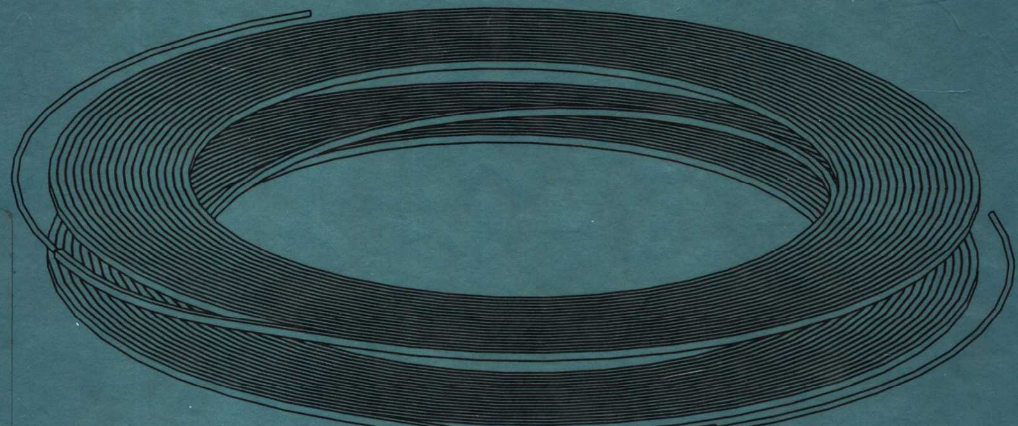
Selected Topics in Superconductivity

Case Studies in Superconducting Magnets

DESIGN AND OPERATIONAL ISSUES



Yukikazu Iwasa

Case Studies in Superconducting Magnets

Design and Operational Issues

Yukikazu Iwasa

Francis Bitter National Magnet Laboratory
and Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts

Plenum Press • New York and London

Library of Congress Cataloging in Publication Data

Iwasa, Yukikazu

Case studies in superconducting magnets: design and operational issues / Yukikazu Iwasa.
p. cm. — (Selected topics in superconductivity)
Includes bibliographical references and index.
ISBN 0-306-44881-5
1. Superconducting magnets. I. Title.
QC761.3.I9 1994
621.34—dc20 94-36837
CIP

10 9 8 7 6 5 4 3 2

ISBN 0-306-44881-5

Printed in the United States of America

Preface

This book is based on *Superconducting Magnets*, a graduate course I started teaching in the Department of Mechanical Engineering at the Massachusetts Institute of Technology, in 1989, shortly after the discovery of high-temperature superconductors. The book, intended for graduate students and professional engineers, covers the basic concepts of superconducting magnet technology, focusing on design and operational issues.

My course consists of ten 3-hour lectures and eight homework sets, each set containing three to four "tutorial" problems to review lecture materials, to discuss topics in more depth than covered in the lecture, or to teach subjects not presented in the lecture at all. My colleague Emanuel Bobrov has helped me with the course, offering lectures on field computation and stress analysis. He has also created a few problems related to his lecture topics.

Because the use of tutorial problems accompanied, a week later, by solutions has been successful in the course, I have decided to use the same format for this book. Most problems require many steps in their solution and through these steps it is hoped that the reader will gain deeper insight. About 75% of the problems are based on those specifically created for the course's homework or quiz problems; the remainder are based on lecture materials. Because the principal magnet projects at the Francis Bitter National Magnet Laboratory (FBNML) have been high-field solenoidal magnets, problems directly related to other applications are not represented. However, important topics covered in this book, particularly on field distribution, magnets, force, thermal stability, dissipation, and protection, are sufficiently basic and generic in concept that solenoidal magnets are suitable examples.

