Lecture 6: Low-Temperature Superconductors

- Concise summary of superconductor; Type I & Type II
- Magnet-grade conductor; Enhancement of $J_c$
- Fabrication Process of Nb-Ti/Cu Composite Wire
- Fabrication Processes of Nb$_3$Sn Composite Wire
- Strain: source and effects; Other A15 materials
- Magnet winding constituents; designer’s goal
- Types of magnet: high-performance (“adiabatic”) & cryostable
- CICC (Cable-in-Conduit Conductor)
- Examples of high-performance & cryostable magnets
- Selected data of Nb-Ti and Nb$_3$Sn
- $J_c$ Scaling laws for Nb-Ti and Nb$_3$Sn
- Selected material properties
Critical Field vs. Temperature Plots of “Magnet” Superconductors

HTS: YBCO; BSCCO; MgB$_2$
LTS: Nb-Ti; Nb$_3$Sn

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Concise Summary

   ✨ Type I (soft) superconductors: Hg, Pb, In.

✨ Critical properties: $T_c; H_c; J_c$.

✨ Meissner effect: perfect diamagnetism.

✨ Penetration depth (London theory, 1935).

$$
\lambda = \sqrt{\frac{m}{\mu_o e^2 n_e}} \\
n_e = \frac{2 \rho N_A}{W_A}
$$

✨ Superelectrons: Copper pair.
Concise Summary (continued)

- Discovery of Type II (hard) superconductors: Pb-Bi (1930).
- Penetration of H in Type II (Mixed state)--new model.
- Vortex model (Abrikosov): normal vortex in super conducting sea.
  Coherehnce (transition) length: $\xi$
  - Type I: $\xi \sqrt{2} \lambda$
  - Type II: $\xi \sqrt{2} \lambda$
- Coherence length affected by alloying. Alloying increases resistivity: $\xi \propto 1/\rho$ and $T_c \propto \rho$.
- Normal state $\rho_{sc}$ of Type II: $10^2$–$10^3$ greater than $\rho_{cu}$. 

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## Selected Type I Superconductors

<table>
<thead>
<tr>
<th>Material (Type)</th>
<th>$T_c$ [K]</th>
<th>$\mu_0 H_c^*$ [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti (metal)</td>
<td>0.40</td>
<td>0.0056</td>
</tr>
<tr>
<td>Zn</td>
<td>0.85</td>
<td>0.0054</td>
</tr>
<tr>
<td>Al</td>
<td>1.18</td>
<td>0.0105</td>
</tr>
<tr>
<td>In</td>
<td>3.41</td>
<td>0.0281</td>
</tr>
<tr>
<td>Sn</td>
<td>3.72</td>
<td>0.0305</td>
</tr>
<tr>
<td>Hg</td>
<td>4.15</td>
<td>0.0411</td>
</tr>
<tr>
<td>V</td>
<td>5.40</td>
<td>0.1403</td>
</tr>
<tr>
<td>Pb</td>
<td>7.19</td>
<td>0.0803</td>
</tr>
</tbody>
</table>

* 0 K
## Selected Type II Superconductors

<table>
<thead>
<tr>
<th>Material (Type)</th>
<th>$T_c$ [K]</th>
<th>$\mu_0H_c$ [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb (metal)</td>
<td>9.5</td>
<td>0.2*</td>
</tr>
<tr>
<td>Nb-Ti (alloy)</td>
<td>9.8</td>
<td>10.5†</td>
</tr>
<tr>
<td>NbN (metalloid)</td>
<td>16.8</td>
<td>15.3†</td>
</tr>
<tr>
<td>Nb$_3$Sn (intermetallic compound: A15)</td>
<td>18.3</td>
<td>24.5†</td>
</tr>
<tr>
<td>Nb$_3$Al</td>
<td>18.7</td>
<td>31.0†</td>
</tr>
<tr>
<td>Nb$_3$Ge</td>
<td>23.2</td>
<td>35.0†</td>
</tr>
<tr>
<td>MgB$_2$ (compound)</td>
<td>39</td>
<td>~15*</td>
</tr>
<tr>
<td>YBa$<em>2$Cu$</em>{3-x}$O$_x$ (oxide: Perovskite)</td>
<td>93</td>
<td>150*</td>
</tr>
<tr>
<td>Bi$_2$Sr$<em>2$Ca$</em>{x-1}$Cu$<em>x$O$</em>{2x+4}$</td>
<td>110</td>
<td>108*</td>
</tr>
</tbody>
</table>

