Fast Fission Assisted Ignition of Thermonuclear Microexplosions

Friedwardt Winterberg

University of Nevada, Reno, USA

Reprint requests to Prof. F. W.; E-mail: winterbe@physics.unr.edu

Z. Naturforsch. **61a,** 559 – 563 (2006); received June 27, 2006

It is shown that the requirements for fast ignition of thermonuclear microexplosions can be substantially relaxed if the deuterium-tritium (DT) hot spot is placed inside a shell of U-238 (Th-232). An intense laser – or particle beam-projected into the shell leads to a large temperature gradient between the hot DT and the cold U-238 (Th-232), driving thermomagnetic currents by the Nernst effect, with magnetic fields large enough to entrap within the hot spot the α-particles of the DT fusion reaction. The fast fission reactions in the U-238 (Th-232) shell implode about 1/2 of the shell onto the DT, increasing its density and reaction rate. With the magnetic field generated by the Nernst effect, there is no need to connect the target to a large current carrying transmission line, as it is required for magnetized target fusion, solving the so-called "stand off" problem for thermonuclear microexplosions. – PACS number: 28.52.-s.

Key words: Fast Ignition; Inertial Confinement Fusion.

1. Introduction

One of the more promising inertial confinement thermonuclear fusion (ICF) concepts, going by the name of the fast ignitor [1], proposes isentropic compression to high densities of a solid deuterium-tritium (DT) target, followed by hot spot ignition with an ultrashort petawatt laser. Estimates indicated a drastic reduction of the total energy needed for compression and ignition to perhaps as little as $\sim$ 100 kJ. The compression could be done as in other ICF concepts by laser or particle beams [2 – 5] or even by soft X-rays from electric pulse powered imploded arrays of thin wires [6]. For the fast ignitor, two petawatt lasers were originally proposed. The first one was to bore a hole into the center of the compressed DT, with the second one delivering the energy needed for ignition to the center of the DT through the hole opened by the first laser. Later, an important modification of the original fast ignitor concept was to replace the first laser needed to bore the hole by a hollow gold cone stuck in the DT with the tip of the cone in the center of the DT [7]. Theoretical and experimental studies showed that the inertia of the gold cone appears to be sufficient to keep the cone open long enough for the laser-ignition pulse to reach the center of the DT [8].

Apart from the complexity of the fast ignitor approach towards ICF, aggravated by the smallness of the DT target assembly, the consensus has emerged that for this concept to work a petawatt laser with a total energy output of more than 100 kJ is needed. Taking into consideration the low efficiency of petawatt lasers, this appears to be a very expensive proposition, and it again raises the question of whether there might be a much less expensive way to achieve the goal of controlled nuclear fusion by inertial confinement. I claim it exists in the coupling of the DT fusion fuel with a comparatively small amount of natural uranium (U-238) or thorium (Th-232).

Large thermonuclear explosive devices are ignited by the explosive energy from a critical mass of U-235 (Pu-239). Not making extravagant such a device, the thermonuclear fusion energy released must be at least as large as the energy released by fission. But because such a device depends on a critical mass of several kilograms at least, this kind of "fast ignition" cannot be scaled down for the ignition of thermonuclear microexplosions. However, for small thermonuclear assemblies a different way to release the energy from a fission reaction, in conjunction with a DT (DD) fusion reaction, can be used profitably, greatly relaxing the requirements for fast ignition. For this process even natural uranium (U-238) and thorium (Th-232) can be used, and, as for large thermonuclear explosive devices, the relative amount of the fission product fall-out can be kept quite small. The importance of this possibility is, that it greatly increases the chance for controlled nuclear fusion to succeed, justifying the price which

