Implosion of a large spherical void

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Abstract. Implosion is the most efficient way to achieve high energy density (HED) or inertial confinement fusion (ICF). Traditional ICF schemes use millimeter size fusion targets, which usually suffer from unsymmetrical driving and easy-to-rise hydrodynamic instabilities. We investigated the physics of the implosion of a thick shell spherical void, with the inside being vacuum or of very low pressure, and the radius being a few centimeters. Very high pressure and temperature will be achieved in a small region, which may lead to the thermal nuclear fusion ignition.

1. Introduction

Current HED or ICF driving methods, such as high average power laser (HAPL) [1, 2, 3], Z-pinch [4], high energy or intense particle beams [5, 6, 7, 8], or high power wire discharge in materials [9], etc., are mostly involved in some undesirable features, such as huge and expensive external devices (laser, pinch, particle beam, hypervelocity impact), non-equilibrium HED states (energy, temperature, pressure of ions, electrons, and radiation are not uniform), difficult to control, etc. On the other hand, implosion [10] or converging matter wave is very efficient in concentrating energy both temporally and spatially, which finds their applications typically in weaponry and ICF. Another live example is the sonoluminescence phenomena [11, 12]. Though the driving energy for each bubble is very small, the collapsing or implosion of the bubble can produce very high pressure and temperature [13, 14]. This even intrigued the controversial bubble fusion idea [15]. However, as the total energy of each bubble is limited (< 1 mJ), and the vapor pressure in the cavity is high (in the order of 100 Pascal), the compression (~ 10^3 fold) is unlikely to produce a temperature well above 10^5 Kelvin [13].

In ICF regime, the inner DT gas has quite high initial density, which prevents a high ratio compression. Premature shockwave heating also increases the inner pressure, which contributes to the Rayleigh-Taylor instability. The amount of the gas is limited by the driving energy and hydrodynamic efficiency.

If we can dramatically raise the total implosion energy and/or greatly reduce the vapor pressure in the cavity, then we can achieve much higher compression ratio, hence much higher pressure and temperature. Particularly, if the cavity is vacuum, the inner surface of the cavity can reach a very high speed. Upon impact at the center, temperature up to ICF regime is achievable.
Figure 1. High energy cavity implosion by conventional drive. The cavity is vacuum or of very low pressure, and the shell is heavy metal. The inside of the shell is coated with fusion fuel.

2. High energy cavity implosion

Fig. 1 shows the sketch of the approach. A shell made of high-Z metal is used as the driving medium. Conventional means such as high explosive or high pressure is used to drive the implosion. In the case of vacuum, the fusion fuel (DT-rich solid compound such as LiB(DT)$_4$) or any material of interest is coated on the inner wall of the shell. The radius of the cavity can be a few centimeters (versus 1–2 mm in ICF targets), to take full advantage of the converging compression effect. There is no or only very low pressure (3–4 orders of magnitude lower than cryogenic ICF targets) DT gas inside.

Compared with current high power short pulsed drives (HPSPD) such as lasers, pinches, or beams, this approach has some significant features:

(i) The device is much simpler and cheaper.
(ii) Conventional drive such as high explosive implosion is well understood [16], with high hydrodynamic efficiency (20–30% vs < 10% in HPSPDs), high total driving energy (up to ~ 100 MJ), and much lower cost.
(iii) Longer driving time, larger driving area, and higher driving efficiency, make the accumulation of energy more easily. The driving times in conventional means are usually 2 to 3 orders of magnitude longer than HPSPDs.
(iv) The thick and dense high-Z shell provides extra confinement in both momentum and optical opacity.
(v) Due to the vacuum inside, the pressure distribution near the inner wall creates a perfect sphere in the driving stage, which will greatly mitigate the hydrodynamic instability problem afterwards.
(vi) Easily adjustable pressure or temperature by setting different gas density in the cavity.

In ICF scenario, it is obvious that most of these features are very desirable. The downside of this approach may be the difficulty of diagnosis, due to the blocking of the thick shell.

A simple one dimensional incompressible analysis is presented in the next section to illustrate the principle features of implosion.

