Summer Student Lecture

Superconductivity and superconducting magnets for the LHC Upgrade

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Introduction
Goal of the lecture

- Overview of **superconducting magnets** for particle accelerators (dipoles and quadrupoles)
  - Description of the components and their function
  - *...past, present, and future*: HiLumi LHC and FCC
- From the superconducting material to the full magnet
Multidisciplinary field: mixture of

- 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 …

Very different order of magnitudes
Outline

- Particle accelerators and superconductors
- Magnetic design and coils
- Mechanics of superconducting magnets
- Quench and protection
- HiLumi LHC and FCC
Particle accelerators and superconductors


  - Units 2 by E. Todesco


- Presentations from Luca Bottura and Martin Wilson
Particle accelerators and magnets

- **Principle of synchrotrons**
  - Driving particles in the same accelerating structure several times

- **Electro-magnetic field** accelerates particles
  \[ \vec{F} = e\vec{E} \]

- **Magnetic field** steers the particles in a ~circular orbit
  \[ \vec{F} = e\vec{v} \times \vec{B} \]

- Particle accelerated \( \rightarrow \) energy increased \( \rightarrow \) magnetic field increased ("synchro") to keep the particles on the same orbit of curvature
  \[ p = eB\rho \]

by E. Todesco
Main field components is $B_y$
- Perpendicular to the magnet axis $z$

**Electro-magnets:** field produced by a current (or current density)

$$B_y = -\frac{\mu_0 J_0}{2} (r_{out} - r_{in})$$

Magnetic field steers (bends) the particles in a \simcircular orbit

$p = eB\rho$

by E. Todesco
Particle accelerators and magnets

Quadrupoles

- The force necessary to stabilize linear motion is provided by the quadrupoles.
- They provide a field equal to zero in the center, increasing linearly with the radius.
- They act as a spring: focus the beam.
- Prevent protons from falling to the bottom of the aperture due to the gravitational force.
  - It would happen in less than 60 ms.

\[ G = \frac{B_y}{r} = -\frac{\mu_0 J_0}{2} \ln \frac{r_{out}}{r_{in}} \]

by E. Todesco
Particle accelerators and magnets

- **Dipoles:** the larger $B$, the larger the **energy**
- **Quadrupoles:** the larger $B$, the larger the **focusing strength**
- **For an electro-magnet,** the larger $B$, the larger must be $J$

\[
p = eB\rho
\]

$B_y = -\frac{\mu_0 J_0}{2} (r_{\text{out}} - r_{\text{in}})$

$G = \frac{B_y}{r} = -\frac{\mu_0 J_0}{2} \ln \frac{r_{\text{out}}}{r_{\text{in}}}$

- **In normal** conducting magnets, $J \sim 5 \text{ A/mm}^2$
- **In superconducting** magnets, $J_e \sim 600-700 \text{ A/mm}^2$
Superconductivity
The discovery

- Superconductivity discovered in 1911 by Kammerling-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)
- At $T > T_c$, superconductor very poor conductor
- 2 kinds of superconductors
  - Type I and Type II
    - Different behaviour with magnetic field
Superconductivity
Type I superconductors

- Meissner-Ochsenfeld effect (1933)
- Perfect diamagnetism
  - With $T<T_c$ magnetic field is expelled
- But, the $B$ must be $<$ critical field $B_c$
  - Otherwise superconductivity is lost

Unfortunately, first discovered superconductors (Type I) with very low $B_c$ ($\leq 0.1$ T)
  - not practical for electro-magnets
So, for 40-50 years, superconductivity was a research activity.

Then, in the 50’s, type II superconductors

- 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 $B_{c2}$
…but, if a current passes through the tubes
- Lorentz force on the fluxoids: \( F_L = J \times B \)

The force causes a **motion** of tubes
- Flux motion \((dB/dt) \rightarrow (V) \rightarrow \text{dissipation} (VI)\)
- Fluxoids must be locked by **pinning centers**
  - Defects or impurities in the structure

The pinning centres exert a pinning force \( F_p \)
- As long as \( F_p \leq J \times B \)
  - 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 supercond. 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 $J_c$
  - Hard work by the producer
Superconductivity
Nb-Ti (1961) and Nb₃Sn (1954)

- Nb and Ti → ductile alloy
  - 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 all the other
    - $\sim 50$-200 US$ per kg of wire (1 euro per m)

- Nb and Sn → intermetallic compound
  - Brittle, strain sensitive, formed at $\sim 650$-$700^\circ$C
  - $T_C$ is $\sim 18$ K at 0 T
  - $B_{C2}$ is $\sim 28$ T at 0 K
  - Used in NMR, ITER
  - $\sim 700$-$1500$ US$ per kg of wire (5 euro per m)
Superconductivity from Cu to Nb$_3$Sn

