( \lambda \): wavelength

\( h \): Planck constant

\( p \): momentum
Why SC accelerator magnets and where are they used?

**COLLIDERS** (LEP, Tevatron, Hera, RHIC, LHC, etc.)

- One of the most important parameter of colliders is the beam energy, as it determines the physics discovery potential.

- LHC: Higgs-boson
- Tevatron: top-quark
- Spps: Z&W-boson
- Petra: gluon
- Spear: charm quark, tau lepton
Magnets in accelerators, why?

The energy $E$ in GeV of particles in a circular accelerator is limited by the strength of the bending dipole magnets $B$ in Tesla and the machine radius $r$ in m:

$$E \approx 0.3 \, B \, r$$
• The magnetic field $B$ steers the particles in a circular orbit:

$$ F = qE + qv \times B $$

• First term ($qE$) negligible: $300 \text{ MV/m}$ corresponds to $1 \text{ T}$

$NI$: Ampere turns in $\text{ A}$  
$J$: Current density in $\text{ A/m}^2$  
$B$: Magnetic flux density in $\text{ T} = N/\text{Am}$  
$v$: velocity in $\text{ m/s}$  
$F$: Force in $\text{ N}$  
$\rho$: particle path radius in $\text{ m}$
Why SC magnets?

Normal-conducting iron-dominated magnets:
- \( B \approx \mu_0 NI / g \)
- Limited by the iron saturation: \( B \lesssim 2 \) T
- Ohmic losses, cooling, power converters, etc.
- \( g = 100 \) mm (gap)
- \( NI = 160 \) kA (Ampere turns)
- \( B = 2 \) T (Magnetic flux density, limit)

Superconducting magnets:
- \( B \approx \mu_0 NI / \pi r \)
- Limited only by SC material properties and cost
- Cooling, power converters, busbars
- \( r = 1/2g = 45 \) mm (aperture radius)
- \( NI = 1 \) MA (Ampere turns)
- \( B = 8.84 \) T (magnetic flux density)
50,000 tons of normal conducting magnets
50,000 tons of superconducting magnets
The LHC dipole magnet
In which domains do we need to work?

Multidisciplinary field:
- Chemistry and material science: superconducting materials
- Quantum physics: the key mechanisms of superconductivity
- Classical electrodynamics: magnet design
- Mechanical engineering: support structures
- Electrical engineering: powering of the magnets
- Cryogenics: keep them cool ...
- Industrialization & large and complex project management
- Cost modelling
- Impact on society

Very different fields and multi-disciplinary field not limited to physics and engineering
What do we need to do to get a good design?

Let’s focus on the main (technical) points:

• Conductor and cable design, which superconducting material, strand and cable to choose?
• How to do the electromagnetic and structural design of the coil (field and field quality load line margin, quench)?

AIM OF LECTURE: Understand the main technical concepts relevant in superconducting accelerator magnets!
Part I

- Superconductivity
- Electromagnetic coil design
- Coil manufacture

Part II

- Margins and quench protection
- Structural design and assembly
- Testing
- Outlook, what brings the future?
Superconducting material

- Superconductivity discovered in 1911 by Kammerlingh-Onnes: ZERO resistance of mercury wire at 4.2 K
- Temperature at which the transition takes place: critical temperature $T_c$
- Observed in many materials: but not in the typical best conductors (Cu, Ag, Au)

Kammerlingh-Onnes proposed 1913 a 10 T solenoid, but it took 50 years (!) of hard work to make this dream come true
Superconductivity – Type I superconductors

Meissner-Ochsenfeld effect (1933):
- Perfect diamagnetism: With $T < T_c$ magnetic field is expelled
- No magnetic field inside the superconductor → no transport current inside a round conductor

