

Superconductor Applications: SQUIDs and Machines

NATO ADVANCED STUDY INSTITUTES SERIES

A series of edited volumes comprising multifaceted studies of contemporary scientific issues by some of the best scientific minds in the world, assembled in cooperation with NATO Scientific Affairs Division.

Series B: Physics

SOME VOLUMES IN THIS SERIES

- Volume 1* — Superconducting Machines and Devices: Large Systems Applications
edited by Simon Foner and Brian B. Schwartz
- Volume 2* — Elementary Excitations in Solids, Molecules, and Atoms (Parts A and B)
edited by J. Devreese, A. B. Kunz, and T. C. Collins
- Volume 9* — Electronic Structure of Polymers and Molecular Crystals
edited by Jean-Marie André and János Ladik
- Volume 11* — Fluctuations, Instabilities, and Phase Transitions
edited by Tormod Riste
- Volume 13* — Weak and Electromagnetic Interactions at High Energies — *Cargèse 1975*
(Parts A and B)
edited by Maurice Lévy, Jean-Louis Basdevant,
David Speiser, and Raymond Gastmans
- Volume 16* — Electronic Structure and Reactivity of Metal Surfaces
edited by E. G. Derouane and A. A. Lucas
- Volume 17* — Linear and Nonlinear Electron Transport in Solids
edited by J. T. Devreese and V. van Doren
- Volume 19* — Defects and Their Structure in Nonmetallic Solids
edited by B. Henderson and A. E. Hughes
- Volume 20* — Physics of Structurally Disordered Solids
edited by Shashanka S. Mitra
- Volume 21* — Superconductor Applications: SQUIDS and Machines
edited by Brian B. Schwartz and Simon Foner



The series is published by an international board of publishers in conjunction with NATO Scientific Affairs Division

A	Life Sciences	Plenum Publishing Corporation
B	Physics	New York and London
C	Mathematical and Physical Sciences	D. Reidel Publishing Company Dordrecht and Boston
D	Behavioral and Social Sciences	Sijthoff International Publishing Company Leiden
E	Applied Sciences	Noordhoff International Publishing Leiden

Superconductor Applications: SQUIDs and Machines

Edited by

Brian B. Schwartz and Simon Foner

Francis Bitter National Magnet Laboratory

M. I. T.

Cambridge, Massachusetts

PLENUM PRESS • NEW YORK AND LONDON

Published in cooperation with NATO Scientific Affairs Division

Library of Congress Cataloging in Publication Data

Nato Advanced Study Institute on Small-Scale Applications of Superconductivity, Gardone Riviera, Italy, 1976.

Superconductor applications: SQUIDs and machines.

(Nato Advanced Study Institute series; Series B, Physics; v. 21)

Includes index.

1. Superconductors—Congresses. I. Schwartz, Brian B., 1938-Simon. III. Title. IV. Series.

TK7872.S8N2 1976

621.39

II. Foner,

76-51750

The Francis Bitter National Magnet Laboratory is sponsored by
the National Science Foundation

Proceedings of a NATO Advanced Study Institute on Small-Scale Applications of
Superconductivity held in Gardone Riviera (Lago di Garda), Italy, September
1–10, 1976

ISBN-13: 978-1-4684-2807-0

e-ISBN-13: 978-1-4684-2805-6

DOI: 10.1007/978-1-4684-2805-6

© 1977 Plenum Press, New York

Softcover reprint of the hardcover 1st edition 1977

A Division of Plenum Publishing Corporation

227 West 17th Street, New York, N.Y. 10011

All rights reserved

No part of this book may be reproduced, stored in a retrieval system, or transmitted,
in any form or by any means, electronic, mechanical, photocopying, microfilming,
recording, or otherwise, without written permission from the Publisher

PREFACE

This book includes small and large scale applications of superconductivity. Part I, SQUIDS, comprises about 75% of this volume, and is devoted to small scale applications, mainly Superconducting QUantum Interference Devices (SQUIDS), and the remainder, Part II, Machines, presents an updated review of large scale applications of superconductivity. The present book combined with the previous book Superconducting Machines and Devices: Large Systems Applications edited by S. Foner and B.B. Schwartz, Plenum Press, New York (1974) represents a detailed and most up-to-date review of the applications of superconducting technology. The text of the current book is suitable for advanced undergraduates or graduate students in applied physics and engineering courses. The book should be valuable to scientists, engineers and technologists interested in the current status and future applications of superconductivity technology. The last 7 chapters in Part I review the major national efforts on small scale technology and should prove useful for industrial and government planners as well as scientists and engineers.

