Preface to the Second Edition

In the 5 years since the appearance of this book, an enormous progress has been made in the field of free-electron lasers. The world's first hard X-ray FEL, the Linac Coherent Light Source (LCLS) at Stanford (USA), was commissioned in 2009, and the second X-ray FEL, the "Spring-8 Angstrom Compact free-electron LAser" (SACLA) at Harima (Japan), went into operation in 2012. This has been the motivation to change the title of our book to *Free-Electron Lasers in the Ultraviolet and X-Ray Regime*. Chapter 9 has been completely rewritten to describe the existing X-ray FEL facilities and report important results obtained with these machines. A second new achievement is the successful implementation of various seeding schemes at FELs working in the ultraviolet and soft X-ray spectral regions. Chapter 7 covers now Self-Amplified Spontaneous Emission and FEL seeding. Another new feature of the book is a novel derivation of the important third-order differential equation of the high-gain FEL.

The field of free-electron lasers has undergone a rapid expansion in the past few years and is still growing fast. Within the scope of this university textbook, we can cover only a small fraction of the exciting new ideas and developments. We apologize for having to omit many important results and refer to the Free-Electron Laser conferences (FEL) and the International Particle Accelerator Conferences (IPAC) as well as to the scientific journals quoted in the book for a more complete overview.

C. B. is very grateful for the hospitality extended to him at SLAC and the opportunity to participate in important scientific investigations at LCLS. We thank Hitoshi Tanaka for valuable information and comments. Particular thanks go to Zhirong Huang for his advice and numerous stimulating discussions.

Hamburg, October 2013

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Preface to the First Edition

The high scientific interest in coherent X-ray light sources has stimulated worldwide efforts in developing X-ray lasers. In this book, a particularly promising approach is described, the free-electron laser (FEL), which is pursued worldwide and holds the promise to deliver ultra-bright X-ray pulses of femtosecond duration. Other types of X-ray lasers are not discussed nor do we try a comparison of the relative virtues and drawbacks of different concepts.

The book has an introductory character and is written in the style of a university textbook for the many newcomers to the field of free-electron lasers, graduate students as well as accelerator physicists, engineers, and technicians; it is not intended to be a scientific monograph for the experts in the field. Building on lectures by one of us (J. R.) at the CERN Accelerator School, and motivated by the positive response to a series of seminars on "FEL theory for pedestrians", given by P. S. within the framework of the Academic Training Program at DESY, we have aimed at presenting the theory of the low-gain and the high-gain FEL in a clear and concise mathematical language. Particular emphasis is put on explaining and justifying the assumptions and approximations that are needed to obtain the differential equations describing the FEL dynamics. Although we have tried our best to be "simple", the mathematical derivations are certainly not always as simple as one would like them to be. However, we are not aware of any easier approach to the FEL theory. Some of the more involved calculations are put into the appendices.

The starting points are the Maxwell equations and the basic elements of special relativity. We avoid the Hamiltonian formalism in the main text because many potential readers may not be familiar with this powerful formalism. A short introduction into the Hamiltonian treatment of the electron motion in an undulator magnet and its interaction with the radiation field is given in Appendix A. The FEL equations are derived in the framework of classical electrodynamics. Quantum theory is not needed to explain the theoretical basis and the functioning of presently existing or planned FEL facilities.

The differential equations describing the time evolution of the laser light wave are derived in a one-dimensional approximation and turn out to be quite powerful. In this book, they are evaluated using rather straightforward programs for computing the FEL gain curve, laser saturation, bandwidth, and other quantities of interest.

The implications and modifications of the full three-dimensional treatment are discussed.

The available experimental data on high-gain ultraviolet and soft X-ray FELs are presented but the wide field of FELs in the visible and infrared regime is not covered. We apologize for having to omit the important results obtained in this field as well as other interesting developments and refer to the literature quoted in the book and to the Free-Electron Laser (FEL) conferences and the American and European Particle Accelerator conferences (PAC, EPAC) for a complete overview over the rapidly growing FEL activities worldwide.

The International System (SI) of units is used throughout to enable the reader to obtain practical numbers from the equations in the book. Our mathematical codes (written by M. D.) are available on request. The majority of the illustrations and graphical presentations shown in the book have been prepared by us using these codes, except when otherwise noted.

We have benefited a great deal from fruitful discussions with our colleagues at DESY and other laboratories and want to thank them for their advice, in particular Evgueni Saldin, Evgeny Schneidmiller, and Mikhail Yurkov. We are very grateful to Erich Lohrmann and Sara Casalbuoni for a thorough reading of an early version of the manuscript and many valuable suggestions, and to Sven Reiche for a critical reading of the complete manuscript and his suggestions for improvement. Bernd Steffen's help with LATEX problems and editing of figures is gratefully acknowledged as well as Roxana Tarkeshian's help in checking the references. We are particularly grateful to all members of the TESLA collaboration and of the FLASH team for their invaluable contributions to the design, construction and operation of a superconducting free-electron laser in Hamburg.

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