INTEGRATED CODE DEVELOPMENT AND ANALYSIS OF IMPLOSION AND HYDRODYNAMIC EXPERIMENTS

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Abstract

The computational simulations play an important role in the study of inertial confinement fusion physics. For the understanding of the physics, integrated implosion code which includes all physics important in the implosion has been developed. On the other hands, several computational codes have been developed in order to verify the physics models and analyze experimental results. The characteristics of these computational codes and recent progress of implosion, ignition, Rayleigh-Taylor instability, ripple shock propagation, and burn dynamics analysis are reported here.

1. INTRODUCTION

Physics of the inertial confinement fusion is based on a variety of elements such as compressible hydrodynamics, radiation transport, non-ideal equation of state, non-LTE atomic process, and relativistic laser plasma interaction. In addition, implosion process is not in stationary state and fluid dynamics, energy transport and instabilities should be solved at the same time. In order to study such complex physics, and integrated implosion code including all physics important in the implosion process should be developed. The details of physics elements should be studied and the resultant numerical modeling should be installed in the integrated code so that the implosion can be simulated with available computer within realistic CPU time. In order to check the modeling of the physics elements, we apply the code to compare to the model experiments, for example, such as Rayleigh-Taylor(R-T) instability at the ablation front. We report at first the present status of our integrated code developed by focusing on a uniqueness of numerical algorithms and physics models. At second, we report the analysis of implosion experiment and hydrodynamic instability experiment. Recent theoretical progress of ripple shock wave propagation will be also reported.

2. CODE DEVELOPMENT

As the first step, for developing the integrated code, we are promoting the following seven items.

(1) Multi-dimensional hydrodynamics: We are developing two different codes. One is an Eulerian code and has been applied to study details of a part of implosion process. For a global simulation of

all implosion process, a Lagrangian code with rezoning and remapping is necessary. The ILESTA code has been modified by installing new rezoning and remapping scheme[1].

(2) Radiation transport: In order to drive implosions or control hydrodynamics, the x-ray radiation produced by lasers can be used. However, the radiation is not in LTE and multi-group transport is essential. This part is most time consuming in the integrated code and we are developing a parallel computing scheme. To solve a diffusion type transport in non-orthogonal mesh implicitly, an iterative method of ILUBCG is used.

(3) Non-local electron transport: It has been suggested that a kinetic effect of electron transport is important in analyzing target acceleration of relatively thin plastic foils. A Fokker-Planck code as been developed to couple with hydrodynamics and has been applied to study growth of the R-T instability. This code is, however, time consuming one to be coupled with the integrated code and is modified to a hybrid one.

(4) Non-LTE atomic and spectroscopic codes: In order to directly compare the results obtained with the integrated code to the experimental data, it is necessary to reproduce X-ray emission numerically. Energetics of radiation is simulated with radiation transport code of (2) in the integrated code, while details of line emission of doped atom in the fuel gas. These data are used to identify core nonuniformity as briefly described below.

(5) Relativistic plasmas: For studying basic processes of the fast ignition, we are developing a PIC codes and Vlasov-Maxwell solver. Since we are interested in laser-plasma interaction in overdense plasmas, collisional process should be modeled in the PIC code. A global phenomena such as hole-boring in inhomogeneous plasamas can be studied with the Vlasov-Maxwell solver. The basic process clarified with such codes should be modeled in the integrated code for target design.

(6) Fusion product transport: The fusion products affect the burn property of ICF fuel through thedeposition of their kinetic energy and momentum. For detailed examination of the ignition and burn dynamics, we have developed one-dimensional transport codes for charged particles and neutron[5]. The transport equations are time-dependent and are written in terms of modified Eulerian (*i.e.* moving mesh) frame, which enables us to take the hydrodynamic motion of the bulk plasma into account and then couple them with the hydrodynamics code. Using this coupled transport/hydrodynamic code, we clarified the roles of fusion products in central spark ignition and low temperature ignition targets. For the purpose of more practical study, we are now undertaking the development of multi-dimensional transport codes for fusion products.

(7) Target design and laser pulse shape optimization: In order to design high-gain target for future inertial confinemnet fusion reactors. The integrated code, ILESTA was coupled with the optimization methods, simplex method or genetic algorism. This code enable to design target structure and laser pulse shape considering all physics important such as hydrodynamic instabilities.

