

Springer Tracts in Modern Physics

Volume 277

Series editors

Yan Chen, Department of Physics, Fudan University, Shanghai, China

Atsushi Fujimori, Department of Physics, University of Tokyo, Tokyo, Japan

Thomas Müller, Institut für Experimentelle Kernphysik, Universität Karlsruhe,
Karlsruhe, Germany

William C. Stwalley, Johannes Gutenberg Universität Mainz, Storrs, CT, USA

Springer Tracts in Modern Physics provides comprehensive and critical reviews of topics of current interest in physics. The following fields are emphasized:

- Elementary Particle Physics
- Condensed Matter Physics
- Light Matter Interaction
- Atomic and Molecular Physics
- Complex Systems
- Fundamental Astrophysics

Suitable reviews of other fields can also be accepted. The Editors encourage prospective authors to correspond with them in advance of submitting a manuscript. For reviews of topics belonging to the above mentioned fields, they should address the responsible Editor as listed in “Contact the Editors”.

More information about this series at <http://www.springer.com/series/426>

Pierre Schnizer

Advanced Multipoles for Accelerator Magnets

Theoretical Analysis and Their Measurement

 Springer

Pierre Schnizer
Helmholtz-Zentrum Berlin für Materialien
und Energie
Berlin
Germany

ISSN 0081-3869 ISSN 1615-0430 (electronic)
Springer Tracts in Modern Physics
ISBN 978-3-319-65665-6 ISBN 978-3-319-65666-3 (eBook)
DOI 10.1007/978-3-319-65666-3

Library of Congress Control Number: 2017950002

© Springer International Publishing AG 2017

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Acknowledgements

This treatise and the work described within this document were developed over the last years. Here, I wish to thank those without whom this treatise would not have been possible.

I am indebted to my colleague and supervisor, Egbert Fischer, who from the start has encouraged me to look aside of the straight path, to take the time to see the interesting topics along the road, yet continue to stay sufficiently focused such that the principal goal could be attained.

The study of the theoretical basis of this work started when its usefulness was only visible to those directly involved. It was the knowledge, experience and dedication of my father, Bernhard Schnizer, which allowed the development of these new tools that are now available to the community.

My sincere thanks are also directed to my mentors, Prof. Achim Denig, Prof. Frank Mass and Prof. Kurt Aulenbacher at the Johannes-Gutenberg-Universität Mainz, for providing me the chance and support to conduct this habilitation at the Institut für Kernphysik.

Experiments require a facility, planning, preparation and the support of many. I am indebted to all my colleagues at GSI and partner institutes, whose work only made it possible to build the measurement mole, to measure the magnets and which freed me from the stress of having to worry about all the particular subsystems required to run a superconducting magnet measurement bench successfully.

Last but not least, I wish to thank my wife Elisabeth for her faith in me, her support and patience and for accepting my absences related to this work over the last years.

Contents

1	Introduction	1
1.1	Motivation	1
1.2	The Laboratory and Its New Project	3
1.3	The Magnets	4
1.4	Scope of this Treatise	7
	References	9
2	Electromagnetic Fields and Particle Motion	11
2.1	Maxwell's Equations	11
2.1.1	Magnetic Quasistatic Approximation	12
2.1.2	Magnetic Field in Linear Material	13
2.2	Particle Motion in Magnetic Fields	17
2.2.1	Particle Motion in a Cyclotron	18
2.2.2	Paraxial Approximations	18
2.2.3	Summary	19
	References	19
3	Coordinate Systems	21
3.1	Orthogonal Curvilinear Systems	21
3.2	Cylindrical Coordinate Systems	23
3.2.1	Cylindrical Circular Systems	23
3.2.2	Cylindrical Elliptical Systems	24
3.3	Toroidal Coordinate Systems	27
3.3.1	Global Toroidal Coordinates	27
3.3.2	Local Toroidal Coordinates	27
3.3.3	Local Toroidal Elliptical Coordinates	29
3.4	Frenet-Serret Coordinates	31
3.5	Summary	32
	References	32

