Low density volume ignition assisted by high-Z shell

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Abstract. Conventionally driven high-Z metal shell implosion, with a large radius (a few centimeters) and a low DT gas pressure ($\sim 10^{-5}$ g/cm^3), is calculated by one dimensional radiation hydrodynamics to find the fusion ignition energy. Calculation shows, with sufficiently high driving pressure and the right amount of fusion fuel, a volume ignition like fusion process can be initiated, at a ignition temperature of about 2 keV, and a relatively low density of about 70 g/cm^3. The total fusion energy released is limited. Excessive kinetic energy and extra confinement provided by the shell is essential in this low density low area density volume ignition.

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1. Introduction

Implosion is highly efficient in concentrating energy both temporally and spatially up to very high energy density [1]. It is the most important mechanism in inertial confinement fusion (ICF).

In concurrent ICF researches, as the high energy density (HED) state required is highly unstable and short lived, high power (~ 1 PW) and short pulse ($10 \sim 20$ ns) drives (HPSPD) are used, such as high average power laser (HAPL) [2, 3, 4], Z-pinch [5], high energy or intense particle beams [6, 7, 8, 9, 10], hypervelocity impact [11, 12, 13], etc. As these drives can deliver not very much energy on the target in the short pulse, the target size is usually small, with a radius of typically $1 \sim 2$ millimeter. The devices are usually huge, expensive, engineering challenging, and share common physical issues such as low hydrodynamic efficiency, and instabilities caused by asymmetric driving.

There are also some efforts trying to exploit the energy concentration feature of cavity implosion in fusion research in the context of single bubble sonoluminescence phenomenon [14, 15, 16], i.e., bubble fusion [18]. However, as the total energy of a collapsing bubble is very small, and the vapor pressure is high, the compression ratio is only about 1000, it is very unlikely that the collapsing bubble can reach a temperature well above 10 eV [16, 17].

However, if we can drastically raise the total implosion energy, increase the cavity radius, and reduce the vapor pressure, we should achieve much higher compression ratio, hence much higher pressure and temperature. The idea has been studied in Heavy Ion Fusion [19] and Z-pinch approaches, while the total driving energy requirement is higher (~ 10 MJ), and the target sized are larger, $r = 5 \sim 10$ millimeters.

On the other hand, conventional drives such as hydrodynamic pressure or converging high speed water jets have much lower power but much more total energy. By taking advantage of the energy concentration mechanism of near vacuum cavity implosion, it is intriguing to know if it is possible to achieve fusion ignition by low power conventional drives.

Though considered long ago as impractical to achieve controlled nuclear fusion by high explosive implosion, there is hardly any public discussion in (ICF) literature on what the challenges are. There is no quantified data supporting common beliefs such as low energy density, fast electron diffusion cooling, hydrodynamic instabilities, etc. In this paper we will do a full one dimensional radiation dynamic simulation of such implosion with reasonable settings, to investigate the physics involved and find the criterion of fusion ignition.

2. Approach setup

Fig. 1 shows the sketch of the approach. A shell made of high-Z metal is used as the driving medium. The drive is conventional. Eventually it would be a large device to concentrate high speed water jet to a larger near vacuum ball, but the inner most

