Applied Superconductivity for Accelerator Magnets

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Overview

- Why superconductors? A motivation
- A superconductor physics primer
- Superconducting magnet design
- The making of a superconducting magnet
- Examples of superconducting magnet systems
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Normal conducting accelerator magnets

- Magnetization ampere-turns are cheap
- Field is generated by the iron yoke (but limited by saturation to ≈ 2 T for iron)
- Low current density in the coils to limit electric power and cooling needs
- Bulky and heavy, large mass of iron (cost driver)

One of the dipole magnets of the PS, in operation at CERN since 51 years
Superconducting accelerator magnets

- *Superconducting* ampere-turns are *cheap*.
- Field generated by the coil current (but limited by critical current to $\approx 10$ T for Nb-Ti).
- High current density, compact, low mass of high-tech SC material (cost driver).
- Requires efficient and reliable cryogenics cooling for operation (availability driver).
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 ⇒ new commercial possibilities
  - energy savings
  - high current density ⇒ smaller, lighter, cheaper magnets ⇒ reduced capital cost
  - higher magnetic fields economically feasible ⇒ new research possibilities

Graphics by courtesy of M.N. Wilson
High current density - dipoles

The field produced by an ideal dipole is:

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

\[ J_E = 375 \text{ Amm}^{-2} \]

9.5x10^6 Amp turns
=1.9x10^6 A.m per m

Graphics by courtesy of M.N. Wilson
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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

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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 Tc...

*Theoretical limit around 30 K*

Superconductivity was a *physicist playground* till the late 1950’s

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**One Thousand and One Superconductors**

B. Matthias (1918-1980)
1986 - A Big Surprise

Bednorz and Mueller
IBM Zuerich, 1986

Temperature, $T_C$ (K)

Year

1900 1920 1940 1960 1980 2000

La-214

$T_C$ (K)

164 K

Hg-1223

Low-$T_C$

Hg

$V_3$Si

Graphics by courtesy of P. Grant
1987 - The prize!

J. Georg Bednorz, left, and K. Alex Müller after learning they had won the Nobel Prize in physics.

2 Get Nobel for Unlocking Superconductor Secret
High-Tc timeline - impressive !!!

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

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

Complete field exclusion

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

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

Partial field exclusion

Lattice of fluxons

Dirty materials: alloys, intermetallic, ceramic
\[ B_C \approx 10 \ldots 10^2 \, T \]

Meissner & Ochsenfeld, 1933

Ginsburg, Landau, Abrikosov, Gor'kov, 1950...1957
Lattice of quantum flux lines

Supercurrent

Flux quantum

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

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

Essmann & Träuble, 1967
Critical temperature and 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 intermetallic compounds.
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 mechanisms

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**:

\[ J_c(B,T,\ldots) = \frac{F_p}{B} \]

\[ J_c(5 \text{ T}, 4.2 \text{ K}) \approx 3000 \text{ A/mm}^2 \]
Superconductors physics - Re-cap

- 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 $I_C = A_{SC} \times J_C$
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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)
Nb-Ti manufacturing route

NbTi billet

extrusion
cold drawing

heat treatments

I_c(5 T, 4.2 K) ≈ 1 kA

≈ 1 mm

LHC wire

NbTi is a ductile alloy that can sustain large deformations

Graphics by courtesy of Applied Superconductivity Center at NHMFL
Best of Superconductors $J_E$

Graphical representation showing $J_E$ (A/mm$^2$) against Applied Field (T) for various superconductors:
- YBCO B|| Tape Plane
- YBCO B⊥ Tape Plane
- Nb-Ti
- RRP Nb$_3$Sn
- MgB$_2$
- Bronze Nb$_3$Sn
- 13+1 MgB$_2$/Nb/Cu/Metal
- 42 filament strand with Ag alloy outer sheath tested at NHMFL
- 2212 OI-ST 28% Ceramic Filaments
- NbTi LHC Production 38%SC (4.2 K)
- Nb$_3$Sn RRP Internal Sn (OI-ST)
- Nb$_3$Sn High Sn Bronze Cu:Non-Cu 0.3

Graphics by courtesy of Applied Superconductivity Center at NHMFL
Current sharing

\[ T < T_{cs} \]

\[ E_{sc} = E_{st} = 0 \]

\[ T_{cs} < T < T_c \]

\[ E_{sc} = E_{st} = I_{st} \frac{st}{A_{st}} \]

\[ T > T_c \]

\[ E_{sc} = E_{st} = I_{op} \frac{st}{A_{st}} \]
Quench and protection recipes

- A good conducting material (Ag, Al, Cu) 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 ($\Leftrightarrow$ operating margin, stability)
  - Reducing operating current density ($\Leftrightarrow$ economics of the system)
  - Reducing the magnet inductance (large cable current) and increasing the discharge voltage to discharge the magnet as quickly as practical.
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

