

Crash Course in Materials Science of Superconductors

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This document provides basic review of superconducting materials from a materials science & engineering perspective. This entails a very basic review of conductivity, magnetism, and superconductivity theory. The remainder is focused on aspects of specific material systems, such as compositional phases that exhibit superconducting phase, mechanical properties, and processing. High-level review of applications is also provided. The intent of this document is to act as a quick digest for someone who plans to dive deeper into the provided references.

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Some Comments

! Important

These are working notes, so there are bound to be errors. Please keep this in mind while going through the notes. Feel free to email [me](#) if you want to provide corrections.

i Note

Much of the notes derived from various sources, please checkout the [references](#).

💡 Tip

If you prefer to view this in a report format, you can download a formatted PDF of this presentation [here](#).

Whats all the fuss

- Why did anyone care to begin with?
 - They didn't. Initially Heike Kamerlingh Onnes¹ and others were just interested in cryogenics.
 - Once they achieved liquid Helium, they asked why not study conductive metals at these temperatures.
 - In 1911 Kamerlingh Onnes started with elemental Mercury, the field of superconductivity (SC) was born.
- Physicist focused on measurement of other elemental solids and a theory.
- Observation of SC in Nb is really what begun technological use.

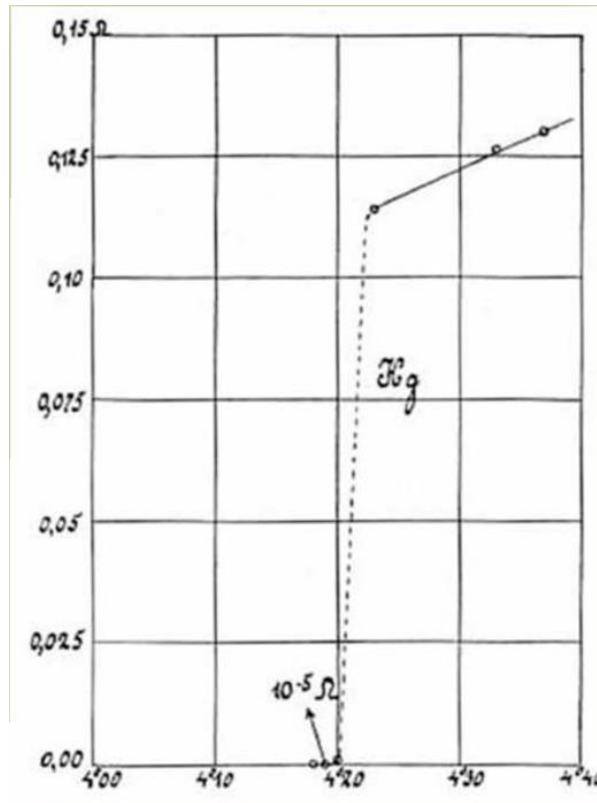


Figure 1: Original plot of Hg transition temperature to SC phase¹.

Technological Interest

Magnetic Resonance Imaging

- Superconducting coils allow for high magnetic fields.
 - **Stronger Magnets:** Enhanced image quality and resolution.
 - **Energy Efficiency:** Lower operational costs due to zero resistance.
 - **Cooling Required:** Increased cost.

