

Springer Tracts in Modern Physics

Volume 239

Managing Editor: G. Höhler, Karlsruhe

Editors: A. Fujimori, Tokyo
J. Kühn, Karlsruhe
Th. Müller, Karlsruhe
F. Steiner, Ulm
J. Trümper, Garching
P. Wölfle, Karlsruhe

Available **online** at
SpringerLink.com

Starting with Volume 165, Springer Tracts in Modern Physics is part of the [SpringerLink] service. For all customers with standing orders for Springer Tracts in Modern Physics we offer the full text in electronic form via [SpringerLink] free of charge. Please contact your librarian who can receive a password for free access to the full articles by registration at:

springerlink.com

If you do not have a standing order you can nevertheless browse online through the table of contents of the volumes and the abstracts of each article and perform a full text search.

There you will also find more information about the series.

Springer Tracts in Modern Physics

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, solid-state physics, complex systems, and fundamental astrophysics.

Suitable reviews of other fields can also be accepted. The editors encourage prospective authors to correspond with them in advance of submitting an article. For reviews of topics belonging to the above mentioned fields, they should address the responsible editor, otherwise the managing editor. See also springer.com

Managing Editor

Gerhard Höhler

Institut für Theoretische Teilchenphysik
Universität Karlsruhe
Postfach 69 80
76128 Karlsruhe, Germany
Phone: +49 (7 21) 6 08 33 75
Fax: +49 (7 21) 37 07 26
Email: gerhard.hoehler@physik.uni-karlsruhe.de
www-tp.physik.uni-karlsruhe.de/

Elementary Particle Physics, Editors

Johann H. Kühn

Institut für Theoretische Teilchenphysik
Universität Karlsruhe
Postfach 69 80
76128 Karlsruhe, Germany
Phone: +49 (7 21) 6 08 35 24
Fax: +49 (7 21) 37 07 26
Email: johann.kuehn@physik.uni-karlsruhe.de
www-tp.physik.uni-karlsruhe.de/~jk

Thomas Müller

Institut für Experimentelle Kernphysik
Fakultät für Physik
Universität Karlsruhe
Postfach 69 80
76128 Karlsruhe, Germany
Phone: +49 (7 21) 6 08 35 24
Fax: +49 (7 21) 6 07 26 21
Email: thomas.muller@physik.uni-karlsruhe.de
www-ekp.physik.uni-karlsruhe.de

Fundamental Astrophysics, Editor

Joachim Trümper

Max-Planck-Institut für Extraterrestrische Physik
Postfach 13 12
85741 Garching, Germany
Phone: +49 (89) 30 00 35 59
Fax: +49 (89) 30 00 33 15
Email: jtrumper@mpe.mpg.de
www.mpe-garching.mpg.de/index.html

Solid-State Physics, Editors

Atsushi Fujimori

Editor for The Pacific Rim

Department of Physics
University of Tokyo
7-3-1 Hongo, Bunkyo-ku
Tokyo 113-0033, Japan
Email: fujimori@wyvern.phys.s.u-tokyo.ac.jp
http://wyvern.phys.s.u-tokyo.ac.jp/welcome_en.html

Peter Wölfle

Institut für Theorie der Kondensierten Materie
Universität Karlsruhe
Postfach 69 80
76128 Karlsruhe, Germany
Phone: +49 (7 21) 6 08 35 90
Fax: +49 (7 21) 6 08 77 79
Email: woelfle@tkm.physik.uni-karlsruhe.de
www-tkm.physik.uni-karlsruhe.de

Complex Systems, Editor

Frank Steiner

Institut für Theoretische Physik
Universität Ulm
Albert-Einstein-Allee 11
89069 Ulm, Germany
Phone: +49 (7 31) 5 02 29 10
Fax: +49 (7 31) 5 02 29 24
Email: frank.steiner@uni-ulm.de
www.physik.uni-ulm.de/theo/qc/group.html

Alexander Petrovich Potylitsyn
Mikhail Ivanovich Ryazanov
Mikhail Nikolaevich Strikhanov
Alexey Alexandrovich Tishchenko

Diffraction Radiation from Relativistic Particles

 Springer

Prof. Alexander Petrovich Potylitsyn
Tomsk Polytechnic University
Lenin Ave. 30
634050 Tomsk
Russia
pap@interact.phtd.tpu.ru

