Introduction to Accelerator Physics
Superconducting Magnets

Luca.Bottura@cern.ch

Prague, Czech Republic
31 August - 12 September
Overview

- Why superconductors? A motivation
- A superconductor physics primer
- Superconducting magnet design
  - Superconducting cables
  - Superconducting magnets
- The making of a superconducting magnet
- Uses of superconductivity
- A closing word
Overview

- Why superconductors? A motivation
- A superconductor physics primer
- Superconducting magnet design
  - Superconducting cables
  - Superconducting magnets
- The making of a superconducting magnet
- Uses of superconductivity
- A closing word
Why superconductivity anyhow?

- **Abolish Ohm’s law!**
  - no power consumption (although need refrigeration power)
  - high current density
  - ampere turns are cheap, so don’t need iron (although often use it for shielding)

- **Consequences**
  - lower running cost $\Rightarrow$ new commercial possibilities
  - energy savings
  - high current density $\Rightarrow$ smaller, lighter, cheaper magnets $\Rightarrow$ reduced capital cost
  - higher magnetic fields economically feasible $\Rightarrow$ new research possibilities
High current density - dipoles

- The field produced by an ideal dipole (see later) is:

\[ B = \mu_0 J_e \frac{t}{2} \]

- \( J_E = 375 \text{ Amm}^{-2} \)

- \( J_E = 37.5 \text{ Amm}^{-2} \)

LHC dipole

- \( b = 120 \text{ mm} \)
- \( 660 \text{ mm} \)

- \( \approx 1 \text{ MA-turn} \)
- \( \approx 2.5 \text{ kW/m} \)

- all-SC dipole record field: 16 T (LBNL, 2003)

- \( \approx 5 \times 10 \text{ MA-turn} \)
- \( \approx 6 \text{ MW/m} \)
Overview

- Why superconductors? A motivation
- A superconductor physics primer
- Superconducting magnet design
  - Superconducting cables
  - Superconducting magnets
- The making of a superconducting magnet
- Uses of superconductivity
- A closing word
A great physics problem in 1900

What is the limit of electrical resistivity at the absolute zero?

... electrons flowing through a conductor would come to a complete halt or, in other words, metal resistivity will become infinity at absolute zero.

“X-rays are an hoax”

“I have not the smallest molecule of faith in aerial navigation other than ballooning or of expectation of good results from any of the trials we hear of”

"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement”

W. Thomson (Lord Kelvin)
... thus the mercury at 4.2 K has entered a new state, which, owing to its particular electrical properties, can be called the state of superconductivity...

H. Kamerlingh-Onnes (1911)
Cooper Pairs

- Normal conductor
  - scattering of e⁻
  - finite resistance due to energy dissipation

- Superconductor
  - paired electrons forming a quasi particle in condensed state
  - zero resistance because the scattering does not excite the quasi-particle

Proper physics: a gas of Fermions. The conduction electrons at the Fermi surface have large energy (few eV) and interact with lattice defects, displacements or thermal excitations (hence \( \rho(T) \)).

Proper physics: paired electrons in the vicinity of the Fermi surface, with opposite momentum and spin (bosons with zero spin). The binding energy introduces a small energy gap between paired and unpaired state. An external electric field makes the pair drift.
Pairing mechanism

Lattice displacement

\[ \downarrow \]

phonons (sound)

\[ \downarrow \]

coupling of charge carriers

Only works at low temperature

Bardeen, Cooper, Schrieffer (BCS) - 1957

Proper physics: the binding energy is small, of the order of $10^{-3}$ eV. Pairs can be broken easily by thermal energy. The interaction is long range, and Cooper pairs overlap and can exchange electrons.
First (not last) superconducting magnet project cancelled

A 100 kGauss magnet! (H. K. Onnes)

Third International Congress of Refrigeration, Chicago (1913)

The 10 T magnet project was stopped when it was observed that superconductivity in Hg and Pb was destroyed by the presence of an external magnetic field as small as 500 Gauss (0.05 T)

Solvay conference (1914)

Superconductivity languished for 40 years...
Flourishing of materials, but depressing $T_c$...

There is a theoretical limit around 30 K.

Superconductivity was a *physicist playground* till the late 1950’s.
1986 - A Big Surprise

Bednorz and Mueller
IBM Zuerich, 1986

Temperature, $T_c$ (K)

Year

Low-$T_c$ $V_3Si$

High-$T_c$ $La-214$ $Hg-1223$

164 K
1987 - The prize!

“...for their important break-through in the discovery of superconductivity in ceramic materials”
High-Tc timeline - impressive !!!

It’s not over yet!
Hey, what about field?

