Theoretical and Computational Research on
Inertial Confinement Fusion

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1. Introduction

In connection with the experimental program, we try to get better understanding of physical mechanism in the interaction, transport and implosion fields and to improve the numerical simulation to replicate and predict the experiments. The work, since the last meeting in 1978, deals with : laser scattering (SBS, SRS), resonance absorption, density modification, fast ion generation, transport of the high energy electrons, ablation structure with the high energy electrons, implosion stability, scaling law of the exploding pusher and ablative compressions, X-ray line profile, advanced target design. The program overview at Osaka University is shown in Table 1, while the title of the works at the other Universities shown in Table 2.

Our Recent theoretical understanding on physics involved in laser fusion plasma is briefly present in section II. We introduce basic codes in use and simulation results at Institute of Laser Engineering in section III.

2. Recent Theoretical Works

Let us show now our theoretical understanding on the laserplasma interaction, transport and the implosion stability. The first topic is on the reflectivity estimation due to the stimulated Brillouin scattering. For determining the reflectivity, it is important to find the selfconsistent damping rate of the ion acoustic wave. We take into account the nonlinear ion Landau damping and the enhanced linear Landau damping due to ion heating by the ion acoustic wave itself. We then self-consistently solve the problem to obtain the laser intensity dependent reflectivity. The results are shown in Figs. 1 - 2. Figure 1 is the general reflectivity curve. In the low laser intensity, the reflectivity increases exponentially with the intensity increase and in the next stage, the ion nonlinear Landau damping becomes important to reduce the reflectivity. In the intermediate intensity, say $(\frac{v_{os}}{v_e})^2 \sim .01 \sim .1$, the ion heating sets on and the reflectivity saturates and then starts to decrease. This is due to the fact that the ion linear Landau damping depends strongly on zT_e/T_i . In the high laser intensity, the ions are strongly heated up to $zT_e/T_i \sim 1$ and the damping rate is saturated to be $\text{Im } \omega_{ac} \sim \text{Re } \omega_{ac}$. Therefore, the reflectivity again starts to increase gradually. In Fig. 2, we show the comparison between our theoretical model and the CO_2 experimental results. The typical saturation phenomena due to the ion heating is seen here.

Let us now show the hot electron transport. We found

that the hot electrons are reflected by the anomalously enhanced E-field and the heat transport into the pusher and fuel are strongly reduced. The E-field builds up because of the enhanced resistivity on the cold electron return current. Since the hot electron current should be cancelled by the cold electron return current, the E-field grows up until the hot electron current is substantially reduced to balance with the return current. According to our estimation, the electrostatic potential at the critical point $e\phi_c$ becomes a few times bigger than the hot electron kinetic energy T_h as far as the hot electron density at the critical point is appreciable fraction of the critical density. Furthermore, the density steepening occurs since the hot electron is trapped around the critical point by the E-beam and the hot electron pressure expels the cold plasma. The self-consistent stationary density jump, potential jump and hot electron heat flux normalized by the free streaming limiting flux are shown as the functions of n_{hc}/n_c in Figs. 3 - 4.

Using the multigroup diffusion transport code with 1-D Hydro-code (see next section), we also investigated the effects of anomalous resistivity and the E-field generation. The results are shown in Figs. 5 - 7. As it is expected theoretically, the potential hump and the density jump at the critical point appear. Furthermore, we can see that the hot electrons are trapped around the critical point. The theoretical and computational results agree with each other. Further comparison between the theory and the computer simulation are done for the ablation structure (see Fig. 6).

