Fast Ignition Impact Fusion with DT methane

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Impact fusion concept has some outstanding features such as "standing-off" and high drive efficiency. Historically, as people expected large projectile and excessively high ignition energy, the idea was abandoned because there is no way to accelerate a gram size projectile to necessary hyper speed. Here we present a new approach, using a millimeter-size diamond bullet, and crystal solid DT methane as the fusion fuel. DT methane has twice DT concentration and five times alpha particle stopping power than DT ice. The smaller size of the bullet is to achieve a "fast ignition" like concept, instead of global compression of former schemes. The physics of this new impact fusion is discussed, and an estimation of ignition energy is presented. With all inborn advantages, impact fusion energy can be very promising.

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1. INTRODUCTION

Each fusion approach has its own problems, but there is one in common, i.e., some components and/or the confinement chamber wall are too close to the fusion spot/area. This will cause great damage to the cable, stand, optic lens, etc., and impose too heavy load to the reaction chamber wall. This is the notorious "standing-off" problem of fusion energy research, specially in inertial confinement schemes. Current main stream inertial fusion energy schemes, i.e., laser, Z-pinch, heavy ion, also share another major defect of low drive efficiency. In these schemes, typically less than 10 percent of the injected laser, ion beam, electrical energy can be converted into the hydrodynamic imploding energy.

Impact fusion schemes[1–5] are free of the above two problems. They also have extra benefits which are attractive to fusion researchers, such as no target pre-compression, propagating fusion burn, etc. In these schemes, a macroscopic ($\sim$ 1 g) projectile (bullet, or macron) is accelerated to a hyper-velocity of 200 $\sim$ 1000 km/s, and shot to passive targets, to produce the high density and temperature required. However, the problem comes from the acceleration. As earlier researchers expected a rather large bullet ($\sim$ 1 g) and excessive projectile kinetic energy (10 $\sim$ 50 MJ, depends on whether the impact compression is one dimensional or three) [6, 7], no mass acceleration method can reach even 1 thousandth of that energy. People forgot about this idea soon after the only impact fusion workshop hosted by Los Alamos National Laboratory in 1979.

There have been many theoretical and experimental advances since then. Particle accelerators run at TeV level other than GeV. Klystrons work in higher frequency and power. More importantly, we know more about fusion and high energy density physics, particularly, the electron-ion interaction and alpha energy deposition in inertial confinement fusion (ICF) [8–11], which is vital for the ignition and burning. Among all the acceleration schemes evaluated in 1979 [12], such as two-stage light gas gun, rail-gun, traveling magnetic-wave, plasma-impulse, laser ablative, and electrostatic accelerators, electrostatic approach was among the first ones to be rejected. The arguments are straightforward and strong: macroscopic particles as heavy as 1 gram cannot be charged to high charge-mass ratio, and the accelerator would be of thousands of kilometers long. This situation will change if the projectile is smaller.

In impact fast ignition concepts [5, 13], a very small projectile ($\sim 10^{-3}$ cm) is accelerated to about 1000 km/s, impacts into the pre-compressed fusion pellet, ignites the propagating thermonuclear burn. Our idea looks like an fast ignition version of impact fusion, but with no pre-compression. Special bullet and fusion fuel are chosen to minimize the ignition kinetic energy.

2. FAST IGNITION IMPACT FUSION

High-ratio pre-compression is usually a tough task, and a trouble to standing-off. We will explore the possibility of a non-pre-compressed impact fusion scheme, with properly chosen bullet and fusion fuel, as displayed in Fig. 1.