This book is based on a NATO Advanced Study Institute entitled "Small Scale Applications of Superconductivity" which was held from 1 September to 10 September 1976 in Gardone Riviera on Lake Garda in Northern Italy. This Study Institute complements a previous NATO Advanced Study Institute held in 1973 on Large Scale Superconducting Devices. As with the previous Institute, the focus of the lecturers and the present book involves both applications as well as the scientific principles. Part I, the major part of the present book, treats small-scale applications of superconductivity; and Part II contains an updated review of large scale applications. Part II, together with the previous NATO Institute book (Superconducting Machines and Devices: Large Systems Applications) gives a thorough coverage of large scale applications of superconductivity up to 1977.

Part I provides reviews of all the major principles and devices of small scale superconductivity. The opening chapter by Sir Brian Pippard gives a personal review of some of the historical highlights of superconductivity from the 1930's through the 1960's. Professor Pippard was Brian Josephson's thesis advisor at Cambridge and places Josephson's discovery within the context of the rapid theoretical and experimental developments in superconductivity in the late 1950's and early 1960's.

Chapters 2-6 discuss the basic principles of macroscopic quantum interference phenomena and weak links, superconducting quantum interference devices (SQUIDs), equivalent circuits and analogs, superconducting devices for metrology and standards, and high frequency applications of Josephson Junctions. Chapters 7 - 12 involve special topics including reviews of junction fabrication techniques, biomagnetism applications, status of commercial instruments in the United States, resistive superconducting devices, nonequilibrium properties of superconductors, and application of SQUIDs to computers. The last 7 chapters of Part I (13 - 17) in this book continue an innovation we introduced in the 1973 NATO Institute proceedings; reviews of national efforts. These reviews for Canada, France, Germany, Italy, The Netherlands, United Kingdom and the United States give an up-to-date summary of the current programs in the area of small scale devices. Part II, Chapter 20 presents a thorough review of Large Scale Applications of Superconductivity. (For convenience we have subdivided the subject index into two parts, Index Part I – SQUIDs, Index Part II – Machines.)

The 1976 NATO Institute which resulted in the present volume involved planning which dates back to the 1973 NATO Institute. We were fortunate in having a very effective advisory committee which helped us with the planning. Dr. Edelsack of the Naval Research Laboratory helped us throughout the planning of the Institute. We also profitted from many useful suggestions by S. Shapiro, University of Rochester, A. Baratoff, IBM Zurich, and A.D. Appleton, IRD, England, throughout the planning of the Institute. Members of our International Advisory Committee included R. Adde, G. Bogner, I. Giaever, B. Josephson, R.A. Kamper, C. Rizzuto, and K. Saermark.

We wish to thank Dr. T. Kester and Dr. M. Di Lullo, from the NATO Scientific Affairs Division for their continued interest and encouragement, and the NATO Science Council for their support of the Advanced Study Institute. We also wish to thank the National Science Foundation for Travel Grants to three students.

In addition to the lecturers, the NATO Institute had approximately 95 participants from 23 countries. Professor Carlo Rizzuto was the Local Chairman. He and his associates at the University of Genoa gave continuous help in all aspects of the planning and operation of the Institute. Professor Cerdonio of the University of Rome with Professor Rizzuto helped us to choose the site of the Institute. We would like to thank the Gardone Riviera region, the town of Salò, and the Lake region tourist agency for their hospitality.

We received excellent cooperation from all the lecturers, and we wish to thank them for their excellent talks and prompt completion of the manuscripts. Their cooperation in meeting our deadline dates has allowed us to adhere to a very tight publication schedule. We apologize to all the lecturers for the many demands we made, and wish to thank each of the lecturers for their dedication to the Institute. The success of the Institute required the continued cooperation of each lecturer before, during, and after the Institute. In addition to our personal thanks, we hope that the response of the students at the Institute and the present volume justifies their efforts. In return, we have attempted to set a record in rapidly publishing these contributions.

We would especially like to thank Dr. G. Bogner, Siemens for his review lectures on Large Scale Applications which comprise Part II of these Proceedings. His lectures and notes gave the participants a broad perspective of many additional areas of superconductor applications which are not normally encountered in Small Scale Applications.