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c$ (K)</th>
<th>$\mu_0H_c$ (mT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>1.2</td>
<td>9.9</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.52</td>
<td>3.0</td>
</tr>
<tr>
<td>Gallium</td>
<td>1.1</td>
<td>5.1</td>
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<tr>
<td>Indium</td>
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<td>27.6</td>
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<tr>
<td>Iridium</td>
<td>0.11</td>
<td>1.6</td>
</tr>
<tr>
<td>Lanthanum $\alpha$</td>
<td>4.8</td>
<td>4.9</td>
</tr>
<tr>
<td>Lanthanum $\beta$</td>
<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td>Lead</td>
<td>7.2</td>
<td>80.3</td>
</tr>
<tr>
<td>Lutecium</td>
<td>0.1</td>
<td>35.0</td>
</tr>
<tr>
<td>Mercury $\alpha$</td>
<td>4.2</td>
<td>41.3</td>
</tr>
<tr>
<td>Mercury $\beta$</td>
<td>4.0</td>
<td>34.0</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.9</td>
<td>~6.3</td>
</tr>
<tr>
<td>Osmium</td>
<td>0.7</td>
<td>~20.1</td>
</tr>
<tr>
<td>Rhenium</td>
<td>0.7</td>
<td>~4.9</td>
</tr>
<tr>
<td>Ruthenium</td>
<td>0.5</td>
<td>~6.6</td>
</tr>
<tr>
<td>Tantalum</td>
<td>4.5</td>
<td>~83.0</td>
</tr>
<tr>
<td>Thallium</td>
<td>2.4</td>
<td>~17.1</td>
</tr>
<tr>
<td>Thorium</td>
<td>1.4</td>
<td>~16.2</td>
</tr>
<tr>
<td>Tin</td>
<td>3.7</td>
<td>~30.6</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.4</td>
<td>~0.016</td>
</tr>
<tr>
<td>Tungsten</td>
<td>0.4</td>
<td>~0.12</td>
</tr>
<tr>
<td>Uranium $\alpha$</td>
<td>0.6</td>
<td>~1.8</td>
</tr>
<tr>
<td>Zirconium</td>
<td>0.8</td>
<td>~5.3</td>
</tr>
</tbody>
</table>
Superconductivity – Type I superconductors

Question: Which experiment demonstrates the Meisner-Ochsenfeld effect?

Rope
Permeant magnet

Pb, T < 7.2 K

- Temperature is kept constant
- Magnet does not fall down after releasing the rope

T < 7.2 K

T > 7.2 K

- Cool down
- Magnet starts hoovering
Superconductivity – Type I superconductors

- Pb, $T < 7.2 \text{ K}$
- Permeant magnet
- Eddy currents are generated. No resistance is present in the superconductor. Therefore, the small permanent magnet hoovers.
Superconductivity – Type I superconductors

Perfect diamagnetism: Meissner-Ochsenfeld effect. Magnetic field lines are expelled from the Type I superconductor. As a result the magnet starts hoovering.

Pb, T < 7.2 K

Rope

Permeant magnet

T > 7.2 K

T < 7.2 K
Superconductivity – Type II superconductors

- So, for 40-50 years, superconductivity was a research activity
- Then, in the 50’s, type II superconductors were discovered:
  - Between $B_{c1}$ and $B_{c2}$: mixed phase
  - $B$ penetrates as flux tubes: fluxoids with a flux of $\phi_0 = h/2e = 2 \cdot 10^{-15}$ Wb
- Much higher fields and link between $T_c$ and $B_{c2}$

\[ B < B_{c1} \]

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

by L. Bottura
Superconductivity – Hard superconductors

• …but, if a current passes through the tubes
  • Lorentz force on the fluxoids: \( f = J \times B \)
• The force causes a motion of tubes
  • Flux motion \((dB/dt) \rightarrow (V) \rightarrow \text{dissipation (VI)}\)
• Fluxoids must be locked by pinning centres
  • Defects or impurities in the structure

• The pinning centres exert a pinning force as long as \( f \leq J \times B \):
  • No flux motions \( \rightarrow \) no dissipation
  • \( J_c \) is the current density at which, for a given \( B \) and at a given \( T \) the pinning force is exceeded by the Lorentz force
A type II material is superconductor below the critical surface defined by

- Critical temperature $T_c$ (property of the material)
- Upper critical field $B_{c2}$ (property of the material)
- Critical current density $J_c$ (property of the material but in practice hard work by the producer)
Technical superconductors: Nb-Ti (1961) and Nb$_3$Sn (1954)

• Nb and Ti: ductile alloy
  • Production route: Extrusion + drawing
  • $T_c$ is $\sim$9.2 K at 0 T
  • $B_{c2}$ is $\sim$14.5 T at 0 K
  • Firstly in Tevatron (80s), then in HERA, RHIC and LHC
  • $\sim$250 EUR/kg of wire (1 euro per m)

• Nb and Sn → intermetallic compound
  • Brittle, strain sensitive, formed at $\sim$650-700°C
  • $T_c$ is $\sim$18 K at 0 T
  • $B_{c2}$ is $\sim$28 T at 0 K
  • Used in NMR, ITER, HL-LHC and baseline for FCC
  • $\sim$700-1500 EUR/kg of wire (target price for FCC: 450 EUR/kg of wire)
Conductors: from Cu to Nb₃Sn

- **Cu**
  - $J_e \sim 5 \text{ A/mm}^2$
  - $I \sim 3 \text{ A}$
  - $B = 2 \text{ T}$

- **Nb-Ti**
  - $J_e \sim 600-700 \text{ A/mm}^2$
  - $I \sim 300-400 \text{ A}$
  - $B = 8-9 \text{ T}$