* 0 K   † 4.2 K

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A-15 ($\beta$-W) Structure

**Nb (6/cube)  Sn (2/cube): Nb$_3$Sn**
# Materials vs. Magnet-Grade Conductors

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Number</th>
<th>Discipline</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Superconductivity?</td>
<td>~10,000*</td>
<td>Physics</td>
</tr>
<tr>
<td>2. $T_c &gt; 10$ K ($\mu_0H_{c0} &gt; 10$ T)?</td>
<td>~100*</td>
<td>Physics</td>
</tr>
<tr>
<td>3. $J_c &gt; 1$ MA/cm² (@ $B &gt; 5$ T)?</td>
<td>~10*</td>
<td>metallurgy</td>
</tr>
<tr>
<td>4. Magnet-grade superconductor?</td>
<td>~1*</td>
<td>metallurgy</td>
</tr>
</tbody>
</table>

* Order of magnitude
Magnet-Grade Conductors

- Satisfies rigorous specifications required for use in a magnet.
- Readily available commercially.
- Currently, only three: Nb-Ti; Nb$_3$Sn; BSCCO2223

R&D Stage:
BSCCO2212 (NMR); YBCO (Electric devices);
Nb$_3$Al (limited interest for Fusion & NMR)

Promising: MgB$_2$ (cost said to be comparable with Nb-Ti)
### Material-to-Conductor Development Stages — $\text{Nb}_3\text{Sn}$ —

<table>
<thead>
<tr>
<th>Stage</th>
<th>Event</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Discovery</td>
<td>Early 1950s</td>
</tr>
<tr>
<td>2</td>
<td>Improvement $J_c$</td>
<td>Early 1960s</td>
</tr>
<tr>
<td>3</td>
<td>Co-processing with matrix metal</td>
<td>Mid 1960s</td>
</tr>
<tr>
<td>4</td>
<td>Multifilament/twisting, $I_c&gt;100$ A</td>
<td>Early 1970s</td>
</tr>
<tr>
<td>5</td>
<td>Long length, typically ~1 km</td>
<td>Mid 1970s</td>
</tr>
<tr>
<td>6</td>
<td>Full specifications for magnets</td>
<td>Late 1970s</td>
</tr>
</tbody>
</table>


**Enhancement of \( J_c \)**

- Of the three critical parameters—\( H_c, T_c, J_c \)—\( J_c \) may be improved by metallurgical processing.
- Alloying enhances “flux pinning” which increases \( J_c \).
- Force on vortex:
  \[
  \vec{F}_v = \vec{J}_c \times \mu_0 \vec{H}
  \]
- Pinning of vortices: 1) crystal impurities – small crystals, grain boundary densities, dislocation density; 2) creation of artificial pinning sites by cold working, heat treatment.

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Schematic drawing of “pinned” vortices
Heat Treatment

* Window of opportunity—dependent on composition.
* Trade-off between grain size and boundary growth.
* Time/temperature for heat treatment (Nb-Ti: 390°C/~100 h).
  * HT time must be “reasonable” for the plant (<100 h).
Effects of cold work and heat treatment on $J_c$
Cold Working (Drawing)

- Increase dislocation density (increased $J_c$).
  - Experimental evidence of increased $J_c$ with smaller grain size: true for every known superconductor.

![Graph showing $J_c$ vs. $g^{-1}$ with markers for different temperatures: 625°C, 700°C, and 800°C. The graph includes annotations for $H_{\parallel}$ and $H_{\perp}$. The x-axis represents $g^{-1}$ (μm)$^{-1}$ and the y-axis represents $J_c$ (A/cm²).](image)
Fabrication Process of Nb-Ti/Cu Composite Wire

- Extrusion of Nb-Ti billet co-processed with copper.
- Low-resistance path during transition to the normal state.
- Mechanical strength and ductility.
Production of MF Nb-Ti/Cu Composite

Stage 1: Stacking & Hexagonal Nb-Ti/Cu Rod

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* Nb-Ti (continued)

  * Multifilamentary wire
    * Flux jumping: filament size (<critical size)
    * Increased grain boundary density.
  * Cold drawing and heat treatment (repeated).
  * Twisting: strain limits—pitch length 5-15 times wire dia.
  * Anneal Cu and insulate.
Stage 2: MF Composite

