Hybrid Chemical-Nuclear Convergent Shock Wave High Gain Magnetized Target Fusion*

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*Dedicated to the memory of Sylvester Kaliski.

Preface

I dedicate this paper to the memory of Sylvester Kaliski for his pioneering work in his hybrid laser-chemical high explosion inertial confinement fusion research. A summary of his extensive work was published in the Proceedings of the Laser Interaction and Related Plasma Conference, held in 1974 at the Rensselaer Polytechnic Institute [S. Kaliski, Laser Interaction and Related Plasma Phenomena, Ed. H.J. Schwarz and H. Hora, Plenum Press, New York, 1974, p. 495-517].

Abstract

In DT fusion 80% of the energy is released in 14 MeV neutrons. To utilize this energy the neutrons must in all proposed DT fusion concepts (including the ITER) be slowed down in a medium, heating the medium up to a temperature not exceeding a few thousand degrees, from which this energy is converted into mechanical energy, and ultimately into electric energy. While the conversion from mechanical into electric energy goes at a high efficiency (90%), the conversion of the thermal energy into mechanical energy is limited by the Carnot process to about 30%. To overcome this limitation, I propose to slow down the neutrons in the combustion products of a convergent spherical detonation wave in HMX, for example, which ignites a magnetized DT target which is placed in the center of convergence, prior to the ignition of the high explosive from its surface. The thermonuclear ignition is achieved by the high implosion velocity of 50km/sec reached in the center, compressing and igniting the preheated magnetized target. Even though the thermonuclear gain of a magnetized target is modest, it can become large if it is used to ignite unburnt DT by propagating burn. There the gain can conceivably be made 1000 times larger, substantially exceeding the yield of the high explosive. And if the spherical high explosive has a radius of about 30cm, the 14 MeV DT fusion reaction neutrons are slowed down in its dense combustion products, raising the temperature in it to 100000 K. At this temperature the kinetic energy of the expanding fire ball can be converted at a high (almost 100%) efficiency directly into electric energy by an MHD Faraday generator. In this way most of the 80% neutron energy can be converted into electric energy, about three times more than in magnetic (ITER) or inertial (ICF) DT fusion concepts.

1.Introduction

Back in 1966 it was proposed by Linhart [1] to release energy by nuclear fusion through the compression of cylindrical magnetized deuterium-tritium DT plasma by a high explosive. The idea failed because of the cost of the high explosive which could not be recovered by the energy set free in the DT thermonuclear reaction. In effect, the gain was much too small, which is typical for magnetized target fusion. This situation is changed if the energy released by the magnetized fusion target is used to drive a second stage high gain fusion target. In this magnetized target booster stage concept [2], it was proposed to hit a small cm-size magnetized DT fusion target with a cm-size projectile accelerated to a velocity up to 50 km/s. The projectile could for example be accelerated by a travelling magnetic wave. Unlike for impact fusion where a projectile velocity of 200 km/s is required, a magnetic travelling wave accelerator to reach 50km/s would be in length 16 times shorter compared to more than 10km long accelerator to reach 200 km/s.

Recognizing that a velocity of 50 km/s is sufficient to ignite a small magnetized fusion target suggests to reach this velocity with a convergent spherical shock wave. To ignite a thermonuclear reaction with a convergent shock wave is one of the oldest non-fusion ignition ideas. According to Guderley [3], the temperature and pressure in a convergent spherical shock wave rises as a function of the distance r from the center of convergence by

$$\left.\begin{aligned} T &= T_0\left(\frac{R}{r}\right)^{2\kappa} \\ p &= p_0\left(\frac{R}{r}\right)^{2\kappa} \end{aligned}\right\} \tag{2}$$

where R is the initial radius of the shock wave, and κ is approximately given by [4]

$$\kappa^{-1} = \frac{1}{2} + \frac{1}{\gamma} + \left[\frac{\gamma}{2(\gamma-1)}\right]^{1/2} \tag{3}$$

In (3) $\gamma = c_p/c_v$ is the specific heat ratio. If $\gamma = 5/3$, valid for a monatomic gas one finds that $\kappa \cong 0.45$. As an example we take a convergent shock wave in the high explosive HMX.

Following the pre-heating and magnetization of the DT placed in the center of the high explosive, the convergent detonation shock wave is launched by simultaneously igniting the spherical surface of the high explosive.

