Preface

With the appearance of lasers have come real possibilities of 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 monographs 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. Whereas 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 — 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 high energy laser accelerators of charged particles. It is noteworthy that a great deal of the works on free–free transitions is 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 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 are 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 downshift 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 becomes 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 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 monographs 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 a third 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 the coherent processes like Cherenkov, Compton, and undulator essentially differ due to a peculiarity, which 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 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 open 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 three 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 process. It was necessary to increase the laser intensity a bit to reveal the existence of critical intensity and electron acceleration due to the "reflection" phenomenon, proving thereby the peculiarity of the induced Cherenkov process with its nonlinear threshold nature.

It is worthy emphasizing another threshold phenomenon of nonlinear cyclotron resonance in an arbitrary 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 reducing the particles' acceleration and other coherent classical and quantum effects. As a periodic system with high coherency and having the same character of 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 the present 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 the nonlinear interaction, one can reach the effective outgrowth from the point of view of the above-mentioned problems. In particular, Stimulated Bremsstrahlung (SB) is of interest in plasma in the presence of an electromagnetic radiation field, since bremsstrahlung is one of the major electrodynamic processes in plasma, and is the actual mechanism for plasma heating (a scattering center performs the role of a third body for actual absorption/radiation of the wave photons by a charged particle). Besides, the role of SB is significant in the process of particle acceleration with plasma/laser fields, as well as in the process of high harmonics generation in atomic/ionic systems through the continuum states in strong laser fields as an alternative means for implementation of coherent 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 monographs). We will also consider the coherent SB in crystals, which is of relativistic nature in itself, having in mind consideration of a high-gain X-ray FEL scheme based on coherent bremsstrahlung in a crystal.

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 femtosecond 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 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. I included only the ones that are most directly related to this monograph.

Indeed, the problems discussed in this monograph do not exhaust the frame of induced nonlinear phenomena at the interaction of charged particles with strong electromagnetic radiation. By considering a certain class of induced processes, we have aimed at revealing principal features of nonlinear behavior of a particle–strong wave interaction in coherent and noncoherent induced processes, which are of primary importance for the implementation of contemporary problems of FEL, laser accelerators, and electron–positron pair production from superintense laser fields. And if the consideration of these nonlinear processes based on relativistic classical and quantum theories and the presentation of the main results are helpful to specialists in this field, then the publication of this monograph will be justified.

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