Magnetic Booster Fast Ignition Macron Accelerator

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Abstract

A new fast ignition scheme was recently proposed where the ignition is done by the impact of a small solid projectile accelerated to velocities in excess of 10^8 cm/s, with the acceleration done in two steps: First, by laser ablation of a flyer plate, and second by injecting the flyer plate into a conical duct. The two principal difficulties of this scheme are: First, the required large mass ratio for the laser ablation rocket propelled flyer plate, and second, the Rayleigh-Taylor instability of the flyer plate during its implosive compression in the conical duct.

To overcome these difficulties it is suggested to accelerate a projectile by a magnetic fusion booster stage, made up of a dense, wall-confined magnetized plasma brought to thermonuclear temperatures. After ignition this plasma undergoes a thermonuclear excursion greatly increasing its pressure, resulting in the explosion of a weakened segment of the wall, with the segment becoming a fast moving projectile. The maximum velocity this projectile can reach is the velocity of sound of the booster stage plasma, which at a temperature of 10^8 K is of the order 10^8 cm/s.

1. Introduction

As a promising way towards the controlled release of energy by nuclear fusion, the idea of fast ignition for inertially confined deuterium-tritium (DT) plasmas, first proposed by Basov et al. [1], followed by Tabak et al. [2], has found a growing interest. In this concept a precompressed DT target is ignited by a petawatt laser pulse generating a hotspot in a central location of the target. Apart from having a higher gain, the advantage of this concept is that is does not need a perfectly spherical shape of the precompressed DT, as it is required if the hot spot in the center of the sphere is created by a convergent spherical shock wave. One problem of this concept is to guide the petawatt laser pulse to a central location of the precompressed DT target. A solution of this problem proposed by Kodama et al. [3], is to stick a hollow cone into the DT target, which would remain open during the short time the DT is compressed, letting the petawatt laser pulse passing through this cone into the center of the DT target. Another problem for this fast ignition scheme to work, with or without the cone, is that it depends on a petawatt laser with an energy in excess of 100kJ. Since this is a very expensive proposition, it was most recently proposed by Murakami and Nagatomo [4], followed up with initial experiments done by Murakami et al. [5], to perform the fast ignition with a small solid projectile accelerated to a velocity of ~10^8 cm/s, by laser ablation rocket propulsion of a small flyer plate followed by the projection of the flyer plate in a conical duct stuck into the DT target. A projectile velocity of 10^8 cm/s is needed to reach upon impact a temperature of 10^8 °K [6]. In this scheme a laser power ten times smaller is sufficient, which means that the same laser used for the precompression of the DT target can be used for the flyer-plate acceleration. However, to reach the needed high projectile velocity of 10^8 cm/s, a large (difficult to reach) mass ratio is needed for the rocket propelled flyer plate. In addition, there is the problem of the Rayleigh-Taylor instability of the flyer plate during its compression in the conical duct, exacerbated by the difficulty to end up with a flyer plate of uniform mass, density, and shape following its laser ablation acceleration.

In this communication I will show that both of these problems are avoided in an idea I had proposed back in 1983 [7]. There the large required projectile velocity is reached with a “magnetic booster stage”, where a weakened segment of the wall confining a dense magnetized plasma is blown out, following a thermonuclear excursion of the magnetized DT plasma after its ignition. The blown out segment can reach the velocity of sound for the hot DT plasma, which for a temperature of $\sim 10^8$ °K is of the order 10^8 cm/s. This gun-type acceleration is not saddled with the problem of a large mass ratio of the flyer plate. The only place where the Rayleigh-Taylor instability still enters is in the compression of the magnetized DT plasma, a much easier problem compared to the implosive compression of a flyer-plate. Here too, no petawatt laser is needed.

2. The Magnetic Booster Two-Stage Concept

The idea is explained in Fig. 1 and 2, describing a two stage configuration, consisting of the booster stage I and the main high gain stage II, with both stages connected by the gun barrel GB, but with the particle number density in the booster stage much smaller than in the main stage. To provide the booster stage with a sufficiently strong magnetic field, it is proposed to let a mega-ampere current pass through a laser-generated ionized trail in the gas of the booster stage, as it was suggested by Tidman [8] to make a gas embedded z-pinch, with the return current flowing through the wall of the chamber.