We would like to thank R.B. Frankel for his help with the Institute. We would also like to thank Mary Filoso, Michael McDowell, Delphine Radcliffe and Nancy Brandon for helping with the typing and correcting of these manuscripts. We particularly wish to thank Mary Filoso who, as in 1973, was closely involved with the planning and execution of the Institute and Proceedings. Her experience and continued attention to the Institute arrangements and the present book were invaluable.

Cambridge, Massachusetts
October 1976

Brian B. Schwartz
Simon Foner

CONTENTS

PART I - SQUIDS

CHAPTER 1: THE HISTORICAL CONTEXT OF
JOSEPHSON'S DISCOVERY
A. B. Pippard

HISTORY 1

CHAPTER 2: MACROSCOPIC QUANTUM
PHENOMENA IN SUPER-
CONDUCTORS
R. de Bruyn Ouboter

I. INTRODUCTION	21
A. Meissner Effect and Flux Quantization	21
B. The dc Josephson Effect	26
C. The Critical Current Through a Double Point Contact as a Function of the Applied Magnetic Field	32
II. AC QUANTUM EFFECTS	42
A. Extension of the Two-Fluid Interpretation of the London Theory	42
B. The ac Josephson Effect	46
III. RESISTIVE STATES IN WEAR LINK JUNCTIONS	49
A. The Current-Voltage Characteristics and the Resistive-Superconductive Region of a Single Superconducting Weak Link	49
B. The Double Point Contact in the Resistive Superconducting Region, the dc SQUID	56

CHAPTER 3: SUPERCONDUCTING QUANTUM
INTERFERENCE DEVICES FOR
LOW FREQUENCY MEASURE-
MENTS

J. Clarke

I. INTRODUCTION	67
II. SUPERCONDUCTIVITY AND THE JOSEPHSON EFFECTS	68
A. Flux Quantization	68
B. The Josephson Equations	69
C. Types of Josephson Junctions, and their Current-Voltage Characteristics	69
III. DC SQUID	71
A. Theory of the dc SQUID	71
B. Operation of the dc SQUID	76
C. Theory of Noise in the dc SQUID	79
D. Practical dc SQUIDS: Fabrication and Performance	82
E. Future Improvements in the dc SQUID	89
IV. RF SQUID	90
A. Theory of the rf SQUID	90
B. Operation of the rf SQUID	97
C. Noise in the rf SQUID	97
D. Practical rf SQUIDS: Fabrication and Performance	103
E. Future Improvements in the rf SQUID	106
V. SQUIDS AS MAGNETOMETERS, GRADIOMETERS, SUSCEPTOMETERS, AND VOLTMETERS	108
A. Flux Transformer	108
B. Measurement of Magnetic Field	110
C. Measurement of Magnetic Field Gradient	112
D. Measurement of Magnetic Susceptibility	113
E. Measurement of Voltage	116
VI. PRACTICAL APPLICATIONS OF SQUID-BASED DEVICES	118

CHAPTER 4: EQUIVALENT CIRCUITS AND
 ANALOGS OF THE JOSEPHSON
 EFFECT

T. A. Fulton

I. INTRODUCTION	125
II. SMALL JUNCTIONS	126
A. Model of the Supercurrent Flow	126
B. Voltage Biased Model	127
C. Stewart-McCumber Model	127
1. Circuit equations	127
2. Mechanical analogues	130
3. I - $\langle V \rangle$ curves	132
4. Plasma oscillations	136
5. Punchthrough	136
6. Interaction with rf currents	138
D. Inductively-Connected External Elements	143
1. Circuit and mechanical analogues	143
2. Resistive shunts	144
3. Capacitive shunts	146
4. ac SQUID	153
E. The dc SQUID	155
III. LARGE JUNCTIONS	160
A. Two-Dimensional Systems	160
1. Circuit models	160
2. Two-dimensional mechanical analog	164
B. One-Dimensional Junctions	165
1. Circuit equations	165
2. Mechanical analogue	165
3. Small oscillations and displacements	166
4. Magnetic diffraction and Fiske modes for $\ell \ll \lambda_J$	167
5. Junctions having $\ell \gg \lambda_J$ -vortices and critical currents	168
6. Magnetic field behavior for $\ell \gg \lambda_J$	172
7. Vortex motion	174
8. Resonant vortex propagation	177
9. Finite $\langle V \rangle$ behavior for $\ell \gg \lambda_J$	179
10. Vortex oscillations	179
IV. CONCLUSIONS	182

