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The Physics of Inertial Fusion

Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter

STEFANO ATZENI
JÜRGEN MEYER-TER-VEHN

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The physics of inertial fusion

BEAM PLASMA INTERACTION, HYDRODYNAMICS, HOT DENSE MATTER

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Foreword

The authors of this excellent book have asked me for a brief foreword, giving some emphasis to the early work on laser fusion at the Lawrence Livermore National Laboratory (LLNL). This work was motivated by the possibility that lasers could create states of matter and thermal radiation that were similar to those found in thermonuclear weapons; and, in the longer term, the possibility that a small amount of DT could be compressed and ignited without the help of fission. The basic principles of high yield-to-weight nuclear weapon design had largely been learned and put into practice in 1962, but the intriguing challenge of 'pure fusion' remained.

Meanwhile in the Summer of 1961, the technique of cavity 'Q-spoiling' was demonstrated at the Hughes Research Laboratory at Malibu, and applied to produce powerful short-duration light pulses with the ruby laser that also had been invented there in 1960. At the same time at the American Optical Company it was shown that a laser could be made with any one of a number of rare-earth oxides dissolved in glass, instead of ruby. This made it posible to use relatively inexpensive material as the laser medium, and offered the prospect of building pulsed lasers of greatly increased size and power.

As a result of this promising outlook, the (then-named) Lawrence Radiation Laboratory began an exploratory research programme in the Spring of 1962 to study the interaction of intense light with plasma, to evaluate the feasibility of constructing a laser with enough energy and power to ignite DT, and to investigate suitable implosion and ignition configurations. Preliminary calculations suggested that a laser pulse of at least 100 kJ of energy and at most 10 ns duration would be required. Similar programmes were begun at several European laboratories, including the Lebedev Physical Institute in Moscow, USSR, and the Comissariat l'Energie Atomique Laboratory in Limeil, France.

This exploratory programme continued from 1962 to 1972. Lasers considered for possible large-scale development were the neodymium-glass and atomic-iodine lasers. The former was chosen, and a prototype amplifier consisting of 16 face-pumped disks, oriented at Brewster's non-reflecting angle, was built. This amplifier, in a multi-pass configuration, was used to amplify single 5 ns pulses for laser–plasma interaction studies. An important result was the discovery, shared with the Lebedev Institute, of energetic 'hot' electrons that could cause excessive pre-heating of the DT fuel being compressed. This effect, together with greatly improved laser/target coupling obtained with light of shorter wavelength, led to the use of the third harmonic of the laser light to drive target implosions.

The close relation between the physics of the H-bomb and the physics of inertial confinement fusion (ICF) caused the United States and other nuclear weapons states to classify some aspects of ICF that were considered sensitive, especially the importance of fuel-compression and the use of thermal X-rays to drive an implosion. The former was not declassified until 1971 when it was disclosed in a Soviet paper presented at a meeting of the European Physical Society in England. The latter remained classified until 1981 when the following statements were officially released:

1. In thermonuclear weapons, radiation from a fission explosive can be contained and used to compress and ignite a physically separate component containing thermonuclear fuel (the Teller-Ulam 'radiation implosion' principle).
2. In some ICF targets radiation from the conversion of focused energy (e.g. laser or particle beam) can be contained and used to transfer energy to compress and ignite a physically separate component containing thermonuclear fuel (the 'indirect-drive' approach to ICF).

Shortly after the declassification of compression, a landmark paper was given in May of 1972 at the International Quantum Electronics Conference in Montreal by a group from Livermore. The results of computer simulations of a direct-drive implosion of a droplet of liquid DT suggested that central 'hot spot' fuel ignition together with 10,000-fold fuel compression could be achieved by properly programming the time-dependence of the laser power driving the implosion; and that 60 kJ of laser energy would be sufficient to generate 1800 kJ of thermonuclear energy, a 30-fold gain in energy. These important results prompted a major increase in ICF interest both in the United states and abroad.

At Livermore, a decision was made to substantially increase the size of the programme, and focus attention on developing the large laser system needed to achieve thermonuclear ignition by means of indirect drive. A succession of lasers of increasing size and output energy were developed and tested, leading to the present construction of a 192-beam, 1.8 MJ laser at the National Ignition Facility (NIF). A laser of similar capability, Laser Megajoule (LMJ), is being constructed at Bordeaux, France.

The NIF and LMJ are expected to be completed in 2008. They will provide an unprecedented capability for the laboratory study of matter at high energy density, its interaction with intense radiation, and for meeting the long-standing challenge of 'pure fusion'. A relative newcomer to the field of high energy density is the 'ultra-intense chirped-pulse laser' capable of producing light at energy densities orders of magnitude greater than the ICF lasers, and with possible applications to ICF and nuclear physics.