The fusion fuel is the most condensed form of crystal DT methane (CD_2T_2). Under a not very high pressure (9.8 kbar), methane (CH_4) has a crystal phase at not very low temperature (melting point 252 Kelvin), with a density of 0.593 g/cm^3, or 0.82 g/cm^3 for CD_2T_2. The molar density is 0.037 mol/cm^{-3} [14], corresponding to the DT density of 0.89×10^{23}/cm^{-3}, more than twice as many as that of liquid DT (0.035 mol/cm^{-3}, or 0.42×10^{23}/cm^{-3}). Another benefit of DT methane is that carbon provides more stopping to fusion produced alpha particles. From the theory of charged particle stopping in plasmas [10], the stopping power of uncompressed DT methane plasma to alpha particles is five times as that of liquid DT, as shows in Fig. 2. This is favorable, because the precious

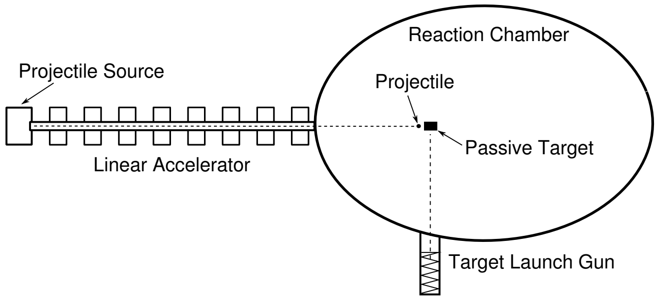

FIG. 1: Diamond DT methane impact fusion. A centimeter size crystal DT methane target is tossed from the bottom of the reaction chamber. When it reaches its highest point, a ~ 1 mm size diamond bullet at the speed of $\sim$ 1000 km/s shots into the target. The bullet will ionize, compress and heat up the target, initiate a propagating thermonuclear burn.

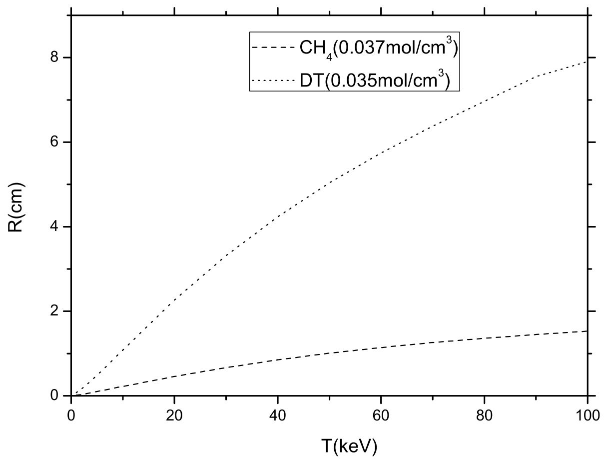

FIG. 2: D-T fusion alpha particle stopping range in uncompressed liquid DT and DT methane plasma. Y-axis is the stopping range in unit of centimeter, Abscissa is the plasma temperature in unit of (keV).

alpha particle energies is now kept in a much smaller range.

The major concern of the introduction of carbon is the much higher bremsstrahlung radiation, which is about 25 times as much as the pure DT plasma of the same DT density. However, because bremsstrahlung radiation concentrates on low frequency soft X rays (< 2 keV), the optical thickness of the target can keep most of them. Of cause the dissociation and ionization also take some bullet energy, but they are insignificant. Another concern is that the extra electron and carbon ions will share more of the alpha particle energy. This is partly compensated by the fact that carbon ions have a stopping power 8 to 10 times higher than DT ions, and they pass their energy to DT ions in thermalization much faster than to electrons. The details of radiation loss and ion-ion, ion-electron energy passing is discussed later.

The bullet is a millimeter size diamond pellet (cubic or cylindric in simulation). Diamond has high strength and relatively low mass density, both important in charging and acceleration. Comparing with the metal bullets in earlier schemes, carbon's relatively low Z number can reduce the extra ionization and bremsstrahlung loss. A 1000 km/s diamond bullet is in fact an extremely high intensity and low energy light ion beam, each ion has a kinetic energy of 62 keV. In heavy ion fusion schemes (HIF), beams have high energy (a few GeV) and low density, neither helpful.

Tossing of the target is to ensure the standing-off. The size of the target is about one centimeter. It can stay half a millimeter under its highest point for 0.02 second. The total acceleration time for the bullet is typically shorter than this time, and can be precisely controlled, so there is no difficulty for the impact to happen at desired time. Pre-compression schemes (laser or heavy ion) can not take advantage of this strategy, because they need precise positioning.

