Superconductivity for accelerators
- why bother?

Abolish Ohm's Law

- no power consumption
  (although do need refrigeration power)
- high current density ⇒ compact windings, high gradients
- ampere turns are cheap, so don’t need iron ⇒ high fields
  (although often use it for shielding)

Consequence

- 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
Superconducting Magnets: plan of the lectures

1 Introduction to Superconductors
- critical field, temperature & current
- superconductors for magnets
- manufacture of superconducting wires
- high temperature superconductors HTS
- where to find more

2 Magnetization, Cables & AC losses
- superconductors in changing fields, critical state model
- filamentary superconductors and magnetization
- coupling between filaments ⇒ magnetization
- why cables, coupling in cables
- mini tutorial
- AC losses in changing fields

3 Magnets, ‘Training’ & Fine Filaments
- coil shapes for solenoids, dipoles & quadrupoles
- engineering current density & load lines
- degradation, training & minimum quench energy MQE
- flux jumping

4 Quenching and Protection
- the quench process
- resistance growth, current decay, temperature rise
- calculating the quench
- mini tutorial
- quench protection schemes

5 Cryogenics & Practical Matters
- working fluids, refrigeration
- cryostat design
- current leads
- accelerator magnet manufacture
- some superconducting accelerators

mini tutorials
get a feel for the numbers, bring a calculator
The critical surface of niobium titanium

• NbTi is the standard commercial ‘work horse’ of the superconducting magnet business

• critical surface is the boundary between superconductivity and normal resistivity in $J$, $B$, $\theta$ space

• superconductivity prevails everywhere below the surface, resistance everywhere above it

• upper critical field $B_{c2}$ (at zero temperature and current)

• critical temperature $\theta_c$ (at zero field and current)

• $B_{c2}$ and $\theta_c$ are characteristic of the alloy composition

• critical current density $J_c$ depends on processing

• keep it cold!
The critical line at 4.2K

- Magnets usually work in boiling liquid helium, so the critical surface is often represented by a curve of current versus field at 4.2K.

- Niobium tin Nb₃Sn has a much higher performance than NbTi.

- But Nb₃Sn is a brittle intermetallic compound with poor mechanical properties.

- Both the field and current density of both superconductors are way above the capability of conventional electromagnets.
Two kinds of superconductor: type 1

- the materials first discovered by Kammerlingh Onnes in 1911 - soft metals like lead, tin mercury
- sphere of metal at room temperature
- apply magnetic field
- reduce the temperature - resistance decreases
- reduce the temperature some more - resistance decreases some more
- at the critical temperature $\theta_c$ the field is pushed out - the **Meissner effect** - superconductivity!
- increase the field - field is kept out
- increase the field some more - superconductivity is extinguished and the field jumps in
- thermodynamic critical field $B_c$ is trade off between reducing energy via condensation to superconductivity and increasing energy by pushing out field $\sim 0.1T$
Two kinds of superconductor: type 2

- apply magnetic field

- reduce the temperature - resistance decreases

- at the critical temperature $\theta_c$ the field is pushed out

- increase the field - field jumps back in without quenching superconductivity

- it does so in the form of quantized fluxoids

- lower critical field $B_{c1}$

- supercurrents encircle the resistive core of the fluxoid thereby screening field from the bulk material

- higher field $\Rightarrow$ closer vortex spacing

- superconductivity is extinguished at the (much higher) upper critical field $B_{c2}$
Type 1 and type 2 superconductors

- Meissner effect is not total
- magnetic field penetrates a small distance $\lambda$
- the London Penetration Depth.

- another characteristic distance is the coherence length $\zeta$ - the minimum distance over which the electronic state can change from superconducting to normal

- theory of Ginsburg, Landau, Abrikosov and Gorkov GLAG defines the ratio $\kappa = \lambda / \zeta$

if $\kappa < 1/\sqrt{2}$ material is Type 1

if $\kappa > 1/\sqrt{2}$ material is Type 2
Critical fields of type 2 superconductors

- recap thermodynamic critical field $B_c$ (slide 6)
- lower critical field $B_{c1} = B_c / \kappa$
- above $B_{c1}$ magnetic field penetrates as discrete quantized fluxoids