The booster stage is a conical cavity filled with DT gas. Into it a flyer plate is shot with a velocity of $v \simeq 10^7$ cm/s. To reach this velocity, the flyer plate is ablatively accelerated by intense laser- or particle beams. In making electrical contact with cavity wall, the current is short-circuited, entrapping the magnetic field inside the booster stage.

If the solid angle of the cavity is $\Omega < 4\pi$, and its height is r_c, the implosion of the cavity is equivalent to the implosion of a spherical shell with radius $r = r_c\sqrt{\Omega / 4\pi}$, as it was previously suggested for impact fusion where the implosion of a sphere is replaced by the implosion of a cone [9]. Fig. 2 shows the sequence of the implosive states until the moment where the high velocity projectile is accelerated inside the gun barrel.

Because the compression of the booster stage does not have to be perfectly symmetric, (what matters is only going from a larger to a smaller volume), Rayleigh-Taylor instability is here a much less serious problem. Still even less serious is it in the alternative booster stage configuration shown in Fig. 3, taken from the above quoted paper by the author [7]. There the booster stage consists of two conical cavities facing each other, with one at rest and connected to the gun barrel, while the other one replaces the flyer plate of Fig. 1. In this configuration the implosion velocity is effectively increased by the “scissors” effect for a large aspect ratio of the cavity made up by two cones. Because the implosive decrease of the cavity volume involves here less plastic deformation, Rayleigh-Taylor instability is a less serious problem. However, to prevent jetting, the angle where the two cones meet must be about less than $\sim 10^{\circ}$, as experiments for shape charges have shown.

The preheating of the booster stage plasma to a temperature of $\sim 10^6$ °K is done by a combination of pinch discharge and impact heating. Upon impact on a DT plasma with a velocity v [cm/s], one obtains a temperature T [°K], which is $T \simeq 5 \times 10^{-9} v^2$. To reach $T \simeq 10^6$ °K thus requires an impact velocity of $v \simeq 10^7$ cm/s.

After having reached the ignition temperature of the DT reaction, the magnetic entrapment of the charged He4 fusion reaction products in the booster stage results in a rapidly rising thermonuclear burn excursion. This raises the temperature and pressure in the booster stage, leading to the blowout of the window **W** at the weakest segment of the booster stage, positioned at one end of the gun barrel, where the pinch discharge channel reaches the wall of the booster stage chamber. The blown out segment of the chamber becomes a rapidly moving projectile ***P***, accelerated in the gun barrel ***GB*** to a velocity equal to the velocity of sound of the hot DT plasma. To prevent the gun barrel from exploding during the acceleration of the projectile, it is held together by a cylindrical convergent laser pulse. But to prevent the gun barrel, under this strong external pressure, from completely imploding, it can be placed in an externally applied magnetic field which in the course of the implosion is amplified to $\gtrsim 10^8$ G, bringing the implosion to a halt and keeping the gun barrel open.

As it was described in my 1963 paper [6], in entering the highly compressed DT of the main stage, the projectile generates a supersonic bow shock, further increasing the density inside the bow by a factor of 4 with a thermonuclear detonation wave launched from the bow shock into the surrounding dense DT.

This completes the description of the proposed fast ignition concept.

3. An Example

I. The Booster Stage:

We assume that the initial and final radius of the spherical chamber are $r_o = 0.25$ cm and $r_1 = 0.025$ cm, respectively. With $\gamma = 5/3$ the specific heat ratio of a fully ionized hydrogen plasma, and with $Hr^2 = const.$ where H is the magnetic field strength inside the imploding spherical booster stage cavity, we have for the particle number density, the temperature, and the magnetic field

$$\left.\begin{aligned} n/n_o &= (r_o/r)^3 \\ T/T_o &= (r_o/r)^2 \\ H/H_o &= (r_o/r)^2 \end{aligned}\right\} \quad (1)$$

The latter two of these scaling laws are valid in the absence of losses.