Cool down

**Type I** \( (\kappa < 1/\sqrt{2}) \)

*Complete field exclusion*

Pure metals

\[ B_C \approx 10^{-3} \ldots 10^{-2} \, \text{T} \]

Meissner & Ochsenfeld, 1933

Example of magnetic levitation

Superconducting disk

Levitated magnet

**Hey, what about field?**

W. Meissner, R. Ochsenfeld
Let us define the Gibbs free energy of a material in a magnetic field:

\[ G = U - TS - \mu_0 M \cdot H \]

Thermal energy   Magnetic energy

A system in equilibrium will tend to a minimum of \( G \).

In zero applied field, the SC phase (being in a condensed state) has lower free energy than the normal phase:

\[ G_{\text{sup}}(H=0) < G_{\text{normal}}(H=0) \]

The field expulsion \((M=-H)\) corresponds to a magnetic energy density:

\[ -\mu_0 M \cdot H = \frac{\mu_0}{2} H^2 \]

The material prefers to expel the magnetic field (Meissner effect) until the free energy of the SC phase in field equals the free energy of the normal state:

\[ \frac{\mu_0}{2} H_c^2 = G_{\text{normal}} - G_{\text{sup}}(H=0) \]

**Thermodynamic critical field**
Type I – critical field

- The difference in free energy $\Delta G$ among the SC and normal state is small.
- The corresponding values of the thermodynamic critical field are also small, i.e. in the range of few mT to barely above 100 mT.

$\mu_0/2 \ H_c^2 = \Delta G$

Not very useful for magnet engineers!
London penetration length $\lambda_L$

- Field profile

$$B(x) = B_0 \exp \left( - \frac{x}{\lambda_L} \right),$$

- *London* penetration length

$$\lambda_L = \left( \frac{m}{\mu_0 n q^2} \right)^{\frac{1}{2}}$$

$\lambda_L$ is of the order of 20 to 100 nm in typical superconducting materials

H. and F. London, 1935
Coherence length $\xi$

- At an interface the density of paired electron $n_S$ rises smoothly from zero (at the surface) to the asymptotic value (in the bulk).
- The characteristic length of this transition is the coherence length $\xi$.

\[ \xi = \sqrt{\frac{\hbar^2}{2m|\alpha|}} = \frac{2\hbar v_f}{\pi E_g} \]

$\xi$ is of the order of 1 to 1000 nm in typical superconducting elements and alloys.

Ginzburg–Landau, 1950
Energy efficient fluxons

Type I \((\kappa < 1/\sqrt{2})\)

*Complete field exclusion*

Pure metals

\[ B_C \approx 10^{-3}...10^{-2} \text{ T} \]

Meissner & Ochsenfeld, 1933

Type II \((\kappa > 1/\sqrt{2})\)

*Partial field exclusion*

*Lattice of fluxons*

Dirty materials: alloys, intermetallic, ceramic

\[ B_C \approx 10...10^2 \text{ T} \]

Ginsburg, Landau, Abrikosov, Gor’kov, 1950...1957
Values of $\lambda_L$, $\xi$ and $\kappa$

<table>
<thead>
<tr>
<th>Material</th>
<th>$\lambda_L$ (nm)</th>
<th>$\xi$(B=0) (nm)</th>
<th>$\kappa$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>16</td>
<td>1600</td>
<td>0.01</td>
</tr>
<tr>
<td>Pb</td>
<td>32</td>
<td>510</td>
<td>0.06</td>
</tr>
<tr>
<td>In</td>
<td>24</td>
<td>360</td>
<td>0.07</td>
</tr>
<tr>
<td>Cd</td>
<td>110</td>
<td>760</td>
<td>0.15</td>
</tr>
<tr>
<td>Sn</td>
<td>30</td>
<td>170</td>
<td>0.18</td>
</tr>
<tr>
<td>Nb</td>
<td>40</td>
<td>39</td>
<td>1</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>200</td>
<td>12</td>
<td>$\approx$ 20</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>185</td>
<td>5</td>
<td>$\approx$ 40</td>
</tr>
<tr>
<td>YBCO</td>
<td>200</td>
<td>1.5</td>
<td>$\approx$ 75</td>
</tr>
</tbody>
</table>

Type I

Type II
Lattice of quantum flux lines

\[ \Phi_0 = \frac{h}{2e} = 2.07 \times 10^{-15} \text{ Wb} \]

Observation on Pb-4at% In magnetised by a field of 3000 Oe and decorated by Co particles

Essmann & Träuble, 1967
Type II – critical field

The upper critical field $B_{c2}$ and temperature $T_c$ of metallic superconductors are mutually related.

Both $B_{c2}$ and $T_c$ are determined by the chemistry of the material.

**NOTE:** of all the metallic superconductors, only NbTi is ductile. All other are brittle inter-metallic compounds.

Graphics by courtesy of M.N. Wilson
Hey, what about current?

