I. Essential Materials Properties for Useful Conductors

II. Development of High Jc in Conductor Forms

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Outline of Lectures

• I. Basics of the Critical Current Density
• II. Basic Materials Issues
• III. Niobium Titanium
• IV. Niobium Tin
• V. BSCCO
• VI. YBCO
• VII. Summary Issues
Ia. “Zero Resistivity”

- **Non-Superconducting Metals**
  - $\rho = \rho_o + aT$ for $T > 0 \text{ K}^*$
  - $\rho = \rho_o$ Near $T = 0 \text{ K}$
  *Recall that $\rho(T)$ deviates from linearity near $T = 0 \text{ K}$

- **Superconducting Metals**
  - $\rho = \rho_o + aT$ for $T > T_c$
  - $\rho = 0$ for $T < T_c$

- **Superconductors**
  - Superconductors are more resistive in the normal state than good conductors such as Cu
**lb. Perfect Diamagnetism**

- Perfect Diamagnetism:
  - \( \chi_m = -1 \)

\[ B = \mu_o (H + M) \]
\[ B = \mu_o (H + \chi_m H) \]
\[ B = 0 \]

- Means:
  - Normal Metal
    - Flux is excluded from the bulk
      - by supercurrents flowing at the surface to a penetration depth \( \lambda \) ~ 200-500 nm
  - Superconductor
Ic. $T_c$ History

- **Oxide, high temperature superconductors**
  - HgBa$_2$Ca$_3$Cu$_4$O$_y$
  - Tl$_2$Ba$_2$Ca$_2$Cu$_3$O$_{10}$
  - YBa$_2$Cu$_3$O$_7$

- **Metallic low temperature superconductors**
  - (La, Ba)$_2$CuO$_4$
  - Nb$_3$Sn
  - Nb$_3$Ge
  - NbN
  - Pb
  - Hg
### Id. Low Temperature Superconductors

**TABLE 21.7** Critical Temperatures and Magnetic Fluxes for Selected Superconducting Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Critical Temperature $T_C$ (K)</th>
<th>Critical Magnetic Flux Density $B_C$ (tesla)$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Elements</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.18</td>
<td>0.0105</td>
</tr>
<tr>
<td>Lead</td>
<td>7.19</td>
<td>0.0803</td>
</tr>
<tr>
<td>Mercury ($\alpha$)</td>
<td>4.15</td>
<td>0.0411</td>
</tr>
<tr>
<td>Tin</td>
<td>3.72</td>
<td>0.0305</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.40</td>
<td>0.0056</td>
</tr>
<tr>
<td>Tungsten</td>
<td>0.02</td>
<td>0.0001</td>
</tr>
<tr>
<td><strong>Compounds and Alloys</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nb–Ti alloy</td>
<td>10.2</td>
<td>12</td>
</tr>
<tr>
<td>Nb–Zr alloy</td>
<td>10.8</td>
<td>11</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>18.3</td>
<td>22</td>
</tr>
<tr>
<td>Nb$_3$Al</td>
<td>18.9</td>
<td>32</td>
</tr>
<tr>
<td>Nb$_3$Ge</td>
<td>23.0</td>
<td>30</td>
</tr>
<tr>
<td>V$_3$Ga</td>
<td>16.5</td>
<td>22</td>
</tr>
<tr>
<td>PbMo$_6$S$_8$</td>
<td>14.0</td>
<td>45</td>
</tr>
</tbody>
</table>

**Type I**

**Type II**
I.e. Type I and Type II

- **Type I**
  - Material Goes Normal Everywhere at $H_c$

- **Type II**
  - Material Goes Normal Locally at $H_{c1}$, Everywhere at $H_{c2}$

Complete flux exclusion up to $H_c$, then destruction of superconductivity by the field

Complete flux exclusion up to $H_{c1}$, then partial flux penetration as vortices

*Current can now flow in bulk, not just surface*
If. Vortex properties

- Two characteristic lengths
  - coherence length $\xi$, the pairing length of the superconducting pair
  - penetration depth $\lambda$, the length over which the screening currents for the vortex flow

- Vortices have defined properties in superconductors
  - normal core dia, ~$2\xi$
  - each vortex contains a flux quantum $\phi_0$
  - currents flow at $J_d$ over dia of $2\lambda$
  - vortex separation $a_0 = 1.08(\phi_0/B)^{0.5}$

\[
H_{c2} = \phi/2\pi\xi^2
\]
\[
\phi_0 = h/2e = 2.07 \times 10^{-15} \text{ Wb}
\]
\[
B/B_{c2} (=b) \sim 0.2
\]
Ig. Vortex Imaging by Decoration

Vortex state can be imaged in several ways
- Magnetic decoration
- Small angle neutron scattering
- Hall probes
- Scanning probe methods

First was by sputtering magnetic smoke on to a magnetized superconductor in the remanent state
- Lattice structure confirmed
- and defects in lattice seen

Trauble and Essmann 1967
**Ih. Bean Model**

- Bean (1962) and London (1963) introduced the concept of the critical state in which the bulk currents of a type II superconductor flow either at $+J_c$, $-J_c$ or zero.

