Engineering Materials

Springer-Verlag Berlin Heidelberg GmbH

Robert Kratz · Peter Wyder

Principles of Pulsed Magnet Design

With 110 Figures and 29 Tables

Springer

Dr. Robert Kratz
General Atomics
3550 General Atomics Court, San Diego, CA 92121-1122, USA
e-mail: Robert.Kratz@gat.com

Professor Dr. Peter Wyder
Hochfeld-Magnetlabor Grenoble
Avenue des Martyrs (C.N.R.S.), B.P. 166, F-38042 Grenoble Cedex 9, France
e-mail: wyder@labs.polycnrs-gre.fr

Library of Congress Cataloging-in-Publication Data.

Kratz, Robert, 1961-
Principles of pulsed magnet design / Robert Kratz, Peter Wyder. p. cm. - (Engineering materials)
Includes bibliographical references and index.

1. Electromagnets–Design and construction. I. Wyder, Peter, 1934- II. Title. III. Series.

QC760 .K686 2002
621-34–dc21 2002070590

ISBN 978-3-642-07829-3 ISBN 978-3-662-04969-3 (eBook)
DOI 10.1007/978-3-662-04969-3

http://www.springer.de

Originally published by Springer-Verlag Berlin Heidelberg New York in 2002.
Softcover reprint of the hardcover 1st edition 2002

Typesetting: Camera-ready from the authors using a Springer LaTeX 2_ε macro package
Cover design: de'blik, Berlin

Printed on acid-free paper SPIN: 10880169 57/3141 - 5 4 3 2 1 0

Preface

This book deals with the design of pulsed coils for the generation of high magnetic fields. The scope is limited to nondestructive coils. The book's purpose is to provide the designer of a pulsed field facility, the inquisitive student and the scientist with a concise and comprehensive text which describes every aspect of coil design. Special emphasis is laid upon first-order principles, which allow an estimation with paper and pencil and are important for an understanding of the basic design principles. These design formulas are then supplemented by numerical calculations and simulations. The physics necessary to describe a pulsed coil are the theories of electromagnetism, of continuum mechanics and of thermodynamics. It is the combination of these fields of physics which make the construction of a coil at first sight seem a rather tedious process. In this book we want to lead any newcomer to the club through this jungle and we describe the meaning of all possible design variables. The path to the final construction starts with only the most important of these design variables, and later the finer details of 'second order' get incorporated.

We have divided the book into four chapters. In Chapter 1 we give an introduction to the necessary physics. We give an overview of several methods for calculating the magnetic field of a coil and describe the law of Biot-Savart and introduce the scalar magnetic potential and the magnetic vector potential. Furthermore we introduce the inductance of a coil and finally apply methods we have developed to solenoids. The chapter dealing with continuum mechanics introduces the stress and strain tensors and derives the equation for the equilibrium of forces in a rigid body, which relates the external forces to the intrinsic stresses in the body. This equation is completed with the so-called stress-strain relations. Again, after the theoretical description we describe the situation for a solenoid. Finally, we write down the equations necessary to predict the heating of the coil. In a pulsed coil this heating process can be regarded as adiabatic. The heating effects we consider are ohmic heating and heating due to the magnetoresistance. The data for a few conductive materials are presented and the superiority of copper, if only heating from liquid nitrogen to room temperature is considered, as a material for pulsed magnets is demonstrated.

Chapter 2 discusses the analytical calculations of coils. We follow here a somewhat historical path and concentrate first on the optimal use of the available power in a solenoid. With increasingly sophisticated current distributions the power efficiency can be increased. The coil with constant current density, which is easy to manufacture, is surpassed in efficiency by the Bitter coil and the Gaume coil, and the best power efficiency is achieved with the so-called Kelvin distribution. Even with the optimal current density the generation of ever-higher fields needs more and more power, and eventually there occur two limitations, namely the build-up of huge Lorentz forces and the finite cooling capability. For an optimized coil both limitations lead to a current density different from the Kelvin distribution. The limited cooling capability does not occur if one goes over to pulsed magnet systems, where the field generating current flows only for a short time interval, during which the heat capacity of the coil serves as a reservoir. The optimization of real coils with respect to the dissipated power can be performed in an analytical way. This is not so however, for the mechanical stresses, which means that a simplified model becomes mandatory. For this purpose we treat the coil as extended to infinity in the axial direction. The axial field as well as the stresses can then be calculated by hand. We describe this technique for several coil types, for instance for polyhelix coils, wire-wound coils and two-coil systems. Additionally, we investigate various distributions of the current density such as the constant current density, the $1/r$-distribution of the Bitter coil or a current density distribution resulting in constant stresses. A concluding section deals with eddy currents and we derive estimations for a closed cylinder and a cylinder with a slit, both being important geometries in a solenoid.

Chapter 3 deals with numerical simulations and calculations. It is the numerical equivalent of the analytical calculations of Chapter 2. Besides being one step closer to reality, the comparison with the analytical estimations provides a check on the quality of such estimations. Coils of the polyhelix type are simulated with a standard optimization algorithm, and the calculation of wire-wound coils is performed by the method of finite elements.

In Chaper 4 we describe pulsed field facilities, by which we mean the complete system of energy source and high-field coil. Depending on the type of the energy source, the equations for the system describe either capacitive or inductive energy storage systems. We describe capacitive energy storage and begin with the simplest case of constant circuit elements, which we then refine gradually with the incorporation of the heating of the high-field coil, the magnetoresistance and finally eddy currents in the coil. For inductive energy storage we restrict the discussion to constant coil parameters, but deal more extensively with possible mutual inductances between the inductive storage coil and the high-field coil. Furthermore, we discuss how to increase the energy transfer for the inductive storage method. We end with an overview of several possible energy sources.

San Diego, Grenoble *Robert Kratz*
May 2002 *Peter Wyder*

Contents