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PROGRESS IN LASERS AND LASER FUSION

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PREFACE

This volume contains a portion of the presentations given at the session on Laser-Fusion and Laser Development of Orbis Scientiae II, held at the Center for Theoretical Studies, University of Miami, from January 20 through January 24, 1975. This second in the new series of meetings held at the CTS strove to implement the goals professed in the organization of Orbis Scientiae in 1974, namely to encourage scientists in several disciplines to exchange views, not only with colleagues who share similar research interests, but also to acquaint scientists in other fields with the leading ideas and current results in each area represented. Thus, an effort has been made to include papers in each session that discuss fundamental issues in a way which is comprehensible to scientists who are specialists in other areas. Also in keeping with the philosophy of Orbis Scientiae, the major topics each year are to be varied, with the invariant being the inclusion of developments in fundamental physics.

The discussions of the current state of the art in lasers and fusion represented in this volume are not only of interest because they deal with newly unfolding branches of physics, but also because of their potential technological and societal significance. The paper by V. N. Lugovoi and A. M. Prokhorov was not presented at Orbis Scientiae II, but is included because of its relevance to the topics in this volume.

Special gratitude is due to the following for their contributions as organizers and moderators of the sessions on lasers and laser fusion: Edward Teller, Richard Morse, Arthur Kantrowitz, Marlan Scully and Willis Lamb, Jr. The editors wish to express their appreciation to Mrs. Helga Billings and Mrs. Jacquelyn Zagursky for their dedication in the preparation of the manuscripts for publication and for their capable assistance during the meetings.

A companion volume, entitled Theories and Experiments in High Energy Physics, incorporates the papers delivered at Orbis Scientiae II complementary to those included in the present one.

The Orbis Scientiae II was supported in part by the United States Energy Research and Development Administration, High Energy Physics Division.

The Editors

Some of the participants of the Orbis Scientiae II in attendance during the Laser and Laser Fusion Session

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OPENING REMARKS

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From the time that the first hydrogen bomb was exploded, administrators and politicians have urged the rapid development of controlled fusion. It is indeed a wonderful prospect to harness fusion energy since the fusion fuel is abundant, fusion reactors would be exceptionally safe, and the storage of waste products would present practically no problem. Some of us foresaw that to achieve controlled fusion would take research that would not only take a long time, but would also be extremely interesting, and yield many scientific by-products.

This prediction was justified. Today throughout the world plasma physics is being pursued not only for the sake of producing controlled fusion, but also for the sake of understanding the stars and for the sake of many practical applications. Incidentally, plasma physics in its own right is one of the most exciting branches of applied research. In all this work we have been considering plasmas which were to burn in a quiet and more or less continuous fashion.

In recent years interest has turned to a new principle: the micro-explosion. If one compresses thermonuclear fuel to a thousand times its liquid density, simple similarity considerations (based on the fact that the most important processes are binary collisions) show that the scale of a hydrogen bomb explosion can be reduced a million fold. The similarity consideration is not exact, but is a good approximation. In actual fact, a reduction by more than one million can be accomplished.

This opens the possibility of a nuclear-fusion "internal combustion" engine. Tiny droplets of thermonuclear fuel may be exploded and the process may be repeated billions of times. This could in the end lead to a new practical energy source.

There are, of course, a few difficulties. First, we have to concentrate energy into a volume of about a cubic millimeter in a time shorter than a nanosecond. This might be done in a variety of ways. Today the most popular scheme employs lasers whose energy is focussed on the small droplet. The lasers of sufficient energy and hopefully short wavelength are not yet available. The short wavelength is a great advantage because CO_2 laser light gets reflected and absorbed in exceedingly dilute plasma which always will surround the droplet that is to be imploded.

The mechanism of the implosion can be easily understood in a crude way. Lasers of the requisite energy carry electric fields greater than the fields that hold outer electrons in their atomic orbits. Thus absorption is connected with instant generation of of plasma. The plasma will evaporate and, by recoil, compress the remaining part of the droplet.

But at this point our difficulties have merely started. A thousand fold compression (an even higher compression would be preferable) requires great symmetry. Otherwise the droplet will disintegrate into a spray of tiny fragments rather than be compressed to an exceedingly high density. Even so, given enough time and work, I believe the experiment will succeed.

But after this is done we will have to face problems of engineering. The individual explosions will not be small. To create an economically viable system several explosions per second will be needed and the processes will have to continue--in a somewhat radioactive surrounding--for many years. How to make such a system survive, how to keep it adjusted, and above all, how to produce it for a moderate amount of money seem to be tremendous problems. I believe that laser fusion can in no sense be the short-term answer to the energy crisis. Unfortunately, this crisis does demand short-term answers.

It has been argued that in a few years laser fusion has made great progress and is going to catch up and surpass the older procedure of burning plasmas at a low density. To a superficial observer this prediction may seem justified. I want to quote Niels Bohr's definition of an expert: "A person who through his own painful experience has found out all the mistakes which one can commit in a narrow field". In controlled fusion there are not experts as yet. But in the burning of dilute plasmas (within confining magnetic fields) we are approaching the stage of expertise. In the field of laser fusion we have the enjoyable experience ahead of us to commit many interesting mistakes.

The commission of these mistakes will mean physics research in the truest sense of the word. We are already beginning to compress small pieces of matter to high densities and these pieces of matter are out in the open, except that they are surrounded by a dilute envelope of plasma. This makes it possible to explore the state of matter at high densities in a direct and novel way.

Furthermore, x-ray bursts and neutron bursts derived from compressed matter and from initial thermonuclear burning will be research tools of real interest. As in all cases, research in a new field does not stand by itself, but produces stimulation in many neighboring areas.

