Lecture II

Superconductivity
(A brief and limited overview)

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The purpose of this lecture is to give you a brief overview of superconductivity.

This introduction will cover some history, basic principles and a few aspects of superconductivity that are relevant to designing accelerator magnets.
Superconductivity

First observation of “Superconductivity” by Onnes (1911)

Resistance of Mercury falls suddenly below measurement accuracy at very low temperature

Resistivity of Cu as a function of Temperature

High purity copper has larger RRR

\[ \text{RRR} = \frac{\rho(273\text{K})}{\rho(\sim 4\text{K})} \]

Temperature (K)

Resistance (Ohms)

ELECTRICAL RESISTIVITY VERSUS TEMPERATURE FOR COPPER

January 16-20, 2006, Superconducting Accelerator Magnets
Superconducting Accelerator Magnets
A Brief History

1908  Heinke Kemerlingh Onnes achieves very low temperature (<4.2 K)
1911  Onnes and Holst observe sudden drop in resistivity to essentially zero
      Superconductivity is born!
1914  Persistent current experiments
1933  Meissner-Ochsenfeld effect observed
1935  Fritz and London theory
1950  Ginsburg - Landau theory
1957  BCS Theory
1967  Observation of Flux Tubes in Type II superconductors
1980  Tevatron: The first accelerator using superconducting magnets
1986  First observation of High Temperature Superconductors

It took ~70 years to get the first accelerator with conventional superconductors.

How long will it take for HTS to get to accelerator magnets? Have patience!
Critical Surface

The surface on 3-d (J,T,B) volume within which the material remains superconducting.

Figure 2.11: Sketch of the critical surface of Nb-Ti. Also indicated are the regions where pure niobium and pure titanium are superconducting. The critical surface has been truncated in the regime of very low temperatures and fields where only sparse data are available.

Magnet designers dream material:
A material that remains superconducting at higher temperatures and at higher fields!
But it must also have good material properties!!!
A remarkable observation in superconductors:

They exclude magnet flux lines from going through them.

Meissner and Ochsenfeld (1933)
Type I and Type II Superconductors

Type I:
Also known as "soft superconductors".
Completely exclude flux lines (Meissner Effect).
Allow only small field ($\ll 1$ T).
Not good for accelerator magnets.

Type II:
Also known as "hard superconductors".
Completely exclude flux lines up to $B_{c1}$ but then part of the flux enters till $B_{c2}$.
- Important plus: Allow much higher fields.
- These are the one that are used in building accelerator magnets.

Figure 10: Magnetisation of type I and type II superconductors as a function of field.
Type I superconductors are obviously **NOT** suitable for high field magnet applications.
Magnesium Diboride ($\text{MgB}_2$)

**Figure 12:** (a) The phase diagram of a type II superconductor.

All present accelerator magnets are made with NbTi. High field R&D magnets are being built with Nb$_3$Sn.

$\text{MgB}_2$ is LTS with high Tc (perhaps highest possible)
All present superconducting accelerators operate at ~4.5 K and use Nb-Ti. LHC magnets will operate at ~1.8 K, to generate higher fields, while still using Nb-Ti.
Critical Current Density as a Function of Field

Performance of 0.8 mm dia wire as of year 2000

- BSCCO2212 (4.2K)
- Nb3Sn (4.2K)
- NbTi (4.2K)
- NbTi (1.8K)
Conductors that are currently being used in building accelerator magnets are all Type II Low Temperature Superconductors.

NbTi, a ductile material, has been the conductor of choice so far. All accelerator magnets that have been and are being built, use this superconductor.

For future high field magnet applications one must turn to Nb₃Sn, etc. (higher Bc₂). However, Nb₃Sn is brittle in nature, and presents many challenges in building magnets.
**Type I and Type II Superconductors**

**London Penetration Depth and Coherence Length**

- "London Penetration Depth" tells how field falls or the depth to which field may penetrate.
- "Coherence Length" tells how Cooper pair density increases (indicates the range of interaction between Cooper pairs).

**Ginzburg-Landau Parameter**

\[ \kappa = \frac{\lambda_L}{\xi} \]

- **type I**: \( \kappa < 1/\sqrt{2} \)
- **type II**: \( \kappa > 1/\sqrt{2} \)

### Table

<table>
<thead>
<tr>
<th>Material</th>
<th>In</th>
<th>Pb</th>
<th>Sn</th>
<th>Nb</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_L ) [nm]</td>
<td>24</td>
<td>32</td>
<td>( \approx 30 )</td>
<td>32</td>
</tr>
<tr>
<td>( \xi ) [nm]</td>
<td>360</td>
<td>510</td>
<td>( \approx 170 )</td>
<td>39</td>
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</tbody>
</table>

**Note:** Pure Niobium (Nb) is type II superconductor.

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*Figure 13: Flux tubes in a type II superconductor.*

*Figure 14: Attenuation of field (a) in a thick slab and (b) in thin sheet. (c) Subdivision of a thick slab into alternating layers of normal and superconducting slices.*

*Figure 15: The decay of the magnetic field and the rise of the Cooper pair density at a normal-superconductor interface.*

*Courtesy: Schmuser*
Figure 2.7: (a) Fluxoid pattern in niobium (courtesy U. Essmann). The distance between adjacent flux tubes is 0.2 μm. (b) Scheme of fluxoid motion in a current-carrying type II superconductor.