Prof. Mikhail Ivanovich Ryazanov
National Research Nuclear University
MEPhI
Kashirskoe Sh. 31
115409 Moscow
Russia
ryazanov-m@mail.ru

Prof. Mikhail Nikolaevich
Strikhanov
National Research Nuclear University
MEPhI
Kashirskoe Sh 31
115409 Moscow
Russia
MNStrikhanov@mephi.ru

Prof. Alexey Alexandrovich
Tishchenko
National Research Nuclear University
MEPhI
Kashirskoe Sh. 31
115409 Moscow
Russia
tishchenko@mephi.ru

A.P. Potylitsyn et al., *Diffraction Radiation from Relativistic Particles*, STMP 239 (Springer, Berlin Heidelberg 2010), DOI 10.1007/978-3-642-12513-3

ISSN 0081-3869 e-ISSN 1615-0430
ISBN 978-3-642-12512-6 e-ISBN 978-3-642-12513-3
DOI 10.1007/978-3-642-12513-3
Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2010931600

© Springer-Verlag Berlin Heidelberg 2010

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution under the German Copyright Law.

The use of general descriptive names, registered names, trademarks, 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.

Cover design: Integra Software Services Pvt. Ltd., Pondicherry

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Foreword

This monograph presents the results of theoretical and experimental investigations of diffraction radiation accompanying the motion of charged particles near a conducting surface. The foundations of the theory of diffraction radiation are systematically presented for the first time. Particular attention is focused on radiation from periodic structures (Smith—Purcell radiation). Although some results refer to the nonrelativistic and moderately relativistic cases, the major part of the monograph is devoted to radiation generated by relativistic and ultrarelativistic charged particles and from bunches of these particles. The experimental results on diffraction radiation are presented in comparison with the theory. The problems of the application of diffraction radiation to non-invasive diagnostics of charged particle beams in modern accelerators are discussed. The monograph is addressed to researchers in such fields as electromagnetic radiation and the accelerator physics. It also can be useful for higher year and postgraduate students.

Tomsk-Moscow, October 2009

Alexander Petrovich Potylitsyn
Mikhail Ivanovich Ryazanov
Mikhail Nikolaevich Strikhanov
Alexey Alexandrovich Tishchenko

Preface

Diffraction radiation appearing in the optical range when charged particles move in vacuum along a periodically deformed surface (grating) was observed for the first time in the early 1950s by S.J. Smith and E.M. Purcell [1]. This radiation was theoretically predicted by I.M. Frank in the early 1940s [2]. In the next two decades, this type of radiation was investigated in detail on beams of nonrelativistic electrons in the centimeter wavelength range. At the same time, theoretical methods were developed for calculating the characteristics of diffraction radiation for various configurations of measuring instruments and various parameters of a beam. A new field appeared in microwave electronics [3] and development of this field actively continues to date [4, 5].

At present, it has been shown that the intensity of visible and ultraviolet diffraction radiation generated by relativistic particles can be comparable with the intensity of transition radiation, which is widely used in high energy physics and accelerator physics. In contrast to transition radiation, diffraction radiation is not accompanied by the direct interaction of beam particles with a target and this circumstance opens prospects for non-invasive diagnostics of beams in modern accelerators.

Diffraction radiation can be used to analyze the structure of micron objects for which traditional X-ray methods are ineffective because of the absence of X-ray lenses with the required luminosity.

We point to the potentialities of coherent diffraction radiation generated by a beam of moderately relativistic electrons that are grouped into bunches shorter than 1 mm. In this case, the radiation spectrum covers the terahertz range, which is of considerable interest for applied investigations in physics, chemistry, and biology [6].