- A current flowing in a magnetic field is subject to the Lorentz force that deviates the charge carriers:
  \[ \mathbf{F} = \mathbf{J} \times \mathbf{B} \]

- This translates into a *motion of the fluxoids* across the superconductor \( \Rightarrow \) energy dissipation \( \Rightarrow \) loss of superconductivity

- To carry a significant current we need to *lock the fluxoids* so to resist the Lorentz force. For this we mess-up the material and create *pinning centers* that exert a *pinning force* \( F_p \)
Pinning centers

Precipitates in alloys

Microstructure of Nb-Ti

Grain boundaries in inter-metallic compounds

Microstructure of Nb$_3$Sn
The maximum current that can be carried by the superconductor is the current at which:

\[ |\mathbf{J} \times \mathbf{B}| = F_P \]

The above expression defines a **critical surface**:

\[ J_C(B,T,...) = \frac{F_P}{B} \]

\[ J_c (5 \, T, 4.2 \, K) \approx 3000 \, A/mm^2 \]
Superconductors – the bottom line

- Superconducting materials are only useful if they are *dirty* (type II - high critical field) and *messy* (strong pinning centers)

- A superconductor is such only in conditions of temperature, field and current density within the critical surface, and it is a normal-conductor above these conditions. The transition is defined by a critical current density $J_C(B,T,...)$

- The maximum current that can be carried is the $I_C = A_{SC} \times J_C$
Overview

- Why superconductors? A motivation
- A superconductor physics primer
- **Superconducting magnet design**
  - Superconducting cables
  - Superconducting magnets
- The making of a superconducting magnet
- Uses of superconductivity
- A closing word
From materials to magnets

- Materials must be made in **high-current wires, tapes and cables** for use in magnets
- The manufacturing route depends, among others on:
  - The material (e.g. alloy or chemical compound),
  - The material synthesis (e.g. reaction conditions or a crystal growth method)
  - The material mechanical properties (e.g. ductile or fragile)
  - The compatibility with other materials involved (e.g. precursors or mechanical supports)
# A summary of technical materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Nb-Ti</th>
<th>Nb\textsubscript{3}Sn</th>
<th>Nb\textsubscript{3}Al</th>
<th>MgB\textsubscript{2}</th>
<th>YBCO</th>
<th>BSCCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tc (K)</td>
<td>9.2</td>
<td>18.2</td>
<td>19.1</td>
<td>39</td>
<td>≈93</td>
<td>95(*)</td>
</tr>
<tr>
<td>Bc (T)</td>
<td>14.5</td>
<td>≈30</td>
<td>33</td>
<td>36...74</td>
<td>120(‡)</td>
<td>250(‡)</td>
</tr>
</tbody>
</table>

**NOTES:**

- (†) B parallel to c-axis
- (‡) B parallel to ab-axes
- (*) BSCCO-2212
- (#) BSCCO-2223

**Power transmission cables and SC links**

**Tevatron**

**HERA**

**RHIC**

**LHC**

**HL-LHC**

20 T and beyond!
Nb-Ti manufacturing route

NbTi billet

I_c(5 T, 4.2 K) \approx 1 \text{kA}

extrusion
cold drawing
heat treatments

1 \text{mm}

NbTi is a ductile alloy that can sustain large deformations

LHC wire
**Nb$_3$Sn manufacturing routes**

Nb$_3$Sn is brittle and cannot be drawn in final form. The precursors are drawn and only later the wire is heat-treated to $\approx 650$ C for several hrs, to form the Nb$_3$Sn phase.

$I_c(12 \, T, \, 4.2 \, K) \approx 1.5 \, kA$
Oxide powder in tube OPIT

1) draw down BSCCO powder in a silver tube

2) stack many drawn wires in another silver tube and draw down again

3) roll the final wire to tape and heat treat at 800 - 900C in oxygen to melt the B2212

BSCCO is also brittle: a special sequence of rolling and sintering heat treatments must used. Silver has the important feature that it is transparent to Oxygen at high temperature, but does not react with it.
YBCO has excellent critical properties, but grains do not align during processing. If grains are not aligned the supercurrent cannot jump between the grains. All manufacturing processes force a certain degree of alignment in the microstructure.

- produce a tape with an aligned texture
- coat the tape with a buffer layer
- coat the buffer with a layer $\text{YBa}_2\text{Cu}_3\text{O}_7$ such that the texture of the YBCO follows that of the buffer and substrate

All routes use a ion deposition technique (laser, plasma, evaporation) in vacuum (cost & length !)
Practical conductors: high $J_E$

- Multifilamentary wires have current carrying capability of 100... 1000 A
- Insulated with varnish or glass-braids they can be used to make all kind of small size magnets