Courtesy: Schmuser

Motion of these fluxoids generates heat.
These defects are crucial for a superconductor to become usable for magnetic field application. These are the ones that allow fields.

High critical current density microstructure in a conventionally processed Nb-Ti microstructure. Courtesy: P.J. Lee (University of Wisconsin-Madison)
• For superconducting magnet applications, the presence of certain defects is essential.

• For superconducting RF cavities, one needs very high purity materials, with no defects.

• RF cavities are made with high purity Niobium

Note: Niobium (Nb) is only one of three metals that is Type II superconductor (others are vanadium and technetium).

$H_{c1}$ of Niobium $\sim$ kG.

Note that high purity bulk Niobium (RRR $>$ 150) is Type I superconductor.
Initially, when the field is raised, large screening currents are generated to oppose the changes. These current densities may be much larger than $J_c$ (critical current density till which material remains superconducting). A current higher than $J_c$ will create Joule heating. However, these large currents soon die and attenuate to $J_c$, which persists.

Figure 2.12: Current and field distribution in a slab of hard superconductor according to the critical-state model. The external field is parallel to the surface. (a) Initial exposition to a small external field. (b) The penetrating field $B_p$. (c) External field first raised above $B_p$ and then lowered again.
Instability from Flux Jumping

Flux Jumping

Unstable behavior shown by all type 2 superconductors when subjected to a magnetic field.

It arises because:

a) magnetic field induces screening currents, flowing at critical density
b) change in screening currents allows flux to move into the superconductor
c) flux motion dissipates energy
d) thermal diffusivity is low, so energy dissipation causes local temperature rise
e) critical current density falls with increasing temperature
f) go to b)

Small filament diameter is required to reduce flux jumping.

 Courtesy: Wilson
Magnetization Effects in Superconducting Filaments

The above magnetization creates persistent current, a major issue in SC magnets.

Animesh Jain to discuss persistent currents in significant details.

Persistent current induced magnetization:

\[ 2\mu_0 M = 2\mu_0 \frac{2}{3\pi} \nu J_c d \quad (1) \]

- \( J_c \), critical current density
- \( d \), filament diameter
- \( \nu \), vol. fraction of NbTi

\[ M_S = \frac{M}{\nu} \quad (2) \]
Persistent current induced magnetization:

\[ 2\mu_0 M = 2\mu_0 \frac{2}{3\pi} J_c d \]

- \( J_c \), Critical Current Density
- \( d \), Filament Diameter
- \( \nu \), Vol. Fraction of NbTi

\[ M_s = M/\nu \]

Problem in Nb3Sn Magnets because:
(a) \( J_c \) is several times higher
(b) Filament size is big and gets bigger after reaction due to sintering

In most Nb3Sn available today, the effective filament diameter is an order of magnitude larger than that in NbTi. The obvious solution is to reduce filament diameter; however, in some cases it also reduces \( J_c \).

**A small filament diameter is important for:**
- increasing stability
- reducing persistent currents
**Persistent Current-induced Harmonics**
(may be a problem in Nb$_3$Sn magnets, if nothing done)

Nb$_3$Sn superconductor, with the technology now in use, is expected to generate persistent current-induced harmonics which are a factor of 10-100 worse than those measured in Nb-Ti magnets.

In addition, a snap-back problem is observed when the acceleration starts (ramp-up) after injection at steady state (constant field).

Measured sextupole harmonic in a Nb-Ti magnet

![Image of Nb-Ti magnet](image1)

Measured sextupole harmonic in a Nb$_3$Sn magnet

![Image of Nb$_3$Sn magnet](image2)

Magnetization:

$$M = \frac{4}{3\pi} J_c a$$

Either reduce the effective filament diameter or come up with a magnetic design that minimizes the effect of magnetization in the magnets (LBL, FNAL, TAMU).
Manufacturing of Nb-Ti Wires

A monofilament billet consists of a single niobium-titanium bar of about 15-cm diameter and 55 to 75-cm long, wrapped with niobium foil and inserted into a 20-cm diameter thick-walled copper can. Top and bottom end caps are attached by electron-beam welding. The sealed can is evacuated and compressed.

The monofilament billet is hot-extruded at 800-700°C to a composite rod approximately 3.5-cm in diameter.

The extruded rod is drawn down in multiple passes to a smaller size.

Resulting bar is compacted to a hexagonal-shaped cross-section about 3.5 mm across, cut into 30 to 75-cm lengths, and cleaned.

