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BOOK REVIEW

Inertial confinement fusion: The quest for ignition and energy gain using indirect drive

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Abstract

Inertial confinement fusion (ICF) is an alternative way to control fusion which is based on scaling down a thermonuclear explosion to a small size, applicable for power production, a kind of thermonuclear internal combustion engine.

This book extends many interesting topics concerning the research and development on ICF of the last 25 years. It provides a systematic development of the physics basis and also various experimental data on radiation driven implosion. This is a landmark treatise presented at the right time.

It is based on the article ``Development of the indirect-drive approach to inertial confinement fusion and the target physics basis for ignition and gain'' by J.D. Lindl, published in *Physics of Plasmas*, Vol. 2, November 1995, pp. 3933-4024. As is well known, in the United States of America research on the target physics basis for indirect drive remained largely classified until 1994. The indirect drive approaches were closely related to nuclear weapons research at Lawrence Livermore and Los Alamos National Laboratories. In Japan and other countries, inertial confinement fusion research for civil energy has been successfully performed to achieve DT fuel pellet compression up to 1000 times normal density, and indirect drive concepts, such as the `Cannon Ball' scheme, also prevailed at several international conferences. In these circumstances the international fusion community proposed the Madrid Manifesto in 1988, which urged openness of ICF information to promote international collaboration on civil energy research for the future resources of the

human race. This proposal was also supported by some of the US scientists. The United States Department of Energy revised its classification guidelines for ICF six years after the Madrid Manifesto.

This first book from the USA treating target physics issues, covering topics from implosion dynamics to hydrodynamic stability, ignition physics, high-gain target design and the scope for energy applications is enthusiastically welcomed.

The author joined Lawrence Livermore National Laboratory in 1972 to perform intensive theoretical and computational research on implosion and ignition. He was awarded the Edward Teller Medal in 1993. One therefore expects the topics to be treated with authority, and this expectation is well fulfilled.

The general treatment throughout the book is to begin with the basic physics of implosion and show how its development leads to an explanation of many fundamental ideas about implosion, via direct drive or indirect drive, particularly ideas associated with radiation transport. This approach is generally successful, with the reader immediately able to relate the theoretical treatments to physical problems. One danger in this approach, however, is that fundamental concepts in implosion often become stressed within the framework of indirect radiation drive of hohlraum targets oriented towards research in the National Ignition Facility. The references in this book to Livermore or Los Alamos internal documents are not yet publicly available, because many are in the process of review for declassification. The reader will have to become accustomed to this situation, which has lasted for a long time but now seems to be gradually improving.

The treatise is composed of 13 chapters, including 271 illustrations. An overview of ICF and the historical development of indirect drive in the ICF programme are described in Chapters 1 and 2.

Direct drive and indirect drive have different features. The choice of which to use is a very interesting issue. The former has a higher laser-target coupling efficiency but is less uniform in laser irradiation due to discrete beams of lasers. Beam smoothing techniques have a key role in direct drive. The indirect drive by soft X rays which are generated at the inner surface of a hohlraum can have a higher uniform irradiation to reduce the growth of perturbations due to Rayleigh-Taylor (RT) instabilities. The soft X ray drive has much higher ablation rates and is less sensitive to hot electron preheat. A potential disadvantage of indirect drive is the larger scale length of the plasma travelled by the laser beam from the inlet hole to the hohlraum wall. Parametric instabilities in hohlraums have problems because of energy loss and coupling. One of the most important issues for indirect drive is a radiation drive concept which is essentially independent of the driver, such as laser or particle beam. The historical progress of ICF in the USA mainly depended upon the resolution of the fusion database for weaponry. This was a reason to choose indirect drive as the main scheme. Several structures of hohlraum target are described which for a long time were closed to the public. As the minimum energy for ignition depends strongly on the achievable implosion velocity, a great deal of benefit is derived from operating at the highest possible hohlraum temperature and in-flight aspect ratio (IFAR). The conclusion of Chapters 3, 4 and 5 is that achieving an implosion velocity of 3×10^7cm/s with an IFAR-30 Fermi degenerated shell would require a minimum drive temperature of about 200 eV. The hydrodynamic instability, ignition threshold and capsule gain are discussed in Chapter 6. The RT hydrodynamic instability began at the upper limit of the IFAR and hence at the peak implosion velocity. The growth rate of the instability in the acceleration phase was found to be suppressed by the ablation flow at Osaka. Instability during the deceleration phase was primarily stabilized by electron conduction. The combined effects of acceleration, feed-through and deceleration show that the principal modes contributing to perturbations in the fuel have spherical harmonic mode numbers less than about 30-40. The higher modes are rapidly reduced by rarefaction. The lower modes are killed by so-called `fire polishing'. The target uniformity and irradiation uniformity are very effective at suppressing instabilities. The maximum number of e-foldings sets the upper limit of the implosion velocity. This gives the threshold energy of ignition. The minimum capsule energy for ignition for indirect drive is compared with Nuckoll's projections for direct drive. The estimation depends strongly upon the effects of hydrodynamic instability and symmetry in the compressed fuel volume. If the margin of energy is 2, the necessary capsule absorbed energy is about 90 kJ with a radiation temperature of 300 eV. The coupling between driver and capsule is 10-15%, and the driver energy is 0.6-0.9 MJ. The scaling laws for the capsule absorbed power, radius and pulse length with a certain IFAR are given. It is concluded (Chapter 6) that the optimum strategy for gain is operation at the minimum implosion velocity consistent with the desired capsule size and yield, because at the excess implosion velocity the capsules tend to ignite earlier than the optimal point in the compression process.