- Typical operational conditions (0.85 mm diameter strand)

Cu

\[ J_e \sim 5 \text{ A/mm}^2 \]
\[ I \sim 3 \text{ A} \]
\[ B = 2 \text{ T} \]

Nb-Ti

\[ J_e \sim 600-700 \text{ A/mm}^2 \]
\[ I \sim 300-400 \text{ A} \]
\[ B = 8-9 \text{ T} \]

Nb$_3$Sn

\[ J_e \sim 600-700 \text{ A/mm}^2 \]
\[ I \sim 300-400 \text{ A} \]
\[ B = 12-13 \text{ T} \]
Typical operational conditions (0.85 mm diameter strand)

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

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

- **Nb$_3$Sn**
  - $J_e \sim 600-700 \text{ A/mm}^2$
  - $I \sim 300-400 \text{ A}$
  - $B = 12-13 \text{ T}$
Superconducting materials are produced in small filaments and surrounded by a stabilizer (typically copper) to form a *multi-filament wire* or *strand*.

A superconducting cable is composed by several wires: *multi-strand cable*. 
Practical superconductors
Multi-filament wires motivations

- Fluxoid distribution depends on $B$ and $J_c$
- Thermal disturbance $\rightarrow$ the local change in $J_c$ $\rightarrow$ motion or "flux jump" $\rightarrow$ power dissipation

Stability criteria for a slab (adiabatic condition)

\[
a \leq \sqrt{\frac{3\gamma C(\theta_c - \theta_0)}{\mu_0 j_c^2}}
\]

- $a$ is the half-thickness of the slab
- $j_c$ is the critical current density [A m$^{-2}$]
- $\gamma$ is the density [kg m$^{-3}$]
- $C$ is the specific heat [J kg$^{-1}$]
- $\theta_c$ is the critical temperature.

- Filament diameters usually $< 50$ µm

by L. Bottura
**Superconductor magnetization**

- When a filament is in a varying $B_{ext}$, its inner part is shielded by currents distribution in the filament periphery.
  - They **do not decay** when $B_{ex}$ is held constant → **persistent currents**

- These currents produce **field errors** and **ac losses** proportional to $J_c r_f$
  - LHC filament diameter 6-7 µm.
  - HERA filament diameter 14 µm.
**Inter-filament coupling**

- 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 $\rightarrow$ **ac losses**
- If the strands are magnetically coupled the effective filament size is larger $\rightarrow$ **flux jumps**

**To reduce these effects, filaments are twisted**

- twist pitch of the order of 20-30 times of the wire diameter.
**Practical superconductors**

**Multi-filament wires motivations**

**Quench protection**

- Superconductors have a very high normal state resistivity
  - If quenched, could reach very high temperatures in few ms.
- If embedded in a **copper matrix**, when a quench occurs, current redistributes in the low-resistivity matrix $\rightarrow$ **lower peak temperature**

The copper matrix provides **time to act** on the power circuit

In the case of a small volume of superconductor heated beyond the critical temperature the current can flow in the copper for a short moment, allowing the filament to **cool-down and recover** supercond.

The matrix also helps stabilizing the conductor against **flux jumps**
Practical superconductors
Multi-filament wires motivations

- Flux jumps
- Persistent currents
- AC losses
- Quench protection
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
Multifilament wires
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 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

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Superconductivity and superconducting magnets for the LHC Upgrade, July 13, 2017

Paolo Ferracin
Most of the superconducting coils for particle accelerators wound from a multi-strand cable (*Rutherford cable*)

- Reduction of strand **piece length**
- Reduction of **number of turns**
  - easy winding
  - smaller coil inductance
    - less V for power supply during ramp-up;
    - after a quench, faster discharge and V
- **current redistribution** in case of a defect or a quench in one strand

The strands are **twisted** to

- Reduce **inter-strand coupling currents**
  - Losses and field distortions
- Provide more **mechanical stability**
Filling ratio: 0.25-0.3
Outline

- Particle accelerators and superconductors
- Magnetic design and coils
- Mechanics of superconducting magnets
- Quench and protection
- HiLumi LHC and FCC
References

Magnetic design and coils


  - Units 5, 8, 9 by E. Todesco

Magnetic design and coils

- How do we create a **perfect** field?
- How do we **express** field and its “**imperfections**”?
- How do we design a coil to **minimize field errors**?
- How do we **fabricate** a coil?
Perfect dipole field
Intercepting circles (or ellipses)

Within a cylinder carrying $j_0$, the field is perpendicular to the radial direction and proportional to the distance to the centre $r$:

$$B = -\frac{\mu_0 j_0 r}{2}$$

- Combining the effect of two intersecting cylinders

$$B_x = \frac{\mu_0 j_0 r}{2} \left\{ -r_1 \sin \theta_1 + r_2 \sin \theta_2 \right\} = 0$$

$$B_y = \frac{\mu_0 j_0 r}{2} \left\{ -r_1 \cos \theta_1 + r_2 \cos \theta_2 \right\} = -\frac{\mu_0 j_0}{2} s$$

