RADIATION ASSISTED THERMONUCLEAR BURN WAVE DYNAMICS IN HEAVY ION FAST IGNITION OF CYLINDRICAL DT FUEL TARGET

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Dynamics of thermonuclear burn wave propagation assisted by thermal radiation precursor in a heavy ion fast ignition of cylindrical deuterium-tritium (DT) fuel target are studied by two dimensional radiation hydrodynamic simulations using Multi-2D code. Thermal radiations, as they propagate ahead of the burn wave, suffer multiple reflections and preheat the fuel, are found to play a vital role in burn wave dynamics. After fuel ignition, the burn wave propagates in a steady state manner for some time. Multiple reflection and absorption of radiation at the fuel-tamper interface, fuel ablation and radial implosion driven by ablative shock and fast fusion rates on the fuel axis, at relatively later times, result into filamentary wave front. Strong pressure gradients are developed and sausage like structures behind the front are appeared. The situation leads to relatively reduced and non-uniform radial fuel burning and burn wave propagation. The fuel burning due to DD reaction is also taken into account and overall fusion energy and fusion power density, due to DT and DD reactions, during the burn wave propagation are determined as a function of time.

Introduction

Fast ignition (FI) inertial fusion is a varied concept of standard central ignition by converging shock wave and it involves the separation of DT fuel compression and ignition phases. Small part of the fuel compressed by long range heavy ion beams or conventional long pulse lasers is ignited in a short time by separate powerful heavy ions or lasers pulse. Thermonuclear burn initiated in that part of the fuel is supposed to propagate as a burn wave throughout the precompressed fuel [1, 2]. While studies using short pulse laser beam ignition involve complicated processes of laser hole boring to access the compressed fuel density [3, 4], laser energy coupling at critical density and stable transport to ignition spot through fast electron beams [5, 6], realization of the concept using heavy ion beams, is comparatively simple and has been given much interest in the recent years [7, 8].

To realize the FI concept using heavy ion beams, the cylindrical fuel configuration is a natural choice due to long range of these ions in matter. Analytical as well as computational studies have been performed for FI with heavy ion beams in cylindrical targets under specific conditions [9-11]. Recently, propagation of thermonuclear burn wave in a pre-compressed cylindrical DT target ignited by heavy ion beam pulse has been studied [12]. However, the study mostly emphasizes the burn wave dynamics shortly after the driver energy deposition in the fuel and does not take into account precisely the role of thermal radiation in burn wave propagation dynamics, in particular, those which occur at and around the front of burn wave.

Here we explore in somewhat more detail the role of thermal radiation that they play in dynamics of thermonuclear burn wave propagation in the present scenarios. Furthermore, the formation of on axis filamentary wave front with high thermodynamic properties (i.e. high density, temperature and pressure etc.) and, in particular, the sausage like structures due to strong pressure gradients at and behind the filamentary front observed to appear at relatively later times are explained. Formation of these structures results into higher, on axis, burn rates but reduced and non-uniform radial burning of the DT fuel.

We performed two dimensional (2D) radiation hydrodynamic simulations for ignition and burn wave propagation dynamics in a pre-compressed DT-gold (DT fuel surrounded by gold tamper) cylindrical configuration by using Multi-2D code [13]. It is assumed that the configuration is uniformly compressed with ρ_{DT} = 100g/cm^3 and R_{DT} = 50μm which corresponds to inertially confined fusion criteria $(\rho R)_{DT}$ = 0.5g/cm^2, the value suitable enough for the burn wave to be set after ignition [12]. The density of the pre-compressed gold is taken as ρ_{Au} = 400g/cm^3. As it will be explained in the next section, the high density tamper in this configuration plays two major roles, i.e. to increase the confinement time thereby allowing more DT fuel to burn before being expanded to low $(\rho R)_{DT}$ values and most importantly the thermal radiation chamber which ultimately leads to radiative preheating and ablation driven radial fuel implosions. To perform simulations, the DT fuel cylinder is ignited at one end by depositing 400 kJ energy of heavy ions pulse with focal radius equal to radius of the fuel, 50μm, and energy deposition range of 6g/cm^2. The ion pulse deposits its energy in the fuel according to the Braggs law i.e., energy deposition peaks at the end of the range. For thermodynamic and radiative properties of the DT fuel and gold tamper, tabulated EOS and opacity data are used. To calculate the EOS data table, quotidian equation of state (QEOS) model [14] has been used. For calculations of opacity data the code OPAQS, developed based on quantum statistical model, has been used. The details of OPAQS and calculated opacity data are presented in a separate manuscript [15].

Role of thermal radiation precursor

In present configuration of pre-compressed DT fuel surrounded by high Z gold tamper, the fuel when ignited by heavy ions pulse, releases thermonuclear energy that is deposited in the vicinity of burning area by thermal conduction, thermonuclear reaction product charged particles or radiation transport. The tamer in contact with hot multikev thermonuclear material is heated to high temperatures and therefore, becomes a secondary source of soft x-rays radiation. Soft x-ray radiations are also emitted by small portion of the fuel pushed to high density by pressure shock from burning area. When the intensity of soft x-ray radiation is increased to high values, they are transported into the DT fuel as precursor radiation and heat the fuel ahead of the burning area.