In creating problems I have relied heavily on the magnet projects at FBNML and I am indebted to my colleagues in the Magnet Technology Division, specifically John Williams, Mat Leupold, Bob Weggel, and Emanuel Bobrov, with whom I have had the good fortune of working on these projects over a long period. Materials contributed by the other members of the Division, Alex Zhukovsky, Vlad Stejskal, Andy Szczepanowski, Dave Johnson, and Mel Vestal are also included and their contributions are acknowledged. I have also benefitted much through participation in the Technology Division of the Plasma Fusion Center (PFC) of MIT; I would particularly like to thank Bruce Montgomery from whom I have learned a great deal since my graduate student days. I would also like to thank Joe Minervini and Makoto Takayasu of the PFC, Dr. Larry Dresner of Oak Ridge National Laboratory, and Dr. Luca Bottura of Max-Planck Institut für Plasmaphysik, Garching, Germany, for advice on the creation of problems related to cable-in-conduit (CIC) conductors, and Dr. Ted Collings of the Battelle Memorial Institute, Ohio, for discussion on enabling technology *vs* replacing technology. In addition, I would like to thank many visiting scientists to FBNML, mostly from Japan—really too many to cite individually here—with whom I have collaborated with fruitful results, particularly in the areas of mechanical dissipation, magnet monitoring, and protection.

I would like to thank Don Stevenson, the retired Assistant Director of the FBNML, who read several versions of the manuscript and offered helpful suggestions, and Albe Dawson of PFC for suggestions on early chapters. Many of my former and present students helped me on this project and I express my deepest gratitude to them. Philip Michael combed through the three last editions and offered many insightful suggestions. Rick Nelson painstakingly read early drafts, checked and corrected solutions, and offered many suggestions on the phrasing of the questions, writing, and equation style; he also assisted me in the preparation of early editions of the Glossary. Mamoon Yunus created beautiful field plots and graphs; Hunwook Lim produced most of the figures and prepared the Index; Jun Beom Kim rechecked several derivations, collected much of the data presented in the Appendices, and produced most of the graphs; Abraham Udobot also prepared many figures and laid out all the figures.

I am also indebted to Dr. Hiroyasu Ogiwara of Toshiba Corporation for first suggesting a book based on my course materials, particularly on the problem sets. He has also arranged for me to offer lectures based on the course to magnet engineers at the Kanagawa Academy of Science and Technology, Kawasaki, Japan.

Thanks are also due to the National Science Foundation (FBNML's sponsor); the Department of Mechanical Engineering; the Department of Energy Office of Fusion Energy; the Department of Energy Office of Renewable Energy; the Department of Energy Office of Basic Sciences; and Daikin Industries, Ltd. for their support of this book project. I have used D.E. Knuth's indispensable TEX in typesetting the entire text, equations, tables, and even some figures.

Finally, I would express a word of appreciation to Kimiko who has made it possible for me to continue working on this project in the relaxed atmosphere of our home and thus to carry it forward to completion.

Yukikazu Iwasa

Weston, Massachusetts
August, 1994

"You know nothing till you prove it! FLY!" —Jonathan Livingston Seagull

CONTENTS

Chapter 1
Superconducting Magnet Technology

1.1 Introductory Remarks

Superconducting magnet technology comprises engineering aspects associated with the design, manufacture, and operation of superconducting magnets. In its bare essence, a superconducting magnet is a highly stressed device: it requires the best that engineering has to offer to ensure that it operates successfully, is reliable, and at the same time is economically viable. A typical 10-tesla magnet is subjected to an equivalent magnetic pressure of 40 MPa (400 atm), whether it is superconducting and operating at 4.2 K (liquid helium cooled) or 77 K (liquid nitrogen cooled), or resistive and operating at room temperature (water cooled). Superconducting magnet technology is interdisciplinary in that it requires knowledge and training in many fields of engineering, including mechanical, electrical, cryogenic, and materials.

Table 1.1 lists "first" events relevant to superconducting magnet technology. Particularly noteworthy events since the discovery of superconductivity in 1911 by Kamerlingh Onnes, who was also first to liquefy helium in 1908, are:

1. Development of water-cooled 10-T magnets by Francis Bitter in the 1930s;
2. Marketing of helium liquefiers, developed by Collins, in 1946;
3. Development in 1961 by Kunzler and others of magnet-grade superconductors;
4. Formulation, chiefly by Stekly, of design principles for cryostable magnets in the mid 1960s; and
5. Discovery of high-temperature superconductivity (HTS) in perovskite oxides by Müller and Bednorz in 1986.

We may safely state that Bitter initiated modern magnet technology. Although Bitter magnets are water cooled and resistive, resistive and superconducting magnets share many engineering requirements.

