Outline

• why bother with superconductivity?
• properties of superconductors: critical field, temperature & current density
• magnetic fields and how to create them
• load lines, training and how to cure it
• screening currents and the critical state model
• fine filaments, composite wires & cables
• magnetization, field errors & ac losses
• quenching and protection
• hardware
• where to get more info
Superconducting magnets for Accelerators

Who needs superconductivity anyway?

Abolish Ohm’s Law!
• no power consumption
  (although do need refrigeration power)
• high current density ⇒ compact windings, high gradients
• ampere turns are cheap, so we don’t need iron
  (although often use it for shielding)

Consequences
• lower power bills
• higher magnetic fields mean reduced bend radius
  ⇒ smaller rings
  ⇒ reduced capital cost
  ⇒ new technical possibilities
    (eg muon collider)
• higher quadrupole gradients
  ⇒ higher luminosity
The critical surface of niobium titanium

- Niobium titanium NbTi is the standard ‘work horse’ of the superconducting magnet business
- it is a ductile alloy
- picture shows the critical surface, which is the boundary between superconductivity and normal resistivity in 3 dimensional space
- superconductivity prevails everywhere below the surface, resistance everywhere above it
- we define an upper critical field $B_{c2}$ (at zero temperature and current) and critical temperature $\theta_c$ (at zero field and current) which are characteristic of the alloy composition
- critical current density $J_c(B,\theta)$ depends on processing
The critical line at 4.2K

- because magnets usually work in boiling liquid helium, the critical surface is often represented by a curve of current versus field at 4.2K
- niobium tin Nb$_3$Sn has a much higher performance in terms of critical current field and temperature than NbTi
- but it is brittle intermetallic compound with poor mechanical properties
- note that both the field and current density of both superconductors are way above the capability of conventional electromagnets

Critical current density A.mm$^{-2}$

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<tr>
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<th>Nb$_3$Sn</th>
<th>NbTi</th>
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<td>10$^2$</td>
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Magnetic field (Tesla)

2 4 6 8 10 12 14 16 18 20 22

Conventional iron yoke electromagnets
Filamentary composite wires

- for reasons that will be described later, superconducting materials are always used in combination with a good normal conductor such as copper

- to ensure intimate mixing between the two, the superconductor is made in the form of fine filaments embedded in a matrix of copper

- typical dimensions are:
  - wire diameter = 0.3 - 1.0mm
  - filament diameter = 5 - 50μm

- for electromagnetic reasons, the composite wires are twisted so that the filaments look like a rope
Fields and ways to create them: conventional

- iron yoke reduces magnetic reluctance
  ⇒ reduces ampere turns required
  ⇒ reduces power consumption
- iron guides and shapes the field

Iron electromagnet – for accelerator, HEP experiment transformer, motor, generator, etc

BUT iron saturates at ~ 2T
Fields and ways to create them: superconducting dipoles

- simplest winding uses racetrack coils
- 'saddle' coils make better field shapes
- special winding cross sections for good uniformity
- some iron - but field shape is set mainly by the winding
- used when the long dimension is transverse to the field, e.g., accelerator magnets
- known as dipole magnets (because the iron version has 2 poles)

LHC has 'up' & 'down' dipoles side by side
Dipole Magnets

- made from superconducting cable
- winding must have the right cross section
- also need to shape the end turns
**Fields and ways to create them: superconducting quadrupoles**

- gradient fields produce focussing
- quadrupole windings

\[
B_x = ky \\
B_y = kx
\]
Engineering current density

equation: \( J_{\text{eng}} = J_{\text{sup}} \times \text{dilution} \)

dilution (by copper, insulation, structure) \( \sim 33\% \)

\[ J_e = 37.5 \text{ Amm}^{-2} \]

