Development of Fast Ignition Integrated Interconnecting Code (FI^3) for Fast Ignition Scheme

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Abstract. The numerical simulation plays an important role in estimating the feasibility and performance of the fast ignition. There are two key issues in numerical analysis for the fast ignition. One is the controlling the implosion dynamics to form a high density core plasma in non-spherical implosion, and the other is heating core plasma efficiency by the short pulse high intense laser. From initial laser irradiation to final fusion burning, all the physics are coupling strongly in any phase, and they must be solved consistently in computational simulation. However, in general, it is impossible to simulate laser plasma interaction and radiation hydrodynamics in a single computational code, without any numerical dissipation, special assumption or conditional treatment. Recently, we have developed "Fast Ignition Integrated Interconnecting code" (FI^3) which consists of collective Particle-in-Cell code, Relativistic Fokker-Planck hydro code, and 2-dimensional radiation hydrodynamics code. And those codes are connecting with each other in data-flow bases. In this paper, we will present detail feature of the FI^3 code, and numerical results of whole process of fast ignition.

1. Introduction

The fast ignition scheme is one of the most fascinating and feasible ignition schemes for the inertial fusion energy [1]. The numerical simulation plays an important role in demonstrating the performance of the fast ignition, designing the targets, and optimizing laser pulse shapes for the scheme. There are two key issues for the fast ignition. One is controlling the implosion dynamics to form high density core plasma in non-spherical implosion, and the other is heating the core plasma efficiently by the short pulse high intense laser. The time and space scale in the fast ignition scheme vary widely from initial laser irradiation to solid target, to relativistic laser plasma interaction and final fusion burning. These all the physics are desired to be self-consistently described in numerical calculation. However, it is a formidable task to simulate relativistic laser plasma interaction and radiation hydrodynamics in a single computational code, without any numerical dissipation, special assumption or conditional treatment.

Recently, we have developed "Fast Ignition Integrated Interconnecting code" (FI^3) [2] which consists of collective Particle-in-Cell code (FISCOF1: Fast Ignition Simulation COde with collective and Flexible particles), Relativistic Fokker-Planck with hydro code (RFP-hydro) code [3], and 2-dimensional Arbitrary-Lagrangian-Eulerian (ALE) radiation hydrodynamics code

(PINOCO : Precision Integrated implosion Numerical Observation COde) [4]. Those codes are sophisticated in each suitable plasma parameters, and boundaries and initial conditions for them are imported/exported to each other by way of DCCP, a simple and compact communication tool which enable these code to communicate each others in different machines. In this paper, we will present the feature of the FI^3 code, and numerical results of whole process of fast ignition.

2. Numerical Methods

Figure 1 shows the image of plasma density of fast ignition implosion and computational code which can solve those plasma parameters. These codes are best optimized for each plasma parameter regions to avoid undesired numerical dissipations or unwilling huge computing time. At first, cone-guided implosion dynamics is calculated by PINOCO because radiation hydrodynamics is dominant in implosion process. At a shot timing of peta watt laser, the mass density, temperatures, and other profiles calculated by PINOCO are exported to both collective PIC and RFP-hydro code for their initial and boundary conditions. The relativistic laser plasma interaction inside the cone target is simulated by collective PIC code, which exports the time-dependent energy distribution of fast electron to REP-hydro code. The fast electrons calculated by the FISCOF1 are exported to the RFP-hydro code. Therefore, the core heating process is simulated using both physical profiles of imploded core plasma and fast electron as the boundary conditions. The abstract of the profile data flows are illustrated in Fig.2.

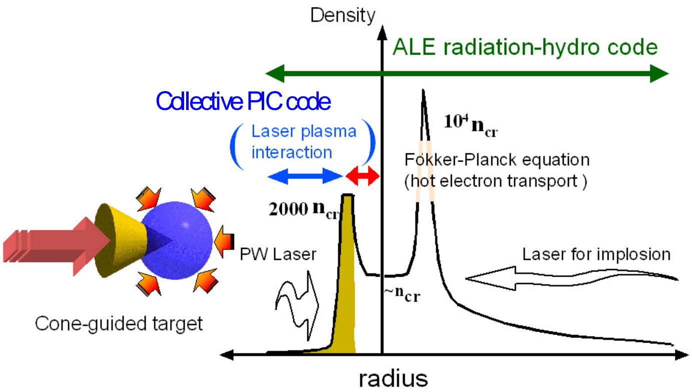


FIG.1. Fast Ignition Integrated Interconnecting code (FI^3)