These radiations enter into and propagate along the fuel material according to basic principles of physical optics, i.e. those entering obliquely from higher density regions to lower ones will be refracted away from the normal and vice-versa and those entering normally will follow the same path etc. Similarly, those which are incident on a surface at some angle might suffer some absorption and also reflection at an angle equal to or greater than the incident angle. Therefore, they suffer some absorption into fuel or tamper and multiple reflections along fuel-tamper interface and fuel axis and thus, preheat the fuel and play a vital role in the dynamics of burn wave propagation. The pre-heated fuel temperatures and $(\rho R)_{DT}$ conditions ahead of the burning area are such that they set a burn wave which propagates into the fuel with precursor radiation always ahead of that wave down to the fuel length. Normally, when a material is heated by an energy source, e.g. thermal radiation, the ionization or radiative heat front initially propagates ahead and leads the shock wave until energy from the source starts decreasing where shock wave reaches the ionization front and then ultimately over takes it [16]. However, the situation in the present case is different as a matter of the fact that burning of the DT fuel takes place continuously and acts as strong source of energy all over the time. Therefore, radiative heat wave always moves ahead of the burn wave shock and preheats the fuel.

Filamentary wave front and sausage like structures

As long as reflection angles of precursor radiation along fueltamper interface and fuel axis are not so large that they propagate almost uniformly ahead of the burn wave, they pre-heat it to near ignition temperatures and a steady state burning of the thermonuclear fuel takes place, as shown in Fig. 1(a-d) at time 0.98 ns. The peak ion temperatures, Fig. 1(a), rise to 130 keV. The higher ion temperatures are due to local deposition of α energy. The peak radiation temperatures are found on fuel-tamper interface at a specific location due to radiation incident and absorption at preferred refraction angles and re-emitted soft x-ray radiation from tamper.

Radiations propagate into the fuel and heat it to 8-10 keV temperatures. The peak fuel density at the shock front rises to 230 g/cm^3, Fig.1(c), and reduces to 20g/cm^3 in the burning area due to thermonuclear reactions. The power density due to thermonuclear fusion peaks at fuel axis and burn wave gradually extends to fuel surface in radial direction thereby making a bow like wave front, Fig. 1(d). Fig. 1(e) shows the distribution of pressure which peaks to 15 Tbar at the wave front. Similarly, Fig. 1(f&g) show the radial and axial component of the burn wave velocity. The increase in density and therefore, thermonuclear burn can clearly be understood by looking

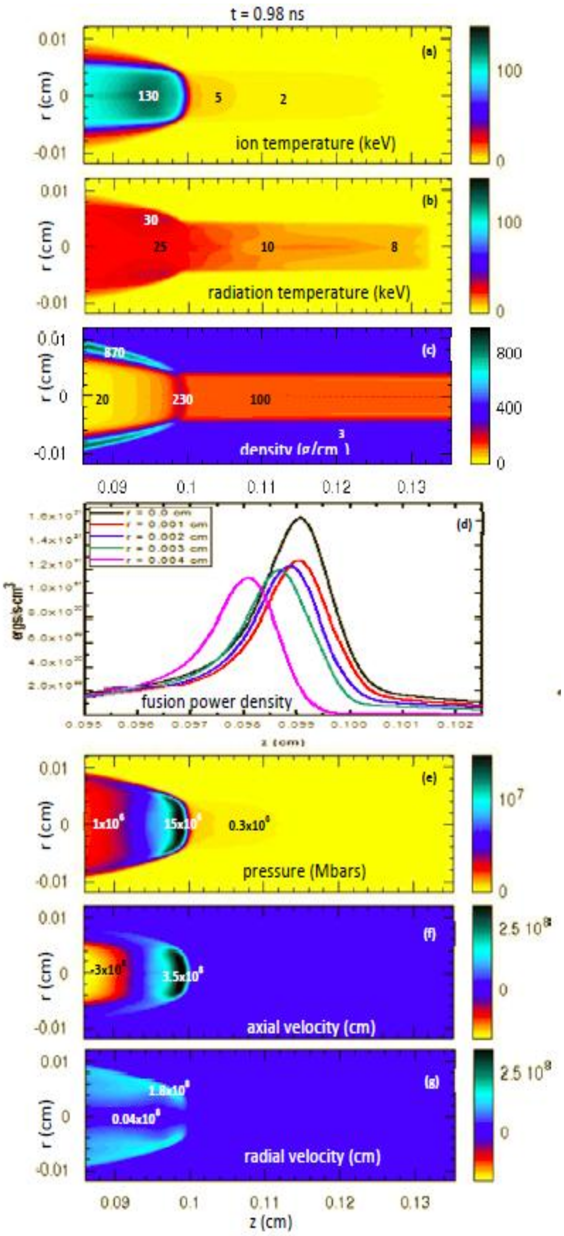

Fig. 1. Distribution of (a) ion temperature, (b) radiation temperature, (c) fuel density, (d) fusion power density, (e) pressure, (f) axil velocity and (g) radial velocity at time t = 0.98 ns.

at the velocity contours. However, an interesting situation occur at relatively later times when soft X-ray emission from gold tamper also contributes and reflection angles from fuel axis become relatively large, the radiation field along the fuel-tamper interface moves ahead of one at fuel axis. Outer layer of the fuel heats up while inner remains cool and therefore, ablates off with higher radial velocities thereby producing an ablative radial implosion of the fuel.