The detonation in the high explosion can be described by an ideal gas equation for which $\gamma = 3$ [5]. According to (3) this makes $2\kappa = 1.18$. The value $\gamma = 3$ maybe too large for pressures $p > 4 \times 10^{11}\,\mathrm{dyn/cm^2}$. In the limit of very large pressures $\gamma \rightarrow 5/3$ (Fermi gas) and $2\kappa = 0.9$. We may therefore approximately set

$$p = p_0\left(\frac{R}{r}\right) \tag{4}$$

To reach the ignition temperature of the DT reaction at $\sim 10^8\,\mathrm{K}$ at a radius $r = 0.1\,\mathrm{cm}$ from the centre of convergence, would require an initial radius of $R \cong 100$ meter where $T_0 \cong 10^3\,\mathrm{K}$. But for a magnetized fusion target it is not a high temperature but a high pressure what is needed, more specifically a pressure high enough to withstand the magnetic pressure of a magnetized target. For a magnetized target where $\beta \cong 1$ and a magnetic field of $B \sim 10^7\,\mathrm{G}$, both the magnetic and the plasma pressure are $\sim 4 \times 10^{12}\,\mathrm{dyn/cm^2}$. With HMX (Octogen) a pressure of $4 \times 10^{11}\,\mathrm{dyn/cm^2}$ be reached [5], which in a convergent detonation shock wave can be amplified from $R \cong 10\,\mathrm{cm}$ to $r \sim 1\,\mathrm{cm}$ to $4 \times 10^{12}\,\mathrm{dyn/cm^2}$. Here then not such a large initial radius of the convergent shock wave is needed as it is needed to reach the ignition temperature. In a magnetized target the ignition temperature is rather reached by isentropic compression of the preheated magnetized plasma.

For the given example of $B \sim 10^7\,\mathrm{G}$ with a magnetic pressure of $\sim 4 \times 10^{12}\,\mathrm{dyn/cm^2}$ and a plasma temperature of $T \sim 10^8\,\mathrm{K}$, the particle number density is $n \sim 2 \times 10^{20}\,\mathrm{cm^{-3}}$, by a factor 250 smaller than the typical number density $n \sim 5 \times 10^{22}\,\mathrm{cm^{-3}}$ of condensed matter.

2. Propagating burn

Because the gain of magnetized target fusion is rather small, and because a high gain is needed to make up for the cost of the high explosive driving the magnetized fusion target, this requires propagating burn into still un-burnt DT, and/or D fuel.

For non-magnetized inertial confinement fusion the condition for propagating burn from a spherical volume of radius r filled with DT of density ρ, is that the sphere is heated to ignition temperature $T \cong 10^8 K$, and that $\rho r > 1 g/cm^2$. The sphere there forms a "hot spot" from which a thermonuclear deflagration can propagate into still un-burnt DT. In a magnetized plasma the corresponding condition is that the Larmor radius of the charged fusion products should be smaller than the radius of the burn zone. The Larmor radius is given by (e, c electron charge and velocity of light):

$$r_L = \frac{Mvc}{ZeB} \tag{5}$$

where M and Z are the mass and the charge number, and v the velocity of the fusion product. B is the magnetic field in Gauss. The radius of the burn zone is here the radius of the magnetized plasma cylinder, given by

$$r = \frac{I}{5B} \tag{6}$$

where I (in Ampere) is current flowing through the plasma. The condition that $r > r_L$, then means that

$$I > \frac{5Mvc}{Ze} \tag{7}$$

or that

$$Br > \frac{Mvc}{Ze} \tag{8}$$

This condition is well satisfied if $Br > 2 \times 10^6 Gcm$ or $I > 10^7$ Ampere replacing $\rho r > 1 g/cm^2$. At $r \approx 1 cm$, one would need $B > 2 \times 10^6 G$. This field strength is also large enough to thermally insulate the plasma against the confining wall. Applied to a pinch discharge this means that if (8) is satisfied a DT fusion detonation wave can propagate along a 10^7 Ampere pinch discharge channel, even if the temperature of the un-burnt cold DT in the channel is far below its ignition temperature. To launch a detonation then only requires to create a hot spot somewhere in the pinch discharge channel, with a temperature of the hot spot equal or above the DT ignition temperature. For DT the hot spot must have a temperature of $T \sim 10^8 K$, and it must be heated in a time shorter than the loss time for bremsstrahlung and heat conduction. In the presence of a strong magnetic field the heat conduction is governed by the thermal motion of the ions, not the electrons, substantially reducing the losses by conduction.

For a magnetized plasma where the plasma pressure is set equal the pressure of the confining magnetic field one has

$$\frac{B^2}{8\pi} = 2nkT \quad (9)$$

From (6) and (9) follows the Bennett pinch relation [6]

$$I^2 = 400NkT \quad (10)$$

There $N = \pi r^2 n$, is the number per length of the plasma cylinder. To achieve ignition $T \sim 10^8$K.