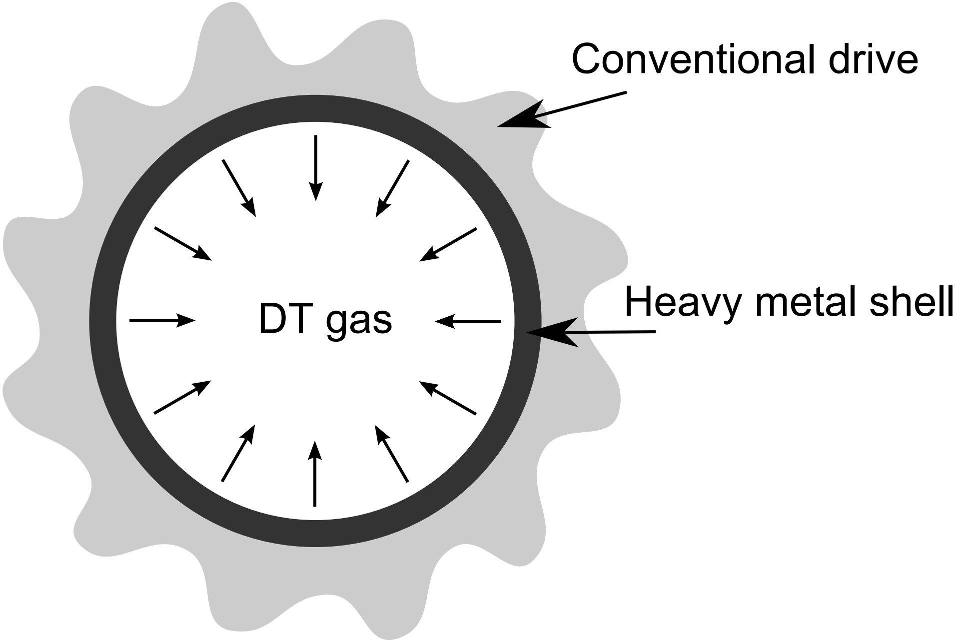

Figure 1. High energy cavity implosion. The cavity is filled with low pressure DT gas, and the shell is high-Z metal. Outside is a multistage converging pressure drive.

target would be as follows: The inner radius of the cavity is 2 to 5 centimeters (versus $1 \sim 2$ mm in ICF targets). The cavity is filled with low pressure DT gas ($\rho \sim 10^{-5}$ g/cm^3), under room temperature. The volume of the cavity is about 10^4 times larger than HPSPD ICF targets, to ensure high compression ratio.

There are some distinct features in this approach comparing with mainstream ICF studies based on HPSPDs.

- The device is much simpler.
- There is no engineering challenges such as high vacuum or low temperature requirements for the reaction chamber.
- The driving energy is cheap and abundant. It is easy to apply hundreds of MJ energy to fusion target, while HPSPDs are usually limited to a few MJs.
- The hydrodynamic efficiency is higher, because there is no energy consuming ablation.
- Longer driving time, larger energy absorbing area, and higher efficiency, make the accumulation of energy easier. The driving time is usually hundreds of times longer than that of HPSPDs.
- Confinement time is much longer, because the shell provides large amount of extra momentum of inertia.
- The optical thickness of the high-Z shell together with the longer confinement time enables low temperature (~ 2 keV) volume ignition.
- Comparing with cryogenic ones, room temperature target is easier to handle.

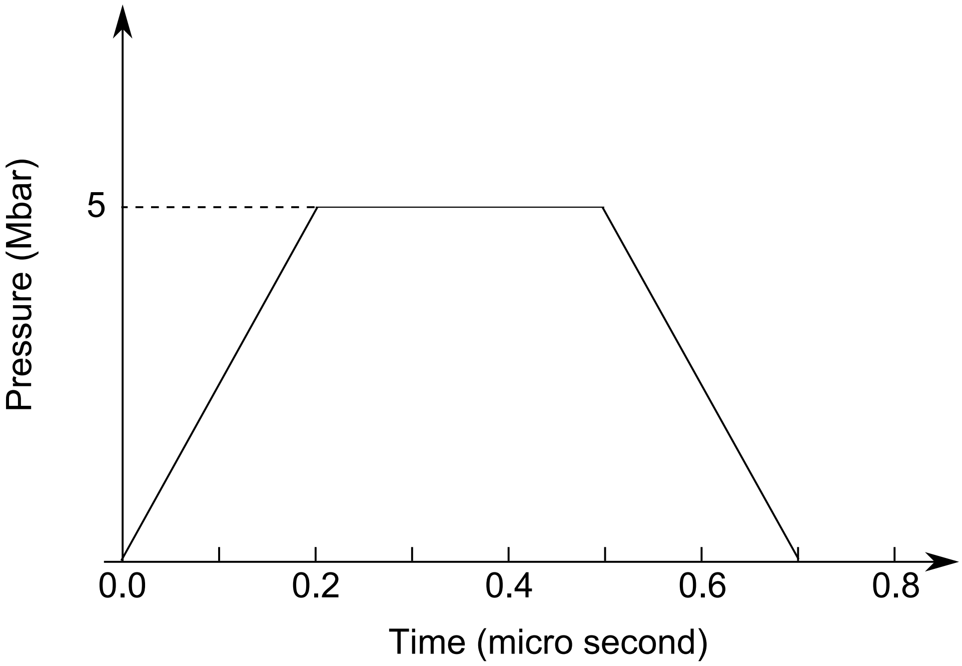

Figure 2. Driving pressure pulse. The x-axis is time and y-axis the pressure.