- **Nb₃Sn**
  - $J_e \sim 600-700 \text{ A/mm}^2$
  - $I \sim 300-400 \text{ A}$
  - $B = 12-16 \text{ T}$

0.85 mm diameter strand
Conductors: from Cu to Nb$_3$Sn

Cu

$J_c \sim 5$ A/mm$^2$

$I \sim 3$ A

$B = 2$ T

Nb-Ti

$J_c \sim 600$-$700$ A/mm$^2$

$I \sim 300$-$400$ A

$B = 8$-$9$ T

Nb$_3$Sn

$J_c \sim 600$-$700$ A/mm$^2$

$I \sim 300$-$400$ A

$B = 12$-$16$ T
Why small filaments? Stability!

- Simple model: SC carries either $J_c$ or no current → If field is changed, eddy currents are resistively damped
- The conductor is stable as long as temperature stays below the critical temperature $T_c$

\[
\begin{align*}
\text{One large filament} & \quad \text{Several (N \gg 1) small filaments} \\
\text{same SC area, i.e. } a_L^2 &= Na_s^2 \\
\text{total volumetric heat [J/m}^3] & \\
Q_L &\approx \frac{8\Delta B}{3\pi} J_c a_L \\
Q_S &\approx \frac{8\Delta B}{3\pi} J_c a_s \\
\frac{Q_S}{Q_L} &= \frac{a_s}{a_L} = \frac{a_s}{a_s \sqrt{N}} \\
\text{for } N = 100 \quad \frac{Q_S}{Q_L} &= \frac{1}{10}
\end{align*}
\]

\[
a \leq \sqrt{\frac{3\gamma C(\theta_c - \theta_0)}{\mu_0 J_c^2}}
\]
Why Cu? Stability & Protection!

Quench protection
• Superconductors have a very high normal state resistivity
• If quenched, could reach very high temperatures in few ms
• If embedded in a high-purity copper matrix, when a quench occurs, current redistributes in the low-resistivity matrix yielding to a lower peak temperature

![Diagram showing quench protection](image1)

![Resistivity vs. Current density](image2)
Stability?

Question: What is the cause of the instabilities seen in the plot below for field levels below ~10 T?

Critical current of a Nb$_3$Sn wire vs. magnetic field (measured)

Courtesy of E. Barzi
What about AC losses? Twisting!

Twisting
• When a multi-filamentary wire is subjected to a time varying magnetic field, current loops are generated between filaments.
• If filaments are straight, large loops with large currents → AC losses
• If the strands are magnetically coupled the effective filament size is larger → flux jumps

To reduce these effects, filaments are twisted, the twist pitch is of the order of 20-30 times of the wire diameter.
And magnetization

Superconductor magnetization

- A hard superconducting filament shows a magnetization curve, as the one shown on the right
- The magnetization stays constant (if no flux jumps occur) at constant field: persistent current
- Field persistent currents produce field errors proportional to $J_c a$
  - HERA filament diameter 14 µm
  - LHC filament diameter 6-7 µm
  - HL-LHC filament diameter 50 µm
  - FCC target filament diameter 20 µm
Practical superconductors: Fabrication of Nb-Ti multifilament wires

- Nb-Ti ingots
- 200 mm Ø, 750 mm long
- Monofilament rods are stacked to form a multifilament billet, then extruded and drawn down
- Can be re-stacked: double-stacking process
Practical superconductors: Fabrication of Nb$_3$Sn multifilament wires

- Since Nb$_3$Sn is brittle it cannot be extruded and drawn like Nb-Ti.
- Process in several steps
  - Assembly multifilament billets from with Nb and Sn separated
  - Fabrication of the wire through extrusion-drawing
  - Fabrication of the cable
  - Fabrication of the coil
- Reaction
  - Sn and Nb are heated to 600-700°C
  - Sn diffuses in Nb and reacts to form Nb$_3$Sn
Conductors: Strand and cables

- Now, we know we need conductors composed out of small filaments and surrounded by a stabilizer (typically copper) to form a multi-filament wire or strand.

- To keep voltages reasonable small, the inductance of the magnet has to be small $\Rightarrow L \propto 1/F \Rightarrow$ we need large currents!

- Large wires are excluded due to self-field instabilities yielding to flux jumps (same argument as for small filaments) $\Rightarrow$ practical limit 1-2 mm

**Solution**: Superconducting cable composed of several wires: multi-strand cable!
What else do we need? Insulation!

Rule in accelerator magnets: never sacrifice the insulation!