Once ignition has been achieved a nuclear deflagration can go from a hot spot where $T \sim 10^8$K into un-burnt regions only if in these regions $Br > 2 \times 10^6 \text{Gcm}$.

3. An example

For HMX the energy density is $\varepsilon \cong 9.0 \times 10^{10}\ \text{erg/cm}^3$, the detonation velocity $v_D = 9.3 \times 10^5\ \text{cm/s}$, and the detonation pressure $p = 4 \times 10^{11}\ \text{dyn/cm}^2$ [5].

In the DT reaction 80% of the energy goes into neutrons with 20% into charged He^4 fusion products. In D burn with the inclusion of the secondary DT and DHe^3 reactions from the D burn, only 38% is released into neutrons with 62% going into charged fusion products. If the neutrons are slowed down in the burnt explosive surrounding the DT or D reaction, all the fusion energy released boosts the energy of the chemical high explosive. With the stopping length of the 14 MeV neutrons in HMX about $\sim 24\text{cm}$ [7], the radius of the high explosive sphere should be of the order R $\sim 30\text{cm}$, with a volume equal to $V \sim 10^5 \text{cm}^3$. With the energy density of HMX, this means that the input energy for ignition is $E_{in} \cong 10^{16} \text{erg} \cong (1/4)\text{ton}$ TNT equivalent.

For a magnetized DT plasma with a pressure $p_1 = 2nkT$ and temperature $T \sim 10^8 \text{K}$, the particle number density is $n_1 = p_1/2kT \cong 3 \times 10^{20} \text{cm}^{-3}$. To satisfy the Lawson $n\tau \geq 10^{14} \text{cm}^{-3}\text{s}$ criterion for $n = n_1 = 3 \times 10^{20} \text{cm}^{-3}$ then requires that $\tau \geq 3 \times 10^{-7} \text{sec}$. This time is of the same order as the time $\tau_s \sim r/v_s$ where $v_s \sim 10^7\ \text{cm/s}$ is the velocity of the incoming convergent shock wave at the distance $r \sim 1\text{cm}$.

4. Creating the strong magnetic field

One way to create a magnetic field equal to $B \cong 1.6 \times 10^7 \text{G}$ at the distance $r = 1\text{cm}$, measured from the centre of the convergent detonation shock wave, is shown in Fig.1. There a pipe with a radius of 1cm passes through the centre of the high explosive. The pipe is filled with DT gas having a particle number density equal to $(1/30)n_1 = 10^{19} \text{cm}^{-3}$. Then, just prior to the ignition of the high explosive, a $10^6\text{A} - 25\text{MeV}$ relativistic electron beam lasting $2 \times 10^{-8} \text{sec}$ and drawn from a Marx generator is shot through the pipe [8]. The beam can be focused onto the entrance of the pipe if its current is below the Alfven limit $I_A \sim 10^4 \gamma \text{A}$, where $\gamma = (1 - v^2/c^2)^{-1/2}$. For 25 MeV electrons $\gamma \cong 50$ and hence $I \cong I_A \cong 10^6 \text{A}$. To keep I below the Alfven current requires to go to a slightly larger voltage than the 25MV. To pass through the

60 cm long pipe, the beam must last at least $\sim 2\times10^{-8}$sec. It has an energy of about 500kJ, delivered at a power of 2.5×10^{13}W, needed to magnetize and preheat the DT.

Inside the pipe the current of 10^{6}A produces an azimuthal magnetic field $B_0 = 0.2\,I/r = 2\times10^{5}$G. With the convergent shock wave imploding the pipe at the front of the wave, the pipe shortens as the detonation front moves towards the centre of convergence. By magnetic flux conservation this increases the magnetic field in inverse proportion to the length of the shortening pipe until that moment where the magnetic pressure balances the pressure of the incoming detonation wave.

In our example this shall happen at a radius r = 1cm measured from the centre of convergence. There the current reaches $\sim10^{7}$A and the plasma pressure becomes equal to magnetic pressure in a reversed field-line configuration as shown in Fig.2. As a result, a toroidal pinch discharge is formed inside a DT filled cavity with closed magnetic field- and electric current- lines [2]. With a current of $\sim10^{7}$A a thermonuclear deflagration can from there advance into unburnt DT and D surrounding the DT burning cavity.