A fluxoid encloses flux

$$\phi_o = \frac{h}{2e} = 2 \times 10^{-15} \text{Wb}$$

$h = $ Planck's constant
$e = $ electronic charge

Upper critical field

$$B_{c2} = \sqrt{2} \kappa B_c$$

in the 'dirty limit' $\kappa \approx 2.4 \times 10^6 \frac{1}{\gamma^2 \rho_n}$

Thus the upper critical field

$$B_{c2} = 3.1 \times 10^3 \gamma \rho_n \theta_c$$

For NbTi: $\gamma \approx 900 \text{ J m}^{-3} \text{ K}^{-2}$ $\rho_n \approx 65 \times 10^{-8} \text{ W m} \quad \theta_c = 9.3 \text{ K}$ hence $B_{c2} \approx 18.5 \text{ T}$

Sommerfeld coefficient of electronic specific heat $C_e = \gamma \theta$

Human hair in earth's magnetic field ~ 50 $\phi_o$
Critical current density: type 2 superconductors

- a single fluxoid encloses flux
\[ \phi_o = \frac{h}{2e} = 2 \times 10^{-15} \text{ Webers} \]

\( h = \text{Planck’s constant, } e = \text{electronic charge} \)

- so density of fluxoids \( \sim \) average field
  \( \Rightarrow \) uniform density \( \Rightarrow \) uniform field
  \( \Rightarrow \) zero \( J \) (because \( \text{Curl } B = \mu_o J \))

- to get a current density we must produce a \textit{gradient} in the density of fluxoids

- fluxoids like to distribute uniformly

- must impose a gradient by inhomogeneities in the material, eg dislocations or precipitates

\[ \alpha\text{-Ti in Nb Ti} \]

\[ \text{precipitates of } \alpha \text{ Ti in Nb Ti} \]

\[ \text{Meingast, P Lee and DC Larbalestier: J. Appl. Phys. 66, 5971} \]
Critical properties

- **Critical temperature** $\theta_c$: choose the right material to have a large energy gap or 'depairing energy' property of the material.

- **Upper Critical field** $B_{c2}$: choose a Type 2 superconductor with a high critical temperature and a high normal state resistivity property of the material.

- **Critical current density** $J_c$: mess up the microstructure by cold working and precipitation heat treatments hard work by the producer.
Critical field & temperature of LTS

Low Temperature Superconductors

Note: of all the metallic superconductors, only NbTi is ductile.

All the rest are brittle intermetallic compounds.
To date, all superconducting accelerators have used NbTi.

Of the intermetallics, only Nb₃Sn has found significant use in magnets.
Practical wires for magnets

- ~ 50 years after its development, NbTi is still the most popular magnet conductor,

- Nb$_3$Sn used for special high field magnets and HTS for some developmental prototypes.

- superconducting materials always combined with a good normal conductor such as copper

- need intimate mixing between the two, so superconductor made as fine filaments in a matrix of copper

- typical dimensions:
  - 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 (see Lecture 2)
NbTi manufacture

- vacuum melting of NbTi billets
- hot extrusion of the copper NbTi composite
- sequence of cold drawing and intermediate heat treatments to precipitate αTi phases as flux pinning centres
- for very fine filaments, must avoid the formation of brittle CuTi intermetallic compounds during heat treatment - usually done by enclosing the NbTi in a thin Nb shell
- twisting to avoid coupling - see lecture 2
Filamentary $\text{Nb}_3\text{Sn}$ wire via the bronze route

- $\text{Nb}_3\text{Sn}$ is brittle and cannot be drawn down. So draw down pure niobium in a matrix of bronze (copper tin).
- At final size heat the wire (~700°C for some days) Sn diffuses through Cu & reacts with Nb ⇨ $\text{Nb}_3\text{Sn}$
- Remaining copper still contains ~3wt% tin ⇨ high resistivity so add 'islands' of pure copper surrounded by a diffusion barrier.

- BUT maximum ductile bronze is ~13wt% tin,
- reaction slows at ~3wt%
- so low engineering $J_c$
$\text{Nb}_3\text{Sn}$ with higher engineering $J_c$

- **Cu sheathed Nb rods**
- **Tin in centre**
- **Extrude**
- **NbSn$_2$ powder**
- **Cu jacket**
- **Nb tube**
- **Stack & extrude**
- **Draw to wire**
- **Heat treat**

- **Both make high $J_{\text{eng}}$ (RRP is the highest)**
- **But large filaments**

Non-Cu:
- 25%
- 40%
- 10%
- 25%

Ternary 64h/675°C

C.M. Fischer
MS thesis
UW-Madison

**SMI SHAPEMETAL INNOVATION B.V.**

**Powder in tube PIT**

**Martin Wilson Lecture 1 slide 16**

**JUAS February 2015**
Measurement of critical current

- spiral sample with current leads and voltage taps
- place in the bore of a superconducting solenoid
- put in cryostat
- immerse in liquid helium
- at each field level slowly increase the current and measure the voltage across the test section
Resistive transition 1

• measured boundary between superconducting and resistive states is not sharp, but gradual.