4	Field Descriptions	35
4.1	Basis: Cylindrical Circular Multipoles	36
4.1.1	Conventions	37
4.1.2	Effect of Transformations	40
4.1.3	Circular Multipoles Using Real Variables	40
4.2	Cylindrical Elliptical Multipoles	41
4.2.1	Complex Elliptical Multipoles	43
4.2.2	Relations Between Circular and Elliptical Multipoles	47
4.2.3	Elliptical Multipole Field Expansions for Elliptical Components	51
4.2.4	Complex Potential for Normal and Skew Elliptical Multipoles	53
4.3	Toroidal Circular Multipoles	55
4.3.1	Approximate R-Separation	56
4.3.2	The Potential	57
4.3.3	Real Basis Vector Field in Local Toroidal Coordinates	58
4.3.4	Approximation Error of the Differential Equation	69
4.4	Toroidal Elliptical Multipoles	69
4.5	Summary	71
	References	72
5	Rotating Coils	75
5.1	Derivation of Coil Probe Geometry Factors	75
5.1.1	Complex Potential	76
5.1.2	Magnetic Flux Through a Surface	76
5.1.3	Magnetic Flux Picked Up by a Rotating Coil	78
5.2	Radial Rotating Coil Layout	79
5.3	Voltage Induced in a Rotating Pick Up Coil	80
5.4	Compensated Systems	81
	References	84
6	Experimental Setup	85
6.1	Test Facility	85
6.2	The Anticyrostat	87
6.3	Magnetic Measurement Equipment	89
6.3.1	History: Choice of Method	89
6.3.2	A Modular Mole	91
6.4	Summary	98
	References	99

- 7 Applications** 101
 - 7.1 Appropriate Handling of Calculation Data 101
 - 7.2 Calculating Cylindrical Elliptical Multipoles. 102
 - 7.3 Summary 105
 - References. 106
- 8 Measuring Advanced Multipoles** 107
 - 8.1 Measuring Straight Elliptical Multipoles. 108
 - 8.1.1 Calculation Procedure 108
 - 8.1.2 Measurement Results. 116
 - 8.2 Measuring Toroidal Multipoles. 116
 - 8.2.1 The Magnetic Flux 120
 - 8.2.2 Conversion Matrices 122
 - 8.2.3 Choosing a Coil Probe Length 124
 - 8.2.4 Magnitude of the Terms 126
 - 8.2.5 Measurement Results on the SIS100 Curved Dipole Magnet 129
 - 8.3 Summary 130
 - References. 130
- 9 Error Propagation**. 133
 - 9.1 Error Propagation of Elliptic Multipoles Measurement. 133
 - 9.1.1 Description of Calculation Procedure 133
 - 9.1.2 Combining the Coefficients. 135
 - 9.1.3 Error Propagation of the Measured Coefficients 138
 - 9.1.4 Error Propagation to Coefficients of the Circular Multipoles. 141
 - 9.1.5 Influence of Coil Probe Displacement. 144
 - 9.2 Toroidal Multipole Measurement 144
 - 9.3 Measurement Accuracy Estimate for the CSLD 145
 - 9.4 Summary 146
 - References. 146
- 10 Conclusions** 149
 - 10.1 Outlook. 151
- Appendix A: Changes to Previous Publications** 153
- Appendix B: Mathematica Scripts**. 155
- Appendix C: Approximate Inversion of a Perturbed Matrix.** 165

Abstract

Studying the transversal beam dynamic of accelerators requires a sound description of the magnetic field homogeneity. Cylindrical circular multipoles, typically used, have shortcomings if the beam aperture is elliptical or the curvature of the particle path has to be taken into account.

Within this treatise, advanced multipoles are described besides their application on numerical data and measurements. These multipoles allow describing the field consistently for elliptical and toroidal reference volumes and estimating the artefacts of the field deterioration. The higher precision of the field description gives better estimates of the beam dynamics and permits one to better estimate the effects of field inhomogeneity than was available before. Thus, the presentation itself does not create spurious artefacts; the margin normally reserved for these artefacts can be reduced due to the better understanding. This research was first necessitated by the R&D for developing the SIS100 magnets for FAIR, then used for describing the field homogeneity of the magnets next to developing appropriate measurement methods.

These findings are then further elaborated demonstrating their usefulness for describing the field of real magnets and their advantages over the cylindrical circular ones. Furthermore, measurement methods for obtaining the coefficients of these advanced multipoles have been developed and are described within this treatise. All these developments provided a basis for the field measurements of the first SIS100 model and first of series dipole magnets. The research results are then complemented with data obtained on the first SIS100 model and first of series dipole magnets.