CHAPTER 5: SUPERCONDUCTING DEVICES FOR
METROLOGY AND STANDARDS
R. A. Kamper

I. INTRODUCTION	189
II. VOLTAGE STANDARDS	190
A. The SI Volt	190
B. Standard Cells and the Defined Volt	191
C. The Josephson Effect and e/h	191
D. Practical Josephson Voltage Standards	193
E. The Microwave Signal Source	193
F. The Josephson Junction	193
G. Shielding, Filtering, and Tempering	196
H. Theoretical Uncertainty	196
I. Present Activities	197
III. CURRENT COMPARATORS AND RATIO MEASUREMENTS	198
A. Resistive Networks	198
B. Inductive Devices	200
C. Cold Resistive Dividers	203
D. Superconducting Inductive Current Comparators	205
IV. MEASUREMENTS OF RF POWER AND ATTENUATION	208
A. Some General Remarks on RF and Microwave Measurements	208
B. The SQUID as an RF Measuring Device	210
C. Practical SQUIDS for RF Metrology	213
D. The Measurement of Attenuation	217
E. The Measurement of Power	219
F. Systematic Errors	220
V. THERMOMETRY	227
A. The Kelvin Scale Below 1 K	227
B. Noise Thermometry with SQUID Sensors	228
C. Magnetic Thermometry with SQUIDS	237
D. Superconducting Fixed Points	238
VI. MEASUREMENTS OF FREQUENCY	238
A. The Stability of Oscillators	238
B. Oscillators with Superconducting Cavity Resonators	241
C. Far Infrared Frequency Synthesis	243
D. Recent Work	244

CHAPTER 6: HIGH FREQUENCY PROPERTIES
AND APPLICATIONS OF JOSEPHSON
JUNCTIONS FROM MICROWAVES
TO FAR-INFRARED

R. Adde and G. Vernet

I. GENERAL PROPERTIES OF JOSEPHSON JUNCTIONS FOR HIGH FREQUENCY APPLICATIONS	249
A. High Frequency Fundamental Properties of the Ideal Josephson Junction	249
B. The Parallel Impedance of Real Josephson Junctions	249
C. Limiting Factors of Josephson Junctions at High Frequencies	251
1. Frequency limitation related to the physical mechanism	251
2. Geometrical structure and coupling	257
3. Thermal effects	258
4. Noise	258
D. The Main Detection Mechanism	259
1. Wide band detection	259
2. Narrow band detection (linear)	260
E. The Josephson Junction and Parametric Amplification	261
F. The Real JJ Analyzed with the RSJ Model	263
1. Voltage source model	263
2. The current source model	264
3. An important example: the Josephson heterodyne mixer with an external oscillator	266
G. Noise	268
1. Physical origin of fluctuations in Josephson junctions	268
2. Josephson junction response in the presence of fluctuations	272
H. Noise Temperature, Minimum Detectable Temperature, NEP	275
1. Noise temperatures	275
2. System sensitivity	277
I. Coupling and Impedance Matching	279
1. General remarks	279
2. Impedance matching	279
3. Signal input coupling	281

II. ANALYSIS AND PERFORMANCES OF HIGH-FREQUENCY JOSEPHSON DEVICES	284
A. Generation of Radiation	285
B. Bolometer	286
1. Bolometer characteristics	286
2. SNS and superconducting transition edge bolometers	287
3. Comparison of devices	290
C. Video Detection	290
1. Junction quadratic response	290
2. Voltage response in the general case	291
3. Noise equivalent power	293
4. Discussion of experimental results and comparison with other video detectors	293
D. Heterodyne Detection	295
1. External local oscillator	296
2. Internal local oscillator	302
3. Discussion of the results and comparative performances of other mixers	306
E. Parametric Amplification	311
1. Parametric amplification with self-pumped JJ	312
2. Externally pumped JJ parametric amplifier	314
3. Discussion	315
F. Conclusions	315