$LHC$ cable prototype
Practical conductors: low $J_E$

- Super-stabilized conductor, a superconducting cable (e.g. Rutherford) backed by a large amount of good normal conductor (e.g. Al)

- Internally-cooled conductor, e.g. Cable-In-Conduit Conductor (CICC), a rope of wires inserted in a robust conduit that provides a channel for cooling

$J_E \approx 50 \text{ A/mm}^2$
Magnetic design

- NC: magneto motive force, reluctance and pole shapes

\[ R = \frac{F}{\Phi} \text{ Hopkinson's law} \]

\[ B \approx \mu_0 NI / g \]

- SC: Biot-Savart law and coil shapes

\[ B = \int \frac{\mu_0 I dl \times r}{4\pi |r|^3} \text{ Biot-Savart law} \]

\[ B \approx \mu_0 NI / \pi r \]

- Constants:
  - \( g = 100 \text{ mm} \)
  - \( NI = 100 \text{ kAturn} \)
  - \( B = 1.25 \text{ T} \)
  - \( r = 45 \text{ mm} \)
  - \( NI = 1 \text{ MAturn} \)
  - \( B = 8.84 \text{ T} \)
Design of an ideal dipole magnet

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

Intersecting circles \( \Rightarrow B_1 = -\mu_0 \frac{J d}{2} \)

Intersecting ellipses \( \Rightarrow B_1 = -\mu_0 \frac{J d b}{(a+b)} \)

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

\[ B_1 = -\frac{2\mu_0}{\pi} J (r_2 - r_1) \sin(\phi) \]

- Quadrupole coil

\[ B_2 = -\frac{2\mu_0}{\pi} J \ln\left(\frac{r_2}{r_1}\right) \sin(2\phi) \]

This is getting much more practical for the construction of superconducting coils!
Technical coil windings

Magnet bore

Coil blocks

Spacers

Superconducting cable
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LHC dipole

- $B_{\text{nominal}}$: 8.3 T
- current: 11850 A
- stored energy: $\approx 10$ MJ
- cold mass: $\approx 35$ tonnes
Superconducting dipole magnet coil

Ideal current distribution that generates a perfect dipole

Practical approximation of the ideal distribution using Rutherford cables
Twin coil principle

Combine two magnets in one
Save volume, material, cost
LHC dipole coils
Coil winding

10 \mu m precision!

Cable insulation

Stored coils

Coil winding machine
Ends, transitions, and any deviation from the regular structure are the most delicate part of the magnet.
Collaring and yoking

85 tons/m

175 tons/m

F

collaring

yoking
Cold mass
Current leads

Warm end (300K)

Intermediate temperature (50K)

HTS

Cold end (4K)
Finally, in the tunnel!
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Magnetic Resonance Imaging (MRI)

photos courtesy of SIEMENS

surgeon's view

patient's view

engineer's view

photo courtesy of OXFORD Magnet Technology
Motors & generators

Motor with HTS rotor
American Superconductor and Reliance

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

HTS Transformer
630 kVA, 18.7 kV to 0.42 kV

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

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)
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...

I put in five pounds for you...

This is only the start.

Letter to Prof. Main, University of Nottingham, 14 April 1997
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 ($B=10\ T \Rightarrow p_{mag}=1600\ bar$!)
  - 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, pub 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, pub quarterly
Where to find out more - 3/3

- Materials - Mechanical properties
  - Nonmetallic materials and composites at low temperatures: Ed AF Clark, RP Reed, G Hartwig pub Plenum
  - Nonmetallic materials and composites at low temperatures 2, Ed G Hartwig, D Evans, pub Plenum 1982
Free energy and critical field

- The Gibbs free energy of a material in a magnetic field is given by:

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

 Thermal energy  Magnetic energy

- The superconducting phase, by excluding the magnetic field \( (M=-H) \), has lower free energy: \( G_{\text{sup}}(H=0) < G_{\text{normal}} \)

- The material will reach critical conditions when the energy of the field will equal the jump in free energy:

\[ \mu_0/2 H_c^2 = G_{\text{normal}} - G_{\text{sup}}(H=0) \]
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
The density of paired electron $n_s$ cannot change quickly at an interface, but rises smoothly from zero (at the surface) to the asymptotic value.

The characteristic length of this transition is the coherence length

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

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

Ginzburg–Landau, 1950
Different behaviors are found as a function of the Ginzburg-Landau parameter $\kappa = \lambda_L / \xi$.

- $\lambda_L \ll \xi \Rightarrow \kappa \ll 1$
- $\lambda_L \gg \xi \Rightarrow \kappa \gg 1$

Ginzburg–Landau, 1950
**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>
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<tr>
<td>Sn</td>
<td>30</td>
<td>170</td>
<td>0.18</td>
</tr>
<tr>
<td>Nb</td>
<td>32</td>
<td>39</td>
<td>0.82</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td></td>
<td></td>
<td>$\approx$ 30</td>
</tr>
</tbody>
</table>

*Type I*

*Type II*