3. PHYSICS OF THE IMPACT PROCESS

In earlier studies, global adiabatic compression [6] or shock wave [2, 5], were believed to be what were happening in the impact process. Adiabatic compression is global, and certainly needs more bullet kinetic energy. As the speed of the bullet exceeds any acoustic speed, it is very unlikely that global adiabatic compression would happen. Shock wave ideas treat the fusion fuel as two parts, each with its own density n, pressure p, and temperature t, which is the standard picture of fluid shock waves. However, as the energy involved here is a few keV, only full ionized plasma existed around the shock front, and the other parts will soon be ionized too, it is hard to define two fluids.

We have a different idea of understanding the impact process. As the temperature is as high as 10 keV and the pressure near 1 Gbar, the bullet and the target should be treated as two bunch of dense plasmas colliding, compressing, and thermalizing. The impact is a particle process, other than fluidal. By this understanding the kinetic energy of bullet carbon ions are directly passed to target ions, creating much higher local temperature and density. The impacting beam (diamond bullet) has very high density ($\sim 10^{23}$ cm^{-3}), but very low energy (~ 5 keV/u, 62 keV per ion), the energy deposition is at the Bragg peak of the charged particle stopping curve, and most of the energy is passed to the DT ions, i.e., hypervelocity impact has high hydrodynamic efficiency. By taking account of the density difference, this impact is equivalent to two 800 km/s DT ion beams colliding with each other. Comparing with the typical DT implosion speed of 300 $\sim$ 400 km/s in laser ICFs, we should have a much higher temperature (~ 5 keV) and a higher density. However, as the compression is one dimensional, the actual density is not as high as in implosion, but the temperature remains.

Upon the impact, the ion temperature of the impact surface rises and DT fuse. 3.5 MeV alpha particles and 14.1 MeV neutrons are released. 14.1 MeV neutrons help little in local ion heating, as discussed in section 4.4. Only alpha particle energy deposition is discussed here.

Recently, Ghosh and Menon [11] calculated electron, ion, and nuclear scattering stopping of fusion produced charged particles in a deuterium plasma, in which Li and Petrasso's formula [10] are used to find out the electron and ion stopping. We followed the same methodology and calculated the energy share of alpha energy between electrons and ions in different temperatures in DT methane plasma. The result is showed in Fig. 3. With nuclear scattering taken into account, the ion percentage is higher than when only charged particle interactions are considered [10].

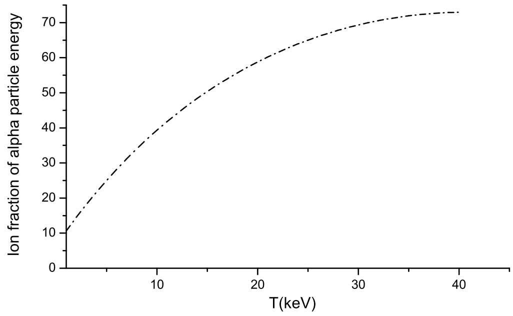

FIG. 3: Energy deposition percentage to ions in DT methane plasma. The abscissa is temperature, and the y-axis is the percentage of alpha particle energy deposited to ions. Nuclear scattering is considered.

At the early stage of the impact, the electron temperature is low. When fusion begins, electrons consumes most of the alpha particle energy, and their temperature T_e rises. As T_e rises up, bremsstrahlung power $P_{\rm br}$ becomes more and more significant, eventually dominates the energy loss and suppresses the rising of T_e. Bremsstrahlung radiation spectrum concentrates on the low frequency end. To low energy X rays, DT methane plasma is dense and opaque. There is a local thermal equilibrium (LTE) radiation temperature T_r at about 2 keV. Higher energy radiation is lost. As bremsstrahlung $P_{\rm br} \propto \sqrt{T_e - T_r}$, at typical temperatures of $T_i \sim 10$ keV, $T_e \sim 5$ keV, the fusion alpha particle energy is larger than the bremsstrahlung loss. This is different from common ICF assumption that $T_i \approx T_e$, and all bremsstrahlung is lost. Under that circumstance, the break even temperature would be $T_i \approx T_e \approx 18$ keV, which is higher than in our part LTE equilibrium scenario. Fig. 4 is the fusion alpha energy versus bremsstrahlung radiation at different temperatures.