Accordingly, the plasma and magnetic pressure rise as

$$\left.\begin{aligned} p/p_o &= (r_o/r)^5 \\ H^2/H_o^2 &= (r_o/r)^4 \end{aligned}\right\} \quad (2)$$

The reaching of the ignition temperature of $T_1 \simeq 10^8\,^\circ$K in the booster stage is followed by a thermonuclear excursion. Let us assume that this raises the temperature and pressure in the chamber ten-fold, and that this excursion takes place in the time of $t \simeq 10^{-9}$ s. For breakeven we have to satisfy the Lawson criterion:

$$n_1 \tau_L \simeq 10^{14} \text{ scm}^{-3} \quad (3)$$

This means that for a ten-fold energy amplification, taking into account that only 20% of the DT fusion energy is released in the charged He4 particles, we must have:

$$e^{t/\tau_L} = 50 \quad (4)$$

from which it follows that

$$\tau_L = 10^{-9} / \ln 50 \simeq 2.5 \times 10^{-10} \text{ s} \tag{5}$$

and hence $n_1 \simeq 2\times10^{14} / \tau_L \simeq 4\times10^{23}\,\text{cm}^{-3}$. Therefore, $n_o = 10^{-3}\, n_1 = 4\times10^{20}\,\text{cm}^{-3}$. The energy required to preheat the DT plasma in the booster stage then is

$$E_o = (4\pi/3) r_0^3 \times 2n_0 kT_0 = 3\times10^{10}\,\text{erg} = 3\text{kJ} \tag{6}$$

The initial and final pressures (prior to the commencement of the fusion burn) are $p_o \simeq 10^{11}$ dyn/cm^2 and $p_1 \simeq 10^{16}$ dyn/cm^2; following the fusion burn it is $p_1^* \simeq 10^{17}$ dyn/cm^2.

The two most important losses are by bremsstrahlung and heat conduction, the latter in the presence of a strong transverse magnetic field. To overcome the bremsstrahlungs losses the implosion must be fast enough. Back in 1968 I had (by numerical integration) shown that for a spherical implosion the velocity must be of the order $\text{v}_{imp} \sim 2\times10^7$ cm/s [9]. This number was also agreed upon in the Los Alamos Impact Fusion Workshop [10].

In the most simple way the bremsstrahlung loss time τ_R can be computed from the bremsstrahlungs loss rate [11], and one obtains

$$\tau_R \simeq 3\times10^{11}\sqrt{T} / n \tag{7}$$

With the scaling laws (1), τ_R scales as r^2, becoming shorter towards the end of the implosion. At the final radius where T = 10^8 °K, $n_1 = 4\times10^{23}$ cm^{-3}, one obtains $\tau_R \sim 10^{-8}$ s, but at the initial radius one has $\tau_R \sim 10^{-6}$ s. The time $\tau_R \sim 10^{-8}$ s also compares well with the implosion time for $\text{v}_{imp} \sim 2\times10^7$ cm/s, to implode a shell a with radius $r_o = 0.25$ cm.

The energy loss time $\tau_{c\perp}$ by heat conduction is obtained from the heat conduction coefficient in the presence of a strong transverse magnetic field, provided $\omega\tau \gg 1$ (ω electron cyclotron frequency, τ electron collision time) [11]. One obtains

$$\tau_{c\perp} \simeq 1.7(Hr)^2\sqrt{T}\,/\,n \tag{8}$$

For the scaling laws (1) this time does not depend on r, and for the given example it is $\tau_{c\perp} \simeq 1.7\times10^{-7}$ s. However, this is only true if $\omega\tau \gg 1$. Unlike (8), $\omega\tau$ scales as r^{-2}. For the given example $\omega\tau$ = 0.04 at $T_0 = 10^6$ °K, and $\omega\tau$ = 4 at $T_1 = 10^8$ °K. To increase the $\omega\tau$ value one can go to a larger size of the booster stage chamber (keeping constant the total number of particles in the chamber), or to a larger initial magnetic field or both. Going to a larger initial magnetic field is difficult but possible because of the r^{-4} dependence of the magnetic pressure versus the r^{-5} dependence of the plasma pressure. If $H_o = 5\times10^6 G$ instead, the plasma and magnetic pressure are equal at the smallest radius $r_1 = 0.025$ cm. And if $H_o = 5\times10^6 G$, one has at this radius $\omega\tau$ = 20, but only 0.2 at $r_o = 0.25$ cm. Therefore, even with $H_o = 5\times10^6 G$, a somewhat larger booster chamber with a smaller particle number density might be needed. In the chosen configuration, as in a gas embedded z-pinch discharge, large magnetic fields are attainable. Similar results for larger size magnetized target chambers have been obtained by Drake et al. [12].