3. IMPLOSION ANALYSIS

It has been already reported that it is difficult to explain many of experimental data only with 1-D implosion code[2]. We have studied the effect of nonuniform implosion with 2-D integrated code. In Fig. 1, the normalized neutron yield [=(2-D yield)/(1-D yield)] is plotted as a function of the mode number of ℓ=1-12 for four different ammplitudes of velocity nonuniformity. The temperature profiles near the time of peak, neutron emission rates are shown for the case of ℓ = 2, 6 and 12 with $\delta v/v_0$ =10%. By focusing on the contribution from ℓ=6 nonuniformity, it is concluded that the experimental neutron yield can be reproduced by assuming that the velocity perturbation of 20% is generated through the acceleration phase. Regarding not only the neutron yield, but also the ion temperature observed with time-of-flight method by the use of the multi-channel neutron detector, we have obtained a good agreement in the same simulation.

In order to study the time evolution of implosion dynamics near the maxmum compression, line emissions from argon doped in the fuel gas have been observed with a space-and-time resolved X-ray spectroscopic method. We have focused on Ly-β line[Ar^{17+} 1s-3p] from H-like and He-β line [Ar $16+$ ($1s^2$-1s3p)] from He-like argon ions. The line emission history has been calculated as post process for the 2-D simulation with non-LTE atomic code[4]

4. RAYLEIGH-TAYLOR INSTABILITY ANALYSIS

The integrated code is applied to study linear and nonlinear R-T instability at the ablation front. In Gekko XII experiments, a planer plastic target with corrugated surface on laser irradiation side was used and accelerated with a green laser of a square pulse. The pulse duration is 2 ns. Around this time the second harmonics appears rapidly in the backlight image calculated with spectroscopic code. In Fig.2, the density contours at 3.5 ns are shown. We have obtained a good agreement for the growth rate and spike-bubble structure to cerresponding wxperimental data has been done by reproducing the backlight and side-light images with the spectroscopic codes.

5. RIPPLE SHOCK WAVE PROPAGATION

Spatial nonuniformity in a laser intensity causes modulation in the ablation pressure, and generates hydrodynamic perturbation in a target. The study of the hydrodynamic perturbation growth in the start-up phase is essential for a better understanding of implosion uniformity. The cloudy day model has been used to setimate the thermal smoothing of the nonuniformity in the absorbed laser intensity. However 2-D simulations show that the thermal smoothing effect is much smaller than that of the cloudy day model for relatively long wavelength perturbations, i.e., $kD \leq 1$, where k and D are a wavenumber of the perturbation and thickness of the ablation layer. It was obserbed in 2-D simulations that temperature and density perturbations increase in the ablation layer for $kD \leq 1$. This increase of the temperature perturbation is founded to be due to the strong nonlinearity of the electron thermal conductivity[3]. Hydrodynamic perturbation growth before the shock breakout is investigated by using 2-D simulation and an analytical model. Nonuniform laser ablation drives a ripple of the shock front and deformation of the ablation surface caused by nonuniform laser absorption. As shown in the figure, the simulation results agree fairly well with the analytical model[3]. Requirement of the laser uniformity is estimated for an ignition target using the analytical model. It shows effectiveness of time varying smoothing of the laser irradiation. Stability of a converging shock has been also studied with the use of 2-D (cylindrical) and 3-D (spherical) codes. Shock front ripples are found to be more stable than that estimated by CCW solutions. We have developed an analytical model that explains the obserbed dependence of the stability on the wavenumber and shock Mach number.

6. IGNITION AND BURN DYNAMICS

On the basis of 1-D coupled transport/hydrodynamic calculations, we investigated the effects of neutronic processes (*i.e.* neutron heating and suprathermal fusion) in *central spark ignition* (CSI) D-T targets[6]. It was found that the neutron heating has little effect on the threshold energy of laser because the deposited neutron energy in the spark region (<0.5 g/cm^2) is quite small. On the other hand, fast and volumetric nature of the neutron energy deposition prevents the main fuel from being sufficiently compressed and accelerates the pellet disassembly. Owing to this, the neutron heating leads to decreasing the target gain by 10-15%. Additional energy release due to suprathermal reactions is not large enough to compensate the gain decrement.

We also made an examination of the ignition and burn dynamics of *low temperature ignition* (LTI) D-T targets, in which the stagnation dynamics was appropriately taken into account[7]. We found that central-peaked profiles of temperature and density are formed through the stagnation. The ignition hence takes place in the central region of fuel and then the burn wave propagates outward owing to the heating by fusion products, without the production of a strong shock wave. In this scheme, the target should be compressed to significantly high areal density ρR, so that the neutronic processes play positive roles, *i.e.* lowering the temperature required for ignition and increasing the energy gain. The central-peaked profile formed at the ignition results in a lower ignition temperature and then a higher energy gain than those previously estimated for *volume ignition* targets. As is shown in Fig.4, the limiting gain is 1.5 times higher than those estimated in previous work[8]. Compared with the CSI scheme, however, the ligh implosion velocity ($4.5 \sim 5.5 \times 10^7$cm/s) is required to achieve significantly high compression. Even in the limiting gain case, thus, the gain of the LTI target is lower than that of the CSI one by a factor of $1.5 \sim 3$. However, high ρR means that the neutrons deposit a large fraction of their kinetic energy inside the fuel, which has some advantages over the CSI targets, such as low induced radioactivity and high energy conversion using a direct energy converter in a D-T inertial fusion reactor.