Soon after the availability of Collins liquefiers, liquid helium—until then a highly prized research commodity available only in a few research centers—became widely available and helped to propel the rapidly growing field of low temperature physics. Many important superconductors were discovered in the 1950s, leading to the development of magnet-grade superconductors.

The formulation of design principles for cryostable magnets by Stekly and others by the mid 1960s demonstrated the feasibility of building large superconducting magnets that operated reliably.

The discovery of HTS lifted superconducting magnet technology from the depth of a liquid helium well and ushered it into a new era with expanded options. It is estimated that the number of people involved in superconductivity jumped by an order of magnitude overnight after the discovery of HTS.

Table 1.1: "First" Events Relevant To Superconducting Magnet Technology

Decade	*Event**
1930s	Meissner effect.
	Type II superconductors identified.
	Phenomenological theories of superconductivity.
	Bitter magnets generating fields up to 10 tesla.
1940s	Marketing of Collins helium liquefier.
1950s	Many more Type-II superconductors identified.
	GLAG and BCS theories of superconductivity.
	Small superconducting magnets (SCM).
1960s	Magnet-grade superconductors developed.
	International conference on high magnetic fields.
	National laboratory for magnetism and magnet technology.
	Bitter magnets generating fields up to 25 T.
	Flux jumps in SCM.
	Composite superconductors.
	Formulation of cryostability criteria.
	Large cryostable SCM (MHD and bubble chambers).
	Superconducting generators.
	Magnets wound with internally-cooled conductors.
	Multifilamentary Nb-Ti superconductors.
1970s	Multifilamentary Nb_3Sn superconductors.
	Maglev test vehicles.
	Superconducting dipoles for accelerators.
	Cable-in-conduit (CIC) conductors.
	Hybrid magnets generating 30 T.
	Commercial NMR systems using SCM.
1980s	Commercial MRI systems using SCM.
	Multinational experiments for fusion magnets.
	Submicron superconductors for 60-Hz applications.
	Superconducting accelerators.
	Discovery of HTS.

* Entries in each decade did not necessarily take place sequentially as listed. Acronyms are described in the Glossary (Appendix VI).

1.2 Superconductivity

The complete absence of electrical resistivity for the passage of direct current below a certain "critical" temperature (usually designated with the symbol T_c) is the basic premise of superconductivity. In addition to T_c, the critical field H_c and critical current density J_c are two other parameters that define a critical surface below which the superconducting phase can exist. T_c and H_c are thermodynamic properties that for a given superconducting material are invariant to metallurgical processing; J_c is not. Indeed the key contribution of Kunzler and others in 1961 was to demonstrate that for certain superconductors it is possible to enhance J_c dramatically by means of metallurgy alone. No formal theories of superconductivity, phenomenological or microscopic, will be presented in this book to explain relationships among T_c, H_c, or J_c; however, the magnetic behavior of superconductivity, which plays a key role in superconducting magnets, will be briefly reviewed by means of simple theoretical pictures.

Figure 1.1 shows the critical surface for a typical magnet-grade superconductor. On this critical surface, the following three important functions are used by the magnet engineer: $f_1(H,T,J=0)$; $f_2(J,T,H_\circ=\text{constant})$; $f_3(J,H,T_\circ=\text{constant})$. f_1 is the H_c *vs* T_c plot; for "ideal" superconductors it is quite straightforward to derive a parabolic function of H_c on T_c from thermodynamics [1.1]:

$$H_c = H_\circ\left[1-\left(\frac{T}{T_c}\right)^2\right] \tag{1.1}$$

$H_\circ$ is given by:

$$H_\circ = T_c\sqrt{\frac{\gamma_e}{2\mu_\circ}} \tag{1.2}$$

where γ_e is the electronic heat capacity constant in the normal state.