- A uniform current density in the area of two intersecting circles produces a pure dipole
  - The aperture is not circular
  - Not easy to simulate with a flat cable

- Similar proof for intersecting ellipses

by M. Wilson
If we assume

- $J = J_0 \cos \theta$ where $J_0 \, [A/m^2]$ is $\perp$ to the cross-section plane
- Inner (outer) radius of the coils = $a_1$ ($a_2$)

The generated field is a pure dipole

$$B_y = -\frac{\mu_0 J_0}{2} (a_2 - a_1)$$

Linear dependence on coil width

Easier to achieve with a Rutherford cable
Perfect quadrupole field

- Intercepting ellipses or circles

- Thick shell with $\cos 2\theta$ current distribution

- If we assume
  - $J = J_0 \cos 2\theta$ where $J_0$ [A/m$^2$] is $\perp$ to the cross-section plane
  - Inner (outer) radius of the coils = $a1$ ($a2$)

$$G = \frac{B_y}{r} = -\frac{\mu_0 J_0}{2} \ln \frac{a_2}{a_1}$$

- And so on...
  - Perfect sextupoles: $\cos 3\theta$ or 3 intersecting ellipses
  - Perfect $2n$-poles: $\cos n\theta$ or $n$ intersecting ellipses
From ideal to practical configuration

- How can I reproduce **thick shell with a \( \cos \theta \)** distribution with a cable?
  - Rectangular cross-section and constant \( J \)

- First “rough” approximation
  - **Sector dipole**

- Better ones
  - More **layers** and **wedges** to reduce \( J \) towards 90°

- As a result, the field is **not perfect** anymore
  - How can I express in improve the “imperfect” field inside the aperture?
Maxwell equations for magnetic field

\[ \nabla \cdot B = \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} = 0 \]
\[ \nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t} \]

In absence of charge and magnetized material

\[ \nabla \times B = \left( \frac{\partial B_y}{\partial z} - \frac{\partial B_z}{\partial y}, \frac{\partial B_z}{\partial x} - \frac{\partial B_x}{\partial z}, \frac{\partial B_x}{\partial y} - \frac{\partial B_y}{\partial x} \right) = 0 \]

If \( \frac{\partial B_z}{\partial z} = 0 \) (constant longitudinal field), then

\[ \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} = 0 \]
\[ \frac{\partial B_x}{\partial y} - \frac{\partial B_y}{\partial x} = 0 \]
Field representation
Analytic functions

If \( \frac{\partial B_z}{\partial z} = 0 \)

Maxwell gives

\[
\begin{align*}
\frac{\partial B_y}{\partial y} - \frac{\partial B_x}{\partial y} &= 0 \\
\frac{\partial B_y}{\partial x} + \frac{\partial B_x}{\partial x} &= 0
\end{align*}
\]

and therefore the function \( B_y + iB_x \) is analytic

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

where \( C_n \) are complex coefficients

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

Advantage: we reduce the description of the field to a (simple) series of complex coefficients
Magnetic design
Harmonics

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

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

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

The field harmonics are rewritten as:

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

The coefficients \( b_n, a_n \) are called normalized multipoles:
- \( b_n \) are the normal, \( a_n \) are the skew (adimensional)

Back to the original issue: From ideal to practical configuration

- How can I reproduce **thick shell with a \( \cos \theta \)** distribution with a cable?
  - Rectangular cross-section and constant \( J \)

- First “rough” approximation
  - **Sector dipole**

- Better ones
  - More **layers** and **wedges** to reduce \( J \) towards 90°

- Now, I can use the multipolar expansion to **optimize** my “practical” **cross-section**
A "good" field quality dipole

**Sector dipole**

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 the one given by a 3 blocks

- Equations to set to zero $B_3, B_5, B_7, B_9$ and $B_{11}$

\[
\begin{align*}
\sin(3\alpha_5) - \sin(3\alpha_4) + \sin(3\alpha_3) - \sin(3\alpha_2) + \sin(3\alpha_1) &= 0 \\
\sin(5\alpha_5) - \sin(5\alpha_4) + \sin(5\alpha_3) - \sin(5\alpha_2) + \sin(5\alpha_1) &= 0 \\
\sin(7\alpha_5) - \sin(7\alpha_4) + \sin(7\alpha_3) - \sin(7\alpha_2) + \sin(7\alpha_1) &= 0 \\
\sin(9\alpha_5) - \sin(9\alpha_4) + \sin(9\alpha_3) - \sin(9\alpha_2) + \sin(9\alpha_1) &= 0 \\
\sin(11\alpha_5) - \sin(11\alpha_4) + \sin(11\alpha_3) - \sin(11\alpha_2) + \sin(11\alpha_1) &= 0
\end{align*}
\]
A “good” field quality dipole
Sector dipole