There is one statement one can make about laser fusion which is certainly true. Laser fusion is a challenge. As physicists, we should not be deterred by the fact that the pay-off in the foreseeable future will be in physics, rather than in the production of cheap energy.

THEORETICAL INTERPRETATIONS OF ENHANCED LASER LIGHT ABSORPTION*

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I. INTRODUCTION

The absorption of intense laser light is obviously one of the very important questions for laser fusion applications. In experiments this absorption has been observed to be substantially more efficient than expected on the basis of classical inverse Bremsstrahlung. An absorption efficiency of $\sim$ 70% has been typically observed in experiments with slab targets[1-4]--even using laser light intensities exceeding 10^{16} W/cm^2 (Nd). It should be noted that a number of experiments with curved targets such as spheres or cylinders have shown a somewhat lower absorption efficiency of $\sim$ 30%, with about half the energy lost to refraction around the target. But even in these experiments the absorption is usually found to be greater than expected classically at high intensities.

*All research performed under the auspices of the U. S. Energy Resource and Development Agency.

We can theoretically understand this enhanced absorption on the basis of collective processes in the plasma; i.e., the conversion of laser light into plasma waves. An overview of our present understanding of laser light absorption will be presented. The aim is to convey the physical ideas using very simple estimates rather than elaborate on the latest technical detail. We will first discuss classical inverse Bremsstrahlung, showing why it becomes inefficient even at moderate intensities (10^{13} - 10^{14} W/cm^2, Nd), and then show how a plasma can be heated collectively. The discussion is made more concrete by applying our estimates to some recent laser plasma experiments. We conclude with a brief discussion of light absorption at high intensity ($I \gtrsim 10^{15}$ W/cm^2, Nd), emphasizing the importance of density profile modifications and the possibility of stimulated scattering of light from the plasma.

II. CLASSICAL INVERSE BREMSSTRAHLUNG

First let's look at some simple estimates in order to see what to expect from classical inverse Bremsstrahlung. In more physical terms, this is simply Joule heating of the plasma by the high frequency laser light. The rise in the kinetic energy of the plasma is

$$\frac{dkE}{dt} = \nu_{ei} \frac{E_L^2}{8\pi} ,$$

where ν_{ei} is the electron-ion collision frequency and E_L is the electric field of the laser light. As is well known, $\nu_{ei} \propto 1/\Theta_e^{3/2}$, where Θ_e is the electron temperature. The decrease with temperature follows from general properties of the Coulomb force law. And so the problem becomes obvious. A hot plasma becomes collisionless, meaning that Joule heating becomes ineffective.

We can illustrate the numbers involved by a very simple "back-of-the-envelope" calculation. Consider the propagation of light into an inhomogeneous plasma slab, assuming for simplicity a linear rise in density from zero to the critical density in a distance L. Then a simple integration shows how the light is classically attenuated as it traverses the plasma (in and out).

$$I_{ABS} = I_o \left[1-\exp\left(- \frac{32}{15} k_o L \frac{\nu_{CR}}{\omega_o}\right)\right], \qquad (1)$$

where I_{ABS} is the absorbed intensity, I_o the incident intensity and ν_{CR} the collision frequency evaluated at the critical density. The collision frequency depends on temperature. For our purposes we will crudely estimate a temperature by using the flux limit, which essentially determines the minimum temperature the plasma must reach in order to carry off the absorbed energy. So, if anything, we are giving an over-estimate of classical absorption. With a little algebra, we then obtain

$$\frac{I_{ABS}}{I_o} \ \ell n \left[1 - \left(\frac{I_{ABS}}{I_o}\right)\right]^{-1} = 10^{11} \ k_o L . \qquad (2)$$

This estimate of the fractional absorption versus incident intensity is plotted in Figure 1. A scale length of 100 λ_o (free space wavelengths) has been assumed, a value estimated for some experiments to be discussed shortly. The absorption efficiency is quite

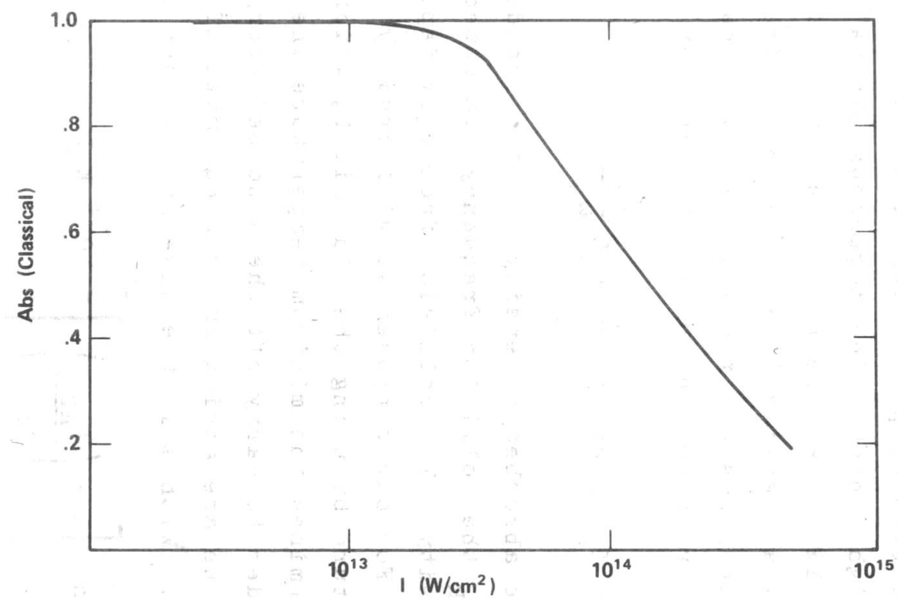

FIG. 1 An estimate of the fractional absorption due to inverse Bremsstrahlung as a function of laser light intensity.