Stacking Nb-Ti/Cu Hex Rods (10-25 cmΦ; 15-200 kg)
Stage 3: Twisting & Spooling

- Heat Treat
- Twist
- Anneal
- Spool
- Test
- Insulate
Fabrication Processes of Nb$_3$Sn Wire

Five processes

- Bronze
- External diffusion
- Internal Sn
- Nb Tube & Sn Tube
- Jelly Roll & Modified Jelly Roll
Bronze

- Diffusion: Sn into Nb
  - Parameters: 700°C, 1-10 days (max. diff. 5-10 µm).
  - Cu: prevents Nb₆Sn₅ from forming; a catalyst
  - Temperature: good stoichiometry vs. small grains
  - Bronze: 16wt.%Sn max. >13% makes drawing difficult
  - Maximum Nb₃Sn:~25wt.%
  - Addition of Cu: ~10³ better electrically/thermally than bronze
  - Con: Sn diffuses more easily into Cu than Nb
- Diffusion barrier, e.g., Ta, to maintain Cu purity
External Diffusion

🌟 Pros: 1) Draw first, then plate with Sn (bronze is hard to draw); No intermediate annealing necessary
2) >13 wt.% Sn possible, yielding higher $J_c$

🌟 Cons: 1) Thick layer of (>~5 µm) of Sn tend to delaminate;
2) Sn melts at 230°C, while reaction temp ~700°C
3) Hard to use with Ta and pure Cu
Internal Sn

**Pros:**
1) Nb intermediate anneal for bronze
2) Cu and Ta can easily be added
3) As with external diffusion, higher $J_c$

**Cons:**
1) Sn concentration limited
2) Extrusion of billet problems
**Nb Tube**

- **Pros:** 1) Nb₃Sn close to Cu stabilizer
  2) Nb acts as a diffusion barrier for Sn (Ta unnecessary)

- **Cons:** 1) Limit to minimum filament size (AC losses)
  2) Because of Nb tubes, process costly
Jelly Roll and MJR

★ Pros: 1) No intermediate anneal
2) Cu and Ta easily wrapped in roll
3) Other trace materials can easily be added to core to improve properties
Other A15 Materials

$V_3Ga$

- Inferior to Nb$_3$Sn in $T_c$ and $H_{c2}$, but better $J_c$
- Can be processed similar to bronze process

Cons: 1) Reaction at 500°C for 500 h
2) More brittle than Nb$_3$Sn

$Nb_3Al$

- Fabrication difficulties; no bronze process equivalent exists
- Bulk Nb$_3$Al requires HT at >1500°C, leading to large grain boundaries and other unwanted Al-rich compounds
- MJR proven quite successful in making multifilamentary composite

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6. Strain: Source and Effects

- Fabrication temperature to operating temperature: strain from mismatch in thermal expansion (contraction) coefficients
- Winding magnet: winding radius limitation
  - winding strain = wire dia./winding i.d.
- Lorentz forces
- Strain generally degrades $J_c$
  - Treat Nb$_3$Sn as you would glass
  - Nb$_3$Sn damaged for strains beyond $\sim$0.7%
**Strain Effect on $J_c$: Nb-Ti**

![Graph showing the strain effect on $J_c$ for Nb-Ti superconductor. The graph illustrates the change in current density with strain at different magnetic fields (3 TESLA, 5 TESLA, 7 TESLA). The NbTi: Cu (1:18) composite with dimensions 0.53 x 0.68 mm and 180 filaments is studied.](image)

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Strain Effect on $J_c$: $\text{Nb}_3\text{Sn}$

Scaling Parameters:

- $n = 1$
- $B_{c2m} = 21 \text{T}$
- $p = 0.5$
- $q = 2.0$
- $u = 1.7$
- $a = \begin{cases} 900 (\epsilon_0 < 0) \\ 1250 (\epsilon_0 > 0) \end{cases}$

Temperature $= 4.2 \text{ K}$
Magnet Winding Constituents

Magnet winding *generally* comprises of:

- **Superconductor**—Nb-Ti, Nb3Sn, or BSCCO2223
- **Electrically conductive normal metal for stability and protection**—Cu, Al, or Ag
- **High-strength metal for mechanical integrity**—high-strength metal, or *work-hardened Cu also used as stabilizer.*
- **Coolant**
Designer’s Goal

Maximize overall (or engineering) current density, \( J_{\text{over}} \) (or \( J_e \)), and still satisfying requirements of:

- Stability; protection; mechanical integrity; and cost —
  for commercially viable units
Types of Magnet

Basically there are two types of magnet:

I. High-performance ("Adiabatic")
II. Cryostable
I. High-performance

☆ $J_{over}$ enhanced by:

☆ Combining superconductor and high-strength normal metal (stability; protection; mechanical).

