Laser Plasma Physics
Forces and the Nonlinearity Principle
Second Edition

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Dedicated to the Memory of
Edward Teller

and with sincere thanks to my collaborators who have
contributed to the progress in this field
# Table of Contents

*Preface to the Second Edition*  
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1. **Introduction to the Ponderomotion Processes and Overview of Related Phenomena**  

2. **Elementary Plasma Properties and Hydrodynamics**  
   2.1 Definition of Plasma  
   2.2 Elementary Plasma Parameters  
   2.3 Hydrodynamics  
   2.4 Concept of Microscopic Plasma Theory  

3. **Electrodynamics and Plasma**  
   3.1 Maxwell’s Equations  
   3.2 Derivation of the Lorentz Force  
   3.3 Schlüter’s Two-Fluid Equations and Optical Properties of Plasma  
   3.4 Waves in Inhomogeneous Media and Phase between $E$ and $H$  

4. **Hydrodynamic Derivation of the Nonlinear Forces with Ponderomotion**  
   4.1 Simple Derivation of the Nonlinear Force for Perpendicular Incidence  
   4.2 Ponderomotive and Nonponderomotive Terms: Predominance of the Nonlinear Force  
   4.3 Numerical and Experimental Results  
   4.4 Problem at Oblique Incidence  
   4.5 General Derivation of the Nonlinear Force and Hydrodynamic Foundation of the Maxwell Stress Tensor  
   4.6 Generalized Ohm’s Law and Solitons  

5. **Hydrodynamic Plasma Properties with the Nonlinear Force**  
   5.1 Momentum Transfer  
   5.2 Ponderomotion: The Electric Analogy to Alfvén Waves  
   5.3 Ponderomotive and Relativistic Self-Focusing  

6. **Single-Particle Derivation of the Nonlinear Force**  
   6.1 Quiver Drift and Electric Double Layers  

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6.2 The Boreham Experiment Concluding Longitudinal Optical Fields and Prediction of the Meyerhofer Forward Drift 123
6.3 A Remark on Stephen Hawking and the Nonlinearity Principle 131

7 Advanced Laser Acceleration of Electrons 155
7.1 Free Wave Accelerator 156
7.2 Umstadter Experiment of MeV Electrons 159
7.3 Nonlinearity Solves Linear Superposition Question of the Lawson–Woodworth Problem 162
7.4 A Scale for Maximum Electron Energy 166
7.5 Paraxial Approximation and Exact Presentation of the Laser Field 169
7.6 Phase Dependence of the Relativistic Acceleration of Electrons in the Laser Fields in Vacuum 171
7.7 Concluding Remarks 175

8 Ultrafast Acceleration of Plasma Blocks by the Nonlinear Force 179
8.1 Extreme Light: Chirped Pulse Amplification 181
8.2 Theoretical Prediction and Measurement of Ultrahigh Acceleration 182
8.3 Picosecond Plasma Block Initiation for Fusion 189
8.4 Block Ignition Updated by Chu–Bobin Fusion Flames 191
8.4.1 Optimum thickness of accelerated plasma blocks and reduced thresholds 191
8.4.2 Inhibition factor 197
8.4.3 Collective effect for alpha particle stopping 202
8.4.4 Hydrodynamic calculations 204
8.4.5 Fusion reactions and high-speed flame fronts 209

9 Laser-Driven Fusion with Nanosecond Pulses 217
9.1 General Approach 217
9.2 A Preliminary View 222
9.3 Historical Remarks on Volume Ignition 223
9.4 Volume Ignition Compared with Spark Ignition 229
9.5 Self-Similar Volume Compression Agrees with Measured Fusion Gains 232
9.6 Thermal Compression and Volume Ignition of Boron Fusion 235
9.7 Outlook for Volume Ignition for NIF Conditions 238