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

\[ 9.5 \times 10^5 \text{ Amp turns} = 1.9 \times 10^6 \text{ A.m per m} \]

\[ 9.5 \times 10^6 \text{ Amp turns} = 1.9 \times 10^7 \text{ A.m per m} \]
we expect the magnet to go resistive 'quench' where the peak field load line crosses the critical current line *
• when the current (and field) of a magnet is ramped up for the first time, it usually ‘quenches’ (goes resistive) at less than the expected current
• at the next try it does better
• known as training

Training of LHC short prototype dipoles (from A. Siemko)
Causes of training:

(1) low specific heat

- the specific heat of all substances falls with temperature
- at 4.2K, it is \(~2,000\) times less than at room temperature
- a given release of energy within the winding thus produce a temperature rise 2,000 times greater than at room temperature
- the smallest energy release can therefore produce catastrophic effects
Causes of training: (2) conductor motion

- Big electromagnetic forces in magnets
- Bursting force in LHC dipoles = 320 tonne/m
- Conductors are pushed by the electromagnetic forces.
- Frictional heating if they move

work done per unit length of conductor if it is pushed a distance $\delta z$

$$W = F.\delta z = B.I.\delta z$$

frictional heating per unit volume

$$Q = B.J.\delta z$$

typical numbers for NbTi:

- $B = 5T$  $J_{eng} = 5 \times 10^8$ A.m$^{-2}$
- so if $\delta = 10 \mu m$
  then $Q = 2.5 \times 10^4$ J.m$^{-3}$

Starting from 4.2K $\theta_{final} = 7.5K$

can you engineer a winding to better than $10 \mu m$?
**Causes of training: (3) resin cracking**

- try to stop wire movement by impregnating the winding with epoxy resin
- the resin contracts much more than the metal - so it goes into tension
- it also become brittle at low temperature.

\[ \text{brittleness + tension} \Rightarrow \text{cracking} \Rightarrow \text{energy release} \]

**Calculate the strain energy induced in resin by differential thermal contraction**

let: \( \sigma = \) tensile stress \( \quad Y = \) Young’s modulus
\( \varepsilon = \) differential strain \( \quad \nu = \) Poisson’s ratio

thermal contraction of Cu \( \sim 3 \times 10^{-3} \) (room to 4K)
thermal contraction of resin \( \sim 11 \times 10^{-3} \)

so \( \varepsilon = (11 - 3) \times 10^{-3} \)

typically \( Y = 7 \times 10^9 \text{ Pa} \) \( n = 1/3 \)

strain energy \( Q_1 = \frac{\sigma^2}{2Y} = \frac{Y\varepsilon^2}{2} \)

\( Q_1 = 2.5 \times 10^5 \text{ J.m}^{-3} \quad (\text{uniaxial strain}) \)

if released adiabatically, raises temperature to \( \theta_{\text{final}} = 16 \text{K} \)
How to reduce training?

1) Reduce the disturbances occurring in the magnet winding
   • make the winding fit together exactly to reduce movement of conductors under field forces
   • pre-compress the winding to reduce movement under field forces
   • if using resin, minimize the volume and choose a crack resistant type
   • match thermal contractions, eg fill epoxy with mineral or glass fibre
   
   *most accelerator magnets are insulated using a Kapton film with a thin adhesive coating*

2) Make the conductor able to withstand disturbances without quenching
   
   • increase the **temperature margin**
   • increase the **minimum quench energy**

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Minimum quench energy MQE

- MQE is the smallest energy input which quenches the conductor.
- measure it by injecting short (100μs) heat pulses at a point on the conductor.

large MQE
⇒ more stable conductor
⇒ less training

for a large MQE we need:
- large temperature margin
- large thermal conductivity – need copper
- small resistivity – need copper
- large specific heat – difficult
- good cooling – winding porous to liquid helium coolant
Persistent screening currents

- when a superconductor is subjected to a changing magnetic field, screening currents are induced to flow
- screening currents are in addition to the transport current, which comes from the power supply
- they are like eddy currents but, because there is no resistance, they don't decay