5. Igniting the magnetized target

To reach the DT ignition of temperature 10^{8}K inside the cavity formed by the imploding pipe, can be done as follows: First by pre-heating the DT plasma in the pipe with the 500kJ electron beam, and second by further heating the plasma through isentropic compression in the imploding pipe. For the number of particles $N = (4\pi/3)r^3 n_1 = 1.2\times10^{21}$ heated by 500 kJ, one obtains a temperature of $T\sim10^{7}$K. For the isentropic compression from $n_0 = n_1/30$ to $n = n_1$, the temperature rises by a factor $\cong 10$. The heating by the electron beam combined with the heating by isentropic compression is therefore sufficient to reach the ignition temperature $T\sim10^{8}$K. This heating is possible because the heat conduction loss into the wall is reduced by the large magnetic field.

6. High gain through propagating burn

Neglecting the energy of the electron beam against the energy of the high explosive, the input energy for the chosen example is still of the same order $E_{in} \cong 10^{16}$erg . The maximum yield is reached if all the DT particles inside the cavity undergo a fusion reaction. For one DT reaction involving two particles this energy is 1.77×10^{7}eV $= 2.83\times10^{-5}$erg , hence for all the 1.2×10^{21} DT particles it is equal to $E = E_{out} = 1.7\times10^{16}$erg . This means the maximum gain $G = E_{out}/E_{in} = 1.7$ is uninterestingly small but typical for magnetized fusion. But here there is a crucial difference : While the volume containing the chemical energy of the high explosive is $(30)^3 \cong 2.7\times10^{4}$ times larger than the volume containing the energy of the magnetized DT fusion explosive, the energy density of the fusion explosive even for a gain G = 1 is larger than the chemical energy density by the same factor. But the energy density of the DT fusion explosive, computed for a particle number density of $n_1 = 3\times10^{20}$cm^{-3}, is still about 100 times smaller than it would be for liquid DT where $n \cong 5\times10^{22}$cm^{-3} . This means, a gain of $G \cong 100$ would be possible for the same volume filled with liquid DT. The volume would be less if the DT in it is compressed to higher than liquid densities. And if a small amount of DT ignites a larger amount of pure D, the amount of tritium needed can conceivably be quite small. This example illustrates that propagating burn into DT and D is needed for a high gain.

Propagating burn can only be analyzed by extensive computer calculations, but one can propose some possibilities with two examples given here:

1. The first possibility is explained in Fig.3. There a number of small cm-size super conducting solenoids are arranged around the burning magnetized DT plasma. With a maximum current density of $\sim 10^5\ \mathrm{A/cm^2}$ and a critical field strength of $\mathrm{B} \sim 10^5 \mathrm{G}$, the cm-size superconducting solenoids can be magnetized up to this field strength [9]. It is then proposed to place inside each of the super-conducting solenoids a small cylinder of liquid or solid state DT, attached to a larger cylinder of D. If the inner radius of the superconducting solenoid is of the order 1cm and is laterally compressed by the convergent detonation wave to about 0.1cm, the magnetic field in it will by magnetic flux conservation rise from $\mathrm{B} \sim 10^5 \mathrm{G}$ to $\mathrm{B} \sim 10^7 \mathrm{G}$, making $\mathrm{Br} > 10^6 \mathrm{Gcm}$ as required for propagating burn into the liquid DT and D ignited by the burning magnetized DT plasma. There, then quite large gains are possible.

2. The second possibility, explained in Fig.4. is even more extravagant. In it the hollow pipe passing through the centre of the explosive is replaced by a co-axial conductor, with liquid DT and D put inside the inner conductor. In this configuration the burning magnetized DT plasma is explosively breaking through the wall of the inner conductor, bombarding and implosively igniting a DT target placed in the centre of the inner conductor. With additional DT and D placed along DT target an autocatalytic detonation wave as shown in Fig.5 becomes possible, where the soft X-rays released from the burning plasma pre-compresses the un-burnt DT or D [10]. There even larger gains are possible.

<u>7. Magneto-hydrodynamic conversion into electric energy</u>

For a gain $\mathrm{G} = \mathrm{E_{out}}/\mathrm{E_{in}} = 100$, with $\mathrm{E_{in}} \cong 10^{16} \mathrm{erg}$, the fire ball of the hybrid chemical nuclear explosion has a kinetic energy of the order $\mathrm{E_{out}} \sim 10^{18} \mathrm{erg}$, equivalent to 25 tons of TNT. The temperature of the fire ball is of the order $\sim 10^5$K. It is highly conducting plasma, which makes possible its conversion into electric energy by a Faraday magneto-hydrodynamic generator. This is possible even at a somewhat lower temperature, realized by adding hydrogen to the expanding fire ball.

