Preface

About a decade has passed since the writing of the book “Relativistic Nonlinear Electrodynamics.” On the one hand, this is a short time period for substantial advancements in a science like physics, on the other hand, the unprecedented development of laser technologies during the last decade, specifically, the implementation of ultrashort laser sources and subcycle pulses of relativistic intensities exceeding the intra-atomic fields, have become real. This radically changes the practical situation in high energy radiation-matter physics, related in particular to the creation of superpower X-ray–γ-ray coherent sources, new type—laser–plasma accelerators of enormous energies, laser-induced nuclear fusion, production of antimatter from vacuum, etc. It is noteworthy the realization of relativistic solid-plasma-targets/nanolayers under ultrashort superintense laser pulses, making available the implementation of high brightness electron and ion beams of solid densities and high energies. In turn, the emergence of such superstrong electromagnetic fields has rapidly initiated extensive fundamental investigations in the area of Relativistic Nonlinear Electrodynamics, revealing various new nonlinear phenomena in the fields approaching to Schwinger one for vacuum Quantum Electrodynamics (QED).

Concerning the degree of nonlinearity in strong radiation–matter interaction processes, it has been revealed that exotic cases of condensed matter possessing huge electromagnetic nonlinearity at which nonlinear effects occur at rather small intensities of exciting field compare to ordinary free–free or bound–bound transitions. The best example of such type of matter is graphene. Thus, nonlinear excitation of the Dirac sea in graphene occurs at a billion time smaller intensities of external radiation field than it is necessary for excitation of the electron–positron vacuum and, in general, for revealing of nonlinear effects in ordinary materials. Therefore, the present book was completed with the new material regarding the unique nonlinear properties of graphene in strong laser fields.

Besides, in this book we added new material concerning the relativistic quantum theory of scattering on the arbitrary potential field beyond the Born and ordinary eikonal approximations. Thus, we developed a new—Generalized Eikonal

Approximation (GEA)—in both elastic and inelastic scattering theory for spinor and scalar particles scattering on the short-range and long-range potential fields of arbitrary form, as well as in the presence of superstrong laser radiation of arbitrary intensities. The latter—Stimulated Bremsstrahlung (SB)—apart from its important role in laser-induced processes of Above-Threshold Ionization (ATI) of atoms and High Harmonic Generation (HHG), is considered here as a basic process for nonlinear absorption of superpower electromagnetic radiation in plasma.

New material has been included devoted to relativistic atoms in strong laser fields considering multiphoton excitation of atoms with high charge numbers and highly charged ions, taking into account the fine structure of relativistic atoms–ions with accompanying coherent effects; nonlinear acceleration of atoms by powerful laser pulses, as well as relativistic theory of ATI of atoms/highly charged ions and HHG on these quantum systems by laser radiation of relativistic intensities.

So, while the present book is introduced as a second edition of the monograph "Relativistic Nonlinear Electrodynamics" published in 2006, this book includes new material with five new chapters (Chaps. 10–14), a new paragraph (5.7), and some numerical treatment of considered processes for actual nonplanar laser pulses.

Now let us introduce briefly the content of this book to the reader.

With the appearance of lasers have come real possibilities for revealing numerous nonlinear phenomena of diverse nature resulting from the interaction of strong electromagnetic field either with matter or with free charged particles. First attempts of investigators, especially experimentalists, were directed toward studying the processes of interaction of laser radiation with matter, which led to the rapid formation of a new field—Nonlinear Optics. The numerous published books on this subject are evidence of that. The situation regarding the processes of interaction of laser radiation with free charged particles (free–free transitions) is different. Whereas the experimental results on atomic systems frequently had preceded the theoretical ones, the experimental investigations on free electrons began gathering power only recently. It is enough to mention that the first experiments on the observation of multiphoton exchange between free electrons and laser radiation started in 1975 (the Cherenkov and bremsstrahlung processes), whereas due to the progress of Nonlinear Optics, the precision laser spectroscopy of superhigh resolution on atomic systems had already been established. This situation is explained by two objective factors. While the experiments on atoms require only laser devices in common laboratories, the experiments on free electron beams require accelerators of charged particles and laser laboratories, i.e., this field is a synthesis of Accelerator and Laser Physics. The second major factor is the smallness of the photon–electron interaction cross section in comparison with the photon–atom one; revealing nonlinear phenomena on free electrons, this requires laser fields of relativistic intensities (e.g., even the observation of the second harmonic in nonlinear Compton scattering). Such superpower femtosecond laser sources have appeared only recently. Hence, the time for experimental development of this branch of Nonlinear Electrodynamics—covering interaction of charged particles with laser fields of relativistic intensities—has come. In presenting the current state of the art in this field and gathering up-to-date theoretical material in this book we have pursued the goal of stimulating the laser-driven experiments on relativistic electron beams and comprehensive theoretical investigations of nonlinear electromagnetic processes in currently available coherent radiation fields of relativistic intensities.