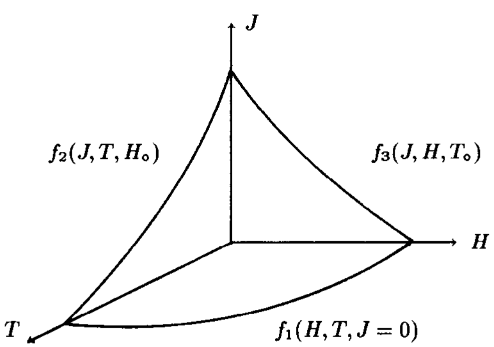


Fig. 1.1 Critical surface of a typical magnet-grade superconductor.

f_2 gives the J_c *vs* T plot, and for *all* superconductors of interest, J_c is a decreasing function of temperature. As we shall study in more detail in Chapter 5, this is the source of inherent instability in superconductors. We shall defer discussion of f_3 until after Sec. 1.2.3, where Type I and Type II superconductors are discussed.

1.2.1 Meissner Effect

Discovered by Meissner and Ochsenfeld in 1934, the Meissner effect describes the absence of magnetic field within the bulk of a superconductor. This complete diamagnetism of a superconductor is in fact more fundamental than the complete absence of electrical resistivity to the extent that a material's perfect diamagnetism *automatically* requires it to be a perfect electrical conductor. Unlike the complete absence of electrical resistivity, however, we do not benefit from perfect diamagnetism. The Meissner effect was in fact responsible for the single most important source of magnet failures in the early 1960s: flux jumping. Even today when flux jumping is no longer an issue due to an important innovation introduced in conductor design in the late 1960s, the Meissner effect is the basis for another important source of losses in the magnets—AC losses—that restricts the use of superconducting magnets primarily to DC applications.

1.2.2 London's Theory of Superconductivity

Although a microscopic theory of superconductivity by Bardeen, Cooper, and Schrieffer—known as the BCS theory—was not completed until 1957, development of phenomenological theories of superconductivity began in the 1930s. Among these is the electromagnetic theory of London (1935), in which the concept of penetration depth was introduced to account for the Meissner effect. Simply stated, a bulk superconductor is shielded completely from an external magnetic field by a supercurrent that flows within the penetration depth (λ) at the surface. According to London's theory, λ is given by:

$$\lambda = \sqrt{\frac{m}{\mu_o e^2 n_e}} \tag{1.3}$$

where m, e, and n_e are, respectively, the electron's mass, charge, and concentration. μ_o is the permeability of free space. n_e in turn is given by:

$$n_e = \frac{2\varrho N_A}{W_A} \tag{1.4}$$

where ϱ is the conductor's mass density, N_A is Avogadro's number, and W_A is its atomic weight. The factor 2 in Eq. 1.4, not in the original London theory, was inserted later because there are two "superelectrons" (a Cooper pair) for each atom. Values of λ and the superconductor's J_c, given by en_ev where v is the speed of sound, have been confirmed by experiment.

1.2.3 Type I and Type II Superconductors

Kamerlingh Onnes discovered superconductivity in pure mercury; subsequently other metals such as lead and indium were found to be superconductors. These materials, now called Type I (also known as "soft") superconductors, are unsuitable as magnet conductor materials because of their low H_c values: less than 10^5 A/m (corresponding to ~0.1 T). Magnet-grade superconductors trace their origin to the first Type II (also known as "hard") superconductor discovered by de Haas and Voogd in 1930 in an alloy of lead and bismuth [1.2].

A Type II superconductor may be modeled as a finely divided mixture of a Type I superconductor and normal conducting material. Indeed, in the early 1960s there were two physical models for this mixture: lamina and island (vortex). In the lamina model, proposed by Goodman, the hard superconductor consists of superconducting laminae separated by normal laminae. In the vortex model, proposed by Abrikosov at about the same time, and later experimentally verified by Essmann and Träuble [1.3], the superconductor consists of many hexagonally-arranged normal-state islands in a superconducting sea. For the hard superconductor to retain its bulk superconductivity well beyond 0.1 T, the width of each superconducting lamina or the radius of each normal island must be smaller than λ. The lamina's half width or the island's radius is the coherence length (ξ), an important spatial parameter, introduced by Pippard in 1953. ξ defines a distance over which the superconducting-normal transition takes place. According to the GLAG theory of superconductivity (after Ginsburg, Landau, Abrikosov, and Gorkov), formulated about the same time as Pippard's to account for the magnetic behavior of Type II superconductors, a superconductor is Type II if $\xi < \sqrt{2}\lambda$; it is Type I if $\xi > \sqrt{2}\lambda$. ξ decreases with alloying, which shortens the mean free path of the normal electrons; ξ is thus inversely proportional to the material's normal-state electrical resistivity. It is noted that the two magnet-grade superconductors—alloys of niobium titanium (Nb-Ti) and an intermetallic compound of niobium and tin (Nb_3Sn)—both have normal-state resistivities that are at least one order of magnitude greater than that of copper at room temperature. Incidentally, it has been noted that the HTS also have ξ much much shorter than λ.

