

This book provides a comprehensive introduction to the theory of magnetic field line reconnection, now a major subject in plasma physics. The book focuses on the various reconnection mechanisms dominating magnetic processes under the different plasma conditions encountered in astrophysical systems and in laboratory devices. The book consists of two major parts: the first deals with the classical resistive approach, while the second presents an overview of weakly collisional or collisionless plasmas. Applications primarily concern astrophysical phenomena and dynamo theory, with emphasis on the solar dynamo and the geodynamo, as well as on magnetospheric substorms, the most spectacular reconnection events in the magnetospheric plasma. The theoretical procedures and results also apply directly to reconnection processes in laboratory plasmas, in particular the sawtooth phenomenon in tokamaks.

The book will be of value to graduate students and researchers interested in magnetic processes both in astrophysical and laboratory plasma physics.

Dieter Biskamp received his Ph.D. from the University of Munich. Following a postdoctoral period at the Max-Planck-Institute for Astrophysics he worked at the Space Research Institute in Frascati and became senior research scientist at the Max-Planck-Institute for Plasma Physics in 1972. Since 1981 he has been head of the General Theory Group and since 1995 has been head of the Nonlinear Plasma Dynamics Group. In 1979 he was visiting professor at the University of Texas and in 1995 COE visiting professor at the National Institute for Fusion Science in Nagoya. His scientific activities cover many areas of plasma physics, in particular magnetohydrodynamics and reconnection theory. He is the author of the book *Nonlinear Magnetohydrodynamics*.

Cambridge University Press
0521020360 - Magnetic Reconnection in Plasmas
Dieter Biskamp
Frontmatter
[More information](#)

CAMBRIDGE MONOGRAPHS ON PLASMA PHYSICS

General Editors: M. G. Haines, K. I. Hopcraft, I. H. Hutchinson, C. M. Surko and K. Schindler

1. D. Biskamp *Nonlinear Magnetohydrodynamics*
2. H. R. Griem *Principles of Plasma Spectroscopy*
3. D. Biskamp *Magnetic Reconnection in Plasmas*

Magnetic Reconnection in Plasmas

Dieter Biskamp

Max-Planck-Institute for Plasma Physics, Garching



Cambridge University Press
0521020360 - Magnetic Reconnection in Plasmas
Dieter Biskamp
Frontmatter
[More information](#)

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 2RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521582889

© Cambridge University Press 2000

This publication is in copyright. Subject to statutory exception
and to the provisions of relevant collective licensing agreements,
no reproduction of any part may take place without
the written permission of Cambridge University Press.

First published 2000
This digitally printed first paperback version 2005

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data

Biskamp, D.
Magnetic reconnection in plasmas / Dieter Biskamp.
p. cm.
Includes bibliographical references and index.
ISBN 0 521 58288 1 (hb)
1. Magnetic reconnection. 2. Plasma (Ionized gases) I. Title.
QC718.5.M3 B53 2000
538'.6—dc21 99-087680 CIP

ISBN-13 978-0-521-58288-9 hardback
ISBN-10 0-521-58288-1 hardback

ISBN-13 978-0-521-02036-7 paperback
ISBN-10 0-521-02036-0 paperback

Cambridge University Press
0521020360 - Magnetic Reconnection in Plasmas
Dieter Biskamp
Frontmatter
[More information](#)

To the memory of my parents

Contents

	<i>Preface</i>	xiii
1	Introduction	1
2	Basic kinematic concepts	10
2.1	Magnetic flux and magnetic helicity	10
2.2	Conservation of magnetic topology	14
2.3	Conditions for magnetic reconnection	17
2.4	Conservation of magnetic helicity in reconnection	21
3	Current sheets	29
3.1	Resistive MHD	30
	3.1.1 The MHD equations	30
	3.1.2 Equilibrium and linear modes	32
	3.1.3 Conservation laws	37
	3.1.4 Reduced MHD models	38
3.2	Resistive current sheets	43
	3.2.1 Current-sheet formation	43
	3.2.2 Basic properties of resistive current sheets	52
	3.2.3 Refined theory of the current-sheet structure	55
3.3	Driven current-sheet reconnection	59
	3.3.1 Syrovatskii's theory of current sheets	60
	3.3.2 Dynamic structure of Y-points	66
	3.3.3 Scaling laws of stationary current-sheet reconnection	69
	3.3.4 Petschek's slow-shock model	75
4	Resistive instabilities	81
4.1	The resistive tearing mode	82
	4.1.1 Linear tearing instability	85