A multifilament billet is now formed from approximately 7,200 hexagonal monofilament rods (for inner SSC cable) or 4,200 rods (for outer SSC cable). The rods are tightly packed into another 30-cm diameter thick-walled copper can, with a center copper island and filler copper added at the edges to reduce the voids. The billet goes through the same process of compaction, extrusion, and drawing as described earlier, except that now the wire is drawn to the final wire size needed for cable production. During the drawing, the wire is heat treated several times to optimize its current-carrying capacity. The wire is twisted just before the last drawing step.

Thus, one multifilament billet for inner wire yields approximately 80,000 meters of wire, sufficient for about 2 SSC dipole magnets. One billet for outer wire yields ~130,000 meters of wire, again sufficient for 2 dipoles.

Final multifilamentary wire, 0.648 or 0.808 mm in diameter with 6-μm diameter filaments. The conductor for the SSC dipoles will subsequently be cabled from 30 or 36 such composite Nb-Ti wires.
A Typical Superconducting Cable

Each copper wire contains several thousand of NbTi superconducting filaments.

Accurately compacted cable which contains typically 30 twisted multi-filamentary wires.

Filaments in an actual cable

(Filament size in SSC/RHIC magnets: 6 micron)
Stability of Superconducting Wire
(Wire is Made of Many Filaments)

Filaments not coupled

Coupled filaments

Coupling of filaments (in changing field) is undesirable because it increases effective radius. This brings back flux jump instability and magnetization.

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

Magnetization:
Twisting: The Key to Stability

A wire composed of twisted filaments

Twisting significantly reduces the influence coupling. The sign of $dB/dt$ reverses every half pitch.

Wires are twisted in cable for the same reason, i.e., to reduce the coupling.

Courtesy: Wilson

Rutherford cable
Cable Measurement Set-up at BNL

DIPOLE BORE TUBE
SILICON BRONZE NUTS
S.S. TOP PLATE
MICARTA SPACER
MICARTA CHANNEL
S.S. STUD
S.S BOTTOM PLATE

Courtesy: Ghosh, BNL
LOCALLY DAMAGED CABLE.

Smooth Cable

Vs (µV)

V ∝ (I/I_c)^n

n-value:
A good indicator of the quality of cable.
A lower “n-value” means a slow transition from superconducting to normal phase, which generally indicates some sort of damage in the cable.
Conventional Low Temperature Superconductors (LTS) and New High Temperature Superconductors (HTS)

Low Temperature Superconductor Onnes (1911)
Resistance of Mercury falls suddenly below meas. accuracy at very low (4.2) temperature

New materials (ceramics) lose their resistance at NOT so low temperature (Liquid Nitrogen)!
High Temperature Superconductors (HTS)
Popular HTS Materials of Today

- BSCCO 2223 ($T_c \sim 110$ K)
- BSCCO 2212 ($T_c \sim 85$ K)
- YBCO ($T_c \sim 90$ K)

- MgB$_2$ is a low temperature superconductor (LTS) with critical temperature $\sim 39$ K (almost highest possible by current theories).

Of these only BSCCO2212 and BSCCO2223 (first generation) are now available in sufficient quantity to make accelerator magnets. YBCO (second generation) HTS is expected to be available soon (couple of years) in sufficient lengths to make magnets. Second generation superconductor is expected to have a much lower cost.
Some Remarkable Properties of HTS (High Temperature Superconductors)

HTS retains their superconductivity to a much higher temperature.

Also compare the high field performance of “High Temperature Superconductors (HTS)” to that of “Low Temperature Superconductors (LTS)”. 
High Temperature Superconductors (HTS) now carry significantly higher current over Low Temperature Superconductors (LTS), at low temperature high fields (see below) or at high temperature low fields (see right).
High Field Superconductors

Differences between Low field and High field superconductors:

Low field superconductors (NbTi) are ductile.
The coils can be wound without significantly damaging the conductors.

High field superconductors (Nb$_3$Sn and HTS) are brittle!

One has to be very careful in winding coils with these brittle material
or use an alternate design to minimize the damage on conductors.

One can also wind the coil before they become brittle (& superconducting) and
react the material after winding to make them superconductor.
This is referred to as “Wind and React” technique and it requires everything in the
coil to go through the high temperature (650 C or more) reaction process. One has
to be careful in choosing material, etc.
Use of superconductors in accelerator magnets generate field much higher than what can be achieved from the normal conductors.

Two major reasons for using superconducting magnets in the accelerators:

**Cost advantage**

In high energy circular hadron colliders, superconducting magnets reduce the size of a machine. This usually translates into a reduction in the overall machine cost. Superconducting magnets also lower the power consumption and hence the cost of operating a high energy machine.

**Performance advantage**

In interaction regions, a few high field and high field quality magnets may significantly enhance the luminosity of the machine. In this case, magnet costs may be large but the overall returns to experimentalists are high.

Courtesy: Martin Wilson