The pressure at the surface of the fireball at its initial radius R = 30cm is of the order $\mathrm{p_0} \sim \rho \mathrm{v_0^2}$. For $\rho \sim 1 \mathrm{g/cm^3}$, $\mathrm{v_0} \cong 10^7\ \mathrm{cm/s}$, it is $\mathrm{p_0} \sim 10^{14}\ \mathrm{dyn/cm^2}$. The pressure decreases with the increasing radius of the expanding fire ball $\mathrm{r} > R$, as $(\mathrm{R/r})^2$. To bring it down to $\sim 10^{10}\ \mathrm{dyn/cm^2}$ (10^4 atmospheres), the maximum pressure sustainable by steel, requires that $\mathrm{r/R} \cong 100$, or that $\mathrm{r} \sim 30\ \mathrm{meter}$. Of the same order must be the radius of a cylindrical Faraday generator. A possible version of such a generator is shown in Fig.6.

By adding hydrogen to the fireball the expansion velocity can be reduced to $v \sim 3 \times 10^6\ cm/s$. In a Faraday generator this would lead to an electric field $E = (v/c)B[esu]$, where we may put $B \cong 10^4 G$ (typical for an electromagnet), hence $E = 1[esu] = 300\ Volt/cm$. For a width $D \sim 30\ meter$ of the generator, that would mean and output voltage $V = ED \cong 10^6 Volt$.

Because of the large temperature gradient between the hot fire ball and the cold wall touched by the fire ball, thermo-magnetic currents are set up near the surface of the wall generating a large magnetic field repelling the plasma from the wall [11].

8. Enriching the outer spherical shell of the high explosive with a neutron absorber.

Because the energy of the high explosive is estimated to be about 10^{16} erg=1000 MJ, is uncomfortable large, a way to reduce it by at least one order of magnitude, would be highly welcome. It is for this reason suggested to enrich the outer shell of the high explosive with a neutron absorbing substance. An inexpensive neutron absorber is boron. Its neutron-absorbing cross section becomes large for thermal neutrons. If the 14 MeV DT fusion neutrons are slowed down to the temperature of the burnt up high explosive through which they diffuse radially outward, their absorption cross section in boron is about 100 barn=10^{-22} cm^2, assuming a thermal neutron energy of 0.5eV, about equal the combustion temperature of the high explosive. The neutrons split the boron (B10) under the release of 3MeV into Li^7 and He^4. Therefore, if the outer spherical shell of the high explosive is enriched by 20% with boron, and if the atomic number-density of the high explosive is 5×10^{22} cm^{-3}, a value typical for condensed matter, a one-cm thick shell would absorb most of the neutrons. This means that the intense burst of the neutrons released by the thermonuclear micro-explosion in the center of the burnt up high explosive would lead to a secondary nuclear explosion in the shell, launching a secondary convergent shock wave towards the center, increasing the confinement time and thus the thermonuclear yield. But since by adding boron the high explosive, the neutrons are not only slowed down but also absorbed, the minimum radius of the high explosive reached to ignite a thermonuclear reaction is likely to be smaller. If the minimum radius could be made ½ as large, the energy of the high explosive could be reduced from 10^{16} erg=1000 MJ to about 10^{15} erg=100 MJ, an energy comparable to large electric pulse power.

9. Conclusion

The proposed hybrid chemical-nuclear pulse fusion concept has the potential of a high nuclear into electrical energy conversion, not possible if most of the energy released in neutrons is not used to heat a plasma to high temperatures. The only drawback this concept might have is the high yield, requiring a Faraday generator of large dimensions. The expansion velocity of the fireball, of the order 100km/sec, if compared with the expansion velocity of a few km/sec for a chemical explosion, demonstrates that the micro-fusion reaction results in a thousandfold amplification of the energy in the high explosive.

Apart from its usefulness to convert DT and possibly D fusion energy into electric energy, it also has for likewise reasons a most interesting application for nuclear rocket propulsion where it eliminates the necessity of a large radiator.

It is not the purpose of this communication to make a detailed analysis of magnetized target fusion, including the stability of these configurations. For such an analysis we may refer to the review paper by Lindemuth and Kirkpatrick [12]. The purpose of this communication rather is to show a way where almost all the energy released in DT fusion can be converted into electric energy, not possible with any of the proposed fusion concepts, by magnetic or inertial confinement.