☆ Eliminating local coolant* and impregnating the entire winding space unoccupied by conductor with epoxy, making the entire winding as one monolithic structural entity. (Presence of cooling in the winding makes the winding mechanically weak and takes up the conductor space.)

☆ High-performance approach universally used for NMR, MRI, HEP dipoles & quadrupoles in which $R \times J \times B$ manageable with a combination of “composite conductor” & “monolithic entity.”

* The conductor always requires cooling but not necessarily exposed directly to the coolant.

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“Adiabatic” Windings

1. Bath Cooled
   ♦ Winding immersed in a bath of cryogen
   ♦ Work-hardened stabilizer or reinforcement added

*Examples: NMR; MRI*
“Adiabatic” Windings (Continued)

2. Forced-Flow Cryogen
   ✮ Winding “globally” cooled by forced-flow single-phase cryogen
   ✮ Work-hardened stabilizer or reinforcement added

*Examples: HEP diploes & quadrupoles*
“Adiabatic” Windings (Continued)

3. Cryocooler-cooled
   ✴ Winding conduction cooled by a cryocooler
   ✴ Work-hardened stabilizer or reinforcement added

Examples: “Dry” research-purpose magnets (up to 15 T)
II. Cryostable

✶ Characterized by the presence of local or “near-local” cooling.

✶ Nearly universally adapted winding configuration for those magnets that must “guarantee” performance. These include “large” research-purpose high-field magnets, e.g., MIT Hybrid III, and those that are key components of the experimental devices, e.g., fusion.

There are two types of cryostable magnets:

1. Magnets with “small” $R \times J \times B$ (and o.d. typically <1 m), “composite conductor,” i.e. combination of superconductor and work-hardened normal metal (stability; protection; mechanical), sufficient to meet mechanical requirements despite the presence of coolant space.

2. Magnets with “large” $R \times J \times B$ (and o.d. typically >1 m), e.g., Fusion magnets, “composite conductor,” no longer sufficient to meet mechanical requirements; CICC (cable-in-conduit conductor) or reinforced composite/forced cooling.
Cryostable Winding

1. Cryogen Well-Ventilated within Winding
   ✷ Work-hardened stabilizer

*Examples: Many “large” magnets of the 1960s-1990s, including MIT 35-T Hybrid; LHD TF coil*
Cryostable Winding (Continued)

2. CICC (Cable-in-Conduit Conductor)
   - Single-phase cryogen forced through conduit that contains cabled Superconductor/stabilizer composite
   - Conduit (steel alloy) reinforces the conductor

Examples: Most fusion magnets; NHMFL 45-T hybrid

Single-phase cryogen forced through a set of pipes placed near the winding comprises of reinforced composite

Example: CMS magnet of the LHC
CICC

Cabled strands of superconductor encased in a conduit, which provides mechanical strength and through which single-phase cryogen (generally helium) is forced to provide cooling to the superconductor

**Advantage**

- Integrates key requirements of a superconductor—current-carrying capacity; stability & protection; AC losses; mechanical integrity—in a single conductor configuration.

**Disadvantage**

- Because of the non-current carrying space occupied by the conduit and cryogen, $I_{op}$ should be "large" to keep $J_{over}$ "reasonable."
  Generally, $I_{op} > 10$ kA; occasionally $I_{op} > \text{a few kA.}$

**Suitable Applications**

- "High" field and "large" volume magnets, i.e., fusion; SMES.
Transposed 37-Strand Cable (c. 1970)

Courtesy of Luca Bottura (CERN, Geneva)

Y. Iwasa (04/03/03)
Tube-Mill Fabrication of CICC
ITER CICC
EURATOM Large Coil Test (LCT) Conductor (c. 1980s)

Rutherford Cable soldered to insulated SS core

Conductor force-cooled by Supercritical He

MF Nb-Ti/Cu composites

SS Jacket seam-welded

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