- If applied to fusion-fission hybrid concept, the shell can be made of fissile material, to increase the energy output.
- Water filled reaction chamber efficiently slows down the fusion neutrons.

3. One dimensional radiation hydrodynamic simulation

Full one dimensional radiation hydrodynamic simulations with 3 dimension geometry are carried out based on the latest version of MULTI-1d [21, 22] code. A module is programmed to enable pressure driving.

In the following simulation, the shell is made of gold, with inner radius $r_0 = 2$ cm, thickness $l = 0.1$ mm. The initial pressure of the DT gas is 1×10^{-5} g/cm^3. The total mass of the DT gas is only 0.34 mg. The gas is divided into ten equal thickness layers, and the shell into 60 layers with a consecutive layer thickness ratio of 1.15, to ensure the layer smoothness as the shell inner radius goes small. The maximum time step is 5 picosecond. Single group radiation is used.

The converging imploding driving is manifested as a external pressure pulse for the target. The pulse used in simulation is displayed in Fig. (2). It is not arbitrarily chosen, but not meticulously optimized either. For practical reasons, the driving pressure is used only to provide sheer momentum. A fine tuned pressure pulse shape is hard to implement experimentally. The fusion fuel is standard equimolar DT mixture, with its Rosseland and Planck opacities taken from [23]. Gold is modeled by tabulated physical EOS and data taken from [24].

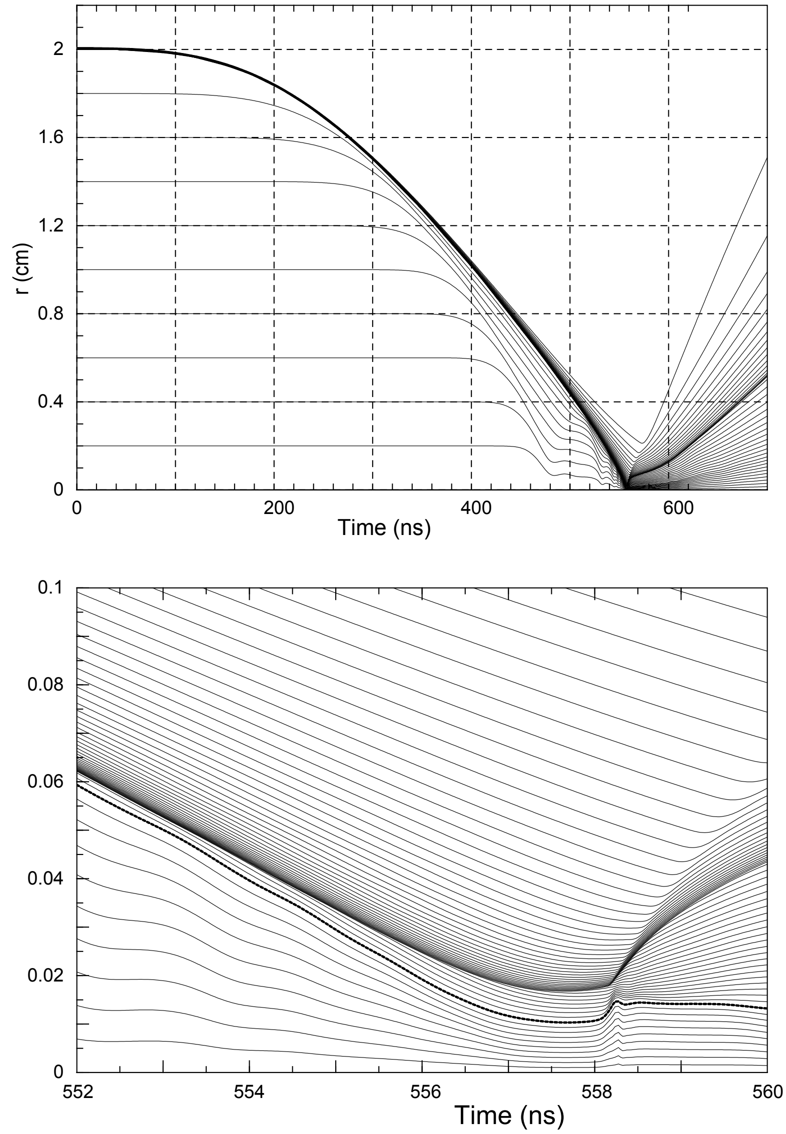

Figure 3. Flow chart. (a) overall. (b) enlarged near fusion peak. The Y-axes are layer radii, in unit of centimeter. The abscissas are time, in unit of nanosecond. The ten lowest layers are DT fuel, and the others are gold. The boundary is indicated by the thick dashed line in (b).