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Figures

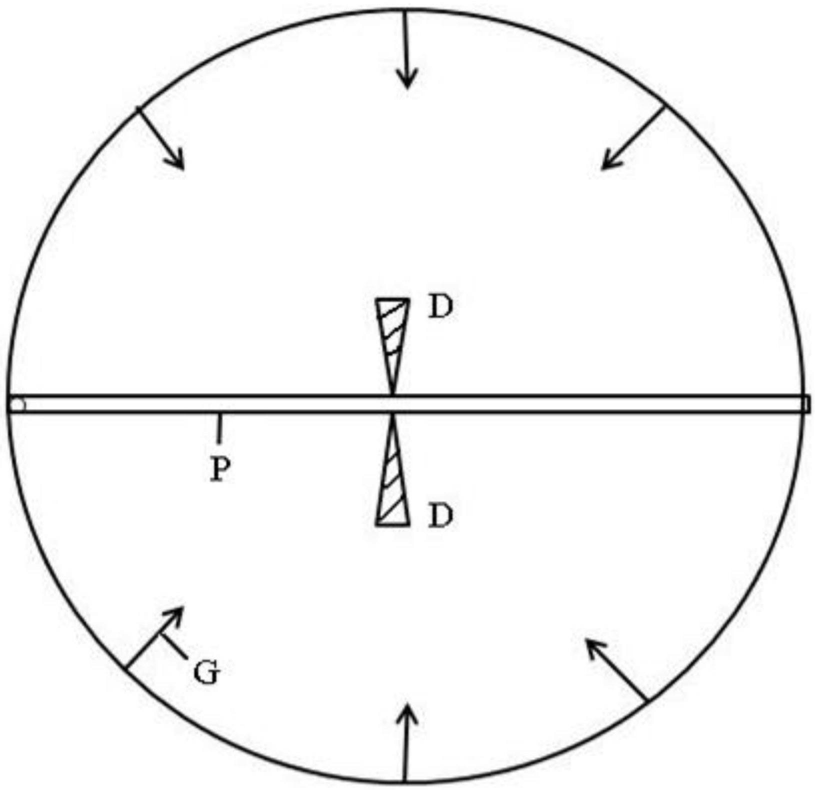

Fig. 1. Convergent Gudeley shock wave G onto magnetized fusion target in hollow pipe P with additional deuterium D for propagating burn into a region with an increasing diameter (horn) for a growing thermonuclear detonation wave.

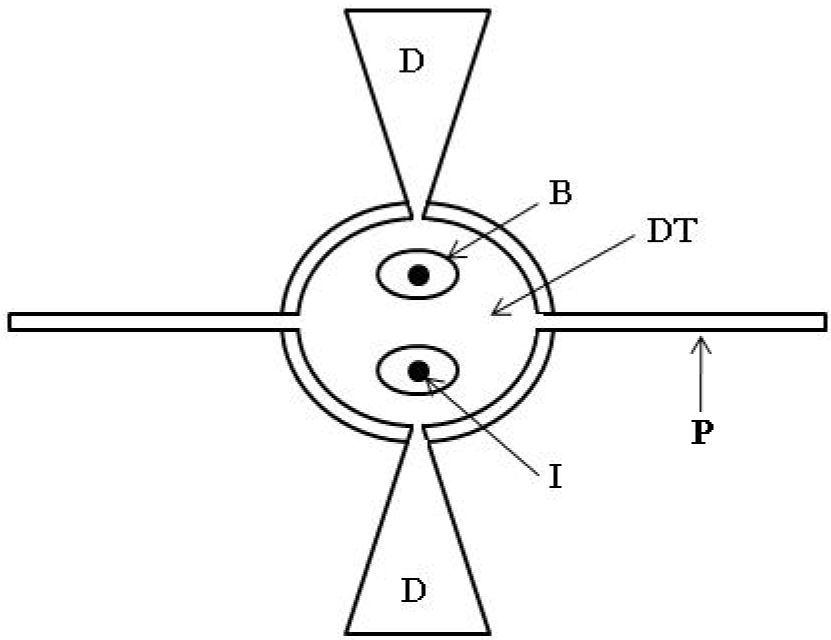

Fig.2. Formation of field reversed configuration of magnetized DT target in the center of convergent shock wave. B and I toroidal magnetic field current; **P** imploded pipe, D solid deuterium.