SC: Supercon-
ductivity. Nb:
Niobium

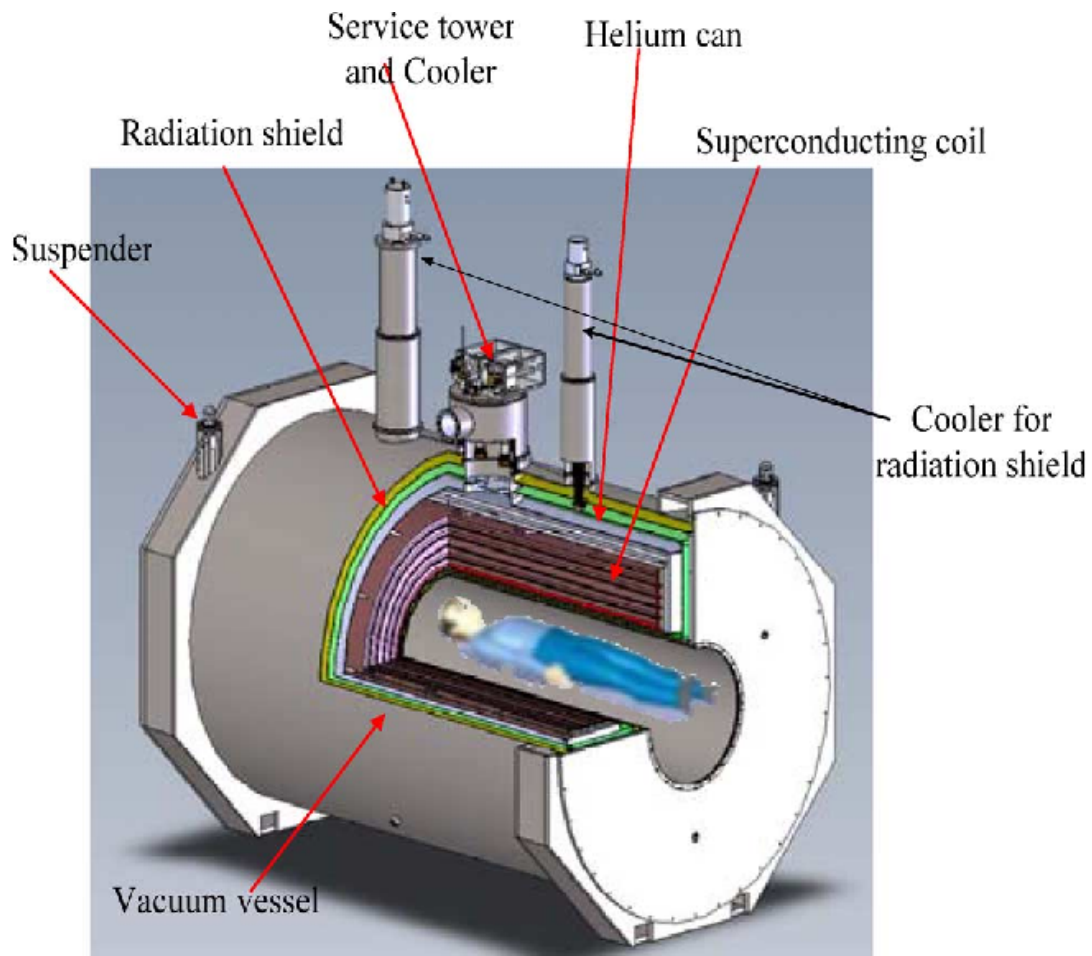


Fig. 2. Configuration of magnet for 0.4 T MRI

Figure 2: Cut-through showing MRI machine and SC coils².

MagLev Trains

- Superconducting materials enable high-speed rail.
 - **Efficient Levitation:** Frictionless, high-speed travel.
 - **High Current Capacity:** Ideal for powerful electromagnets in propulsion.
 - **Downside:** Cryogenic systems maintain superconducting state.

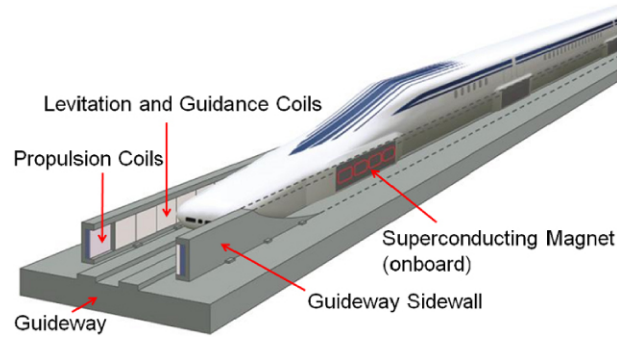


Figure 3: Superconductors are onboard train which interact with propulsion rail coils³.

Energy Storage/Production

- **High Field Strength:** Enables stronger magnetic confinement in fusion.
- **Zero Resistance:** Increases efficiency in energy storage systems.
- **Cooling Trade-off:** Cryogenic needs offset by gains in efficiency.

