INSTABILITIES in LASER–MATTER INTERACTION

Sergei I. Anisimov
Viktor A. Khokhlov
L.D. Landau Institute for Theoretical Physics
Russian Academy of Sciences
Moscow

CRC Press
Boca Raton London Tokyo

CRC Press, Inc., 2000 Corporate Blvd., N.W., Boca Raton, Florida 33431.

International Standard Book Number 0-8493-8660-8
Library of Congress Card Number 94-23471

Contents

PREFACE

The first experimental studies of laser–matter interaction were conducted in the early 1960s when the first high-power lasers were created. In these works, mainly thermal effects were studied including heating, melting, evaporation of condensed matter, and thermionic electron emission. When higher laser intensities were reached, it became possible to study the optical breakdown of gas and solid dielectrics. In the 1960s, the first theoretical models of laser–matter interaction also were proposed. The simplest models were related to moderate laser intensity ranges ($I \simeq 10^5$–10^9 W/cm^2) and took into account the energy transfer in condensed matter, the kinetics of phase transitions, and the dynamics of evaporated material expansion.[1−4] A survey of the results obtained during the initial period of laser–matter interaction studies can be found in Ready[5] and Anisimov et al.[6] Despite many simplifications, theoretical models[1−4] provide a basic outline of the actual interaction of laser radiation with solids at moderate laser intensities. However, it appeared to be difficult to reach a quantitative agreement between theory and experiments. In particular, the detailed analysis of phase composition and energy balance in laser ablation of metals[1,5,7] shows that a considerable part of the ablated material is in the form of liquid droplets, and the specific ablation energy—equal to the ratio of the incident laser energy to the mass of the material removed from the target—is several times less than the specific heat of vaporization. These facts cannot be explained by simple theoretical models. Another manifestation of the very complicated character of actual laser–matter interaction processes and the inadequacies of simple theoretical models follows from studies of target reflectivity changes during laser irradiation.[5,8] The experiments show that total reflectivity and particularly its specular part, is reduced considerably during a laser pulse. This reduction cannot be explained easily by a decrease in surface layer conductivity due to heating. Finally, such important characteristics as the phase composition of the ablated material, the specific ablation energy, and the recoil momentum transferred to the target are extremely sensitive to the specifics of the laser pulse structure and focusing conditions.[9]

These facts can be understood from a single viewpoint if we suppose that laser-induced evaporation of condensed materials can be unstable under certain conditions. The first example of laser-produced evaporation instability, studied by Anisimov, Tribel'skii, and Epel'baum[10] was the corrugation instability of a plane stationary vaporization front in highly absorbing solids. This instability is driven by the temperature gradient in the vicinity of the phase-transition front. A similar instability mode appears in laser-induced evaporation of transparent dielectrics. Furthermore, the thermal and avalanche breakdown of transparent dielectrics also can be considered to be a particular mode of instability of these materials in a strong electromagnetic field. Many other examples of instability have been studied during recent years.[11−13] These studies clearly demonstrate that most of the laser–matter interaction processes are unstable.

In the present book, a review is given of thermal and hydrodynamic instabilities appearing in laser–matter interactions at moderate intensities. These instabilities also can arise in the processes of heating of condensed matter with electron and ion beams, shock waves, etc. Nonresonant interactions are the subject of this book; to include resonant electromagnetic modes related to the generation of surface electromagnetic waves would require a second book. Note also that these phenomena are not characteristic for the the interaction of electron or ion beams with solids. A comprehensive review of the phenomena associated with surface electromagnetic waves can be found in references 11–13. We will not consider here problems of laser-driven inertial confinement fusion; instead, we will restrict our attention to the range of low and moderate laser intensities that are important for technological applications of lasers.

This book is constructed as follows: In the first four chapters, we give a survey of the basic processes of nonresonant laser–matter interactions. Laser-induced breakdown of transparent dielectrics is considered in Chapter **??**, as an example of instability of "thermal explosion" type (see Frank-Kamenetskii[14]). Chapter **??** contains a brief analysis of the effects produced by ultrashort (picosecond and femtosecond) laser pulses. This problem recently has attracted extensive interest due to the important applications of ultrafast laser technology. The problems of stability of thermal processes induced by ultrashort laser pulses have not yet been studied.

In chapters **??** to **??** we consider thermal and hydrodynamic instabilities. This provides a theoretical background to the interpretation of experimental results and an understanding of the effect of instabilities on the processes of laser technology.