CHAPTER 7: FABRICATION OF JOSEPHSON JUNCTIONS
B. T. Ulrich and T. Van Duzer

I. INTRODUCTION	321
II. FABRICATION TECHNOLOGY	323
A. Evaporation Masks	323
B. Photolithography	324
C. Electron Lithography	327
D. Thin-Film Deposition and Ion Etching	329
III. SANDWICH-TYPE JUNCTIONS	332
A. Oxide-Barrier Junctions	333
B. Evaporated Semiconductor Barrier Junctions	337
C. Single-Crystal Silicon-Membrane Junctions	337

IV. JUNCTIONS WITH COPLANAR ELECTRODES	341
A. Variable-Composition Junctions	342
B. Semiconductor Bridge	346
C. Microbridges	347
V. POINT CONTACTS	350

CHAPTER 8: BIOMAGNETISM
S. J. Williamson, L. Kaufman
and D. Brenner

I. INTRODUCTION	355
II. FORWARD AND INVERSE PROBLEMS	357
III. SQUID MEASUREMENT TECHNIQUES	360
IV. MAGNETOCARDIOGRAM	371
V. FETAL MAGNETOCARDIOGRAM	383
VI. MAGNETOMYOGRAM	384
VII. MAGNETO-OCULOGRAM	386
VIII. MAGNETOENCEPHELOGRAM	387
IX. VISUALLY EVOKED FIELD	392
X. EXPECTATIONS	396

CHAPTER 9: A PROGRESS REPORT ON COMMERCIAL
SUPERCONDUCTING INSTRUMENTS
IN THE UNITED STATES
M. B. Simmonds

I. INTRODUCTION	403
II. SQUID SENSORS	404
III. LABORATORY PROBES	405
IV. GEOPHYSICAL MAGNETOMETERS	406
V. MAGNETIC ANOMALY DETECTORS	407

VI.	BIOMEDICAL MAGNETOMETERS	409
VII.	SAMPLE MEASURING INSTRUMENTS	411
VIII.	SHIELDED ENVIRONMENTS	412
IX.	CONCLUSIONS	413

CHAPTER 10: RESISTIVE DEVICES

J. G. Park

I.	INTRODUCTION	415
II.	THE 'CORRESPONDING' SQUID	417
III.	THE RSQUID AND ITS 'CORRESPONDING' SQUID	422
IV.	BEHAVIOR WHEN MODULATION CURRENTS I and i_m ARE ABSENT	426
	A. Stable and Unstable Equilibrium	426
	B. Deviations from the Standard Behavior	427
	C. The Form of $I_k(\Theta_j)$	427
	D. Fluctuations about Equilibrium	430
	E. Behavior when I is small	430
V.	EXPERIMENTS WITH EXTERNAL CURRENT I (AC OR DC)	431
VI.	APPLICATIONS OF RSQUIDS	437
	A. Types of RSQUIDS	437
	B. Picovoltmeters	439
	C. The RSQUID Noise Thermometer	441
	D. Heat Current Measurement	443

CHAPTER 11: "HOT SUPERCONDUCTORS": THE PHYSICS AND APPLICATIONS OF NONEQUILIBRIUM SUPERCONDUCTIVITY

J. -J. Chang and D. J. Scalapino

I.	INTRODUCTION	447
II.	RELAXATION PROCESSES AND THE KINETIC EQUATIONS	454

III.	MAGNITUDES AND THE ROTHWARF-TAYLOR EQUATIONS	468
IV.	SOLUTIONS OF THE BOLTZMANN EQUATIONS	473

CHAPTER 12: COMPUTER APPLICATIONS OF
 JOSEPHSON JUNCTIONS
 P. Wolf

I.	HISTORICAL NOTES	487
II.	THE JOSEPHSON JUNCTION AS A SWITCHING DEVICE	487
III.	DEVICE FABRICATION	489
IV.	CIRCUITS	489
	A. Logic Circuits	489
	B. Memory Circuits	490