x	<i>Contents</i>	
	4.1.2 Small-amplitude nonlinear behavior	88
	4.1.3 Saturation of the tearing mode	91
	4.1.4 Effect of dynamic resistivity	95
	4.1.5 Neoclassical tearing mode	96
4.2	The double tearing mode	99
4.3	The resistive kink mode	103
	4.3.1 Resistive kink instability	104
	4.3.2 Small-amplitude nonlinear evolution	106
	4.3.3 Final state of the resistive kink mode	112
4.4	Coalescence instability	114
4.5	Pressure-driven instabilities	118
	4.5.1 Interchange and ballooning modes	118
	4.5.2 Nonlinear evolution of pressure-driven modes	125
	4.5.3 Finite pressure effects on tearing modes	128
4.6	Shear flow instability	129
	4.6.1 Shear flow instability in neutral fluids	130
	4.6.2 Effect of magnetic field on the Kelvin–Helmholtz instability	133
	4.6.3 Instability of a magnetized jet	135
4.7	Instability of a resistive current sheet	137
	4.7.1 Threshold condition for tearing instability	137
	4.7.2 Plasmoids	142
5	Dynamo theory	145
5.1	Kinematic dynamo theory	148
	5.1.1 Nonexistence theorems and special dynamo solutions	149
	5.1.2 The rope dynamo	151
	5.1.3 Mean-field electrodynamics	153
	5.1.4 α^2 - and $\alpha\Omega$ -dynamoes	155
	5.1.5 Free dynamo modes	159
5.2	Mean-field MHD dynamo theory	161
	5.2.1 Nonlinear quenching processes and magnetic buoyancy	161
	5.2.2 The solar dynamo	164
5.3	MHD theory of thermal convection	168
	5.3.1 Thermal convection in a rotating sphere	168
	5.3.2 The self-consistent MHD dynamo	173
	5.3.3 The geodynamo	179
5.4	MHD turbulence	182
	5.4.1 Homogeneous MHD turbulence	182
	5.4.2 Selective decay and energy decay laws	184
	5.4.3 Spatial scaling properties	189
	5.4.4 Homogenous turbulent dynamo	197

Contents xi

6	Noncollisional reconnection processes	199
6.1	Two-fluid theory	201
6.2	High- β whistler-mediated reconnection	206
	6.2.1 The EMHD approximation	207
	6.2.2 Properties of the reconnection region	208
	6.2.3 Coalescence of EMHD flux bundles	212
	6.2.4 Electron Kelvin–Helmholtz instability of the current layer	215
	6.2.5 Ion-controlled reconnection dynamics	218
6.3	Low- β noncollisional reconnection	221
	6.3.1 The four-field and three-field models	221
	6.3.2 Linear stability theory	224
6.4	Nonlinear noncollisional kink mode	229
	6.4.1 Electron inertia-dominated reconnection	229
	6.4.2 Kinetic Alfvén-wave-mediated reconnection	232
	6.4.3 Influence of diamagnetic effects	237
	6.4.4 Criterion for fast reconnection	239
6.5	Sawtooth oscillation in tokamak plasmas	241
	6.5.1 Basic experimental observations	241
	6.5.2 The safety factor profile	244
	6.5.3 Stabilization and onset of sawtooth oscillations	246
	6.5.4 Observations of the collapse dynamics	248
	6.5.5 Theoretical interpretation of the sawtooth collapse	250
6.6	Laboratory reconnection experiments	252
	6.6.1 The UCLA magnetic reconnection experiment	253
	6.6.2 The PPPL magnetic reconnection experiment	254
	6.6.3 The Tokyo University reconnection experiment	256
7	Microscopic theory of magnetic reconnection	258
7.1	Vlasov theory and microinstabilities	259
	7.1.1 Linear Vlasov theory	260
	7.1.2 Quasi-linear theory	265
	7.1.3 Mode coupling, resonance broadening, and particle trapping	268
	7.1.4 Turbulent transport coefficients	272
7.2	Ion-sound instability	274
	7.2.1 Linear stability characteristics	274
	7.2.2 Nonlinear saturation and long-time behavior	278
7.3	Lower-hybrid-drift instability (LHDI)	285
7.4	Whistler anisotropy instability	292
7.5	The collisionless tearing mode	296
	7.5.1 Linear stability theory	298
	7.5.2 Nonlinear saturation	301