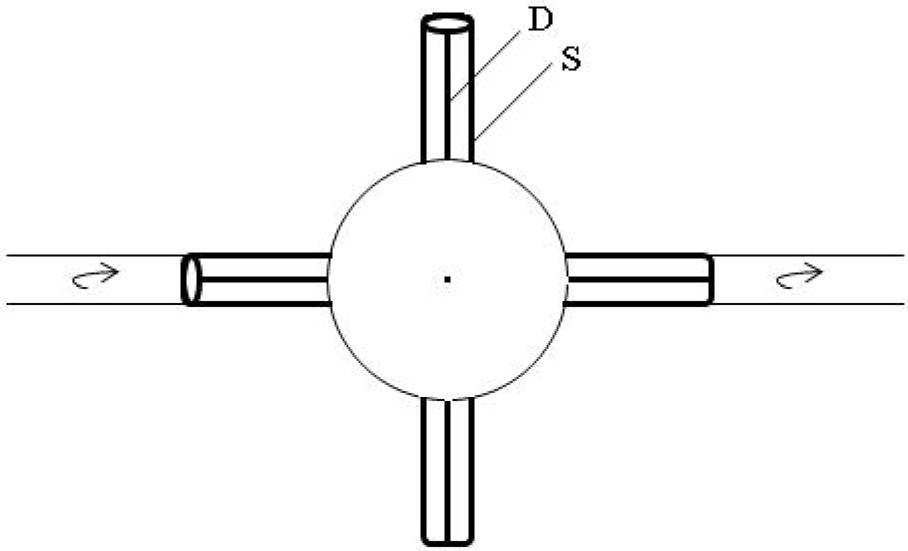

Fig. 3. Propagating burn into DT or D placed inside small magnetized superconducting solenoids S, compressed by imploding convergent shock wave.

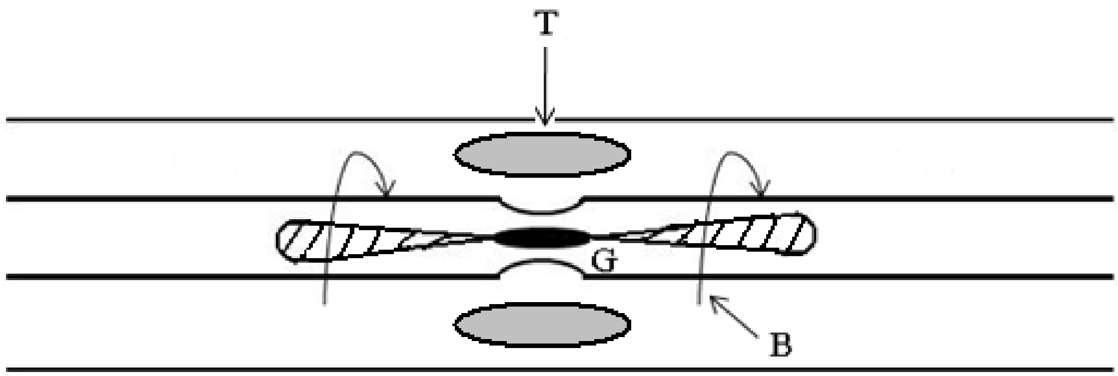

Fig.4. Magnetized target T in coaxial conductor, with propagating burn of high gain target G inside inner conductor ignited by magnetized target ; B magnetic field.