CHAPTER 13: PROGRAMS ON SMALL-SCALE
 SUPERCONDUCTING DEVICES
 IN CANADA
 J. A. Blackburn

PROGRAMS	495
----------	-----

CHAPTER 14: PROGRAMS ON SMALL-SCALE
 SUPERCONDUCTING DEVICES
 IN FRANCE
 R. Adde

PROGRAMS	501
----------	-----

CHAPTER 15: PROGRAMS ON SMALL-SCALE
 SUPERCONDUCTING DEVICES
 IN GERMANY
 S. Ern  

PROGRAMS	505
----------	-----

CHAPTER 16: PROGRAMS ON SMALL-SCALE
SUPERCONDUCTING DEVICES
IN ITALY

M. Cerdonio

PROGRAMS 509

CHAPTER 17: PROGRAMS ON SMALL-SCALE
SUPERCONDUCTING DEVICES
IN THE NETHERLANDS

R. de Bruyn Ouboter

PROGRAMS 513

CHAPTER 18: PROGRAMS ON SMALL-SCALE
SUPERCONDUCTING DEVICES
IN THE UNITED KINGDOM

J. G. Park

PROGRAMS 515

CHAPTER 19: PROGRAMS ON SMALL-SCALE
SUPERCONDUCTING DEVICES
IN THE UNITED STATES

R. Brandt and E.A. Edelsack

I. SUMMARY	521
II. INTRODUCTION	521
III. BIOMEDICAL	525
IV. METROLOGY	527
V. GEOPHYSICAL	529
VI. DETECTION AND RADIATION	531
VII. DIGITAL PROCESSING	535
VIII. DEVICE PROPERTIES	537
IX. TRENDS	540

PART II - MACHINESCHAPTER 20: LARGE-SCALE APPLICATIONS OF
SUPERCONDUCTIVITY

G. Bogner

I.	INTRODUCTION	547
II.	SUPERCONDUCTING MATERIALS AND MAGNETS	549
	A. Introduction	549
	B. High-Field Superconductors	550
	1. Superconducting materials	550
	C. Stabilized High Field Superconductors	553
	1. Cryostatic stabilization	554
	2. Adiabatic stabilization	554
	3. Dynamic stability	554
	D. Conductors for dc and ac Magnets	555
	E. Irradiation Effects in Composite Superconductors	565
	F. General Design Aspects of Super- conducting Magnets	567
	1. Intrinsically stable coils	567
	2. Fully or cryostatically stabilized coils	572
	3. Current leads and coil protection	574
	G. Superconducting Magnets for Laboratory Application	575
	H. Magnets for High Energy Physics	579
	I. Superconducting Magnets for Fusion Reactors and MHD Generators	586
	1. Fusion reactors	586
	2. MHD generators	594
	J. Superconducting Magnets for Inductive Energy Storage	596
	K. Superconducting Magnets for Magnetic Separation	604
III.	LEVITATED VEHICLES WITH SUPERCON- DUCTING MAGNETS	608
	A. Introduction	608
	B. Basic Features of the Electrodynamic Flight	609
	C. Principle of the Electrodynamic Levitation System	609
	D. Various Lift and Guidance Systems	610
	E. Damping	613
	F. Propulsion Systems	615
	G. On-Board Cooling Systems	617

H.	Magnetic Shielding of the Passengers	619
I.	Electrodynamic Levitation Projects	619
	1. FRG - the Erlangen test carrier and track	619
	2. The Japanese National Railway magnetic levitation project	627
	3. The Canadian Maglev-project	632
	4. Work on magnetic levitation in Great Britain	633
	5. The US program on magnetic levitation	633
IV.	ELECTRIC MACHINES	636
	A. Introduction	636
	B. Limits of Conventional Machines	636
	C. Superconducting Machines: General Remarks	638
	D. DC Machines	640
	1. Heteropolar machines	640
	2. Homopolar machines	645
	E. Synchronous Machines	654
	1. Technical limits of conventional turbogenerators	656
	2. Potential advantages of superconducting generators	656
	3. Basic construction of superconducting generators	657
	4. Cooling system	662
	5. Armature winding (stator)	666
	6. Machine screening	667
	7. Electrical operating behavior and characteristic data	667
	8. Economic considerations	669
	9. Superconducting turbine-generator projects	670
V.	SUPERCONDUCTING CABLES	672
	A. Introduction	672
	B. Superconducting Cable Concepts	673
	1. Mechanical construction	673
	2. Conductor configurations	673
	3. Comparison between superconducting direct current and alternating current cables	675
	C. Cryogenic Envelope	677
	D. Superconducting Material	678
	1. Direct current superconductors	678
	2. Alternating current superconductors	679

CONTENTS

xxi

E. Cable Core	684
F. Electrical Insulation	687
G. Cable Cooling	694
H. Cable Terminations	699
I. Superconducting Cable Projects	701
J. The Economics of Superconducting Cables	705
K. Future Development of Superconducting Cables	709

SUBJECT INDEX

PART I - SQUIDS	719
PART II - MACHINES	731