Let us see two coil lay-outs of real magnets

- The RHIC dipole has four blocks

Two wedges, $b_3=b_5=b_7=b_9=b_{11}=0$

$[0^\circ-33.3^\circ, 37.1^\circ-53.1^\circ, 63.4^\circ-71.8^\circ]$
A review of dipole lay-outs

- Tevatron MB
A review of dipole lay-outs

HERA MB
A review of dipole lay-outs

SSC MB
A review of dipole lay-outs

- HFDA dipole
A review of dipole lay-outs

LHC MB
A review of dipole lay-outs
A review of dipole lay-outs

D20
Magnetic design and coils

- How do we create a **perfect field**?
- How do we **express** field and its “**imperfections**”?
- How do we design a coil to **minimize field errors**?
- How do we **fabricate** a coil?
The coil: most **critical component** of a superconducting magnet

Cross-sectional accuracy of few hundredths of millimeters over \(~15\) m

Laminated tooling
The cable is wound around a **pole** on a mandrel.
- The mandrel is made of laminations

**Winding** starts from **pole turn** of the inner layer

Cable maintained in **tension** (200 N)

For large production→ **automated winding machines**
Coil fabrication
Reaction of Nb₃Sn coils

**Heat treatment**
- Sn and Nb are heated to 650-700°C in vacuum or inert gas (argon)
- They react to form Nb₃Sn
- The cable becomes **brittle**
- The reaction is characterized by three temperature steps
- Homogeneity is of about ±3 °C

**Reaction oven with argon gas flow**
- Minimize O₂ content and Cu oxidation
Coil fabrication
Vacuum impregnation of Nb$_3$Sn coils

After reaction, coil placed in a impregnation fixture

- The fixture is inserted in a vacuum tank, evacuated $\rightarrow$ epoxy injected
- high viscosity at room temperature,
- low viscosity at $\sim$60 °C
- Then, **curing** at $\sim$150 °C $\rightarrow$ solid block
Overview of coil fabrication stages

After winding/curing

After reaction

After impregnation
Summary

- Particle accelerators and superconductors

- Magnetic design and coils
Mechanics of superconducting magnets

Quench and protection

HiLumi LHC and FCC
Superconductivity
Nb-Ti vs. Nb₃Sn

![Nb-Ti vs. Nb₃Sn](image-url)
Practical superconductors
Multi-strand cables motivations

- Rutherford cables fabricated by **cabling machine**
  - Strands wound on spools mounted on a rotating drum
  - Strands twisted around a conical mandrel into rolls (Turk’s head)
  - The rolls compact the cable and provide the final shape
Practical superconductors
Multi-strand cables

- **Edge deformation** may cause
  - reduction of the filament cross-sectional area (Nb-Ti)
  - breakage of reaction barrier with incomplete tin reaction (Nb₃Sn)

- In order to avoid degradation
  - strand cross-section investigated
  - Edge facets are measured
    - General rule: no overlapping of facets

- **Keystone angle** is usually of ~ 1° to 2°
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, **fiber-glass** braided or as tape/sleeve.

Typically the insulation thickness: 100 and 200 µm.
There is a minimum bending radius, which depends on the cable dimensions.

- Is there a general rule?
  - No, but usually the bending radius is 10-15 times the cable thickness.

- The cable must be constantly monitored during winding.

If the bending radius is too small

- De-cabling during winding;
- Strands “pop-out”.
In the **end region**, more difficult to constrain the turns
- bent over the narrow edge

To improve the mechanical stability and to reduce the peak field ➔ **end spacers**
- **constant perimeter** approach
  - The two narrow edges of the turn in the ends follow curves of equal lengths.

In Nb-Ti magnets, end spacers are produced by 5-axis machining of epoxy impregnated fiberglass
- Remaining voids are then filled by resins

In Nb$_3$Sn magnets, end spacers are made of aluminum bronze or stainless steel.
The goal of curing
- Glue turns facilitating **handling**

Coils are placed in the **curing mould** equipped with a **heating** system, and **compressed** in press

**Nb-Ti** coils cured up to 190±3 °C at 80-90 MPa (LHC) to **activate resin**

In **Nb₃Sn** coils, **cable insulation is injected with** **ceramic binder**
- Cured at 150° C and at ~10-30 MPa
As we said, we minimize harmonics during design phase.

After fabrication we can measure them:
- Reproducibility of coil positioning is \( \sim 20-50 \text{ mm (1 } \sigma) \)
- If an anomaly is observed - \( \rightarrow \) inverse problem
  - Which coil defect could cause such an anomaly?

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[Images: Missing shim, Coil block mis-placed]