The simple analytical investigation indicates that the density profiles are $n(x) = n_0 \frac{l_{h0}}{l_{h0} - x}$ and $n_h = \frac{l_{h0}^{-x}}{l_{n0}}$ for the cold electron and hot electron respectively. Here l_{h0} is the effective mean free path of the hot electron ; $v_h / (v_{hi} v_{he})^{1/2}$. The remarkable thing is that the scale length of the ablation structure is determined simply by the hot electron effective mean free path. This results tell us that the exploding mode to the ablative mode transition occurs about the shell thickness, $l_{h0}(n_0/n_s) l_n(n_s/n_0)$ where n_0 is the density in which the E field disappears. This gives us the critical shell thickness to be 4 μm for Glass laser experiment for $T_h \approx 10$ keV. The above simple ablation structure is compared with the simulation results and we have good agreement (see Fig. 7 (a), (b)). Finally, the above ablation structure allows us to estimate the hydrodynamic power which is proportional to $(n_{n0} T_n)^{3/2}$ and then, roughly proportional to $(I_{abs.}/v_n)^{3/2} \propto \lambda^{-0.8 \sim -0.5}$.

One of the most important and difficult problem is the stability of the ablation structure. Since the implosion process associates the acceleration of the ablation front ; the Rayleigh-Taylor instability at the ablation front is considered to occur. We have investigated the flow, compressibility and finite thermal conductivity effects. The discontinuous density jump model is used to obtain growth rates which are tabulated in Table 3.

The mechanism of the fast ion generation was also investigated taking into account the effects of two electron temperature plasma and multi species ions.

3. Code Development and Simulation Results

Basic codes in use at Osaka University are shown in Table 4. Two dimensional relativistic and electromagnetic particle code is developed with collaboration of Institute of Plasma Physics at Nagoya University, and two dimensional magneto-hydrodynamic code with Mitsubishi Atomic Power Industries, Inc. (see Table 2).

By using two dimensional electromagnetic particle code we are studying Raman scattering in a two electron temperature plasma. In the two electron temperature plasma there exists an electron acoustic wave. RS can, therefore, occur even in the region $\omega_0 < 2\omega_{pe}$.¹⁾

The purpose of two dimensional electrostatic particle code is to investigate the thermal flux limitation by enhanced E-field discussed in the previous section in the inhomogeneous ablating plasma.

In order to obtain a scaling law of neutron yields for exploding pusher targets, we used one dimensional hydrodynamic code EXPLOD. The high energy electrons generate an electric field in a corona, which accelerates ions outward and reflects the electrons. The high energy electrons deposit their energy to the fast ions when they reflect. The energy loss of the high energy electrons and the acceleration of the corona are taken into account in EXPLOD.

To establish the optimum combination of target and laser-pulse parameters, we have undertaken a multidimensional study using EXPLOD. Figure 8 shows the neutron yields as a

function of the pulse width normalized by compression time with the various target radii and peak power. It should be noted that even if we change the target radius and the peak power, the maximum neutron yields for each parameter is obtained when the compression time is 3 times longer than the pulse width. For this optimum combination of the target and laser pulse width, our simple scaling model¹⁾ predicts that the neutron yield is proportional to $P^{1.8 \sim 2.1}$.

In one dimensional code 'HIMICO', the transport of the high energy electrons are treated by a multi-group flux-limited diffusion method. The electric field is calculated from current neutral condition. The anomalous resistivity due to the ion acoustic turbulence and the joule heating are taken into account in the code. We are developing Monte-Carlo method and higher Legendre expansion method for the high energy electron transport, and also including the effect of Stimulated Brillouin Scattering and Ponderomotive forces.

By using HIMICO, we studied first implosion process of double layer target. Our major interest in this work is to investigate transition from exploding pusher type compression to ablative mode compression by varying the thickness of coating material on a spherical glass microballoon target. We simulated implosion processes of glass microballoon filled with Neon 26 atm, coated by polyethylene. Total laser input power was 2.5 TW in 100 psec. Temperature of hot electrons was determined by using the formula by Estabrook and Kruer. Figure 9 shows calculated flow lines for various

coating thickness. The transition from exploding pusher mode to ablative mode with increasing coating thickness is clearly seen from the figure. This is also confirmed by viewing radial distribution of hot electron, which is completely stopped at 10 μm polyethylene. In Fig. 10, some of plasma parameters are plotted as a function of coating thickness. Peak density of compressed core exponentially increases with thickness whereas peak electron temperature decreases. Experimentally observed density of Neon core are also plotted by circles. Within a factor of 2, both results are in quite an agreement with each other.