The most crucial issues for the hohlraum target are the coupling efficiency and hohlraum radiation uniformity. Various kinds of devices for hohlraum structures and double cone irradiation schemes have been investigated. These technological developments are energetically described. The implosion symmetry reproducibility (Chapters 7 and 8) for the Precision Nova advanced system meets the requirement of 1% uniformity for ignition experiment time averaged flux. Combined tests of symmetry and hydrodynamic instability as well as the hohlraum plasma conditions estimating the simulated Brillouin scattering (SBS) and simulated Raman scattering (SRS) effects and their influence on the hot electron preheat are summarized in Chapters 9, 10 and 11. The tolerable fraction of hot electrons for keeping the DT fuel preheat at approximately the Fermi specific energy indicates that direct drive capsules are 3 to 4 times larger than the indirect drive capsules.

As a conclusion, Chapters 12 and 13 are proudly devoted to the National Ignition Facility and ignition targets. The NIF has a 192 beam, frequency tripled Nd:glass laser system with routine target energies and powers of 1.8 MJ and 500 TW, appropriately pulse shaped. The 192 beams are clustered in groups of 4, so that there are effectively 8 spots in each of the inner cones, and 16 in the outer cones in the hohlraum. Each cluster of 4 beams combines to form an effective f/8 optic. Various kinds of target design are described, for instance, a baseline design 300 eV hohlraum capsule, which absorbs 1.35 MJ of light, an ignition point hydrocarbon (CH) capsule, which is aimed at determining the requirements for symmetry, stability and ignition, and a lower temperature 250 eV capsule with a beryllium ablator, which provides a trade-off between hydroinstabilities and laser-plasma effects. The NIF baseline capsule designs absorb 150 kJ, of which about 25 kJ ends up in the compressed fuel. The central temperature increases to 10 keV when the capsule produces 400 kJ. The fuel energy gain is about 16 at ignition, or when the alpha particle deposition is about 3 times the initial energy delivered to the compressed fuel. The NIF baseline targets are then expected to yield up to 15 MJ and a fuel gain of about 600.

Estimates based on NOVA experiments and modelling indicate that SBS, SRS and other plasma hazard processes can be kept within acceptable limits. If these are not attained, the ultimate recourse is to increase the hohlraum size, reduce the laser intensity and reduce the drive temperature to that of the 250 eV design, which has significantly less plasma. The remaining uncertainties can be mitigated by changes in the target design. The author has confidence ignition will be achieved in NIF, which seems to be strongly supported by the Centurion-Halite underground nuclear experiments demonstrating the excellent performance and the basic feasibility of achieving high gain. He thoughtfully adds a comment that developments in direct drive have reached the point where this approach also looks quite promising. NIF will be able to shift rapidly (⊠ 1 d) between indirect drive and direct drive.

Finally, the short last chapter (Chapter 13) gives an overview on the greatest potential for future ICF power plants.

In a book review, questions are usually asked about the readers the book is primarily intended for, whether the book is written at the appropriate level for those readers and whether there are other books that achieve similar objectives. The last section of the Preface states that this book provides an in-depth analysis of theoretical and experimental work on indirect drive ICF classified up to 1994, as well as work carried out throughout the world. It is intended to serve as a reference guide for researchers in the field. Each topic covered contains enough introductory material that the book can also be used at the graduate level by students or newly interested researchers. Most of the laser technology and diagnostic development are not covered at all. To this reviewer that statement is a succinct summary of what the book achieves. Working fusion physicists, particularly in ICF, will find the book to be both instructive and enjoyable. As a secondary market, the book could well be used as a text for a graduate course in laser plasma physics, although some parts are like review papers. As to which books cover some of the same material, W.L. Kruer published *Physics of Laser Plasma Interactions* (Addison-Wesley, Redwood City, CA, 1988), which is suitable as a textbook for graduate students and also for the plasma physicist in general and C. Yamanaka published *Introduction to Laser Fusion* (Harwood Academic, Chur, 1991), which is the only book treating implosion physics, lasers, target design and diagnostics prior to the USDOE's declassification. As for the Handbook of Plasma Physics series (edited by M.N. Rosenbluth and R.Z. Sagdeev), Vol. 3, *Physics of Laser Plasma* (edited by A.H. Rubenchik and S. Witkowski) (Elsevier Science, Amsterdam, 1991) comes to mind. However, this last book is larger, and covers somewhat diverse topics. The typography of the book presently under review is also much to be preferred.

In summary, I would strongly recommend the book by Lindl to my colleagues in plasma physics, particularly to those engaged in ICF.

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