Increasing interest in free–free transitions is connected with the realization of the two most important problems of modern physics, namely the creation of shortwave coherent radiation sources—X-ray and γ-ray lasers—and small size laser-plasma accelerators of superhigh energies. It is noteworthy that a great deal of the work on free–free transitions are related to the Free Electron Laser (FEL) problem, i.e., to the discussion of concrete schemes of relativistic electron beam radiation amplification in coherent systems, such as the undulator, and to the search for their optimization. A small number of monographs and a large number of reviews are devoted to this problem in the linear regime of amplification. However, particularly for the implementation of X-ray lasers, the most promising candidate of which at the present time is still FEL devices, the need for nonlinear mechanisms of generation of coherent radiation due to induced interaction of electron beam with strong laser fields may be crucial, compared with the current undulator-based FELs in the linear regime of amplification. On the other hand, the present FELs operate in the classical regime where the electron wave packet size over the interaction length is less than a wavelength of radiation. This means that the photon frequency shift due to the electron quantum recoil must be less than the gain bandwidth. This condition is satisfied for current FELs typically operating at optical or smaller frequencies. For the X-ray photons in expected X-ray FELs, the downshifts in frequency as well as other quantum effects become important. Thus, because of the absence of mirrors (resonator) or other drivers operable at these wavelengths, FEL systems currently under consideration for X-ray sources, operate in the so-called Self-Amplified Spontaneous Emission (SASE) regime in which the initial shot noise on an electron beam is amplified over the course of propagation through a long wiggler. In turn, large pulse-to-pulse variations arise in both output power and radiation spectrum, and quantum effects on the start-up from noise will be important.

Finally, the absence of resonators at X-ray wavelengths requires a single-pass high-gain FEL, which in the linear regime will have an extremely large size. Hence, to reach the required gain on distances much smaller than the coherent length in the linear regime of amplification, which would reduce greatly the present size of projected X-ray lasers (several kilometers), nonlinear quantum mechanisms of generation due to laser-induced coherent interaction become of prime importance. On the other hand, the inverse problem of laser-induced nonlinear FEL schemes is the problem of creation of novel accelerators of charged particles of superhigh energies—laser-plasma accelerators. Therefore, the nonlinear interaction of charged particles with strong laser fields will be considered in general aspects from the point of view of both nonlinear quantum FEL schemes and classical laser accelerator problems. At the same time, we will not overload the material of this book, the subject of which is nonlinear electromagnetic processes, with the consideration of linear schemes of FELs taking also into account the existence of well-known books by T. Marshall (1987), C. Brau (1990), H. Freund and T. Antonsen (1996), and

E. Saldin, E. Schneidmiller, and M. Yurkov (1999) devoted especially to this problem.

Besides the mentioned problems there is another important problem concerning the quantum electrodynamic vacuum in superstrong laser fields. With the appearance of superpower lasers of relativistic intensities in recent years, for which the energy of an electron acquired at a wavelength of laser radiation exceeds the electron rest energy, multiphoton excitation of the Dirac vacuum via nonlinear channels becomes real and, consequently, electron–positron pair production becomes available. It is a strongly nonlinear process in superintense laser fields, which occurs inevitably in all processes where the conservation laws for the pair production are permitted. Thus, while considering such nonlinear processes we will give special consideration to the multiphoton electron–positron pair production from superintense laser fields.

Among the considered processes and, in general, stimulated processes with the charged particles, coherent processes like Cherenkov, Compton, and undulator essentially differ due to a peculiarity that fundamentally changes the common picture of electromagnetic processes in dielectric media, and in vacuum—the presence of a second wave or an undulator. Because of the coherent character of the corresponding spontaneous radiation process (the existence of certain coherence condition for radiation) in the presence of an external electromagnetic wave a critical value of the wave field exists above which a plane wave becomes a potential barrier or well for a particle and specific threshold nonlinear phenomena arise. The latter opens new possibilities for laser acceleration and FEL, since in these regimes the induced process proceeds only in one direction: the inverse concurrent process of radiation in acceleration regime, and absorption process for the FEL regime are absent. Therefore, we expect that this book will help to direct the attention of experimentalists to nonlinear phenomena of "reflection" and capture of charged particles by a plane electromagnetic wave in Cherenkov, Compton, and undulator processes, which have been left in the shadows for more than four decades. This especially relates to the experiments on the induced Cherenkov process made at SLAC by R. Pantell and collaborators since 1975, where the laser intensities were left below the critical value for the induced nonlinear Cherenkov resonance. It was necessary to increase the laser intensity slightly to reveal the existence of critical intensity and electron shock acceleration due to the "reflection" phenomenon, proving thereby the peculiarity of the induced Cherenkov process with its nonlinear threshold nature.