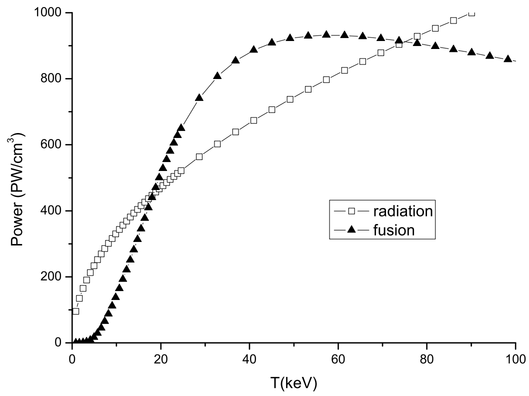

FIG. 4: Fusion alpha versus bremsstrahlung power of DT methane at different temperatures. The first point where the two curves meet is about 18 keV.

In the early stage, the temperature at the hot spot rise over 10 keV and DT density over 3×10^{24} cm^{-3}, which is about 30 times denser than uncompressed. This dense shell expands slowly because the compressional shock wave is supersonic. Simulation shows, as fusion goes on, the shell expands but with little change on density profile. The highest density remain $10 \sim 20$ times higher than uncompressed DT methane plasma. This shell helps both in keeping the alpha particle energy near the hot spot and increasing the optical opacity to keep the radiation temperature. The density and temperature profile are shown in Fig. 5.

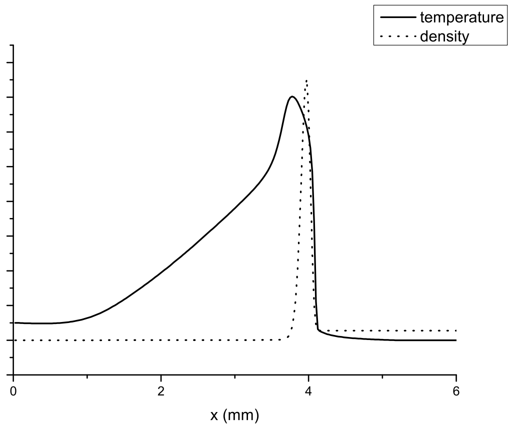

FIG. 5: Ion density and temperature profile of the burning high density shell. The dotted line is the density, and the solid line is ion temperature. The temperature peak is about 12 keV, and the density peak is about 3×10^{24} cm^{-3}. X-axis is the distance from the impact point.

4. SOME PHYSICAL PROPERTIES

Some key physical quantities concerning the impact fusion process, such as the physical process time scales, the opacity of the plasma, photon density, electron and radiation conductivities, fusion energy deposition, etc., are not easily quantify, but some analysis is put as follows. The formula are mostly from Atzeni and Meyer-Ter-Vehn's book [15] and NRL plasma formulary [16].

4.1 Time scales

Let $\tau_{ee}, \tau_{ii}, \tau_{ei}$ be the relaxation time or equilibration time of electron-electron, ion-ion, electron-ion, respectively.

However, if $T_i \approx T_e$, we have

$$\tau_{ee} : \tau_{ii} : \tau_{ei} = 1 : \sqrt{\frac{m_i}{m_e}} : \frac{m_i}{m_e} \approx 1 : 90 : 8100, \quad (1)$$

with the mass of ion averaged according to the percentage of each ion species. This means ion-ion thermalization is much faster than ion-electron's. If $T_i \neq T_e$,

$$\tau_{ee} : \tau_{ii} : \tau_{ei} = 1 : \sqrt{\frac{m_i}{m_e}} \left(\frac{T_e}{T_i}\right)^{3/2} : \frac{m_i}{m_e} \left(\frac{T_e}{T_i}\right)^{3}. \quad (2)$$

Take typical $T_i = 10$ keV, $T_e = 5$ keV, we have

$$\tau_{ee} : \tau_{ii} : \tau_{ei} \approx 1 : 32 : 1020, \quad (3)$$

which means ions are faster in passing its energy to electrons. If T_e is lower, the situation becomes worse, for the ions will lose energy to electrons fast, eventually quench out. The most important one of the three is τ_{ei}, which specifies how fast ions lose energy to electrons, because T_e is lower than T_i due to bremsstrahlung.