- usual model is a superconducting slab in a changing magnetic field $B_y$
- assume it's infinitely long in the $z$ and $y$ directions - simplifies to a 1 dim problem
- $dB/dt$ induces an electric field $E$ which causes screening currents to flow at critical current density $J_c$
- known as the critical state model or Bean model
- in the 1 dim infinite slab geometry, Maxwell's equation says

$$\frac{\partial B_y}{\partial x} = -\mu_o J_z = \mu_o J_c$$

- so uniform $J_c$ means a constant field gradient inside the superconductor
The flux penetration process

Plot field profile across the slab

Field increasing from zero

Everywhere current density is ±$J_c$ or zero

(Bean model)

Field decreasing through zero
Magnetization of the Superconductor

When viewed from outside the sample, the persistent currents produce a magnetic moment.

define a magnetization (magnetic moment per unit volume)

\[ M = \sum_v \frac{I.A}{V} \quad NB \text{ units of } H \]

for a fully penetrated slab

\[ M = \frac{1}{a} \int_0^a J_c x \, dx = \frac{J_c a}{2} \]

when fully penetrated, the magnetization is

\[ M = \frac{2}{3\pi} J_c d_f \]

where \( d_f \) = filament radius

Note: \( M \) is here defined per unit volume of NbTi filament

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Magnetization of NbTi
**Coupling between filaments**

recap \[ M = \frac{4}{3\pi} J_c a \]

- reduce M by making fine filaments
- for ease of handling, filaments are embedded in a copper matrix

- fortunately the coupling currents may be reduced by twisting the wire
- coupling currents behave like eddy currents and produce an additional magnetization

\[ M_e = \frac{dB}{dt} \frac{1}{\rho_t} \left[ \frac{p_w}{2\pi} \right]^2 \]

where \( \rho_t = \) resistivity across the copper and \( p_w = \) wire twist pitch

• but in changing fields, the filaments are magnetically coupled
• screening currents go up the left filaments and return down the right
Coupling ⇒ rate dependent magnetization

recap: magnetization has two components:

- persistent current in the filaments

\[ M_f = \frac{2}{3\pi} J_c(B) df \]

**\( M_f \) depends on \( B \)**

- and eddy current coupling between the filaments

\[ M_e = \frac{dB}{dt} \frac{1}{\rho_t} \left[ \frac{p_w}{2\pi} \right]^2 \]

**\( M_e \) depends on \( dB/dt \)**

Note \( M_f \) defined per unit volume of NbTi filament and \( M_e \) per unit volume of wire
Why cables?

• for good tracking connect synchrotron magnets in series
• if stored energy is $E$, rise time $t$ and operating current $I$, the charging voltage is

$$ E = \frac{1}{2} LI^2 \quad V = \frac{LI}{t} = \frac{2E}{It} $$

**RHIC**  $E = 40\text{kJ/m}$, $t = 75\text{s}$, 30 strand cable
cable $I = 5\text{kA}$, charge voltage per km = 213V
wire $I = 167\text{A}$, charge voltage per km = 6400V

**FAIR at GSI**  $E = 74\text{kJ/m}$, $t = 4\text{s}$, 30 strand cable
cable $I = 6.8\text{kA}$, charge voltage per km = 5.4kV
wire $I = 227\text{A}$, charge voltage per km = 163kV

• so we need high currents!

• a single 5μm filament of NbTi in 6T carries 50mA
• a composite wire of fine filaments typically has 5,000 to 10,000 filaments, so it carries 250A to 500A
• for 5 to 10kA, we need 20 to 40 wires in parallel - a cable
Rutherford cable

- fully transposed - every strand changes places with every other

- cable insulated by wrapping 2 or 3 layers of Kapton

- gaps may be left to allow penetration of liquid helium
- outer layer is treated with an adhesive layer for bonding to adjacent turns.