This book is indeed timely, providing as it does a lucid and comprehensive exposition of the Physics of High Energy Density and Inertial Confinement Fusion, on the threshold of this rapidly expanding field of physics. The authors are both from an academic science environment with no connections to weapons research. Their book may help to establish laboratory high energy density physics with high power beams as a normal branch of plasma physics with many civilian applications.

Pleasanton
July 2003

RAY KIDDER

Preface

This book is devoted to inertial fusion targets and the various branches of physics involved. It covers hydrodynamics, hydrodynamic instabilities, thermal transport, radiative and collisional processes in hot dense matter, equations of state, plasma interaction of high-power laser and ion beams, as well as nuclear fusion reactions. The book addresses researchers working in this field, those teaching it to students as well as students themselves. It is intended as an introduction providing basic understanding, but also as a reference book deriving all the key formulas including scaling exponents and numerical factors.

The book grew out of high-power laser research in Germany and Italy related to inertial fusion energy. Both authors joined the field at about 1980 after the pioneering time, described by Ray Kidder in the foreword. In 1980, it was clear that small fuel capsules had to be imploded to high density, but most of the details, including basic aspects such as the use of thermal radiation, were still classified. This meant that most of the physics ingredients had to be developed from scratch, including simulation codes which then matured over the years.

In Germany, high-power laser research was performed at IPP Garching (and later at MPQ), directed by S. Witkowski. These early activities were upgraded in 1979, when R. Bock initiated research on heavy ion fusion at GSI Darmstadt with a clear focus on fusion energy. It was this experimental environment at MPQ and GSI that strongly determined the work of one of us (MtV). Also the HIBALL reactor study, headed by G. Kessler from KFK Karlsruhe and G. Kulscinski from the University of Wisconsin, set the direction of the target work for many years.

In Italy, research on laser-produced plasmas was pursued at Laboratorio Gas Ionizzati of CNEN (later Fusion Division of ENEA), directed by B. Brunelli, since 1963. A group of researchers, headed first by U. Ascoli-Bartoli and later by A. Caruso, performed pioneering experiments and developed the theory of ablative pressure generation. The activity, interrupted in 1970, was resumed about a decade later, when the construction of the ABC laser was approved, and a small fusion-oriented programme was devised. Just at this time (1978) one of us (S. A.) joined the Frascati group as a student, to prepare a thesis on laser-driven fusion-ignition. This marked the beginning of a two-decade activity on laser-produced plasma and inertial confinement fusion (ICF), first at ENEA, and since 2000 at the University of Rome.

Chapters 3–5 of this book present the basic concepts of ICF: implosion, ignition, and gain. They reflect (and extend) much of the work performed by the authors in the early 1980s. At that time, gaining autonomous understanding of ICF was a key issue at our laboratories. ENEA-Frascati contributed to the theory of hot spot ignition and gain models, developed the 1D IMPLO code and designed ICF targets. S. A. acknowledges the initial guidance of his thesis advisor B. Brunelli, the early work under the direction of A. Caruso, and the cooperation with A. Giupponi and V. A. Pais. He also thanks S. Nakai and H. Takabe for suggesting an in-depth analysis of non-isobaric configurations. The presentation of Chapter 3 owes much to the seminal work by Rochester colleagues, led by R. L. McCrory

and C. Verdon, and to enlightening discussions with S. Bodner. For exchanges of ideas on gain curves, we thank M. Basko, M. Herrmann, J. Lindl, M. Key, M. Tabak, and R. Piriz.

After 1981, the role of thermal radiation to drive target implosions with high symmetry gradually became clearer to us, and it was then the work of R. Sigel on hohlraum targets that determined 12 years of research on radiation hydrodynamics at MPQ, culminating in joint German-Japanese experiments at ILE in Osaka with R. Sigel and H. Nishimura as the leading scientists. Larger portions of Chapter 7 on thermal waves, Chapter 9 on hohlraum targets and the sections of Chapter 10 on opacity modelling are based on results of this period. This includes the heat wave solution (at MPQ first found by R. Pakula), simple high-Z opacity models developed by K. Eidmann and G. Tsakiris, radiatively driven shock wave experiments and opacity measurements performed by T. Löwer, K. Eidmann, and many others. The development of the 1D and 2D MULTI code by R. Ramis allowed us to design hohlraum targets for heavy ion fusion; in particular, we thank J. Honrubia, M. Murakami, A. Oparin, R. Ramis, and Th. Schlegel for their contributions to Chapter 9. Similar work was performed at ENEA Frascati, which led to the first published 1D simulation of an indirect drive high gain target (by A. Caruso and V. A. Pais) and to analytical results on radiation symmetrization. All this work was driven in some indirect way by the corresponding research of our Livermore colleagues, even though explicit exchange of results became possible only after the declassification act of 1993.