Secondly, we have studied the transport of the high energy electrons for the ablative mode compression by using 'HIMICO', of which results are discussed in the previous section.

We are now studying the scaling law for the ablative compression target. We chose an initial radius, CH_2 coating thickness on the glass microballoon as target parameters and a peak laser power and a pulse width as laser parameters. Figure 11 (a) shows the neutron yield as a function of laser pulse width for 2 TW, $\phi \sim 80 \mu\text{m}$ (glass microballoon), while Fig. 11 (b) for 4 TW and 200 μm . There exists an optimum combination among coating thickness, pulse width and power. Figure 12 shows the velocity at the interface between the fuel and the pusher as a function of time for $\tau_{\text{las}} \sim 200$ psec (peak at 0.3 nsec), $\Delta R(\text{CH}_2) \sim 20 \mu\text{m}$, $P \sim 2$ TW. For the isentropic compression the velocity can be proportional to $(t - t_0)^{-1/2}$. Even if the laser pulse is Gaussian, the

compression obtained for these parameters is expected to be close to the isentropic compression. This fact is also confirmed by the $T - \rho$ relation as shown in Fig. 13. It should be noted that the optimum neutron yield is also achieved for this case.

Figure 14 shows the optimum neutron yield as a function of peak power. For large thickness of CH_2 coat, the scaling of the neutron yield is close to P^3 .

We are now including the transport of the high energy electrons (multi-group flux-limited diffusion method) and the effect of magnetic field on the transport in two-dimensional hydrodynamic code. The code is used not only to study nonlinear evolution of Rayleigh-Taylor instability, but also to design for nonspherical advanced targets.

We are studying two kinds of advanced targets by using two dimensional code. One is Tamago (elliptic) target shown in Fig. 15. Symmetric compression is required to obtain large ρR . The symmetric illumination is, however, difficult problem to be solved for a reactor system. The purpose of this study is to seek possibility to achieve symmetric compression by two beam laser illumination. Comparison between Tamago target and spherical target is shown in Fig. 15.

The other is the target proposed first at Daisen laser fusion workshop in 1975²⁾. The target is composed of double shells, of which outer shell has a hole. A laser light is irradiated on the inner shell through the hole. Figure 16 shows ray trace for the case $f = 1.2$ illumination. The

feature of the target is high absorption rate. Simulation results predict six times larger in enhancement in total (three to four times for the inner shell), compared with 4π illumination for a single shell target. If we use massive outer shell, it acts as a tumper, and the compression efficiency can also increase. If we use fusion or fusion materials as the outer shell, the gain amplification can be achieved.

In order to examine whether the code calculations replicate the experimental results correctly, we have developed diagnostic codes to obtain numerically such as pinhole and streak image of X-ray, X-line profile and α -particle energy spectrum. The rate equation is solved for 30 ~ 60 levels for each atom, for example, Si, Ne, Ar and Al, and coupled with radiation transport equation. Figure 17 shows He-like satellites near Ly α of Ar for the exploding pusher mode compression, and Ly β line profiles of Ne for the ablative mode compression.

References

- 1) Annual Progress Report on Laser Fusion Program, ILE-APR-78, December (1978).
- 2) Daisen Laser Fusion Workshop, IPPJ-235, (1975).

Table 1

Table 2

Titles of Study at Other Laboratories

Hiroshima University

Institute for Fusion Theory; K. Nishikawa, T. Watanabe
and T. Tange

Laser plasma interaction
Fast ion generation and spectrum

Keio University

; M. Ogasawara

Magnetic field generation and resonance absorption

Mitsubishi Atomic Power Industries Inc.