To entrap the DT fusion reaction He4 particles inside the booster stage plasma requires that:

$$r_L << r \tag{9}$$

where

$$r_L \approx 2.7\times10^5/H \quad \text{[cm]} \tag{10}$$

is the Larmor radius of the He4 particles. From (9) and (10) then follows that:

$$Hr >> 2.7\times10^{5} \quad [\text{Gcm}] \tag{11}$$

For $r_0 = 0.25$ cm, this requires that $H_0 >> 10^6$ G, but for $r_1 = 0.025$ cm, that $H_1 >> 10^7 G$, a condition well satisfied with the r^{-2} scaling law for H.

Choosing $r > r_1$ for the radius of the hard cone pinch, the maximum (azimuthal) magnetic field in the booster stage is $H_o^{\max} < 8I$, where I is the current in Amperes. For $I \simeq 10^6$ A, most certainly attainable with on the shelf pulse power technology, $H_o \sim 5\times10^6 G$ seems attainable.

The energy $E_o \simeq 3$ kJ, needed for preheating the booster stage plasma must be supplied in a time less than $\tau_R \simeq 10^6$ s, that is with a power larger than 3×10^{10} Watt. With the preheating done by laser radiation, its frequency must be about equal to the plasma frequency ν_p at $n_o = 4\times10^{20}$ cm^{-3}, which is $\nu_p \simeq 2\times10^{14}$ s^{-1}, located in the infrared.

II. High Gain Stage:

The initial density of the high gain stage is the density of liquid DT, $n_o = 5\times10^{22}$ cm^{-3}. Isentropically compressing liquid DT thousand-fold requires a pressure of $p_1 = 2\times10^{16}$ dyn/cm^2, about the same as the final pressure in the booster stage. This means that both stages can be ablatively compressed by a 100 TW laser.

4. Discussion

The motivation for the proposed novel concept is the high cost of a ~100 kJ petawatt laser, but not the only. It is also the uncertainty if a petawatt laser can achieve the fast ignition of a highly compressed DT target. In contrast, there can be little doubt that the fast impact ignition by a small 10^{-3} to 10^{-4} gram size projectile, accelerated to a velocity of the order 10^8 cm/s, should have a much better chance for success. In the petawatt laser ignition scheme, the elections are heated first, with the ions heated by the electrons via electron-ion collisions. In impact ignition it is the ions which are heated first, followed by the electrons, but it is the ions which release the energy by nuclear fusion reactions, and it is for this reason the ions should be heated first. In addition, in impact ignition the already highly compressed DT is further four-fold compressed inside the bow shock of the impacting projectile, with the bow shock forming the fast ignition hot spot.

The novel proposal presented combines four ideas:

1. The laser ablation induced isentropic compression of solid DT to high densities.
2. The volume heating and ignition of a magnetized target.
3. The acceleration of a projectile in a gun barrel to high velocities.
4. The attainment of high temperatures upon impact by a high velocity projectile.

Of these four concepts, the first one has been realized in reaching the required ~ 10^3 fold solid density. The second one is fairly well established, both theoretically and experimentally, through the neutron yield by the implosion of magnetized targets, including the implosion with high explosives, first proposed by Linhart [13]. It is less certain if a magnetized target as small as suggested is technically feasible. However, if this should turn out to be a problem, one can place in between the booster and high gain stage an intermediate small dense z-pinch stage, with the booster stage driving the intermediate z-pinch stage, and the z-pinch stage propelling the projectile. The third one, the ballistic gun-like acceleration of a small projectile to the required high velocity is the least certain. Unexplored are here the extreme conditions which have to be satisfied by the gun barrel, from not flying apart and not from imploding, for which a unique solution is here presented. The fourth one, the reaching of high temperatures by the impact of a high velocity projectile, is well established, both theoretically and experimentally, for velocities up to ~100 km/s, through the impact of meteorites and up to ~10 km/s through the impact of projectiles accelerated to these velocities in light gas guns, and there can be little doubt that these results can be extrapolated to velocities of ~10^3 km/s.