Courtesy of A. Siemko, CERN
Typical insulation schemes for Nb-Ti and Nb$_3$Sn

Typically the insulation thicknesses: 100 and 200 µm
- The cable insulation must feature good electrical properties to withstand turn-to-turn V after a quench
- Good mechanical properties to withstand high pressure conditions
- Porosity to allow penetration of helium (or epoxy)
- Radiation hardness

In Nb-Ti magnets overlapped layers of polyimide

In Nb$_3$Sn magnets, fibre-glass braided or as tape/sleeve.
Let’s take the cable and do an electromagnetic design!

- How do we express field and its “imperfections”? 
- How do we create a perfect field? 
- How do we design a coil to minimize field errors? 
- How do we select the current density in the coil?
How do we generate a perfect dipole?

- How to generate a dipolar field:
  - Two infinite slabs
  - Two intersection cylinders
  - Cos-theta current distribution
- Many different winding schemes typically classified as
  - Block type magnets (block, common-coil)
  - Cos-theta/shell type magnets (traditional cos-theta, canted cos-theta)
Magnetic design: Harmonics

The field can be expressed as (simple) series of coefficients:

So, each coefficient corresponds to a “pure” multipolar field

\[ B_y(x, y) + iB_x(x, y) = \sum_{n=1}^{\infty} C_n(x + iy) = \sum_{n=1}^{\infty} (B_n + iA_n)(x + iy) \]

Magnetic design: Harmonics

The field can be expressed as (simple) series of coefficients.
So, each coefficient corresponds to a “pure” multipolar field.

\[ B_1 = \frac{2\mu_0}{\pi} J (R_{\text{out}} - R_{\text{in}}) \sin \varphi = \frac{2\mu_0}{\pi} J w \sin \varphi \]

\[ B_n = \frac{2\mu_0}{\pi} J \frac{(R_{\text{out}}^{2-n} - R_{\text{in}}^{2-n})}{n(2 - n)} r_{\text{ref}}^{n-1} \sin(n\varphi), \quad n = 3, 5, 7, \ldots \]
Magnetic design: Optimization of one layer designs

- We compute the central field given by a sector dipole with 2 blocks
- Equations to set to zero \(B_3, B_5\) and \(B_7\)

\[
\begin{align*}
\sin(3\alpha_3) - \sin(3\alpha_2) + \sin(3\alpha_1) &= 0 \\
\sin(5\alpha_3) - \sin(5\alpha_2) + \sin(5\alpha_1) &= 0
\end{align*}
\]

- And with 3 blocks
- Equations to set to zero \(B_3, B_5, B_7, B_9\) and \(B_{11}\)

\[
\begin{align*}
\sin(3\alpha_5) - \sin(3\alpha_4) + \sin(3\alpha_3) - \sin(3\alpha_2) + \sin(3\alpha_1) &= 0 \\
\sin(5\alpha_5) - \sin(5\alpha_4) + \sin(5\alpha_3) - \sin(5\alpha_2) + \sin(5\alpha_1) &= 0 \\
\sin(7\alpha_5) - \sin(7\alpha_4) + \sin(7\alpha_3) - \sin(7\alpha_2) + \sin(7\alpha_1) &= 0 \\
\sin(9\alpha_5) - \sin(9\alpha_4) + \sin(9\alpha_3) - \sin(9\alpha_2) + \sin(9\alpha_1) &= 0 \\
\sin(11\alpha_5) - \sin(11\alpha_4) + \sin(11\alpha_3) - \sin(11\alpha_2) + \sin(11\alpha_1) &= 0
\end{align*}
\]

\(\alpha_1\) and \(\alpha_2\) are the wedge angles. Two wedges, \(b_3=b_5=b_7=b_9=0\) [0°-33.3°,37.1°-53.1°,63.4°-71.8°]
A review of coil layouts: RHIC

- Let us see two coil lay-outs of real magnets
- The RHIC dipole has four blocks

Two wedges, $b_3=b_5=b_6=b_4=0$

$[0^\circ-33.3^\circ,37.1^\circ-53.1^\circ,63.4^\circ-71.8^\circ]$
A review of coil layouts: LHC MB

- LHC MB: Two layers
A review of coil layouts: Existing

TEVATRON
USA, 1983-2011

HERA
Germany, 1991-2007

RHIC
USA, since 2000

LHC
CERN, since 2008
Winding of Fresca2

Winding machine with dedicated tooling

Winding machine with dedicated tooling
The Winding House at CERN (bld. 180)
Reaction furnace(s)

Dedicated ovens with controlled atmosphere
Ramp at 25°C/h, held during 72 h at 210°C
Ramp at 50°C/h, held during 48 h at 400°C
Ramp at 50°C/h, held during 50 h at 650°C
Impregnation tank

Dedicated autoclave for vacuum impregnation with epoxy
Part I

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