The on axis fuel density increases that helps to increase the fuel burn rate and hence the release of large fusion energy thus generating a filamentary structure of the wave front. The so generated large pressures push the fuel with higher axial velocities to even higher densities ahead of the burn wave filament. The whole scenario can be easily understood from Fig. 2(a-g) at time 1.05 ns.

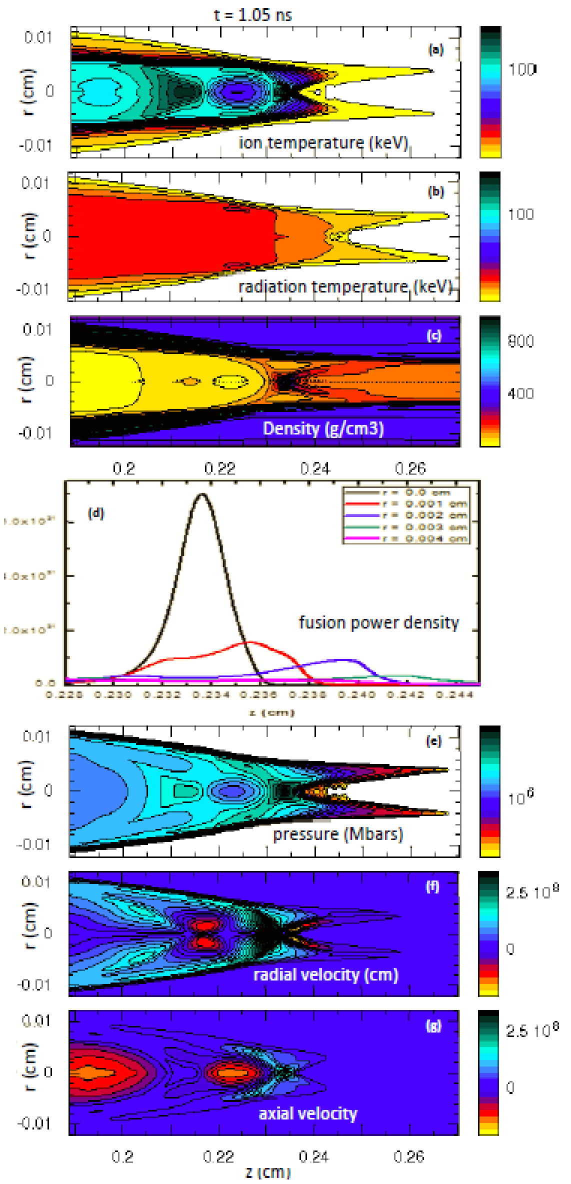

Fig. 2. Distribution of (a) ion temperature, (b) radiation temperature, (c) fuel density, (d) fusion power density, (e) pressure, (f) radial velocity and (g) axil velocity at time t = 1.05 ns.

The actual dynamics as explained earlier and shown in Fig. 1(a-g) are also accompanied this scenario behind the filamentary front at z = 0.213 cm. The whole situation involves strong pressure gradients that help to develop the sausage like structures behind the filamentary wave front, as shown in Fig. 2(e). The role of precursor radiation, in particular, the processes of radiative fuel ablation and ablatively driven radial implosions in the burn wave dynamics, which are not precisely discovered in the previous studies [12], are clearly demonstrated in the present study. The dynamics of the burn wave propagation keep continuing forward in the similar way until radiation field along the fuel axis also increases. Formation of such structures around the burn wave front although results into higher on axis fuel burn rates but are responsible for the reduced and non-uniform radial burning of the DT fuel, Fig. 2(d).

Since the fuel temperatures are sufficiently high at which DD fusion reaction also has reasonable cross sections and therefore, needs to be taken into account. We have calculated the overall fusion energy and power density due to DD and DT reactions during the burn wave propagation as a function of time. Such results will be presented elsewhere.

Conclusions

We have studied the role of thermal radiation precursor in the dynamics of thermonuclear burn wave propagation in heavy ion fast ignition of pre-compressed cylindrical DT-fuel-goldtamper target configuration. Radiation hydrodynamic simulation using Multi-2D code has been performed. It has been found that thermal radiations play a vital role in burn wave dynamics. They propagate ahead of the burn wave and preheat the fuel. The filamentary wave front and sausage like structures behind the front are appeared to form due to ablatively driven radial fuel implosion, on axis fast fusion rates as well as normal fuel burning behind the front thereby generating strong pressure gradients at relatively later times.

The scenario leads to reduced and non-uniform radial fuel burning and burn wave propagation. The fuel burning due to DD reaction is also taken into account and overall fusion energy and fusion power density during the burn wave propagation are determined.

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