The absolute value of τ_{ei} is about 0.5 ns in uncompressed DT methane plasma [17], and

$$\tau_{ei} \propto \rho^{-1}. \quad (4)$$

The increasing of ρ is not a problem, because the fusion power increases faster,

$$W_{\text{fus}} \propto \rho^2. \quad (5)$$

Simulation shows, for a 1 cm size target, the ignition and burn takes about 10 nanoseconds.

4.2 Opacity, radiation, and photon density

As the electron temperature is a few keV, and there are a lot of carbon ions in the plasma, from Fig. 4 we know the dominant energy loss scheme is bremsstrahlung. The optical thickness of the plasma determines the LTE radiation temperature T_r. T_r and T_e then determines the energy loss rate.

The free-free Planck mean free path is

$$l_P \approx 2.5 \frac{T^{7/2}}{\rho^2} \text{ cm} \quad (6)$$

On the high density shell, the density is $10 \sim 20$ g/cm^3, and the width is $1 \sim 2$ mm. From Eq. 6 we know the shell is optical thick for radiation ≤ 2 keV. Thus, we can say the radiation temperature inside the density shell is about 2 keV.

Photon density is related to the amount of radiation energy and light pressure. It is determined by

$$n_\gamma = 0.25 \left(\frac{k}{\hbar c}\right)^3 T_r^3, \quad (7)$$

with k, $\hbar$, c being the Boltzmann constant, Planck constant, speed of light, respectively. As $T_r \approx 2$ keV, $n_\gamma \approx 2.5 \times 10^{23}$ cm^{-3}, which is close to electron density n_e in uncompressed DT methane plasma.

4.3 Heat conductivities

There are steep density and temperature gradient in the impact process, common electron and radiation conductivity theories are hard to apply directly.

Electron conductivity

$$\chi_e = \chi_{e0} T^{5/2}. \quad (8)$$

It does not depend on the density.

The radiative heat conductivity

$$\chi_r = \frac{16}{3} \sigma_B T^3 l_R(\rho, T) \propto T^{13/2}, \quad (9)$$

while σ_B is the Stefan-Boltzmann constant, and l_R the Rosseland mean free path.

As the counterstreaming electron current is blocked by the cold outer side of the density shell, and χ_e is much smaller than χ_r at high temperatures, the dominant heat conduction must come from radiation. In our simulation, we assume all radiation > 2 keV is lost, which implies the conductivity is infinity.

4.4 Fusion energy deposition

According to high energy charged particle stopping theories [8, 10], carbon ions have a stopping power to fusion alpha particle about 9 times larger than averaged DT ions. Though there are only about 20 percent carbon ions, they provided nearly 70% of total alpha particle stopping. As $\tau_{ii} \ll \tau_{ie}$, those carbon almost instantly pass their energy to DT ions, only a small fraction goes to electrons. However, ions' losing energy to electrons is not negligible.

In the critical ignition stage, T_e can hardly exceeds 5 keV, due to strong bremsstrahlung radiation. According to Fig. 3, no more than 20% of the fusion alpha energy goes to ions, the rest is consumed by the electrons, and most wasted as hard X rays.

On the density shell, as DT methane plasma provides 5 times stopping than uncompressed DT ice density plasma, and the shell is compressed by 10 to 20 fold. The stopping range R of 3.5 MeV alpha particle on the shell is $100 \sim 300$ micron. The density shell has a width of $1 \sim 2$ mm. From Fig. 5 we know the temperature peak is inside the density shell, thus fusion takes place mostly inside the shell, and alpha particle energy is kept inside.

The density and temperature structure of shock density shell favors both keeping alpha particle energy and sustaining the structure itself, because a super hot core and the velocity gradient enables ramping (longitudinal compression). Supersonic shock itself can keep a nearly stable density profile.