In summary the following can be said: The proposed concept combines several different components which can be independently developed without making a single large research effort. The physical principles for each component are well known, and it appears the realization is only a technical problem. If feasible, the proposed fast ignition concept has the potential to reduce the cost of inertial confinement fusion by orders of magnitude.

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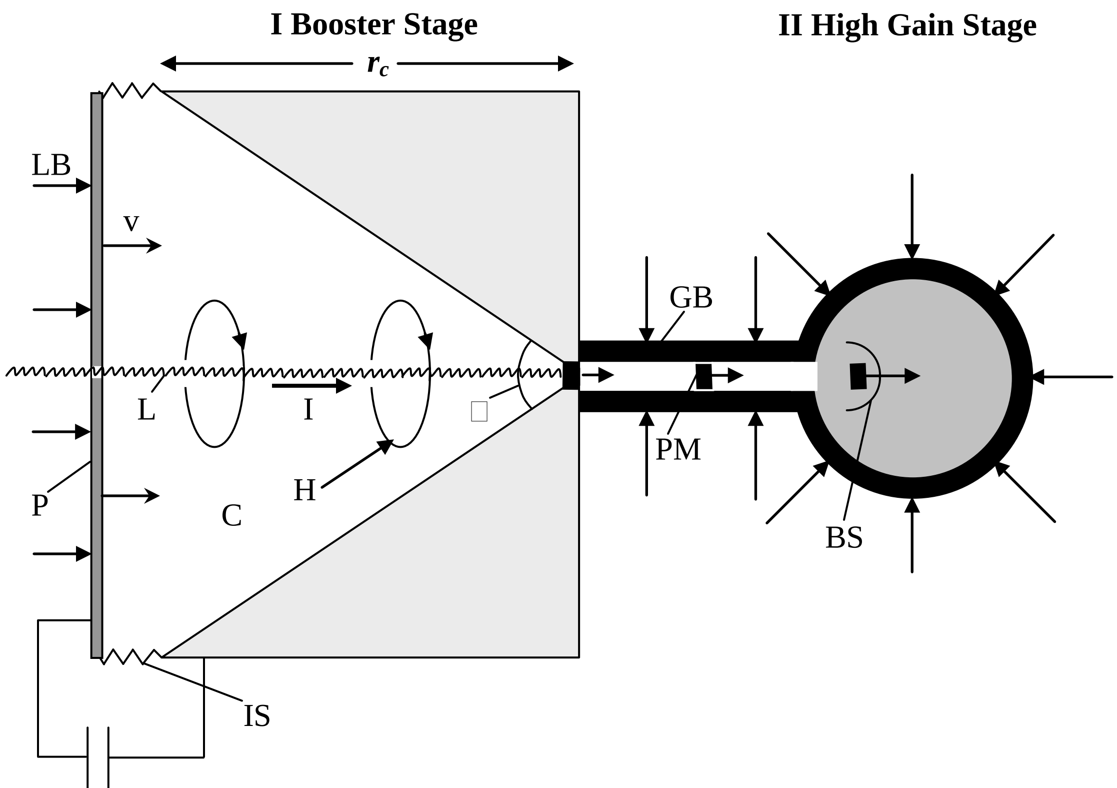

$Hr > 2.7\times10^{5}\,\text{Gcm}$	$\rho r > 1\,\text{g/cm}^2$
$n_0 = 4\times10^{20}\,\text{cm}^{-3}$	$n_0 = 5\times10^{22}\,\text{cm}^{-3}$
$n_1 = 4\times10^{23}\,\text{cm}^{-3}$	$n_1 = 5\times10^{25}\,\text{cm}^{-3}$
$r_0 = 0.25\,\text{cm}$	$r_0 = 0.1\,\text{cm}$
$r_1 = 0.025\,\text{cm}$	$r_1 = 0.01\,\text{cm}$
$p_0 = 4\times10^{11}\,\text{dyn/cm}^2$	$p_0 = 0\,\text{dyn/cm}^2$
$p_1 = 2\times10^{16}\,\text{dyn/cm}^2$	$p_1 = 2\times10^{16}\,\text{dyn/cm}^2$
$T_0 = 10^{6\circ}\,\text{K}$	$T_0 = 0^\circ\,\text{K}$
$T_1 = 10^{8\circ}\,\text{K}$	$T_1 = 0^\circ\,\text{K}$