- Large size magnets (e.g. LHC dipoles) require invariably large operating currents (10 to 100 kA) to:
  - Decrease inductance,
  - Lower the operating voltage,
  - Ease magnet protection
- Rutherford cables are ideally suited for this task

\[ J_E \approx 500 \text{ A/mm}^2 \]
Rutherford cable machine @ CERN

Strands fed through a cabling tongue to shaping rollers

Strand spools on rotating tables
we expect the magnet to go resistive i.e. to 'quench', where the peak field load line crosses the critical current line.
Operating margins

Practical operation always requires margins:

- Critical current margin: \( I_{\text{op}}/I_Q \approx 50\% \)
- Critical field margin: \( B_{\text{op}}/B_Q \approx 75\% \)
- Margin along the loadline: \( I_{\text{op}}/I_{\text{max}} \approx 85\% \)
- Temperature margin: \( T_{CS} - T_{\text{op}} \approx 1\ldots2\ K \)

The margin needed depends on the design and operating conditions.
Engineering current density

- All wires, tapes and cables contain additional components:
  - Left-overs from the precursors of the SC formation
  - Barriers, texturing and buffering layers
  - Low resistance matrices
- The SC material fraction is hence always < 1:
  \[ \lambda = \frac{A_{SC}}{A_{total}} \]
- To compare materials on the same basis, we use an engineering current density:
  \[ J_E = J_C \times \lambda \]
Best of Superconductors J_E

Graphics by courtesy of Applied Superconductivity Center at NHMFL

Applied Magnetic Field (T)

Whole Wire Critical Current Density (A/mm², 4.2 K)

10^4

10^3

10^2

10

4.2 K LHC insertion quadruole strand (Bourboul et al. 2006)
Maximal I_c at 1.9 K for entire LHC NbTi strand production (CERN-T. Bourboul 2007). Reducing the temperature from 4.2 K produces a T^3 T shift in I_c for Nb-Ti

4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)

Bi-2212: OST NHMFL 100 bar OP

Bi-2223: B ⊥ Tape plane (carr. cont.)

Bi-2223: B ⊥ Tape plane (prod.)

YBCO: B || Tape plane

YBCO: B ⊥ Tape plane

MgB_2: 2nd Gen. AIMI 18+1 Filaments, The OSU/ HTRI, 2013

MgB_2: 18+1 Fil. 13% Fill

NbS_2: Internal Sn RRP*

NbS_2: High Sn Bronze

NbS_2: High Sn Bronze

Nb-Ti: LHC 1.9 K

Nb-Ti: LHC 4.2 K

Nb-Ti: Iseult/INUMAC MRI 4.22 K

Compiled from ASC'02 and ICMC'03 papers (J. Parrell OH-3T)

YBCO B || Tape Plane

4.22 K High Field MRI strand (Luvato)

2223: B ⊥ Tape Plane

Suntomo Electric (2012 prod.)

“Corder Controlled” MEM'13

High-J_c Nb_3Sn

“useful” J_E

April 2014
Perturbation spectrum

- **mechanical events**
  - wire motion under Lorentz force, micro-slips
  - winding deformations
  - failures (at insulation bonding, material yield)

- **electromagnetic events**
  - flux-jumps (important for large filaments, old story !)
  - AC loss (most magnet types)
  - current sharing in cables through distribution/redistribution

- **thermal events**
  - current leads, instrumentation wires
  - heat leaks through thermal insulation, degraded cooling

- **nuclear events**
  - particle showers in particle accelerator magnets
  - neutron flux in fusion experiments
Perturbation overview

Typical range is from a few to a few tens of mJ/cm$^3$
Stability as a heat balance

- Perturbation
- Joule heating
- Superconducting cable
- Heat capacity
- Conduction
- Cooling
A prototype temperature transient

...effect of heat conduction and cooling...

heat pulse...

generation > cooling
unstable

generation < cooling
stable

![Graph showing temperature transient with labels for heat pulse, thermal runaway, Tcs, recovery, and time (ms) axes.](image)
Stability - Re-cap

- A sound design is such that the expected energy spectrum is smaller than the expected stability margin

- To increase stability:
  - Increase temperature margin
  - Increase heat removal (e.g. conduction or heat transfer)
  - Decrease Joule heating by using a stabilizer with low electrical conductance
  - Make best use of heat capacity
    - Avoid sub-cooling (heat capacity increases with T, this is why stability is not an issue for HTS materials)
    - Access to helium for low operating temperatures
What if we exceed the limits? Quench!

- A resistive transition in a superconducting magnet, leading to appearance of voltage, Joule heating, temperature increase, thermal and electro-magnetic forces, and cryogen expulsion.

This is a quench of a GE MRI magnet during tests at the plant.
Stored energy

- The energy stored in the magnetic field of accelerator dipoles scales with the square of the bore field.

- A large stored magnetic energy makes the magnet difficult to protect, and requires:
  - Fast detection and dump
  - High terminal voltage and operating current
Energy dissipation

- the magnetic energy stored in the field:
  \[ E_m = \frac{B^2}{2} dv = \frac{1}{2} LI^2 \]

  is converted to heat through Joule heating RI^2.