4. Simulation results

Based on above settings, simulation shows self sustainable fusion happens, with distinct features of volume ignition. The details are as follows.

Fig. (3) is the flow chart of the implosion. The driving (energy cumulation) time is about 550 ns. The maximum kinetic energy of the shell before ignition is 15.6 MJ. The minimum radius of the fuel is about 110 micron, so the maximum volume compression rate is about 6×10^6.

The ion temperature, density, and pressure profiles near fusion peak are displayed in Fig. (4). Electron temperature are almost identical to ion temperature all the time, except around the fusion peak, DT ions are distinctively hotter than electrons, as displayed in Fig. (6). Before ignition, DT shares the same equilibrium temperature with gold wall. The density of the DT plasma around fusion peak is almost uniform, with the highest being 73 g/cm^3. The inner wall of the shell is hotter and less dense due to the direct contact with the hot DT plasma. This can be seen from the small terraces in dashed lines (1–3) in Fig. (4b). After the fusion peak, the terraces grows wider as shown in solid lines (4–5) of Fig. (4b). Fig. (3b) tells the same story. The highest density of the shell registered is over 4000 g/cm^3. This super high density is important in two aspects: (1) retaining a high pressure outside the fusion center, and providing extra confinement time; (2) providing a very high opacity to keep the radiation energy from leaking out.

Comparing Fig. (4b) with Fig. (4c), we can see the pressure of DT plasma is almost the same as the surrounding hot gold plasma. This density and pressure configuration does not favor instability emergence.

Fig. (5) is the fusion power and the DT fraction changes near the fusion peak. The width of the fusion peak extends about 1 nanoseconds, which is much longer than that of typical HPSPD ICF ($\sim$ 50 ps [25]). There is also a “warming up” time of a few nanoseconds, while fusion power is not negligible. This is a typical volume ignition feature, which is more obvious in Fig. (6), as the temperatures of each layer and their variations with time are shown. Both electron and ion temperature are displayed. The upper three pairs of thicker lines are for DT layer number 1 (target center), 5, 10, respectively, and the others are the closest gold layers. For a few nanoseconds, before ignition, the DT ion temperature is above 3 keV. However, as the density is quite low in this time, the fusion power is low. Electron and ion temperatures separated only in the time of the fusion peak, and in the target center. The highest ion temperature is 64 keV. The total fusion energy output is 72.8 MJ, with a fuel burn-up of 65%.

5. Observations and Discussions

Overall, pressure driving ICF via conventional methods is challenging and not so efficient. The initial shell is very thin and the hydrodynamic kinetic energy of the imploding shell is over 15 MJ in above simulation, but releases mere 72.8 MJ of fusion energy. Considering the driving efficiency issues, it is barely a break-even. Hundreds of simulations have been made, this is almost the most plausible case of a true ignition. In most other settings, with a few MJ of imploding kinetic energy, the ion temperature can barely reach 1 keV, and the fusion energy released is only a few Joule or less. For the same driving and shell configuration, only in a narrow DT density window, the fuel can be successfully ignited. A little more or less will fail.

Of cause raising the driving pressure can produce better numbers, but it is highly doubtful that it could be realized in laboratory. In shock compression researches, high