Diffraction radiation generated by relativistic particles is presented very briefly in modern monographs. Monographs [3] and [4] are completely devoted to diffraction radiation generated in periodic structures by nonrelativistic electrons. Among other problems, some applications of diffraction radiation generated by both nonrelativistic and relativistic particles were considered in monograph [5], but with emphasis on the specific features of microwave instruments (modulation of a beam in the process of its interaction with a target, comparatively low energies of the beam particles, and nonlinearity of physical phenomena), whereas the problems of diffraction radiation itself and modern experimental results in this field remained beyond the scope of

that monograph. In each of more general monographs [7, 8] devoted to radiation generated by fast charged particles in a medium, diffraction radiation is discussed only in one section. At the same time, there are many theoretical and experimental studies, where the application of diffraction radiation to non-invasive diagnostics of electron beams and bunches is justified and the corresponding experimental methods are developed. This circumstance stimulates interest of both theorists and experimentalists in the properties of diffraction radiation.

Successes achieved in the past decade in this field of physics lead to significant progress in the investigation and application of diffraction radiation. In this monograph, we review the current status of theoretical and experimental investigations of diffraction radiation generated by ultrarelativistic particles.

Diffraction radiation is very close in nature to transition radiation. Indeed, both kinds of radiation can be treated as radiation from dynamical polarization currents induced in the target material by the Coulomb field of moving charged particles. However, in contrast to well-studied transition radiation, the situation with diffraction radiation is much more complicated, because the expressions for transition radiation (at least, widely known Ginzburg-Frank formulas) are derived for an infinite planar interface and for the far zone (wave zone or Fraunhofer zone in the optical terminology). However, diffraction radiation always implies a much more complex interface. As known, the strict solution of boundary value problems with complex boundary conditions involves significant mathematical difficulties. A number of physical approximations are usually used in real problems, e.g., in physical optics; they make it possible to obtain the results acceptable for applications (see, e.g., the wonderful monograph [9], where the approaches for solving diffraction problems of current interest in stealth technologies are analyzed). For this reason, many approaches presented in this book are different from each other and are based on some physical approximations. These approaches are obviously of interest for researchers working in this field and related fields; in addition, they are useful for young physicists to develop scientific insight into solving particular physical problems by the methods of classical electrodynamics.

Addressing to theoretical and experimental physicists, we aim to strictly justify the approaches used and briefly presenting recent experimental results. We hope that the monograph helps young researchers to acquire knowledge for active investigations in this field.

The problems concerning the effect of currents induced in the target on the characteristics of the beams are not included because of a limited volume of the monograph. Experimental data indicate that such a simplification is justified when energy loss to radiation is much lower than the kinetic energy of the beam. This simplification allows us, on the one hand, to avoid the inclusion of nonlinear phenomena and, on the other hand, to develop the foundations of non-invasive diagnostics of charged particle beams.

The list of references presents available studies used for writing this monograph.

We are grateful to B.M. Bolotovskii, N.F. Shul'ga, N.N. Nasonov, M. Ikezawa, Y. Shibata, J. Urakawa, G. Kube, K.A. Ispiryan, G.A. Naumenko and P.V. Karataev for numerous stimulating discussions and to L.V. Puzyrevich,

N. A. Potylitsina-Kube, D. V. Karlovets, A. R. Wagner and L. G. Sukhikh for assistance in the preparation of the manuscript. We are indebted to R. Tyapaev, translator of the book, for effective cooperation.

Tomsk-Moscow, October 2009

Alexander Petrovich Potylitsyn
Mikhail Ivanovich Ryazanov
Mikhail Nikolaevich Strikhanov
Alexey Alexandrovich Tishchento

References

1. Smith, S.J., Purcell, E.M.: Visible light from localized surface charges moving across a grating. *Phys. Rev.* **92**, 1069 (1953). [vii](#)
2. Frank, I.M.: Doppler effect in a refractive medium. *Izv. Akad. Nauk USSR. Fizika.* **6**, 3 (1942). [vii](#)
3. Shestopalov, V.P.: *Diffraction Electronics*. Kharkov, Ukraine (1976). [vii](#)
4. Shestopalov, V.P.: *The Smith-Purcell effect*. Nova Science Publishers, Commack, NY (1998). [vii](#)
5. Tsimring, S.E.: *Electron Beams and Microwave Vacuum Electronics*. Wiley, Hoboken, NJ (2003). [vii](#)
6. Williams, G.P.: Filling the THz gap-high power sources and applications. *Rep. Prog. Phys.* **69**, 301 (2006). [vii](#)
7. Ter-Mikaelyan, M.L.: *High-Energy Electromagnetic Processes in Condensed Media*. Wiley-Interscience, New York, NY (1972). [viii](#)
8. Rullhusen, P., Artru, X., Dhez, P.: *Novel Radiation Sources Using Relativistic Electrons*. World Scientific, Singapore (1998). [viii](#)
9. Ufimtsev, P.Ya.: *Theory of Diffraction Boundary Problems in the Electrodynamics*, Moscow, Binom (2007) in Russian. [viii](#)