  If this process happened uniformly in the winding pack:
  - Cu melting temperature 1356 K
  - corresponding \( E_m = 5.2 \times 10^9 \) J/m^3

  limit would be \( B_{max} \leq 115 \) T: NO PROBLEM !

  BUT

*the process does not happen uniformly* (as little as 1 % of mass can absorb total energy)
Issues to be considered

- **Temperature** increase and temperature gradients (thermal stresses)
- **Voltages** within the magnet, and from the magnet to ground (whole circuit)
- **Forces** caused by thermal and electromagnetic loads during the magnet discharge transient
- **Cryogen** pressure increase and expulsion

A quench invariably requires **detection** and may need **actions** to safely turn-off the power supply (possibly more)
**Hot-spot limits**

- \( T_{\text{max}} < 300 \text{ K} \) for highly supported coils (e.g. accelerator magnets)

- the quench starts in a point and propagates with a *quench propagation velocity*

- the initial point will be the *hot spot* at temperature \( T_{\text{max}} \)

- \( T_{\text{max}} \) must be limited to:
  - limit thermal stresses (see graph)
  - avoid material damage (e.g. resins have typical \( T_{\text{cure}} \) 100...200 °C)

\( T_{\text{max}} < 100 \text{ K} \) for negligible effect
Detection, switch and dump

\[ \tau_{\text{discharge}} \approx \tau_{\text{detection}} + \tau_{\text{delay}} + \tau_{\text{switch}} + \tau_{\text{dump}} \]

Quench resistance

- the quench propagates in the coil at speed $v_{\text{quench longitudinal}}$ and transversely ($v_{\text{transverse}}$)...

- ...the total resistance of the normal zone $R_{\text{quench}}(t)$ grows in time following
  - the temperature increase, and
  - the normal zone evolution...

- ...a resistive voltage $V_{\text{quench}}(t)$ appears along the normal zone...

- ...that dissipates the magnetic energy stored in the field, thus leading to a discharge of the system in a time $\tau_{\text{discharge}}$.

The knowledge of $R_{\text{quench}}(t)$ is mandatory to verify the protection of the magnetic system!
Quench protection

- The magnet stores a magnetic energy $\frac{1}{2}L I^2$
- During a quench it dissipates a power $R I^2$ for a duration $\tau_{\text{decay}}$ characteristic of the powering circuit

$$R(t)I_{op}^2 dt = \frac{1}{2} LI_{op}^2$$

**Quench protection**

- **Yes**
  - Self-protected: detect, switch-off power and let it go... most likely OK

- **No**
  - Requires protection: detect, switch-off power and do something!

**WARNING:** the reasoning here is qualitative, conclusions require in any case detailed checking
Energy dump

- the magnetic energy is extracted from the magnet and dissipated in an external resistor:
  \[ I = I_{op} e^{\frac{-t}{R_{dump}}} \]
  \[ dump = \frac{L}{R_{dump}} \]

- the integral of the current:
  \[ J^2 dt \bigg|_0^{t_{detection}} + \frac{J_{op}^2}{2} = \frac{dump}{2} \]

- can be made small by:
  - fast detection
  - fast dump (large \( R_{dump} \))
Dump time constant

- **magnetic energy:**
  \[ E_m = \frac{1}{2} LI_{op}^2 \]

- **maximum terminal voltage:**
  \[ V_{\text{max}} = R_{\text{dump}} I_{\text{op}} \]

- **dump time constant:**
  \[ \tau_{\text{dump}} = \frac{L}{R_{\text{dump}} V_{\text{max}} I_{\text{op}}} = \frac{2E_m}{V_{\text{max}} I_{\text{op}}} \]

**Interesting alternative:**
- Non-linear \( R_{\text{dump}} \) or voltage source

Increase \( V_{\text{max}} \) and \( I_{\text{op}} \) to achieve fast dump time
the quench is spread actively by firing heaters embedded in the winding pack, in close vicinity to the conductor
Magnet strings

- magnet strings (e.g. accelerator magnets, fusion magnetic systems) have exceedingly large stored energy (10’s of GJ):
  - energy dump takes very long time (10…100 s)
  - the magnet string is *subdivided* and each magnet is by-passed by a diode (or thyristor)
  - the diode acts as a shunt during the discharge
Quench - Re-cap

- A good conducting material (Ag, Al, Cu: large $Z(T_{\text{max}})$) must be added in parallel to the superconductor to limit the maximum temperature during a quench.