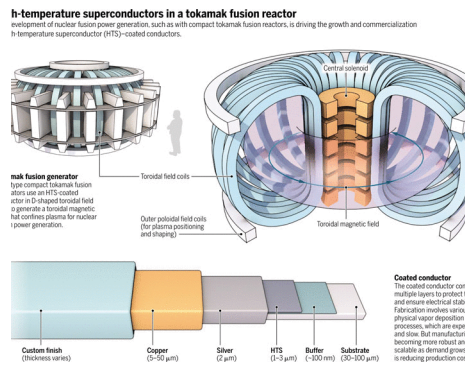


Figure 4: High-temperature SC (ex., REBCO) used in a magnetic fusion torodial device⁴.

Most common complaints

- **Cooling Costs:** Cryogenic systems are energy-intensive and expensive.
- **Material Fragility:** Mechanical stresses can degrade superconducting properties.
- **High Costs:** Fabrication and maintenance of superconducting materials are costly.
- **Limited Current Capacity:** Some materials can't sustain high current densities.
- **Material Complexity:** Difficulties in integration with existing technologies.

Many advances have been achieved in last 30 years or so to address these concerns.

i Note

At this point I won't discuss why these are addressible with advances in refrigeration and processing technology, but this is how I would approach it . Will touch on this at the very end.

Many others seek room-temperature (RT) superconductors. These many exist but who knows if they would have other suitable properties or current processing approaches would work.

RT: room-temperature

Basic Theory

- As we saw in Figure 1, there are materials where electrical conductivity drops to “exactly”¹ zero.
- How is this achieved?
 - Well at low-temperature we have Bardeen, Cooper, and Schrieffer (BCS) to thank⁵.



- What mechanism did they describe?
 - Cooper Pairs!
 - Why Pairs? Blame the phonons.

BCS Theory:
Bardeen,
Cooper, and
Schrieffer
theory of low-
temperature
superconduct-
ivity.

¹Here I use exactly in that it is zero within measurement precision. If your device can only measure to 10^{-10} then you show a resistivity value on that order.

Backmatter



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Note

This presentation can be viewed online at <https://stefanbringuier.github.io/CrashCourseSCMaterials>.

To export `revealjs` presentations to pdf, press ‘e’ then ‘ctrl-p’ ‘save as pdf’

Tip

A report formatted PDF of this presentation can be downloaded [here](#).

References

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Draft Outline

- Slide 4: Importance of Superconducting Materials
- Slide 5: Brief History of Superconductivity
- Applications: Magnetics and Wires
 - MRI Machines
 - Maglev Trains
 - Energy Grids
 - Superconducting Coils
 - Limitations in Applications
- Basics of Superconductivity (Theory)
 - Cooper Pairs
 - Meissner Effect
 - BCS Theory Overview
 - Zero Electrical Resistance
 - Critical Temperature
- Thermodynamics and Phases
 - Type I and Type II Superconductors
 - Critical Fields
 - Diamagnetic Response
 - Phase Diagrams
 - Energy Gaps
- Flux Pinning and Levitation
 - Vortex Lattices
 - Flux Tubes
 - Levitation Applications
 - Pinning Centers
 - YBaCuO Examples
- Niobium-Titanium (NbTi) Alloys
 - Composition and Structure
 - Magnetic Properties
 - Mechanical Properties
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 - Processing Challenges
- Quantum Effects

- Quantum Tunneling
 - Josephson Junctions
 - Macroscopic Quantum Phenomena
 - SQUIDS
- Quantum Computing Applications
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 - Grain Boundary Impact on Properties
 - Microstructure Analysis
 - Sintering Methods
 - Weak Links
 - Influence on Flux Pinning
- Mechanical Properties
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 - Fatigue
 - Thermal Expansion
 - Composite Superconductors
- High-Temperature Superconductors (HTSC)
 - YBaCuO and Other Cuprates
 - Iron-based Superconductors
 - Challenges and Advantages
 - Applications
 - Current Research Trends
- Recent Trends and Future Directions
 - MgB2 Developments
 - Supposedly Room-Temperature Superconductors
 - Topological Superconductors
 - Commercialization Challenges
 - Research Funding and Outlook
- Conclusion and Summary
 - Summary of Key Points