7. CONCLUSION

The present status of integrated implosion code, ILESTA including all physics important in the implosion process, and other individual computational codes are reported. Recent progress of analyzing implosion, ignition, burn dynamics, Rayleigh-Taylor instability, and ripple shock wave propagation are shown.

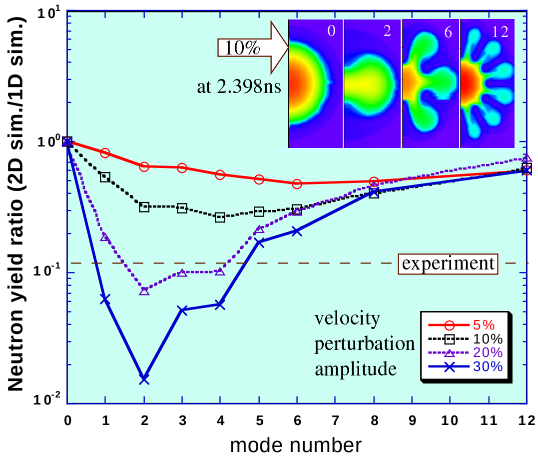

FIG.1. The normalized neitron yield[=(2-D yield)/(1-D yield)] as a function of the mode number.

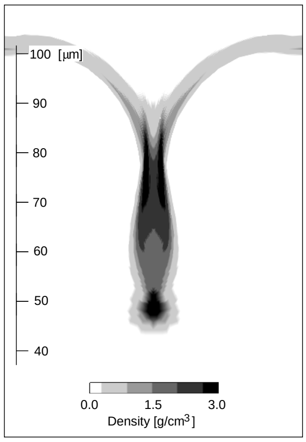

FIG.2. Density contour in nonlinear Rayleigh-Taylor instability simulation by ILESTA-2D.

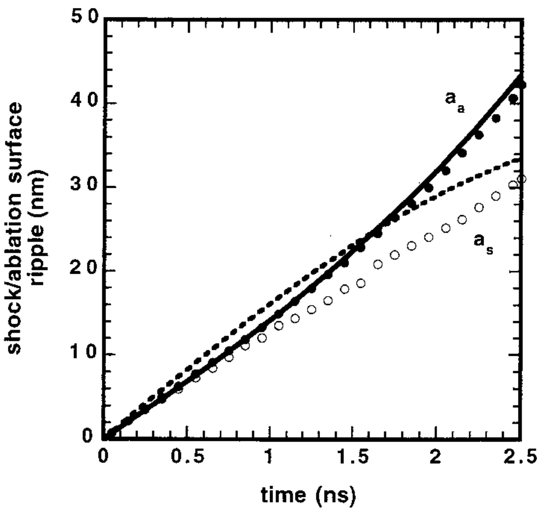

FIG.3. Amplitudes of shock front riple (dotted line and circles), and ablation front ripple (solid line and dots) as functions of time. Line are analytical value and symbols are 2-D simulation results.

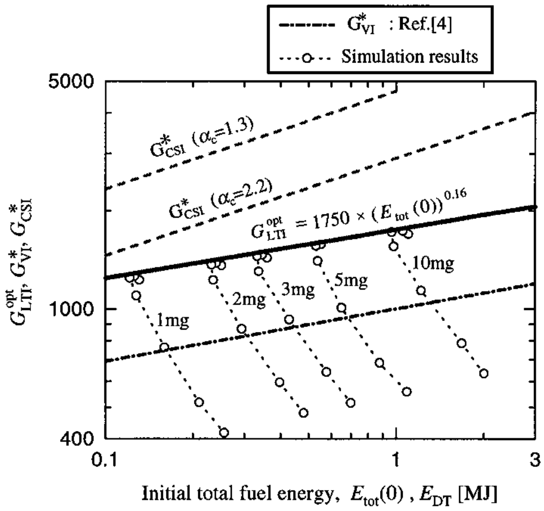

Fig.4. Optimal energy gain G^{opt}_{LTI} as a function of initial fuel energy. The limiting gains for uniformly-compressed targets G^{*}_{VI} and G^{*}_{CSI}[8] are also plotted.

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