• measure $J_c$ with voltage taps across sample

• see voltage rise gradually.

• define $J_c$ at a given electric field or effective resistivity.

• common definitions are $\rho = 10^{-14} \, \Omega \, \text{m}$ or $E = 1 \, \mu \text{V. m}^{-1}$

• this level is about the critical current expected in a resin impregnated winding

• at higher current self heating

  ⇨ temperature rise ⇨ reduced critical current

Overall Current density $10^8 \, \text{A.m}^{-2}$

\[ \rho = 10^{-14} \, \Omega \, \text{m} \]
Resistive transition 2

- empirically find that resistive transition follows a power law

\[ \rho(J) = \rho_o \left( \frac{J}{J_o} \right)^n \]

where \( n \) is called the resistive transition index.

- effect is partly within filaments (flux flow) and partly between filaments

- 'sausaging of filaments, forces current to cross the copper matrix as critical current is approached.

- resistive transition can be the main source of decay in persistent magnets

- 'n' is often taken as a measure of quality - look for \( n > 50 \)

- HTS conductors so far have low \( n \approx 5 - 10 \)
Conductors for accelerator magnets

- to date, all superconducting accelerators have used NbTi superconductor.
- to control field errors and ac losses, filaments must be $< 10\mu m$ diameter (lectures 2 & 3)
- to get high operating currents, many wires must be cabled together.
Engineering current density and filling factors

In magnet design, what really matters is the overall 'engineering' current density $J_{eng}$

$$J_{eng} = \text{current} / \text{unit cell area} = J_{sup} \times \lambda_{su}$$

filling factor of superconductor in unit cell $\lambda_{su} = \lambda_{sw} \times \lambda_{wu}$

\($\lambda_{sw}$ filling factor superconductor in the wire $\lambda_{sw} = 1 / (1+mat)$\)

where $mat = \text{matrix : superconductor ratio}$, typically:

for NbTi $mat = 1.2$ to $3.0$ ie $\lambda_{sw} = 0.45$ to $0.25$

for Nb$_3$Sn $mat = 2.0$ to $4.0$ ie $\lambda_{sw} = 0.33$ to $0.2$

for B2212 $mat = 3.0$ to $4.0$ ie $\lambda_{sw} = 0.25$ to $0.2$

For Nb$_3$Sn and B2212 the area of superconductor is not well defined, so often define $J_{sup}$ over ‘non matrix’ or ‘non Cu’ area, which is greater than superconductor area.

$\lambda_{wu}$ fraction of wire in unit cell taking account of space occupied by insulation, cooling channels, reinforcement etc: typically $\lambda_{wu} \sim 0.7$ to $0.8$

So typically $J_{eng}$ is only $15\%$ to $30\%$ of $J_{supercon}$
A century of critical temperatures

Woodstock of Physics 1987

Paul Chu

BaLaCuO

SmFeAsO$_{\sim 0.85}$

MgB$_2$

PbMo$_6$S$_8$

PbZr

NbGe

Nb$_3$Ge

Nb$_3$Sn

Hg

Sn

Nb


year
Wonderful materials for magnets

- PbBi
- Nb
- PbMo$_6$S$_8$
- Nb$_3$Sn
- NbTi
- NbZr
- MoRe
- YBCO
- YBa$_2$Cu$_3$O$_7$
- B2223
- B2212
- MgB$_2$
- Yttrium Barium Copper Oxide
- Barium Strontium Calcium Copper Oxide BSCCO
- Bi$_2$Sr$_2$CaCu$_2$O$_8$
- Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_6$
- B2212
- B2223
- Magnesium Diboride MgB$_2$

but for two problems

- flux flow resistance
- grain boundary mismatch
1) Flux flow resistance

[Graph showing critical fields, temperatures, and material properties for superconductors like YBCO, B2212, B2223, MgB2, Nb3Al, Nb3Sn, and NbTi, illustrating concepts such as critical line, resistive, flux flow, irreversibility line, and flux pinning.]
Accessible fields for magnets

so here’s the parameter space for future magnets

and we still need to work on the current density
2) Grain boundary mismatch

- crystal planes in grains point in different directions
- critical currents are high within the grains
- $J_c$ across the grain boundary depends on the misorientation angle

- For good $J_c$, must align the grains to within a few degrees

\begin{figure}
\centering
\includegraphics[width=\textwidth]{grain_boundary.png}
\caption{Data on YBCO from Dimos et al. \textit{Phys Rev Let} \textbf{61} 219 (1988)}
\end{figure}