1.2.4 Critical Current Density of Type II Superconductors

As mentioned earlier, J_c may be enhanced dramatically by means of metallurgical processing. The function $f_3(J, H, T_\circ)$ gives J_c *vs* H plots at a given temperature $T_\circ$ for conductors having enhanced J_c performance. This enhanced J_c performance is generally attributed to a "pinning" force that counteracts the $\vec{J_c} \times \vec{H}$ Lorentz force acting on the vortices. The pinning force is provided by "pinning" centers that are created in crystal structures by material impurities, metallurgical processes such as cold working in the form of dislocation cells, or heat treatment in the form of precipitations and grain boundaries. Kim and others, through their investigation of the magnetic behavior of Type II superconductors, obtained the basic J_c *vs* H equation by equating the $\vec{J_c} \times \vec{H}$ Lorentz force to the pinning force [1.4]:

$$J_c = \frac{\alpha_c}{H + H_\circ} \tag{1.5}$$

where α_c and $H_\circ$ are constants. Note that α_c essentially represents an asymptotic force density that balances the Lorentz force density for $H \gg H_\circ$. That is, Eq. 1.5 is really a simple force balance equation.

1.3 Magnet-Grade Superconductors

Although completely specifying a conductor for a given superconducting magnet is an important task in the design phase, issues directly related to magnet-grade superconductors are not specifically treated in this book. Magnet-grade superconductors are those conductors that meet rigorous specifications required for use in a magnet, and are readily available commercially. What follows is a brief comment to point out important differences between superconducting *materials* and *magnet-grade superconductors*, and that it is a laborious task to develop a magnet-grade superconductor from a material discovered in the laboratory.

1.3.1 Materials *vs* Magnet-Grade Superconductors

Table 1.2 lists the number of materials meeting certain criteria on superconductivity and illustrates that as the criteria move towards those required of a magnet-grade superconductor, the number of materials meeting the criteria decreases *logarithmically*. H_{c2} is the "upper" critical field, relevant only to Type II superconductors. Indeed, of nearly 10,000 superconducting materials discovered to date, at present (1994) there are basically only two magnet-grade superconductors, Nb-Ti alloys and an intermetallic compound, Nb_3Sn. A drop of nearly four orders of magnitude attests to the excruciatingly difficult task material scientists and metallurgists face in transforming a material into a magnet-grade superconductor.

1.3.2 A Long Journey

It is a long journey to transform a superconducting material, discovered in the laboratory, into a magnet-grade superconductor. The journey consists of six stages, given in Table 1.3: 1) the discovery of a superconducting material; 2) improvement in J_c performance; 3) co-processing with matrix metal; 4) development of a multi-filamentary conductor having I_c of at least ~100 A; 5) production of a conductor in length from ~10 mm, typical in the material stage, to ~1 km; and 6) meeting other specifications of a magnet. The table also lists an approximate period for the beginning of each stage with Nb_3Sn used as an example.

Despite more than a decade of intense research and development activity beginning immediately after the development of Nb_3Sn conductors in 1961, Nb_3Sn must *still* be custom-designed for each magnet application. Because of its extreme brittleness and intolerance to a minute strain (~0.3%), the material is inherently difficult to process and must be handled with great care.

Table 1.2: Superconducting Materials *vs* Conductors

Criterion	*Number*
1. Superconducting?	~10,000
2. T_c >10 K ($\mu_o H_{c2}$ >10 T)?	~100
3. $J_c > 1\,\mathrm{GA/m^2}$ (@ $B > 5\,\mathrm{T}$)?	~10
4. A magnet-grade superconductor?	~1