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Coupling in Rutherford cables

- Field transverse coupling via crossover resistance \( R_c \)

\[ \dot{B} \]

- Field transverse coupling via adjacent resistance \( R_a \)

\[ \dot{B} \]

\[ M_{tc} = \frac{1}{120} \frac{\dot{B}_t}{R_c} \frac{c}{p} N(N-1) \]

\[ M_{ta} = \frac{1}{6} \frac{\dot{B}_t}{R_a} \frac{c}{p} \]

(crossover resistance \( R_c \) and adjacent resistance \( R_a \))

(Field parallel gives much smaller coupling via adjacent resistance \( R_a \))
Cable coupling adds more magnetization

filament magnetization $M_f$ depends on $B$

$$M_f = \frac{2}{3\pi} J_c(B) d_f$$

coupling between filaments $M_e$ depends on $dB/dt$

$$M_e = \frac{dB}{dt} \frac{1}{\rho_t} \left[ \frac{p_w}{2\pi} \right]^2$$

coupling between wires in cable depends on $dB/dt$

$$M_{tc} = \frac{1}{120} \frac{\dot{B}_t}{R_c} p \frac{c}{b} N(N-1)$$

$$M_{ta} = \frac{1}{6} \frac{\dot{B}_t}{R_a} p \frac{c}{b}$$
Magnetization and field errors

Magnetization is important in accelerators because it produces field error. The effect is worst at injection because
- $\Delta \frac{B}{B}$ is greatest
- magnetization, i.e., $\Delta B$ is greatest at low field

![Graph showing skew quadrupole error in Nb$_3$Sn dipole which has exceptionally large coupling magnetization (University of Twente)]
Synchrotron injection

- Synchrotrons inject at low field, ramp to high field and then down again.

- Note how quickly the magnetization changes when we start the ramp up.

- Much less magnetization change if we ramp down to zero and then up to injection.

- Don't inject here!

- Much better here!
AC losses

For a magnet material, work done by magnetic field

\[ dW = \mu_o H dM \]

around a closed loop

\[ W = \int \mu_o H dM \]

loop comes back to same place
- field energy is same
- so work done is ac loss in material

ac loss is area of hysteresis loop

\[ W = \int \mu_o H dM = \int \mu_o M dH \]

- within filaments
- between filaments
- between wires
Magnetic stored energy

Magnetic energy density  \[ E = \frac{B^2}{2\mu_o} \]  

at 5T \( E = 10^7 \) Joule.m\(^{-3}\)  
at 10T \( E = 4 \times 10^7 \) Joule.m\(^{-3}\)

LHC dipole magnet (twin apertures)  \[ E = \frac{1}{2}LI^2 \]  
\( L = 0.12\)H  \( I = 11.5\)kA  \( E = 7.8 \times 10^6 \) Joules

the magnet weighs 26 tonnes  
so the magnetic stored energy is equivalent to the kinetic energy of:-

26 tonnes travelling at 88km/hr

coils weigh 830 kg  
equivalent to the kinetic energy of:-

830kg travelling at 495km/hr

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The quench process

- resistive region starts somewhere in the winding at a **point** - this is the problem!
- it grows by thermal conduction
- stored energy $\frac{1}{2}LI^2$ of the magnet is dissipated as heat
- greatest integrated heat dissipation is at point where the quench starts
- internal voltages much greater than terminal voltage ( = $V_{cs}$ current supply)
- maximum temperature may be calculated from the current decay time via the $U(\theta)$ function (adiabatic approximation)
The temperature rise function $U(\theta)$

or the 'fuse blowing' calculation (adiabatic approximation)

$$J^2(T)\rho(\theta)dT = \gamma C(\theta)d\theta$$

$J(T)$ = overall current density, $T$ = time, $\rho(\theta)$ = overall resistivity, $\gamma$ = density, $\theta$ = temperature, $C(\theta)$ = specific heat, $T_Q$ = quench decay time.