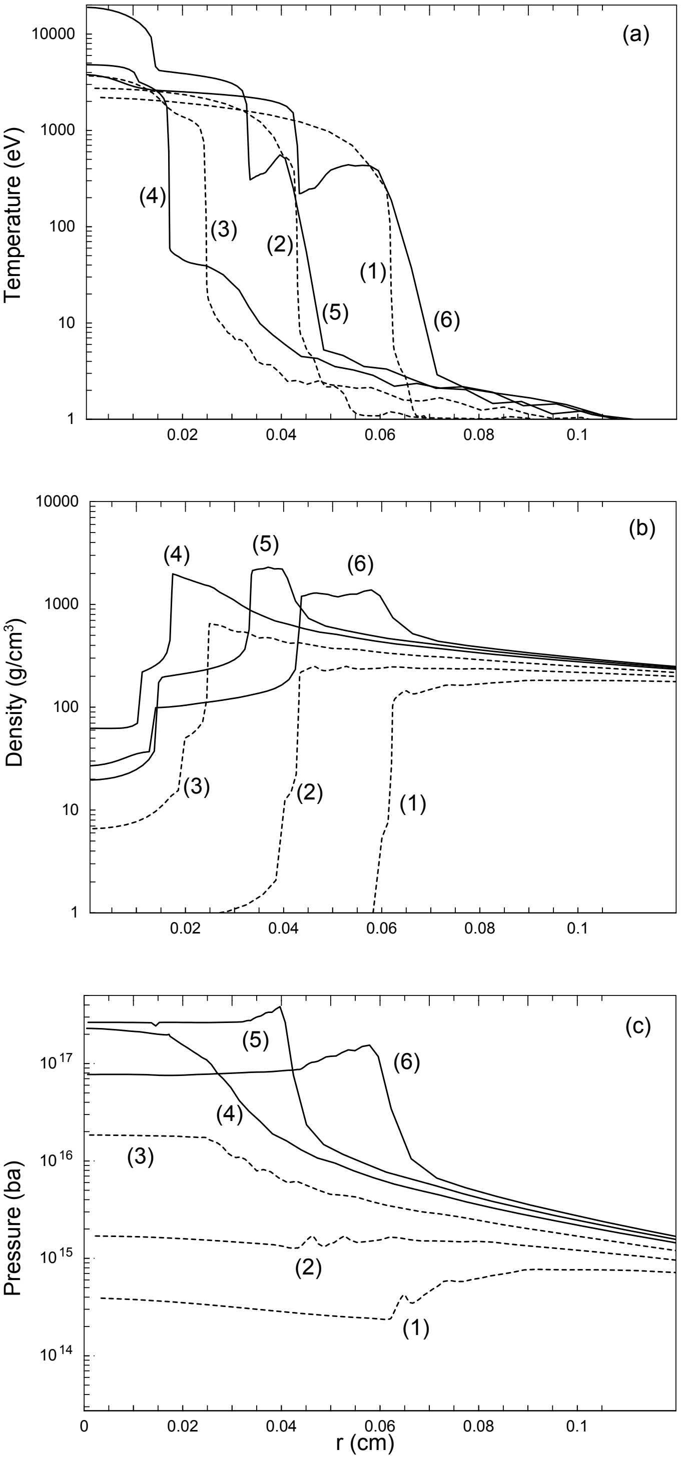

Figure 4. Sequences of radial profiles of (a) ion temperature, (b) density, and (c) pressure. (1) $t = 552$ ns; (2) $t = 554$ ns; (3) $t = 556$ ns; (4) $t = 558$ ns; (5) $t = 559$ ns; (6) $t = 560$ ns . Dash lines are before the fusion peak.