- The effect of a quench can be mitigated by:
  - Adding stabilizer ($\iff$ operating margin, stability)
  - Reducing operating current density ($\iff$ economics of the system)
  - Reducing the magnet inductance (large cable current), increasing the discharge voltage and subdividing (strings) to discharge the magnet as quickly as practical.
Overview

- Why superconductors? A motivation
- A superconductor physics primer
- **Superconducting magnet design**
  - Superconducting cables
  - Superconducting magnets
- The making of a superconducting magnet
- Uses of superconductivity
- A closing word
Magnetic design - basics

- **NC**: magneto motive force, reluctance and pole shapes
  \[ R = \frac{F}{\Phi} \quad \text{Hopkinson's law} \]
  \[ B \approx \mu_0 \frac{NI}{g} \]
  \[ g = 100 \, \text{mm} \]
  \[ NI = 100 \, \text{kAturn} \]
  \[ B = 1.25 \, \text{T} \]

- **SC**: Biot-Savart law and coil shapes
  \[ B = \int \frac{\mu_0 I dl \times r}{4\pi |r|^3} \quad \text{Biot-Savart law} \]
  \[ B \approx \mu_0 \frac{NI}{\pi r} \]
  \[ r = 45 \, \text{mm} \]
  \[ NI = 1 \, \text{MAturn} \]
  \[ B = 8.84 \, \text{T} \]
Design of an ideal dipole magnet

\[ I = I_0 \cos(\theta) \Rightarrow B_1 = -\mu_0 I_0 / 2 r \]

Intersecting circles \(\Rightarrow B_1 = -\mu_0 J d / 2\)

Intersecting ellipses \(\Rightarrow B_1 = -\mu_0 J d b / (a+b)\)

Several solutions are possible and can be extended to higher order multi-pole magnets

None of them is practical!
Magnetic design - sector coils

- Dipole coil
  
  \[ B = -\frac{2\mu_0}{\pi} J (R_{out} - R_{in}) \sin(\varphi) \]

- Quadrupole coil
  
  \[ G = -\frac{2\mu_0}{\pi} J \ln\left(\frac{R_{out}}{R_{in}}\right) \sin(2\varphi) \]

The field is proportional to the current density \( J \) and the coil width \((R_{out} - R_{in})\)

This is getting much more practical!
Evolution of coil cross sections

- Coil cross sections (to scale) of the four superconducting colliders

- Increased coil complexity (nested layers, wedges and coil blocks) to achieve higher efficiency and improved field homogeneity
Technical coil windings

- LHC arc dipole
- Magnet bore
- Superconducting cable
- Spacers
- LHC arc quadrupole
- Coil blocks
Iron to close the magnetic circuit

- flux lines
- gap between coil and yoke
- coil

CERN 87-05, G. Brianti and K. Hubner Ed.
Persistent currents - basics

- Eddy currents that flow in the superconducting filaments to shield the interior from outer field variations

- For accelerator magnets:
  - Neglect flux-creep and flow
  - Neglect outer field changes (decay at I=const)

  Infinite time constant, the eddy currents *last forever*

The current \textit{doublet} in the filament corresponds to a magnetization:

\[
M = \frac{1}{V} \left\{ \frac{1}{2} \int \mathbf{r} \times \mathbf{J} \, dV \right\}
\]

A strand, with round filaments in a resistive matrix ($\lambda = A_{\text{SC}}/A_{\text{tot}}$), fully penetrated:

\[
M = \pm \frac{2}{3\pi} \mu_0 J_c D \lambda
\]
Persistent current multipoles

Magnetization of a typical LHC strand

Sextupole in a typical LHC dipole

Effects are relatively large, cycle and history dependent and require careful design, measurement and control!
A matter of (field) quality

The field homogeneity for an accelerator magnet needs to be in the 100 ppm range (at 1 cm from the coil)

<table>
<thead>
<tr>
<th>Type of error</th>
<th>Origin</th>
<th>Effect on main field</th>
<th>Effect on harmonics</th>
<th>Means to control</th>
</tr>
</thead>
<tbody>
<tr>
<td>geometric</td>
<td>Deviation of conductor from ideal position</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
<td>Respect coil tolerances at $10 , \mu m$ level</td>
</tr>
<tr>
<td>saturation</td>
<td>Iron saturation in vicinity of the coil</td>
<td>$10^{-2}$ to $10^{-3}$</td>
<td>$10^{-4}$</td>
<td>Optimize iron geometry, control permeability to % level</td>
</tr>
<tr>
<td>DC magnetization</td>
<td>Diamagnetism of SC filaments and hysteresis</td>
<td>$10^{-3}$ to $10^{-4}$</td>
<td>$10^{-3}$ to $10^{-4}$</td>
<td>Use small filaments (10...20 $\mu m$) and control wire magnetization homogeneity</td>
</tr>
<tr>
<td>AC magnetization</td>
<td>Coupling currents in strands and cables</td>
<td>$10^{-3}$ to $10^{-4}$</td>
<td>$10^{-4}$</td>
<td>Use resistive matrix in strands (ramped magnets), control strands coupling in cable ($R_c &gt; 10$)</td>
</tr>
</tbody>
</table>
Electromagnetic force