- Critical State is a static force balance between the magnetic driving force $J \times B$ and the pinning force exerted on vortices by the microstructure $F_p$
  - $\left| (B \times (\nabla \times H)) \right| = B J_c(B)$

- Solutions define the macroscopic current patterns and enable the $J_c$ to be determined from magnetization measurements
II. Macroscopic Current Flow and Flux Patterns

Figure 1
Schematic of the flux profile and current flow for (a) a slab in an applied field $B_o$ and (b) a sample with similar dimensions carrying a total current $I$ sufficient to generate a field $B_i$ at the surface of the sample.

Figure 2
Schematic of the critical state flux profile; the different current-applied field trajectories are indicated in the $IB$ diagrams: (a-c) Bean model with $J_c$ constant; (d) as (a) but $J_c(B)$ decreasing strongly with increasing $B$.

Magnetization and the Bean Model

- \( m = MV = 0.5 \int (r \times j) \, dV \)
  - where \( j = (1/m_0) \nabla \times B \) or \( m = MV = \sum I_i \times S_i \)
- Slab geometry is very simple
  - \( dB/dx = \pm J_c(B) \)

Magneto optical image of current flow pattern in a BSCCO tape. The "roof" pattern defines the lines along which the current turns.
Ik. Flux Pinning Theory

- Defects cause variation in $\Delta G$ of FLL
  - up to $10^7$ A/cm² at >30T
- Vortex separation few $\xi$ for $b > 0.5$
- Dense interaction of FLL with defect array
  - unperturbed vortex array is a FLL
  - defects perturb the FLL
  - defects seldom form a lattice
- Experiment measures global summed pinning force $F_p = J_c \times B$, often >20GN/m³
- Elementary interaction is $f_p$, generally small, e.g.~$10^{-14}$ N for binding to a point defect
- Predictive, quantitative theory of flux pinning is mostly lacking
- 3 step process
  - compute $f_p$
  - compute elastic/plastic interactions of defect(s) and FLL
  - Sum interactions over all pins and vortices
- 2 main cases:
  - weak pinning, statistical summation (Labusch, Larkin and Ovchinnikov)
  - strong pinning with full summation
- Useful materials try to fall into the second category
II. Defect-FL Interactions

- Magnetic interactions on $\sim \lambda$
- Perturbations to currents by interfaces and surfaces
  - no normal component of $J$
- Strong in low-$\kappa$ materials

- Vortex core interactions on $\sim \xi$
- Possibility for point defects, precipitates, dislocations to pin
- Perturb local $|\Psi|^2$ through $\Delta_{\text{density}}, \Delta_{\text{elasticity}}$ or $\Delta_{\text{electron-phonon}}$
- Can also perturb electron mean free path and hence $\xi$

\[
F = \int d^3r (A|\Delta|^2 + (B/2)|\Delta|^4 + C|\partial \Delta|^2 + (h^2/2\mu_0) ,
A = N(0)(1-t), \quad B = 0.1N(0)/(k_B T_c)^2, \quad C = 0.55\xi^2N(0)\chi(\alpha)
\]

Core interactions dominate in useful materials
Im. Summation and Scaling

- Strong pinning materials (Nb-Ti wires, irradiated HTS) often exhibit full summation
  \[ F_p = n_{\text{defects}} f_{\text{p-defect}} \]

- Weak pinning requires statistical summation as already noted
  - many adjustable, often non-verifiable parameters

Scaling of the global pinning force with \( H, T \) can often be seen:

\[ F_p(B,T) = b^p(1-b)^q \quad \text{Nb-Ti often } b(1-b), \text{Nb}_3\text{Sn } b^{0.5}(1-b)^2 \]

HTS scaling functions complicated by thermal activation effects.
In. The Irreversibility Field

Simple H-T diagram for LTS:

Complex H-T diagram for HTS

FIG. 3. $T_c(H)$ and $T_c'(H)$ [$H_{c2}(T)$] for Nb$_3$Sn ($\sim$3.5 $\mu$m) and the melting temperature $T_M(H)$ from Eqs. (1) and (2). The crosses are the irreversibility fields $H_r(T)$ as determined from hysteresis measurements at constant temperature.

Figure 7. The vortex-matter phase diagram in untwinned YBa$_2$Cu$_3$O$_y$. The transition lines $T_m(H)$, $T_r(H)$, and $H^*(T)$ terminate at the critical point and divide into three different phases of the vortex liquid, the vortex glass, and the Bragg glass. The full curve is a fit to the field-driven transition line $B_{dis}(T)$. 
Io. Summary of Current Density
Issues

- Enormous $J_c$ can be obtained in some systems
  - $\sim 10\%$ of depairing current density ($\sim H_c/\lambda$) in Nb-Ti and for many HTS at low temperatures
  - HTS suffer from thermal activation and lack of knowledge about what are the pins
- Practical materials want full summation to get maximum $J_c$
- To compute $F_p$ a priori in arbitrary limit is so far beyond us
- Useful materials tend to be made first and optimized slowly as control of nanostructure at scale of 0.5-2 nm is not trivial