We would like to note that the instabilities discussed in this book are important for the interpretation of laser interaction experiments and technological applications of lasers. The instabilities are also of interest from the standpoint of fundamental physics. There are many examples of physical systems whose stable steady states have a symmetry that does not correspond to the symmetry of external conditions. In these cases, it is customary to discuss spontaneous symmetry breaking. Many examples of this general phenomenon are known in the fields of atomic and molecular physics, solid state physics, hydrodynamics, and quantum field theory.[15−17] Laser-matter interactions give additional examples of symmetry breaking due to instability. The analysis of the symmetry breaking and structure formation is a part of the general theory of self-organization, which has been given notice during the past 20 years. The concepts and methods of this theory can be employed, as we will see later, in laser-matter interaction studies.

This book is devoted mainly to the theoretical analysis of laser–matter interaction and instability phenomena. This analysis is based primarily on the results of studies carried out by Russian physicists during the past 10–15 years. These results were published primarily in Russian journals and were delayed in reaching western readers.

The authors are grateful to their friends and colleagues: D. Bäuerle, A. M. Bonch-Bruevich, M. N. Libenson, B. S. Luk'yanchuk, J. Meyer-ter-Vehn, M. I. Tribel'skii, and S. Witkowski for helpful discussions and criticism during the preparation of this book. One of the authors (S. A.) acknowledges with gratitude the kind hospitality of the Max-Planck-Institute for Quantum Optics (Garching, Germany) and the support of the Alexander von Humboldt Foundation.

REFERENCES

1. Anisimov, S. I., Bonch-Bruevich, A. M., Elyashevich, M. A., Imas, Ya. A., Pavlenko, N. A., and Romanov, G. S., Effect of powerful light fluxes on metals, *Sov. Phys.–Tech. Phys.*, **11**, 945, 1967

2. Ready J. F., Effects due to absorption of laser radiation, *Journ. Appl. Phys.*, **36**, 462, 1965

3. Anisimov, S. I., Evaporation of light-absorbing metals, *High Temperature*, **6**, 110, 1968

4. Aleshin, I. V., Bonch-Bruevich, A. M., Imas, Ya. A., Libenson M. N., Rubanova G. M., and Salyadinov, V. S., Laser-induced evaporation of nonlinearly absorbing dielectrics, *Sov. Phys.–Tech. Phys.*, **22**, 1400, 1977

5. Ready, J. F., *Effects of High-Power Laser Radiation*, Academic Press, New York, 1971

6. Anisimov, S. I., Imas Ya. A., Romanov, G. S., and Khodyko, Yu. V., *Action of High-Power Radiation on Metals*, Natl. Tech. Inform. Service, Springfield, VA, 1971

7. Panteleev, V. V. and Yankovskii, A. A., Use of laser beams for vaporizing materials in spectral analysis, *Journ. Appl. Spectroscopy*, **3**, 260, 1965

8. Bonch-Bruevich, A. M., Imas, Ya. A., Romanov, G. S., Libenson, M. N., and Mal'tsev, L. N., Effect of a laser pulse on the reflecting power of metals, *Sov. Phys.–Tech. Phys.*, **13**, 640, 1968

9. Bass, M., Nassar, M. A., and Swimm, R. T., Impulse coupling to aluminum resulting from Nd: glass laser irradiation induced material removal, *Journ. Appl. Phys.*, **61**, 1137, 1987

10. Anisimov, S. I., Tribelskii, M. I., and Epelbaum, Ya. G., Instability of a plane evaporation front in the interaction of laser radiation with a medium, *Sov. Phys.–JETP*, **51**, 802, 1980

11. Bonch-Bruevich, A. M. and Libenson, M. N., Laser-induced surface polaritons and optical breakdown, In *Nonlinear Surface Electromagnetic Phenomena*, Ed. by Ponath ,H.-E. and Stegman, G. I., Elsevier Science Publ., 1991, 561

12. Bonch-Bruevich, A. M., Libenson, M. N., Makin, V. S., and Trubaev, V. V., Surface electromagnetic waves in optics, *Optical Engineering*, **31**, 718, 1992

13. Akhmanov, S. A., Emel'yanov, V. I., Koroteev, N. I., and Seminogov, V. N., Interaction of powerful laser radiation with the surfaces of semiconductors and metals: nonlinear optical effects and nonlinear optical diagnostics, *Sov. Phys.–Uspekhi,* **28**, 1084, 1985

14. Frank-Kamenetskii, D. A., *Diffusion and Heat Transfer in Chemical Kinetics*, Plenum Press, New York, 1969

15. Elliott, J. P. and Dawber, P. G., *Symmetry in Physics*, **12**, Macmillan Press, London, 1979

16. Haken, H., *Synergetics*, Springer-Verlag, New York, 1978

17. Anisimov, S. I. and Tribel'skii, M. I., Instability and spontaneous symmetry breaking in macroscopic laser–matter interaction, *Sov. Sci. Rev., A Phys.*, **8**, 259, 1987