Contents

1	Radiation from Relativistic Particles	1
1.1	General Properties of Radiation from Relativistic Particles.....	1
1.2	Radiation Formation Length	6
1.3	Radiation from a Heavy Charged Particle Colliding With an Atom ..	9
1.4	Transition Radiation and Diffraction Radiation	13
1.5	Wakefield in Linear Accelerators	19
	References	26
2	General Properties of Diffraction Radiation	29
2.1	Diffraction Radiation as Radiation from Polarization Currents.....	29
2.2	Formation Length of Diffraction Radiation	32
2.3	Radiation from Relativistic Particle Near a Screen.....	35
2.4	Diffraction Radiation from Ultrarelativistic Particles.....	38
2.5	Effect of the Excitation of the Medium on Diffraction Radiation	43
2.6	Diffraction Radiation from a Charged Particle Reflected from a Single Crystal	49
	References	53
3	Diffraction Radiation at Optical and Lower Frequencies	55
3.1	Diffraction Radiation from a Circular Hole in an Opaque Screen.....	55
3.2	Diffraction Radiation from an Inclined, Perfectly Conducting Half- Plane	64
3.3	Radiation Generated by a Charge Passing Through a Slit in a Perfectly Conducting Screen	81
3.4	Polarization Characteristics of Diffraction Radiation.....	92
	References	101
4	Diffraction Radiation in the Ultraviolet and Soft X-Ray Regions	105
4.1	Polarization Current and the Radiation Field	105
4.2	Forward Diffraction Radiation	109
4.3	Backward Diffraction Radiation	115

4.4	X-ray Diffraction Radiation Under Conditions of the Cherenkov Effect	119
4.5	Diffraction Radiation from a Crystal Target	123
	References	134
5	Diffraction Radiation at the Resonant Frequency	137
5.1	Diffraction Radiation at the Resonant Frequency from a Nonplanar Surface	137
5.2	Diffraction Radiation at the Resonant Frequency from a Wedge	142
	References	147
6	Diffraction Radiation from Media with Periodic Surfaces	149
6.1	Smith—Purcell Radiation	149
6.2	Scalar Theory of the Diffraction of the Self Field of an Electron from a Plane Semitransparent Grating	153
6.3	Smith—Purcell Effect As Radiation Generated by Induced Surface Currents	156
6.4	Smith—Purcell Effect As Resonant Diffraction Radiation	162
6.5	Resonant Diffraction Radiation Generated by Electrons Moving Near a Tilted Planar Grating	177
6.6	Smith—Purcell Radiation from a Thin Dielectric Layer on a Conducting Substrate	186
	References	194
7	Coherent Radiation Generated by Bunches of Charged Particles	197
7.1	Coherent Radiation Generated by Short Electron Bunches	197
7.2	Coherent Synchrotron Radiation in the Millimeter and Submillimeter Wavelength Ranges	207
7.3	Coherent Diffraction Radiation	211
7.4	Coherent Smith—Purcell Radiation	216
	References	219
8	Diffraction Radiation in the Pre-wave (Fresnel) Zone	221
8.1	Transition Radiation in the Pre-wave (Fresnel) Zone	221
8.2	Diffraction Radiation in the Pre-wave (Fresnel) Zone as a Tool for Beam Diagnostics	231
	References	249
9	Experimental Investigations of Diffraction Radiation Generated by Relativistic Electrons	251
9.1	Experimental Results on Diffraction Radiation and Comparison with Theoretical Calculations	251
9.2	Optical Diffraction Radiation from a Slit Target and the Possibility of the Measurement of the Transverse Size of an Electron Beam	260

9.3	Experimental Investigations of the Generation of Smith—Purcell Radiation by Ultrarelativistic Electron Beams	265
9.4	Some Prospects of Application of Diffraction Radiation	271
	References	275