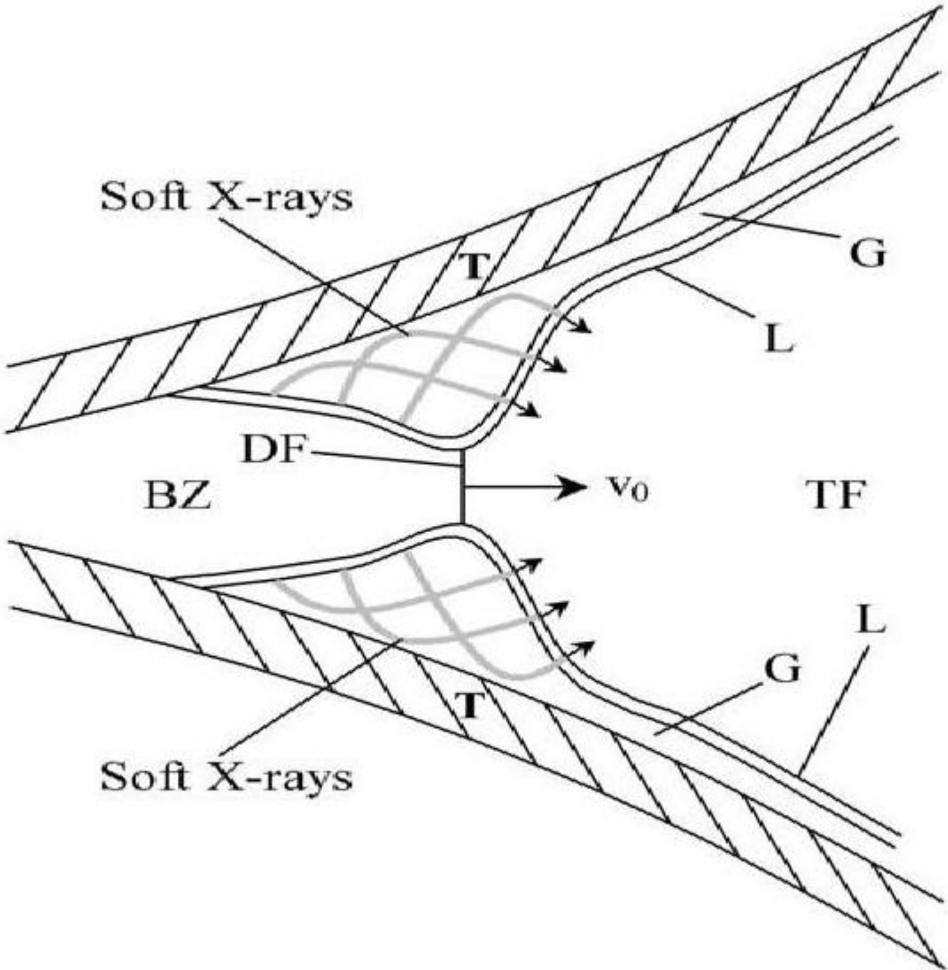

Fig.5. Autocatalytic thermonuclear detonation using a soft X-ray precursor from the burn zone BZ to precompress the thermonuclear fuel TF ahead of the detonation front DF. The soft x-rays travel through the gap G between the tamp T and the linear L.

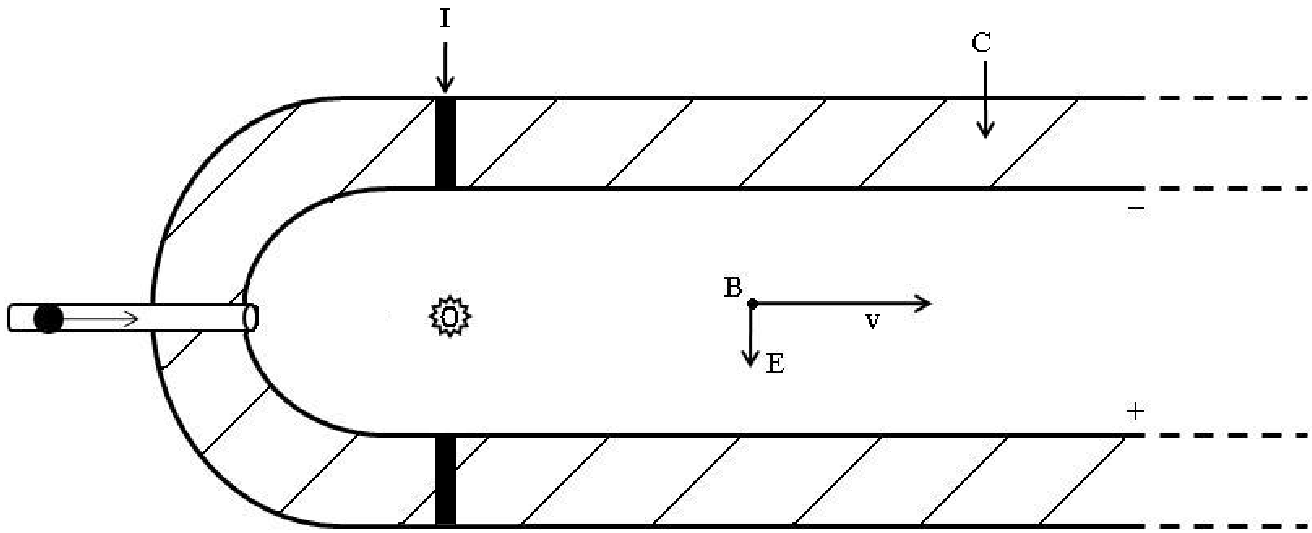

Fig.6. Faraday generator for chemical-nuclear energy conversion into electric energy : F hybrid chemical-fusion mini-bomb, B magnetic field directed perpendicular to plane of drawing and produced by electromagnets, v velocity of plasma fire ball which induces electric field $\mathbf{E} = (v / c) \times \mathbf{B}$, C wall confining plasma flow, I insulator.