It is worth emphasizing another threshold phenomenon of nonlinear cyclotron resonance in an arbitrary dispersive medium—dielectric or plasma. That is so-called electron hysteresis, which can serve as an actual mechanism for laser acceleration of charged particle beams in plasma media where the use of superpower laser fields is not restricted and significant acceleration may be reached.

As is known, the spontaneous radiation of relativistic electrons and positrons channeled in a crystal is of great interest due to two major factors: the radiation is in the X-ray and γ-ray domains, and its spectral intensity noticeably exceeds that of other radiation sources in the short-wave range. Thus, induced channeling radiation in the presence of an external wave field becomes important as a potential source for short-wave coherent radiation. On the other hand, due to the induced channeling effect the inverse process—absorption of the wave photons by the particles—will also take place leading the particles' acceleration and other coherent classical and quantum effects. As a periodic system with high coherency and having the same character as a particle motion, the crystal channel may be compared with an undulator—it is a "micro-undulator" with the space period much smaller than the undulator one. We thus give consideration to the induced channeling process in general aspects of coherent interaction of relativistic electrons and positrons with a plane electromagnetic wave in a crystal.

Concerning the consideration of induced noncoherent processes, please note that in this book we included only induced processes related to plasma media where they provide actual energy conversion between the particles and transverse electromagnetic wave and, due to nonlinear interaction, one can reach the effective outgrowth for the aforementioned problems having as origin the real energy exchange between the particles and laser beams. From this point of view SB, being an inevitable induced process in laser-plasma system, is the actual mechanism for absorption of plane electromagnetic radiation by plasma electrons at the scattering on the ions. So, it has a significant role in the problems of plasma heating, laser-plasma accelerator, as well as HHG in atomic/ionic systems through the continuum states in strong laser fields as an alternative means for implementation of coherent VUV–X-ray sources, which has witnessed significant experimental advancement in recent years. However, the consideration of these processes is beyond the scope of this book. We will consider here the relativistic SB in strong and superstrong radiation fields in regard to general aspects with nonlinear effects (nonrelativistic SB in various approximations has been considered in many books). We will also consider the case of coherent SB process in crystals, which is of relativistic nature by itself, having in mind consideration of a high-gain X-ray FEL scheme based on coherent bremsstrahlung in the crystals.

A separate chapter has been devoted to the so-called induced nonstationary transition effect based on the spontaneous transition radiation effect in a medium at the abrupt variation of its properties, to describe the nonlinear particle–strong wave interaction processes in plasma. Such a situation takes place inevitably at the interaction of superintense ultrashort laser pulses with any medium, which instantly turns into plasma. It is thus of certain interest to study the nonlinear processes at the formation of laser plasma. This process may also be of great interest in astrophysics related to conversion of electromagnetic radiation frequencies in nonstationary plasma, in particular formation of hard γ-quanta of relativistic energies, electron–positron pair production, and other nonlinear processes at the abrupt variation of the matter properties in high energy cosmic objects.

In order not to overload the reader, the references on a given subject are presented separately in each chapter. My apologies go to all authors whose works are not covered in this book. We included only the ones that are most directly related to this book.

Indeed, the problems discussed in this book do not exhaust the frame of induced nonlinear phenomena at the interaction of charged particles or condensed matter with strong and superstrong electromagnetic radiation. By considering a certain class of induced processes, we have aimed at revealing the principal features of nonlinear behavior of a particle/matter–strong wave interaction in laser-induced processes, which are of primary importance for the implementation of contemporary problems, the most significant of which are creation of powerful X-ray–γ-ray lasers, laser-plasma accelerators, and production of high density antimatter from superintense laser fields of ultra-relativistic intensities. And if the presentation of relativistic nonlinear theory of interaction of charged particles, QED vacuum, condensed matter, and specific quantized systems with strong and superstrong electromagnetic fields are helpful to specialists in this field, then the publication of this book will be justified.

In closing, I would like to thank Dr. G. Mkrtchian for assistance in preparation of the manuscript, and Dr. Tom Spicer, Senior Physics Editor, Springer-Verlag New York, for his efforts in the publishing of this book.

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