Since the mid-1980s, aspects of symmetry and stability became the focus of theoretical and simulation research at ENEA-Frascati. In particular, this led to the development of the 2D code DUED, results of which are essential for Chapters 3, 8, and 12. Here S. A. wishes to thank M. L. Ciampi, A. Guerrieri, S. Graziadei, and M. Temporal for their contribution to DUED and to the simulation studies. Another stimulus came in the 1990s from an European initiative to study heavy ion fusion, promoted by C. Rubbia and promptly supported by R. A. Ricci in Italy and R. Bock in Germany. Chapter 8, on hydrodynamic instabilities, profited strongly from discussions with a number of colleagues. In particular, we thank H. Azechi, S. Bodner, S. Haan, N. A. Inogamov, A. R. Piriz, D. Shvarts, H. Takabe, and J. G. Wouchuk. The presentation also takes advantage from the review papers by H.-J. Kull on the potential flow model and by R. Betti and collaborators on ablative instabilities.

J. MtV wants to express his special gratitude to S. Anisimov from the Landau Institute for Theoretical Physics in Moscow, who provided invaluable insight and advice to essentially all matters of this book. This concerns in particular Chapter 6 on hydrodynamics and the fundamental aspects of similarity solutions. The annual German–Russian seminars (1984–89), organized on the Russian side by S. Anisimov and V. Fortov, gave us contact to leading Russian scientists and access to the important Russian literature. We acknowledge numerous discussions with V. Fortov on shock waves and high energy density physics. J. MtV also acknowledges a one-month stay at GSI in 1994, when first parts of this book were written. He thanks I. Hofmann from GSI for many discussions on accelerator issues of heavy ion ICF and also D. Hoffmann and the GSI plasma group for their substantial input to Chapter 11 on ion beam stopping. This includes fruitful discussions with M. Basko and B. Sharkov from ITEP Moscow as well as T. Mehlhorn from the Sandia laboratories.

Both authors enjoyed a guest professorship at ILE in Osaka (Japan), S. A. in 1993, and J. MtV in 1995. Several sections of this book are based on our lecture notes at ILE. We both want to thank the directors S. Nakai and later K. Mima as well as all our colleagues at ILE for the very stimulating atmosphere at their institute. Discussions with K. Nishihara, M. Murakami, H. Takabe as well as H. Azechi and Y. Kato are gratefully acknowledged.

J. MtV thanks Grant Logan for a stay at UC Berkeley in 2003, where Chapters 10 and 11 were finalized and from where he had frequent contacts to his Livermore colleagues to check special parts of the book, in particular with J. Hammer, S. Hatchett, M. Herrmann , J. Lindl, and M. Rosen. Concerning Chapter 12, the authors owe a lot to the recent workshops on fast ignition of fusion targets and in particular to S. Hatchett, M. Key, P. Norreys, M. Roth, and M. Tabak. J. MtV acknowledges in particular 6 years of most fruitful cooperation with A. Pukhov on relativistic laser–plasma interaction based on particle simulations. This also comprises K. Witte and the MPQ experimental crew with K. Eidmann, E. Fill, G. Tsakiris, and their excellent students. S. A. acknowledges the skilful contribution to 2D fast ignition simulations by M. L. Ciampi and M. Temporal.

Finally we are indebted to R. Bock and R. Kidder for reading the whole manuscript, S. Anisimov, F. V. Frazzoli, and S. Hatchett for their comments on special chapters, A. Krenz, Ke Lan, Th. Schlegel, and, in particular, Zh. M. Sheng for help with the figures.

Writing this book turned out to be a fascinating, but far more time consuming task than initially expected. It is only thanks to the patience, understanding, and support of our families, especially our wives Beatrice and Helga, that we could complete this book. S. A. thanks Helga for her warm hospitality at MtV´s home in Garching; both authors are indebted to Mrs Caterina Tomassi-Atzeni (S. A.'s mother), whose mountain home at Petrella Liri in the Italian Appennins served us as a refuge, where we could work together efficiently.

S. ATZENI (ROMA)

July 2003 J. MEYER-TER-VEHN (GARCHING)

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