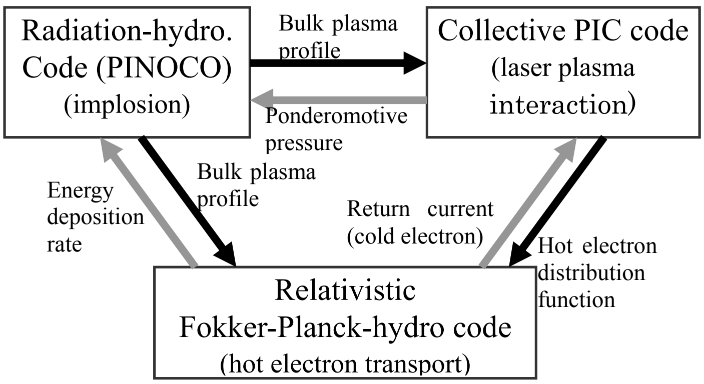


FIG.2 Data flow in FI^3 system. Black arrows are already executable data flows, and gray arrows are next plan to be considered.

2.1 Radiation Hydrodynamics Code (PINOCO)

In PINOCO code, mass, momentum, electron energy, ion energy, equation of states, laser ray-trace, laser absorption, radiation transport, surface tracing and other related equations are solved simultaneously. In general, in implosion codes[5], hydrodynamic is solved by ALE code based on Lagrangian method, in which the computational grids move along with the target. Therefore, they will meet the distorted mesh problem or rezoning/remapping problem. To avoid those problems, ALE-CIP method which is a simple and sophisticated hydrodynamic solver is developed using CIP[7]. In the energy equations, diffusion equations which are the Spitzer-Harm type thermal transport model are solved using the implicit 9-point differencing with ILUBCG method. For the radiation transport, multi-group diffusion type model is installed in the code, in which we can use LTE or non-LTE (CRE) opacity database as table lookup.

2.2. Collective PIC code

For evaluation of fast electron generation due to relativistic laser-plasma interactions, we use the 1D collective PIC code (FSCOF1) [2], where collective particles are used to represent many normal particles and then total number of particles and computations are drastically reduced. Even though, the FISCOF1 code enables us to treat a wide range in space and high density region, the exact condition can not be considered for the computer resource limitation. Therefore, we simulated the small region of relativistic laser plasma interaction and this fast electron bean profile was extended to the realistic scale size. This assumption was temporal and will be eliminated after developing fully parallelized two-dimension Collective PIC code is developed in near future.

2.3. Relativistic Fokker-Planck hydrodynamic (RFP-hydro) code

A 2-D Relativistic Fokker-Planck (RFP) code [8] has been developed for analysis of the fast electron transport and energy deposition processes in dense core plasma, which was coupled with a Eulerian hydro code to examine core-heating properties. In this code, cold bulk electrons and ions are treated by a 1-fluid and 2-temperature hydro model, and the fast electrons generated by the ignition laser-plasma interactions are treated by the RFP model. In the coupled RFP-hydro code includes magnetic field generated by fast electron current, gradient of plasma resistivity and pressure gradient.

2.4. Distributed Computing Collaboration Protocol (DCCP)

We have three set of codes which have quite different properties in FI^3 project. PINOCO and RFP-hydro codes are optimized for vector parallel machine, and C-PIC is optimized for scalar parallel machine. Therefore, it is preferable to be combined with each others which use different machines by way of simple and easy communication tool for computational scientists. Since communication in our project is not complex and very straightforward, we design a special lightweight communication protocol, Distributed Computing Collaboration Protocol (DCCP), to transfer data between codes. DCCP is implemented with two kinds of daemon programs and simulation code itself. One of daemon programs is called Communicator that actually transfers data instead of the code, and the other is called Arbitrator that manages communication between Communicators. The code does not send data directly to another code, but only asks the local Communicator, which is running in the background at his site, to transfer his data. The sender code, therefore, does not have to know details of the receiver code, such as IP address of the receiver computer. And then, the sender side Communicator inquires of the Arbitrator where is the remote Communicator that is handling the receiver code, and forwards the requested data to the appropriate Communicator via the Internet. The receiver side Communicator stores the data to storage, and is waiting for a demand. Finally the receiver code requires the data from the receiver side Communicator, and then the Communicator sends the data to the code and communication between two codes has just finished. If the receiver code does not run yet when the sender code sends data to the local Communicator, the Arbitrator orders it to save the data to storage for a future usage. Once the receiver code is invoked, the Arbitrator directs the sender side Communicator to restore and transfer data to the receiver side Communicator, and now the receiver code can get the desired data. Thus the sender code does not also have to take care of a situation whether the receiver code is running or not. Furthermore, if a broadband dedicated line is available between the Communicators, the Arbitrator tells both Communicators to use that dedicated line instead of the Internet, and high-speed communication will be performed even both codes do not know about details of network configuration. TCP/IP based lightweight protocol does not transfer data directly to another code manage information of codes Arbitrator.