$$\int_{\theta_o}^{\theta_m} J^2(T)dT = \int_{\theta_o}^{\theta_m} \frac{\gamma C(\theta)}{\rho(\theta)} d\theta = U(\theta_m)$$

$J_o^2T_Q = U(\theta_m)$

- GSI 001 dipole winding is 50% copper, 22% NbTi, 16% Kapton and 3% stainless steel

- NB always use overall current density
Measured current decay after a quench

Dipole GSI001 measured at Brookhaven National Laboratory
Calculating the temperature rise from the current decay curve

\[ \int J^2 dt \text{ (measured)} \quad U(\theta) \text{ (calculated)} \]
Growth of the resistive zone

the quench starts at a point and then grows in three dimensions via the combined effects of Joule heating and thermal conduction
Quench propagation velocity

• resistive zone starts at a point and spreads along the conductor and transverse to it
• the force driving it forward is the heat generation in the resistive zone, together with heat conduction along the wire

Along the conductor

\[ v_{long} = \frac{J}{\gamma C} \left\{ \rho k \left( \frac{\theta_t - \theta_0}{\theta_t} \right) \right\}^{\frac{1}{2}} \]

where: \( J \) = engineering current density, \( \gamma \) = density, \( C \) = specific heat, \( \rho \) = resistivity, \( k \) = thermal conductivity, \( \theta_t \) = transition temperature

Transverse to the conductor

\[ \alpha = \frac{v_{trans}}{v_{long}} = \left\{ \frac{k_{trans}}{k_{long}} \right\}^{\frac{1}{2}} \]

Typical values

\[ \nu_{ad} = 5 - 20 \text{ ms}^{-1} \quad \alpha = 0.01 - 0.03 \]
Computation of resistance growth and current decay

start resistive zone 1

in time $\delta t$ zone 1 grows $v.\,dt$ longitudinally and $\alpha.\,v.\,dt$ transversely

temperature of zone grows by $\delta \theta_i = J^2 \rho(\theta_i) \delta t / \gamma C(\theta_i)$

resistivity of zone 1 is $\rho(\theta_i)$

calculate resistance and hence current decay $\delta I = R / L. \, \delta t$

in time $\delta t$ add zone n:

$v.\,\delta t$ longitudinal and $\alpha.\,v.\,\delta t$ transverse

temperature of each zone grows by $\delta \theta_i = J^2 \rho(\theta_i) \delta t / \gamma C(\theta_i)$

resistivity of each zone is $\rho(\theta_1) \rho(\theta_2) \rho(\theta_n)$ resistance $r_1 = \rho(\theta_1) * f_{g1}$ (geom factor) $r_2 = \rho(\theta_2) * f_{g2}$ $r_n = \rho(\theta_n) * f_{gn}$

calculate total resistance $R = \sum r_1 + r_2 + r_n$ and hence current decay $\delta I = (I R / L) \delta t$

when $I \Rightarrow 0$ stop
Methods of quench protection:

1) External dump resistor

- detect the quench electronically
- open an external circuit breaker
- force the current to decay through the resistor

2) Quench back heater

- detect the quench electronically
- power a heater in thermal contact with the winding
- this quenches other regions of the magnet, forcing the normal zone to grow more rapidly
  ⇒ higher resistance
  ⇒ shorter decay time
  ⇒ lower temperature rise at the hot spot

*method most commonly used in accelerator magnets ✓*
Winding an LHC dipole

photo courtesy of Babcock Noell
Curing press
Collars

How to make an external structure that
• fits tightly round the coil
• presses it into an accurate shape
• has low ac losses
• can be mass produced cheaply
• ???