xii	<i>Contents</i>	
	7.5.3 The ion tearing mode	304
7.6	Particle simulation of collisionless reconnection	307
	7.6.1 Particle simulation methods	307
	7.6.2 Collisionless electron dynamics	310
	7.6.3 Collisionless ion dynamics	312
	7.6.4 GEM Magnetic Reconnection Challenge	316
	7.6.5 Three-dimensional simulations	318
8	Magnetospheric substorms	320
8.1	The structure of the magnetosphere	321
	8.1.1 The solar wind	321
	8.1.2 Magnetopause and bow shock	325
	8.1.3 The internal structure of the magnetosphere	329
8.2	Magnetospheric convection	333
8.3	Magnetopause reconnection	336
8.4	Magnetospheric substorms	339
	8.4.1 Substorm-related observations	340
	8.4.2 MHD modeling of substorms	343
	8.4.3 Collisionless reconnection in the magnetotail	350
	8.4.4 Nonreconnective substorm model	351
	8.4.5 Particle acceleration by magnetotail reconnection	353
	Epilogue	357
	<i>Bibliography</i>	359
	<i>Index</i>	381

Preface

This book is in a sense a sequel to my previous book *Nonlinear Magneto-hydrodynamics*, which contained a chapter on magnetic reconnection. Judging from many discussions it appeared that it was this chapter that was particularly appreciated. The plan to write a full monograph on this topic actually took a concrete shape during a stay at the National Institute for Fusion Science at Nagoya, where I found the time to work out the basic conception of the book. It became clear that resistive theory, to which most of the previous work was restricted, including that chapter of my previous book, covers only a particular aspect of this multifaceted subject and not even the most interesting one, in view of the various applications, both in fusion plasma devices and in astrophysical plasmas, where collisionless effects tend to dominate over resistivity.

While resistive reconnection theory had reached a certain level of maturity and completion about a decade ago (few theories are really complete before becoming obsolete), the understanding of collisionless reconnection processes has shown a rapid development during the past five years or so. The book therefore consists of two main parts, chapters 3–5 deal with resistive theory, while chapters 6–8 give an overview of the present understanding of collisionless reconnection processes. I mainly emphasize the reconnection mechanisms, which operate under the different plasma conditions, to explain the apparent paradox that formally very weak effects in Ohm's law account for the rapid dynamic time-scales suggested by the observations.

Applications concern primarily astrophysical phenomena. Chapter 5 introduces dynamo theory, considering in some detail the generation of the solar and the geomagnetic field, while chapter 8 deals with magnetospheric substorms, the most important reconnection process in the Earth's magnetosphere. Both chapters are rather autonomous and can be read independently of the remainder of the book. Concerning laboratory plas-

mas I resume the discussion of the sawtooth phenomenon considered in some length in *Nonlinear Magnetohydrodynamics*, giving an update of the experimental and theoretical situation. I also discuss briefly several laboratory experiments designed specifically to study magnetic reconnection physics.

It is a pleasure to express my gratitude to the many colleagues with whom I enjoyed fruitful and illuminating discussions on the topics of this book, in particular Jim Drake, who taught me the importance of collisionless reconnection, and Wolfgang Baumjohann, Michael Hesse and Manfred Scholer for introducing me to the realm of magnetospheric physics. I also acknowledge the financial support by the COE programme of Monbusho and the kind hospitality of the National Institute for Fusion Science with special thanks to Tetsuya Sato. Finally I would like to thank Brian Watts for his painstaking copy-editing of the manuscript.

Garching, January 2000

Dieter Biskamp