10 Laser-Driven Fusion Energy with Picosecond Pulses for Block Ignition 243
10.1 New Aspects by Subpicosecond Laser Pulses 243
10.2 New Results for Boron Fusion 245
10.3 From Plane Geometry to Usable Irradiation 247
### Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.4 Solutions with Ultrahigh Magnetic Fields</td>
<td>254</td>
</tr>
<tr>
<td>10.5 Measured Avalanche Boron Reaction for an Absolutely Clean Fusion Power Station</td>
<td>265</td>
</tr>
<tr>
<td>10.6 Concluding Remarks</td>
<td>269</td>
</tr>
<tr>
<td><strong>Appendix: Collective Interaction of Plasma Blocks</strong></td>
<td>273</td>
</tr>
<tr>
<td><strong>References</strong></td>
<td>299</td>
</tr>
<tr>
<td><strong>Subject Index</strong></td>
<td>325</td>
</tr>
</tbody>
</table>
Preface to the Second Edition

Since 1845, Lord Kelvin’s discovery of how electrically neutral materials can be moved by electric fields has formed the basis of plasma theory. This force of ponderomotion is nonlinear, as it combines mechanical macroscopic forces with quadratic terms of the force quantities of electric and magnetic fields. It has now been shown that this is interwoven with electron clouds as seen in the Boreham experiment, the Umstadter experiment, and in the particle-in-cell (PIC) computations where electric double layers appear as a Debye sheath in the target normal sheath acceleration (TNSA). It should be noted, however, that there is a basic difference in the optical properties of the forces defined by laser fields in contrast to the sheath layer of plasma boundaries (Snively et al. 2000). This is the topic of the new Chapter 7.

Along with subsection 6.3, this new Chapter 7 shows how the nonlinearity principle is compatible with fundamentals of physics as described by Richard Feynman, thereby dispelling any concerns about the saturation or end of physics, and showing instead that nonlinearity is opening a new dimension of physical knowledge.

This leads into a new Chapter 8, which discusses the measurements of ultrahigh acceleration of plasma blocks first experimentally verified by Sauerbrey (1996) and Földes et al. (2000), proving numerical predictions from 1978 (Hora 1981). Such measurements were made possible by the work of Mourou and collaborators since 1986 on laser CPA (chirped pulse amplification). The 1978 theory predicted that the ultrafast accelerated plasma blocks contained (space-charge neutralized) ultrahigh ion current densities (Hora et al. 2002) a million times higher than accelerators could produce. So instead of using huge accelerators, such ions in the 100 MeV range could lead to an important new application that is independent of nuclear fusion: very compact hadron therapy for cancer (Banati et al. 2014).

This second edition presents several specific insights into the breadth of developments during the 15 years since the first edition’s publication.

A new Chapter 9 addresses how ultrahigh accelerated plasma blocks driven by the nonlinear force can be applied to laser ignition of controlled...
nuclear fusion. The chapter also integrates the two appendices of the first edition. It clarifies how laser-driven fusion with nanosecond (ns) pulses using thermal processes for heating, compressing, and igniting fusion fuel differs from picosecond (ps) and shorter laser pulse interaction for realizing the complex systems of the contrary thermal processes. It describes how to arrive at non-thermal direct conversion of laser pulse energy into macroscopic mechanical energy of motion by ultrahigh acceleration, described in terms of complex systems by Lord May of Oxford (May 1972) and a basic note by Edward Teller (2001) in Chapter 1.

This all culminates in Chapter 10 with an exploration of the new possibilities gained by fast ignition of laser fusion as envisioned by Campbell (2006) in 1991 and formulated by Tabak et al. (1994). The result is rather interesting because it shows how fusion is possible beyond the usual fuel of deuterium-tritium (DT). It is now possible to burn protons with boron-11 (HB11) where the generation of very dangerous nuclear radiation can be ignored, because it is no more dangerous than from burning coal. Finally, producing magnetic fields in the range of 10 kilotesla may provide the potential for developing power stations where picosecond (ps) laser pulses with power no more than a few dozens of petawatts (PW) are needed. These pulses are likely to be developed in the near future for many other important basic applications aside from fusion energy, led by the work of Mourou (Mourou et al. 2014; 2014a). This is described at the beginning of the new Chapter 8.

The first edition of this book covered the fundamental physics of the past. In this new edition, we turn our attention to research covering a wide field of unexplored phenomena, thereby changing the character of this book. While these explorations are connected to classical knowledge, including Richard Feynman’s thoughts on the Nonlinearity Principle (Section 6.3), there are a number of new points requiring clarification. These may offer fascinating insights into the exploration of physics in general, as well as into the production of safe, clean, and low-cost energy in the near term.