3. Numerical Results

Most of the simulations for fast ignition are performed under the very simple initial conditions, where spherical main fuels are assumed. But they are not realistic, and initial profile may affect the hot electron transport and burning process. Therefore, an overall simulation was performed by FI^3 to demonstrate the realistic numerical fast ignition. It must be remarked that the communications for the profile data transfer to each others are on-line during the individual calculations.

We have performed an integrated fast ignition simulation, which was the first numerical example of FI^3 project. The cone with an opening angle of 30 degrees is attached to a spherical shell of polystyrene, which has a uniform thickness of 8 μm (Fig.3). Gaussian laser was irradiated uniformly to the CH target for the implosion And at nearly maximum mass density, peta watt laser (300J) was irradiated from left hand side to the right on the axis in the gold cone. 4.5 kJ, At The similar experiment was performed at GXII laser facility, ILE Osaka Univ. [7].

At first, cone-guided implosion was simulated by PINOCO [4]. In Fig. 4, simulated result of the mass density contours (upper), and electron temperature are shown. The black line is material interface. In the acceleration phase (Fig.4(a)), around the gold cone, slow flow of over dense plasma is existing, and the laser energy absorption is obstructed. At the maximum compression (Fig. 4(b)), there is no hot spot at the center of the implosion and it is shifted to the left hand side toward

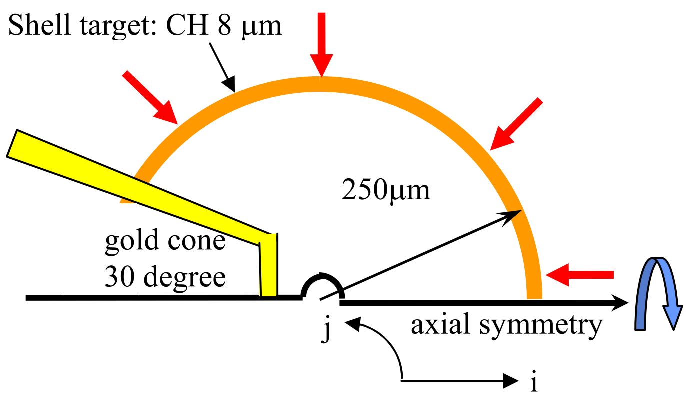
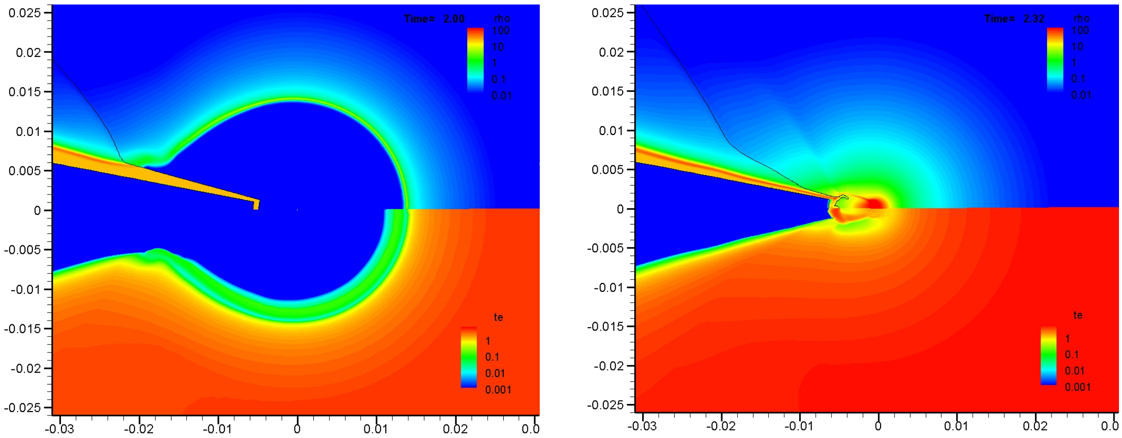


FIG.3. Initial condition of target



(a) (b)

FIG. 4. Imploding non-spherical CH shell with gold cone at t=2.0 ns (a) and t=2.30 ns. The upper contours indicate mass density contours and the lower that indicate electron temperature.

the tip of the gold cone. This phenomena is main advantage of the non spherical implosion. 50 psec before Fig.4(b) mass density profiles are transfer to the RFP-hydro code.