\textit{the key measurement of Dimos et al}
BSCCO conductors

- BSCCO powder in silver matrix
- silver is transparent to oxygen
- grains tend to line up during processing in contact with silver
- but low irreversibility field

\[
\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_6 \quad \text{B2223}
\]
- \(\theta_c \sim 110\) K \(\Rightarrow 77\) K use
- complex thermo-mechanical fabrication route to produce uniaxial texture
- reaction of 2212 + stuff to 2223 occurs primarily in the solid state at \(\sim 840^\circ\)C
- texture requires pressing to a large aspect ratio tape (4 x 0.2 mm)
- anisotropic \(J_c\)
- mature conductor – semi commercial production for > 10 years

\[
\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8 \quad \text{B2212}
\]
- \(\theta_c \sim 85\) K
- produced by melting B2212 powder inside silver matrix
- round filaments in round wires
- Isotropic and high \(J_c\), but originally only in short length
- recently achieved high \(J_c\) in long lengths by heat treatment under high pressure \(O_2\)
- engineers like round wire
- can make Rutherford cables
Coated YBCO tape

- YBCO has the best irreversibility field, but it is very sensitive to grain boundary misalignment.
- The grains do not line up naturally - they must be persuaded.
- Deposit YBCO on a substrate where the grains are aligned and the lattice roughly matches YBCO.

![Diagram of YBCO tape structure](image)
YBCO coated tape at SuperPower Inc.

Ag sputtering

IBAD

MOCVD

Buffer

2 µm Ag
1 µm YBCO - HTS (epitaxial)
~ 30 nm LMO (epitaxial)
~ 30 nm Homo-epi MgO
~ 10 nm IBAD MgO

50µm Hastelloy substrate
20µm Cu
Lecture 1: concluding remarks

- superconductors allow us to build magnets which burn no power (except refrigeration)
- ampere turns are cheap, so don’t need iron
  ⇒ fields higher than iron saturation (but still use iron for shielding)
- performance of all superconductors described by the critical surface in $B J \theta$ space,
- three kinds of superconductor
  - type 1: low temperature, unsuitable for high field
  - type 2: low temperature, good for high field - but must create flux pinning to get current density
  - HTS: high temperature, high field - but current density is still a problem
    – accelerators will probably settle for low temperature to get high field and current density
- NbTi is still the most common superconductor - standard commercial product
- $\text{Nb}_3\text{Sn}$ has higher critical field & temperature - specialized commercial production
- BSCO high temperature or high field, but not both - prototype commercial production
- YBCO high temperature and high field, but must align the grains - prototype commercial production
- measure $I_c$ to check specification, the index $n$ indicates quality
- Accelerators to date are (almost) all NbTi, usually in Rutherford cables
Some useful references

Superconducting Magnets
- Proc Applied Superconductivity Conference: pub as IEEE Trans Applied Superconductivity, Mar 93 to 2015, and as IEEE Trans Magnetics Mar 75 to 91

Superconducting Materials
- Superconductor Science and Technology, published monthly by Institute of Physics (UK).

Materials Mechanical
- 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

Cryogenics
- Cryogenics: published monthly by Butterworths
- Cryogenie: Ses Applications en Supraconductivite, pub IIR 177 Boulevard Malesherbes F5017 Paris France
on the Web

- **Lectures on Superconductivity** [http://www msm cam.ac.uk ascg/lectures](http://www msm cam.ac.uk ascg/lectures).  A series of lectures produced for SCENET by Cambridge University: fundamentals, materials, electronics, applications. Also available as a DVD

- **Superconducting Accelerator Magnets** [http://www mj b-plus.com](http://www mj b-plus.com).  A course developed from SSC experience, available from website for $20

- [www.superconductors.org](http://www.superconductors.org) website run by an enthusiast; gives some basic info and links


- **European Society for Applied Superconductivity**  [http://www.esas.org/](http://www.esas.org/)  News, events and people in the area of applied superconductivity

- **CONECTUS**  Consortium of European Companies determined to use Superconductivity  [http://www.conectus.org/](http://www.conectus.org/)

Materials data on the Web

- 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

- Thermodynamic properties of gases (and liquids) available free as a programme which you can interrogate for your own temperature interval etc. http://webbook.nist.gov/chemistry/fluid/

- Plots and automated data-look-up using the NIST equations are available on the web for a fee from www.cpia.jhu.edu

- Other fee web sites that use their own fitting equations for a number of cryogenic material properties include: www.cryodata.com (cryogenic properties of about 100 materials), and 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

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 and Charles Monroe for this information