(O. Heaviside) E.A. Lorentz, P.S. Laplace

- An electric charged particle $q$ moving with a velocity $v$ in a field $B$ experiences a force $F_L$ called electromagnetic (Lorentz) force (N):

$$F_L = qv \times B$$

- A conductor carrying current density $J$ (A/mm$^2$) experiences a (Laplace) force density $f_L$ (N/m$^3$):

$$f_L = J \times B$$
Electromagnetic forces - dipole

- The electromagnetic forces in a dipole magnet tend to push the coil:
  - Vertically, towards the mid plane \((F_y < 0)\)
  - Horizontally, outwards \((F_x > 0)\)
In the coil ends the Lorentz forces tend to push the coil:

- Outwards in the longitudinal direction ($F_z > 0$), and,
- similar to solenoids, the coil straight section is in tension.
The real challenge of very high fields

- Force increases with the square of the bore field
- Requires massive structures (high-strength materials, volume, weight)
- The stress limit is usually in the superconducting coil (superconductor and insulation, mitigated by $J_e \approx 1/B$)
- In practice the design of high field magnets is limited by mechanics
Overview

- Why superconductors? A motivation
- A superconductor physics primer
- Superconducting magnet design
  - Superconducting cables
  - Superconducting magnets
- The making of a superconducting magnet
- Uses of superconductivity
- A closing word
LHC dipole

- $B_{\text{nominal}}$: 8.3 (T)
- Current: 11850 (A)
- Stored energy: $\approx 10$ (MJ)
- Cold mass: $\approx 35$ (tonnes)
Rutherford cables

LHC inner cable

LHC Nb-Ti strand

LHC outer cable cross section

7500 km of superconducting cables with tightly controlled properties (state-of-the-art production)
Coil winding

Cable insulation wraps

Insulated cable

Bare cable

10 \mu m precision!

Coil winding machine

Stored coils
Ends, transitions, and any deviation from the regular structure are the most delicate part of the magnet.
Collaring operation

Pre-collared coil assembly under a press, load the coil to the desired pre-stress (in the range of 50...100 MPa)

Insert keys to “lock” the collars, unload the assembly that is now self-supporting and provides the desired pre-load to the coil
Collaring of an LHC dipole

Collaring force: 1400 tons/m

Maximum press force: 37500 tons

76 hydraulic cylinders (600 bar)

Planarity $\pm 0.3$ mm/m
LHC dipole coils
LHC Iron yoke
“Yoking” of a dipole magnet
Yoke welding press

Yoking force: 400 tons/m
Maximum press force: 19000 tons
48 hydraulic cylinders (600 bar)
Cold mass
Cryostat

Vacuum enclosure

Low conduction foot

Thermal screens
Finally, in the tunnel!
Overview

- Why superconductors? A motivation
- A superconductor physics primer
- Superconducting magnet design
  - Superconducting cables
  - Superconducting magnets
- The making of a superconducting magnet
- Uses of superconductivity
- A closing word
The Hall of Fame of SC colliders

<table>
<thead>
<tr>
<th></th>
<th>Tevatron</th>
<th>HERA</th>
<th>RHIC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum energy (GeV)</td>
<td>980</td>
<td>920(^{(1)})</td>
<td>250(^{(2)})</td>
<td>7000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100/n(^{(3)})</td>
<td></td>
</tr>
<tr>
<td>Injection energy (GeV)</td>
<td>151</td>
<td>45</td>
<td>12</td>
<td>450</td>
</tr>
<tr>
<td>Ring length (km)</td>
<td>6.3</td>
<td>6.3</td>
<td>3.8</td>
<td>26.7</td>
</tr>
<tr>
<td>Dipole field (T)</td>
<td>4.3</td>
<td>5.0</td>
<td>3.5</td>
<td>8.3</td>
</tr>
<tr>
<td>Aperture (mm)</td>
<td>76</td>
<td>75</td>
<td>80</td>
<td>56</td>
</tr>
<tr>
<td>Configuration</td>
<td>Single bore</td>
<td>Single bore</td>
<td>Single bore</td>
<td>Twin bore</td>
</tr>
<tr>
<td>Operating temperature (K)</td>
<td>4.2</td>
<td>4.5</td>
<td>4.3-4.6</td>
<td>1.9</td>
</tr>
</tbody>
</table>

(1) energy of the proton beam, colliding with the 27.5 GeV electron beam
(2) energy for proton beams
(3) energy per nucleon, for ion beams (Au)
Champion dipoles cross sections