3. An ICF scenario example in one dimensional incompressible fluid model

Under high power driving, the heavy metal shell can be treated as fluid. To simplify the analysis and illustrate the main features of the imploding process, we assume the shell is incompressible and the viscosities are zero.
Table 1. The velocities, radii and pressures of selected moments. The bottom line is from typical ICF simulation [17].

| $r_1$ (cm) | $R_1$ (cm) | $u_1$ (km/s) | $f_h$ | $p_{\text{max}}$ (Mbar) |
|------------|------------|--------------|-------|-------------------------|
| 2.00       | 2.05       | 10.0         | 0.49  | 0.004                   |
| 0.50       | 0.90       | 18.7         | 0.23  | 3.186                   |
| 0.125      | 0.85       | 108          | 0.014 | 238.0                   |
| 0.031      | 0.85       | 815          | $3.1 \times 10^{-4}$ | $1.5 \times 10^4$ |
| 0.010      | 0.85       | 4443         | $1.1 \times 10^{-5}$ | $4.56 \times 10^5$ |
| 0.010      | –          | 350          | –     | $\sim 10^6$             |

An inertial fusion oriented calculation is carried out as follows. Supposing at the end of the driving, the shell gains a speed of $u_0 = 10$ km/s, with an inner radius of $r_0 = 2$ cm, a thickness of $l = 0.5$ mm, and a density of $\rho = 10$ g/cm$^3$, the mass of the shell is $M = 25.7$ gram, and the total kinetic energy is $E = 1.2$ MJ.

Fig. 2 shows the fraction of the integrated kinetic energy starting from $r_1$. It is clear that the smaller the $r_1$ becomes, the more concentrated the kinetic energy will be to the center of the shell. At $r_1 = r_0/64 = 0.31$ mm, the small layer between $r_1 = 0.31$ mm and $r = 0.6$ mm will have half the total kinetic energy, but its volume (mass) fraction ($f_h$) is only 0.03%.

![Figure 2](image_url)

**Figure 2.** Energy concentration. Kinetic energy fraction integrated from the inner wall. The inner radii for (a), (b), (c) and (d) are 2.0 cm, 0.5 cm, 0.125 cm and 0.031 cm, respectively, and the half points (kinetic energy fraction 0.5) are 2.025 cm, 0.644 cm, 0.218 cm and 0.06 cm, respectively.

For comparison, the inner and outer radii $r_1$ and $R_1$, the velocities of the inner wall $u_1$, half kinetic energy fraction $f_h$, and the maximum pressures $p_{\text{max}}$ of the imploding shell at selected moments, as well as some comparable identities in typical ICF simulation [17] are displayed in Table 1. Note the inner radius $r$, implosion velocity $u$, and pressure $p$ have different meanings in ICF. For $r_1 = 0.01$ cm, the small half kinetic energy region has a kinetic energy density of $2 \times 10^9$ J/g, which is of the same order as in ICF ignition, but the total energy $E = 0.6$ MJ is much higher.
4. Discussions
Mathematically, the implosion center is singular, and the implosion speed tends to infinity. We did not calculate inner radii cases less than 100 $\mu$m for two reasons. One is $r \sim 100 \mu$m is the typical ICF stagnation radius. The other is that realistically there may be a small amount of matter in the cavity, the vacuum assumption is no longer true.

The incompressibility assumption is hard to meet in high energy cases. High-Z metal such as gold or uranium is chosen to reduce the compressibility in HED. The calculations in the last section are only illustrative, not qualitatively trustworthy. However, they do reveal some of the attractive features as a HED drive: a), high hydrodynamic efficiency. Total kinetic energy concentrates to the center; b), very high pressure and velocity is achievable.

For compressible fluid, a large portion of the total hydrodynamic kinetic energy would be transferred into internal energy. At pressure as high as $\sim 1$ Gbar, high Z materials may have an internal energy density of $\sim 1$ MJ/g. However, as the ultra high pressure region is very limited as shown in Table 1, there should be still a large portion of imploding kinetic energy left.

A preliminary one-dimensional radiation hydrodynamic simulation is carried out by a modified MULTI code [18]. Simulation shows, with the shell to be gold, and the inside to be low pressure DT gas, 3 $\sim$ 4 MJ of imploding dynamic energy can produce a DT ion temperature of about 1 $\sim$ 2 keV, and DT density of about 100 g/cm. Fusion neutron yield is around 10$^{12}$ to 10$^{15}$. Ignition is hard to achieve in reasonable settings. The major energy loss is the electron heat transfer of the shell and radiation.

However, there are some facts missing in current simulations: (a) as the shell is much thicker and denser than that in mainstream ICF approaches, neutron heating is not negligible, but is absent in current code. (b), as opacity is important, hybrid shell can lower the radiation loss [19]. (c) If the shell is depleted Uranium, extra heating by fast neutron induced fission will be of great help. In this case, the total energy output would be mainly fission energy.

Further investigation is worthwhile to find out if this approach is applicable in energy production.

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