; H. Doi and F. Ishii

Two dimensional code development

Nagoya University

Department of Physics; T. Taniuti and K. Nozaki

Thermonuclear reaction wave

Deflagration wave

Institute of Plasma Physics; T. Kamimura

Particle code simulation on laser plasma interaction

Tokyo Gakugei University

Department of Physics; T. Shimojo

Turbulence in laser absorption

Tokyo University of Agriculture and Technology

Department of Applied Physics; T. Okada

Electromagnetic instabilities and heat flux reduction
in laser plasma

Tokyo Institute of Technology

Department of Energy Science; K. Niu and Y. Abe

Light ion beam study

Resonance absorption

Tokyo Metropolitan College

Department of Aeronautics; H. Murakami

Particle simulation of high energy electron transport

Waseda University

Department of Applied Physics; T. Kato

Turbulence in REB-plasma interaction

Table 3

	$K \lesssim 1/L_g$	$1/L_g < k \ll 1/L_a$	$K > \frac{1}{L_a}$
No Flow $M_1, M_2 = 0$	$(k^2 g C_1)^{1/3}$	$(gk)^{1/3}$	$\sqrt{g/L_a}$
Finite Flow $M_1 \ll 1$ $M_2 < 1$	?	$(kg + k^2 U_1 U_2)^{1/2}$	?
Supersonic Flow $M_1 \ll 1$ $M_2 > 1$	?	γ	?

Notations: $g = C_1^2/L_g$, L_a is a scale length of an ablation structure and γ is a solution of

$$\frac{\gamma^2}{\gamma^2 + k^2 C_1^2} = \frac{1 + M_2^2}{1 - M_2^2} kg + \frac{M_2^2}{\sqrt{M_2^2 - 1}}$$

Table 4

BASIC CODES IN USE AT INSTITUTE OF LASER ENGINEERING

HYDRODYNAMIC CODES	PURPOSE	GENERAL INGREDIENTS
ONE-DIMENSIONAL CODES		
EXPLOD	Experimental data replication for exploding pusher target	Lagrangian hydrodynamics Fast ions, radiation pressure
HIMICO	One-dimensional target design Heat transport Experimental data replication	Multigroup flux-limited diffusion Transport inhibition by ion turbulence Self-consistent electric field
DIAGNOSTICS	X-ray line profile Pinhole and streak picture α -particle energy spectrum	Rate equation Radiation transport Monte-Carlo
TWO-DIMENSIONAL CODES		
	Non-spherical target design Rayleigh-Taylor instability Experimental data replication	Lagrangian hydrodynamics Laser ray-trace Thermal conduction and transport inhibition
PARTICLE CODES	PURPOSE	GENERAL INGREDIENTS
TWO-DIMENSIONAL CODES		
	Laser-plasma interaction Transport inhibition by turbulence	Relativistic and electro-magnetic field

Fig. 1 A typical amplitude dependent reflectivity and the temperature ratio.
Density Scale Length; $k_0 L = 200$ $\frac{n}{n_c} = 0.1$

— ; reflectivity
- - - ; reflectivity without nonlinear Landau damping
- · - ; temperature ratio

Fig. 2 Solid line represents a theoretical reflectivity and open circles are experimental reflectivities.
Parameters for a theoretical curve:
 $k_0 L = 300$, $n/n_c = 0.1$ and $T_e = 100\text{eV}$

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7 (a)

Fig. 7 (b)

Fig. 8

IMPLOSION CHARACTERISTICS AT DIFFERENT COATING THICKNESSES

Laser Pulse Width	100 ps
Peak Laser Power	2.5 TW
Glass Microballoon	80 μm diameter
	1.1 μm thickness
Filling Gas	Neon 26 atm

Fig. 9

Fig. 10

Fig. 11 (a)

Fig. 11 (b)

Fig. 12

Fig. 13

Fig. 14

Tamago(Elliptic) Target

Search for possibility of symmetric implosion
by two beam illumination

Tamago:Initial Profile

|·|

Tamago:Profile

|·4

Sphere:Profile

|·4

Fig. 15

Double Shell Target with Hole in Outer Shell

Absorption rate is enhanced 6 times greater than single shell with 4π illumination.

Fig. 16

X-RAY LINE

Exploding Pusher Compression
of Ar Filled Glass Microballoon

Ablative Compression of
Ne Filled Glass Microballoon
Coated with Polyethylene

He-like Satellite

Ly- β

Fig. 17