The neutron energy is ignored in our simulation, but it does help in heating the electrons globally. With simulation obtained shell density and width, about 5% of the 14.1 MeV neutrons will scatter with the ions, and leave approximated one half of their energy to DT ions. The $6 \sim 7$ MeV D or T ions can travel more than 10 times further than 3.5 MeV alpha particles. They can penetrate through the density shell, and leave most of their energy to electrons, due to their high energy. Ions only have a very small share. The scattering between neutron and carbon ion leave 2 MeV energy to carbon ion. Large fraction of this energy is passed to DT ions.

5. SIMULATION AND PRELIMINARY RESULTS

As we view the impact as a particle process, it is formidable to implement an full particle code. In a earlier paper [18], we presented some primary results in an evaluational simulation. The code is a hybrid fluidal and particle one. Particle diffusion and thermalization are considered. The main purpose of the simulation is to estimate the ignition energy of the bullet. We found that a millimeter diamond bullet with the kinetic energy of $1 \sim 2$ MJ, or at the speed of about 1000 km/s, is sufficient to initiate a propagating thermal nuclear burn. This is important, because in 1980s people believe one dimensional compression needs a 50 MJ bullet. This change can reduce the length of the linear accelerator from 10000 kilometer to less than 100 km.

We are working on a more realistic and sophisticated code to guess what really happens in the impact process. There is still a long way to go. However, we are still able to give some qualitative properties of the process.

- As mentioned above, a $10 \sim 20$ g/cm^{-3}, $1 \sim 2$mm thick density shell exists as the shock front. This is very helpful in keeping the fusion alpha energy and raise the electron temperature T_e.
- The ignition energy for a millimeter size diamond bullet is $1 \sim 2$ MJ. This renders electrostatic linear acceleration a practical approach.
- The temperatures of both electron and ion are hard to rise up, because of strong bremsstrahlung and not so weak electron-ion coupling (small τ_{ei}). In the ignition stage, $T_e \approx 5$ keV or a little higher. T_i can not rise well above 10 keV.
- Propagating thermal nuclear burn exists in the inner side of the density shell.
- Surprisingly, if the fusion fuel is DT liquid or ice, the ignition energy is only 50% higher. We had expected a much higher ignition energy, for the stopping range in uncompressed DT ice plasma is 5 times longer. This is because the density shell can rise to the same density as in DT methane, and less electron and carbon means less radiation loss.

6. SUMMARY AND DISCUSSIONS

There are many features or advantages in this fusion scheme which is not available in other fusion energy ideas. For completeness, they are listed as follows:

- "Standing-off" and sustainable. There is no mess of destroyed parts, no close contact, no strong and unpleasant limit posed to reaction chamber wall. The wall can be build only according to thermal, mechanic, technical, and economical requirements.
- High hydrodynamic efficiency. 10 times higher than main stream schemes.
- No pre-compression, greatly simplified the whole system.
- Unlimited and easy tailored energy output, high output/input ratio.
- Extra confinement can be achieved by casing the target with heavy metals. High burn out ratio.
- Close harvest of the fusion energy and neutron. Unlike other fusion schemes, the space near the fusion point is free, we can put anything there to harvest the vast amount of energy or the hyper intensity neutrons. Utilizations like Deuterium breading of Tritium and Helium-3, Uranium-238 burning, radio-active waste treatment are now practical.

- Low-tech and economical accelerator. Low particle speed, low vacuum requirement, no magnets (particle controlled by electric field).

Crystal DT methane has higher DT concentration, stronger alpha particle stopping, and is easier to handle because the melting temperature is much higher than liquid or solid DT. DT methane can be a good option as fusion fuel in ICF. The high density and high stopping means less compression. Rayleigh-Taylor instability situation can be mitigated significantly. It can be very promising in volume ignition ideas, for the ignition temperature is low (1.5 keV), and radiation is not a problem.

Bremsstrahlung lost is the most significant issue in this scheme. If further studies shows this problem is too severe to overcome, we may have to go back to DT ice. Other potential DT compounds like LiDT, $LiB(DT)_4$, have more electrons and the bremsstrahlung situation is even worse. However, even if the ignition energy is a little higher than DT ice, the easy handling of DT methane could make it a better choice.

7 ACKNOWLEDGEMENTS

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