During the production of this book, several new results were reported and incorporated into this text, such as the experimental discovery of the super-high gains of the proton-boron fusion HB11 by Picciotto et al. (2014) and highlighted by Korn et al. (2014a). This lead to the combination with block ignition and cylindrical trapping by ultrahigh magnetic fields (Lalousis et al. 2014a), and then to a clarification of the avalanche ignition of HB11 (Hora et al. 2015a), presenting a possible option for absolutely clean, sustainable and low-cost boron fusion energy.
The enthusiasm for finalizing the production of this book by SPIE under Nicole Harris’s editorial attention is very gratefully acknowledged.

*Heinrich Hora*

*Sydney, August 2015*
Preface to the First Edition

Many renowned physicists speak very articulately about the “ponderomotive potential.” It is now used in a wider context of high intensity laser interaction with plasma, or for acceleration of electrons by lasers, or in free electron lasers and many other related fields. There is now a growing interest in this topic. However, taking the desire for a clear definition into account, we see there are historical difficulties regarding the definition of ponderomotive force. One may a little less precisely say that it relates to electrodynamic forces acting on plasmas or on free electrical charges, which are basically different from the Coulomb force. These forces are essentially nonlinear and in a general sense are called nonlinear forces.

The study of these forces was necessary with the advent of the laser for understanding the very strange observations of interaction with plasma. This fascinating new field has a much broader basic importance than the high intensity laser interaction with materials and plasmas. It was necessary to underline the confusion with the correct definition, insufficiencies in applications and their exact solution for the highly advancing field of laser physics. Diverging opinions of authorities were not helpful. The more or less settled view about this is being presented here.

The following rather abbreviated reviews on hydrodynamics and electrodynamics may be an enlightening path for the advanced student as well as for the expert with many years of experience to see how the theoretical and experimental studies of the nonlinear (ponderomotive) force led to the new foundation and completion of magneto-hydrodynamics. Some colleagues have mentioned to me that they now understood Maxwell’s theory better. It should be mentioned that the waves in inhomogeneous media are presented here in a more general way (within all shortness) than in Ginzburg’s best-selling book.

But this is not the main mission. The reader should know that the work he does in understanding this text mostly in the area of classical physics will result in a very global view about physics in general. The thrilling story of the highly unexpected phenomena of laser–plasma interaction with the generation of GeV ions after relativistic self-focusing, with a stochastically pulsating (stuttering) interaction within a 20 ps scale, electron acceleration, fusion
energy, laser ablation of materials in technology, etc., led to the co-discovery of the longitudinal components of laser beams in a vacuum. What was so surprising is that the mechanical motion of electrons in the intense laser fields depends drastically on very minor changes of these fields. This teaches us that nonlinear physics needs the highest possible degree of accuracy, much higher than that required by linear physics.

This accuracy principle of nonlinearity implies that in the future, completely undreamable phenomena and applications will be derived in all fields of physics if only sufficient accuracy, for example, with the most advanced computations, will be performed. We know now what we have to watch next: we have to be aware that not only curiosities but fully unexpected phenomena will be revealed. This is the new message for a rich future of physics. It was impossible to suppress some remarks against the views of a saturation and “an end” of physics as expressed in some way by Stephen Hawking or Carl Friedrich von Weizsäcker. The work on the nonlinear (ponderomotive) force and the related phenomena of driving plasmas or particles by lasers led unavoidably through this new gate of physics as a further promise for a bright future.

The initial version of the text suffered indeed from a large number of misprints which have been removed, such that this rather unusual and not trivial text may now be absorbed better by the reader. As an appendix, a recent publication has been added as a first step to demonstrate directions to the reader where the applications are following from the rather compactly presented and interwoven development of this new chapter of physics.

Support for the preparation of this text by the Department of Theoretical Physics of the University of New South Wales in Sydney, Australia, and by the new University of Applied Sciences in Deggendorf, Germany, and encouragement by Präsident Prof. Dr. Reinhard Höpfl are gratefully acknowledged.

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