L	laser beam to make an ionization trail
LB	laser or particle beam for compression
P	plate to be shot into C
C	conical cavity
IS	insulating ring
GB	gun barrel
H	magnetic lines of force
PM	macron particle projectile
BS	bow shock
$r_c = r\sqrt{4\pi/\Omega}$	height of the cone

Figure 1

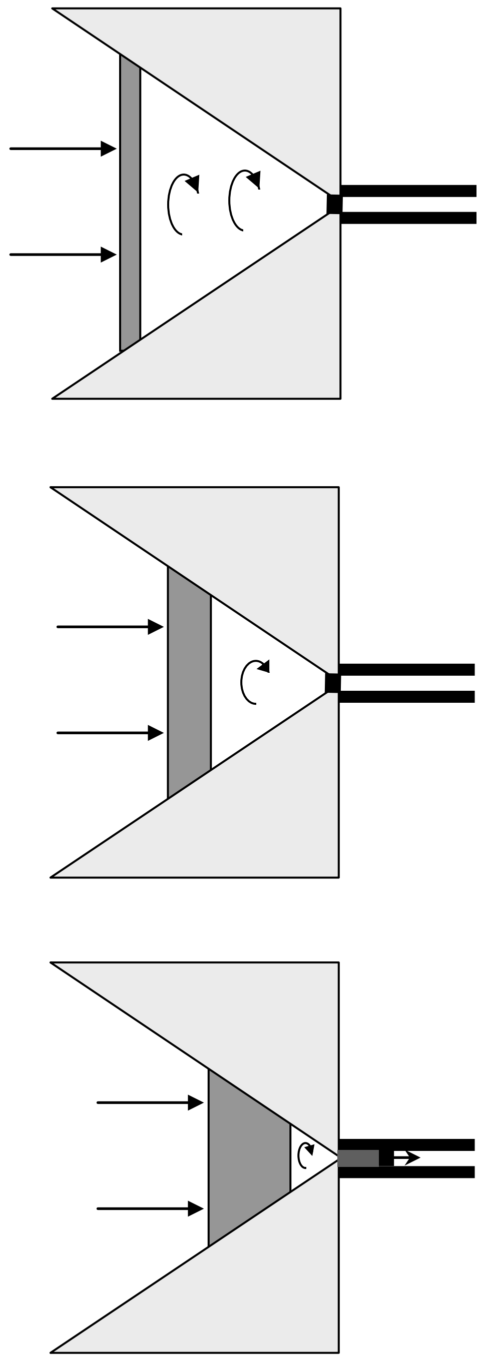

Figure 2

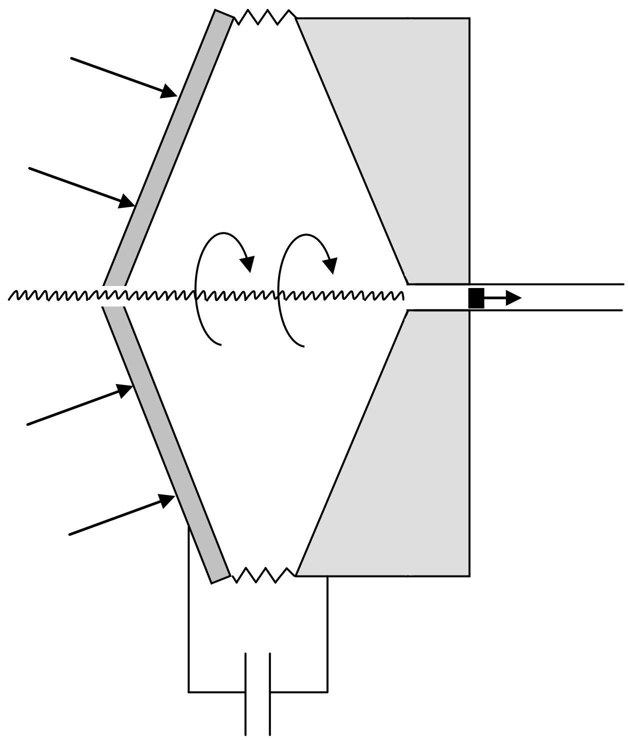

Figure 3