• Answer make collars by precision stamping of stainless steel or aluminium alloy plate a few mm thick
- inherited from conventional magnet laminations

press collars over coil from above and below

invert alternate pairs so that they interlock push steel rods through holes to lock in position

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Collars and end plate (LHC dipole)
Adding the iron

- they are forced into place, again using the collaring press
- remember however that pure iron becomes brittle at low temperature
- the tensile forces are therefore taken by a stainless steel shell which is welded around the iron, while still in the press
- this stainless shell can also serve as the helium vessel
Dipole inside its stainless shell
Complete magnet in cryostat
Make a lot of Magnets and install in the tunnel
Concluding remarks

- superconductivity offers higher magnetic fields and field gradients, with less energy dissipation
- NbTi is the most common superconducting material and has been used in all accelerators to date
- superconducting magnets do not use iron to shape the field, so must use special winding shapes
- magnets don’t reach their expected current/field first time but show training - control training by reducing movement, attention to contraction and increasing MQE
- persistent screening currents produce magnetization of the superconductor which causes field errors and ac loss – need fine ~ 5μm filaments
- accelerators need high currents, so must use many wires in parallel – a cable
- coupling between filament in wire and between wires in cable increases magnetization
- magnets store large inductive energy which is released at quench as heating – must protect
- magnet manufacturing techniques have been developed to ensure accurate winding shape and minimize conductor movement

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Some useful references

Superconducting Magnets

• Proc Applied Superconductivity Conference: pub as IEEE Trans Applied Superconductivity, Mar 93 to 99, and as IEEE Trans Magnetics Mar 75 to 91
• Handbook of Applied Superconductivity ed B Seeber, pub UK Institute Physics 1998
• JUAS lectures on superconducting magnets (and all accelerator topics) http://juas.in2p3.fr
• 'Superconducting Accelerator Magnets' DVD available from mjbball @ comcast.net

Materials Mechanical

• Handbook on Materials for Superconducting Machinery pub Batelle Columbus Laboratories 1977.
• 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
• Austenitic Steels at low temperatures Editors R.P.Reed and T.Horiuchi, pub Plenum1983

Superconducting Materials

• Superconductor Science and Technology, published monthly by Institute of Physics (UK).

Cryogenics

• Helium Cryogenics Van Sciver SW, pub Plenum 86 ISBN 0-0306-42335-9
• Cryogenics: published monthly by Butterworths
• Cryogenie: Ses Applications en Supraconductivite, pub IIR 177 Boulevard Malesherbes F5017 Paris France
Materials data web sites

- Cryogenic properties (1-300 K) of many solids, including thermal conductivity, specific heat, and thermal expansion, have been empirically fitted and the equation parameters are available free on the web at [www.cryogenics.nist.gov](http://www.cryogenics.nist.gov)

- Plots and automated data-look-up using the NIST equations are available on the web for a fee from [www.cpij.jhu.edu](http://www.cpij.jhu.edu)

- Other fee web sites that use their own fitting equations for a number of cryogenic material properties include: [www.cryodata.com](http://www.cryodata.com) (cryogenic properties of about 100 materials), and [www.jahm.com](http://www.jahm.com) (temperature dependent properties of about 1000 materials, many at cryogenic temperatures).

- Commercially supplied room-temperature data are available free online for about 10 to 20 properties of about 24,000 materials at [www.matweb.com](http://www.matweb.com)

Cryodata Software Products

- **GASPAK**: properties of pure fluids from the triple point to high temperatures.
- **HEPAK**: properties of helium including superfluid above 0.8 K, up to 1500 K.
- **STEAMPAK**: properties of water from the triple point to 2000 K and 200 MPa.
- **METALPAK, CPPACK, EXPAK**: reference properties of metals and other solids, 1 - 300 K.
- **CRYOCOMP**: properties and thermal design calculations for solid materials, 1 - 300 K.
- **SUPERMAGNET**: four unique engineering design codes for superconducting magnet systems.
- **KRYOM**: numerical modelling calculations on radiation-shielded cryogenic enclosures.

*thanks to Jack Ekin of NIST for this information*