In Fig. 5, plotted lines are the density contours of the cone-guide implosion obtained by PINOCO. Although, the edge of the shell is delayed under the influence of the conical target, the shell target is compressed to be more than 200 g/cm^3 at the maximum. This profile was transfer to RFP-hydro code to simulate the core heating properties. The time-dependent momentum distribution of fast electrons evaluated by the 1-D collective PIC code was used as the fast electron source. The fast electrons were injected at the inner side of Au-cone by assuming the Gaussian profile of FWHM = 15μm in the perpendicular direction. In Fig. 5, color shows the contours of the heating rate by fast electrons when the heating rate in the dense core becomes the maximum (t = 800fs). (The density contour lines are also plotted in the figure.) It is found from this figure that the fast electrons injected at the inner side of the cone propagate into the dense core and they deposit some fraction of their kinetic energy there due to the Coulomb interactions.

This result shows the capability of FI^3 code, but the maximum core temperature is heated up to nearly 0.5 keV, which is still lower than the experimental result (0.8 keV) reported by Kodaka[7]. We have recognized some differences to experimental results in each simulation codes respectively, and those numerical errors were integrated. For example, the mass density of core plasma obtained by numerical simulation was slightly higher than the experimental result. Some improvements of these codes are under way. For example, we are developing 2-D collective PIC to include the cone shape effect. This code will be one of the modules in

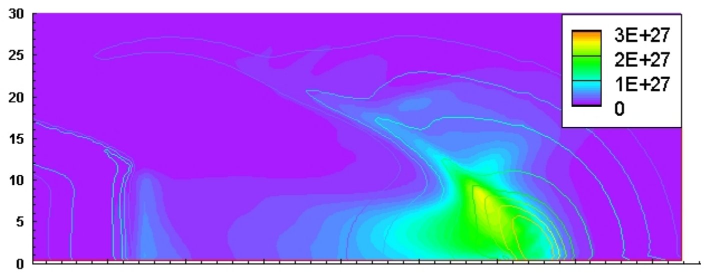


FIG.5. Contours of heating rate by fast electrons (color) and core density (line).

FI^3. One of the authors developed a hybrid-Darwin code, in which fast beam electrons are described as particles and cold background electrons and ions are described as fluids. Therefore, the hybrid-Darwin code can treat hot electron transport in an relatively large scale overdense plasma [8].

4. Summary

We have developed integrated fast ignition simulation code, FI^3, which consists of collective PIC code, RFP-hydro code, and 2-dimensional ALE radiation hydrodynamics code. These codes are coupled with each others by way of DCCP, a communication tool. The first total FI^3 simulation of the GXII fast ignition experiment was run through consistently to show the capability of the codes. In near future, we will design the experiment of FIREX-I [9] to demonstrate the proof-of-principle of fast ignition using FI^3. Some improvement and additional codes development are undertaken. We will be able to simulated fast ignition more accurately after these works are included in the FI^3.

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References

[1] M. Tabak, *et. al.*, *Phys. Plasmas* 1, 1626-1634, (1994).
[2] H. Sakagami, *et. al.*, *Proc. of IFSA '03,* 434-437 (2003).
[3] T. Johzaki, *et. al.*, *Proc. of IFSA '03*, 474-477 (2003).
[4] H.Nagatomo, *et. al.*, IAEA-CN-94/IFP/07, (2002).
[5] H. Takabe, *lecture note*, ILE Osaka Univ. (1997).
[6] T. Yabe *et al*,. *J. Comput. Phys.* **169**, 556 (2001).
[7] R.Kodama, *et. al.*, *Nature* 412 No.6849, (2001) 798-802.
[8] T. Taguchi, *et al*, *Proc. of ICNSP'18* (2003).
[9] T. Yamanaka, *et al*., IAEA-CN-94/OV/3-1, (2002).