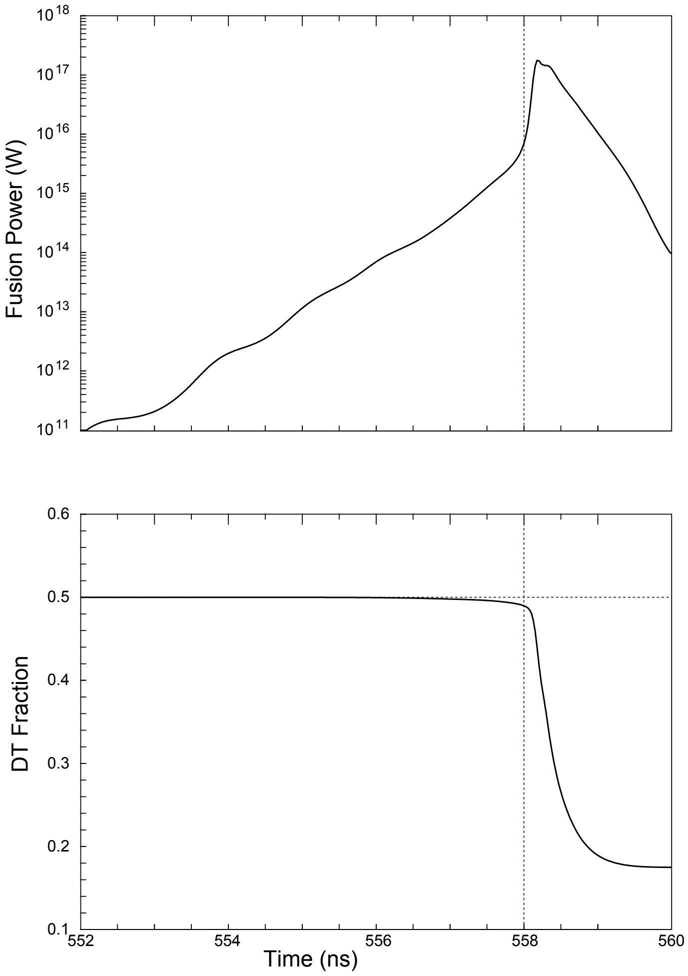

Figure 5. Fusion power and DT fraction variation with time near fusion peak. The abscissas are time, in unit of nanosecond.

explosive devices can generate a pressure of 25 Mbar [20]. We believe a right design with converging high speed water jet or shock wave can achieve a similar driving pressure with above dimensions.

There are also some facts that can improve the situation, but not presented in the simulation yet:

- Shell opacity is important in keeping the radiation energy of the center hot spot. There are methods to increase the opacity [26].
- In fusion studies, neutron energy which is four times of that of alpha particle is usually neglected, for the long range needed to stop the neutron. However, in this approach the dense and thick shell can keep a large portion of neutron energy in, heating the shell, raising the ambient temperature and pressure, and making fusion ignition easier.
- The high-Z shell is not necessarily gold, under the extreme HED conditions quoted

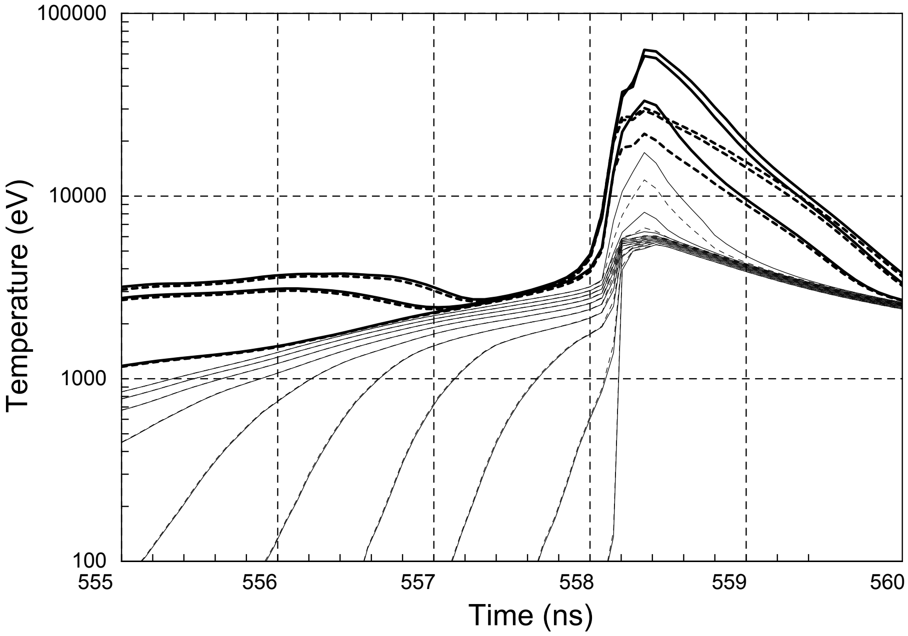

Figure 6. The electron (dashed line) and ion (solid line) temperature of the layers, and their variation with time. The thick lines are inside the DT plasma, and the thinner ones are that of the gold shell. The number of the layers are 1, 5, 10, 11, 13, $\cdots$, 20, from up-left to down-right, respectively, with number 1 being the target center, and number 70 the outmost. The abscissa is time, in unit of nanosecond.

above, lead can be a good candidate.

Usually low temperature volume ignition happens at very high density [25], with the fuel being optical thick. Here the optical thickness is provided by the shell. More over, in the warming up phase, the meager fusion energy produced by the fuel is not enough to heat up the gold plasma close by. Those energy comes from the stagnation of the incoming shell.

6. Acknowlegement

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