**Tevatron**
Bore: 76 mm
Field: 4.3 T

**HERA**
Bore: 75 mm
Field: 5.0 T

**RHIC**
Bore: 80 mm
Field: 3.5 T

**LHC**
Bore: 56 mm
Field: 8.3 T
### Tevatron at FNAL (Chicago, IL, USA)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection (GeV)</td>
<td>151</td>
<td></td>
</tr>
<tr>
<td>Flat-top (GeV)</td>
<td>980</td>
<td></td>
</tr>
<tr>
<td>Length (km)</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>Dipole field (T)</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>Aperture (mm)</td>
<td>76</td>
<td></td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>Commissioned</td>
<td>1983</td>
<td></td>
</tr>
</tbody>
</table>

Image by courtesy of Fermi National Accelerator Laboratory
HERA at DESY (Hamburg, D)

Injection (GeV) 45
Flat-top (GeV) 920
Length (km) 6.3
Dipole field (T) 4.7
Aperture (mm) 75
Temperature (K) 4.5
Commissioned 1991
Closed 2007

Image by courtesy of Deutsches Elektronen Synchrotron
RHIC at BNL (Upton, NY, USA)

Injection (GeV) 12/n
Flat-top (GeV) 100/n
Length (km) 3.8
Dipole field (T) 3.5
Aperture (mm) 80
Temperature (K) 4.3-4.6
Commissioned 2000
### LHC at CERN (Geneva, CH)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection</td>
<td>450 GeV</td>
</tr>
<tr>
<td>Flat-top</td>
<td>7 TeV</td>
</tr>
<tr>
<td>Length</td>
<td>26.7 km</td>
</tr>
<tr>
<td>Dipole field</td>
<td>8.3 T</td>
</tr>
<tr>
<td>Aperture</td>
<td>56 mm</td>
</tr>
<tr>
<td>Temperature</td>
<td>1.9 K</td>
</tr>
<tr>
<td>Commissioned</td>
<td>2008</td>
</tr>
</tbody>
</table>
Magnetic Resonance Imaging (MRI)

photos courtesy of SIEMENS

surgeon's view

photo courtesy of OXFORD Magnet Technology

patient's view

engineer's view
NMR spectroscopy

photo courtesy of Oxford Magnet Technology

$B_0 = 14.1 \, T$

Hz
Motors & generators

Motor with HTS rotor
American Superconductor and Reliance

700 MW generator
NbTi rotor
Hitachi, Toshiba, Mitsubishi
Transformers & energy storage

Toroidal magnet of 200 kJ / 160 kW energy store
(B = 4 T, dia. = 1.1 m)

HTS Transformer
630 kVA, 18.7kV to 0.42 kV

KfZ Karlsruhe
Magnetic separation

- superconducting solenoid, enclosed within iron shield
- stainless steel canister containing ferromagnetic mesh
- pipes feeding the kaolin slurry for separation
Thermonuclear fusion

ITER
International Thermonuclear Experimental Reactor
HEP detectors of the past...

Omega

BEBC
... and HEP of the present (CMS and ATLAS)
Levitation...

JR-Maglev MLX01
581 km/h (Dec. 2003)
Diamagnetic levitation in strong magnetic fields (16 T) as can be produced by superconducting and hybrid magnets.
Other uses of superconductivity

The Church of the Latter Day Snakes
founded 1905, revived 1950

We have a big interest
in this machine...

How big is this magnet, and can it be concealed beneath a floor...

Does it make much noise...

Does it hurt... because it will be me doing the levitating.

...we pull back the curtain in the Snake Chamber and I start to rise up from the ground...

...the Natural Law Party... please do not sell them a machine... they are very bonkers...

Letter to Prof. Main, University of Nottingham, 14 April 1997
Overview

- Why superconductors? A motivation
- A superconductor physics primer
- Superconducting magnet design
  - Superconducting cables
  - Superconducting magnets
- The making of a superconducting magnet
- Uses of superconductivity
- A closing word
A word of closing

- Superconducting magnet design is a lot about superconductors (materials, wires, cables, and their electric and thermal properties)...

- ... but not only!
  - High field & forces bear mechanical problems that are tough to solve (B=10 T ⇒ $p_{mag}=400$ bar !)
  - Materials at low temperature are not what we are used to (mechanical and magnetic properties, thermal expansion, electrical insulation)
  - Cooling is an applied science by itself
Where to find out more - 1/3

- Superconducting magnets:
  - Proc European Conference on Applied Superconductivity EUCAS, UK Institute Physics
Where to find out more - 2/3

- **Cryogenics**
  - Cryogenics: published monthly by Elsevier

- **Materials - Superconducting properties**
  - Superconductor Science and Technology, published monthly by Institute of Physics (UK).
  - IEEE Trans Applied Superconductivity, published quarterly
Materials - Mechanical properties

- Nonmetallic materials and composites at low temperatures, Ed. A.F. Clark, R.P. Reed, G. Hartwig, Plenum Press
- Nonmetallic materials and composites at low temperatures 2, Ed. G. Hartwig, D. Evans, Plenum Press, 1982