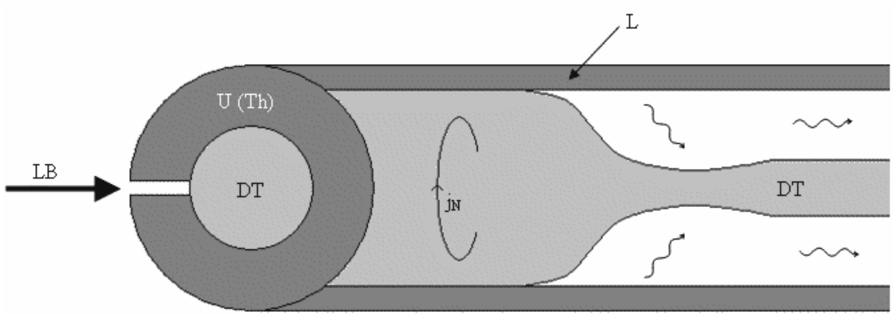

Fig. 1. Bombardment, by a laser or particle beam LB, of a spherical solid DT target surrounded by a natural uranium (thorium) shell, with propagating burn into a DT cylinder inside a liner L.

has to be paid in the release of a comparatively small amount of fission products.

2. Fast Fission Assisted Hot Spot Fast Ignition Assembly

As explained in Fig. 1, a sphere containing DT, surrounded by a shell of metallic U-238 (Th-232), is positioned at one end of a cylindrical thermonuclear microexplosion assembly. The DT inside the shell can be heated through an opening to thermonuclear temperatures by a laser or particle beam. A large temperature gradient between the hot DT plasma and the cold U-238 (Th-232) shell surrounding the DT plasma generates near the DT-U-238 interface currents by the thermomagnetic Nernst effect with magnetic fields large enough to entrap the α-particles from the DT fusion reaction in the DT plasma. In passing through the U-238 (Th-232) shell, some of the 14 MeV DT fusion reaction neutrons perform fast fission reactions in the shell, heating it to high temperatures. If the thickness of the shell is properly chosen, the shell will implode onto the DT increasing the density and reaction rate of the DT plasma inside the shell, further accelerating the implosion of the shell and with it the DT thermonuclear reaction rate, in an "autocatalytic" fusion-fission-fusion reaction.

To set up the magnetic field by the currents of the thermomagnetic Nernst effect, a seed field is needed, which is amplified by the Nernst effect. The seed field can be provided by placing the entire assembly in the center of a large magnetic solenoid, with the axis of the microexplosion assembly in the same direction as the direction of the magnetic field.

From the fission assisted fusion hot spot thus produced, a thermonuclear detonation wave is launched into a DT cylinder. There too, a metallic cylindrical shell surrounding the DT cylinder can set up a large magnetic field by the Nernst effect, making possible a magnetic field assisted thermonuclear detonation wave propagating down the cylinder. In addition, soft X-rays, released from both the hot spot and the rear of the detonation wave, can be utilized to compress the un-burnt DT ahead of the wave. Because the amount of U-238 (Th-232) needed to create the hot spot is small in comparison to the total amount of DT, the amount of the undesirable fission products is relatively small.

3. The Thermomagnetic Nernst Effect

A temperature gradient in a magnetized fully ionized plasma leads to thermomagnetic currents (Nernst effect), with the current density for a hydrogen plasma given by [9]

$$\mathbf{j}_\mathrm{N} = \frac{3nkc}{2H^2}\mathbf{H} \times \nabla T, \tag{1}$$

valid for $\omega\tau \gg 1$, where ω is the electron cyclotron frequency and τ the electron-ion collision time. In (1) n is the number density of electrons and protons, $\mathbf{H}$ the magnetic field strength, ∇T the temperature gradient; k and c are the Boltzmann constant and the velocity of light. The current density (1) has a magnetic body force density acting on the plasma equal to

$$f = \frac{1}{c}\mathbf{j}_\mathrm{N} \times \mathbf{H} = \frac{3}{2}\frac{nk}{H^2}(\mathbf{H} \times \nabla T) \times \mathbf{H}. \tag{2}$$

If $\nabla T \perp \mathbf{H}$, this becomes

$$f = \frac{3}{2}nkT. \tag{3}$$

Inserting (3) into the magnetohydrostatic equation

$$\nabla p = f \tag{4}$$

and setting $p = 2nkT$, valid for a hydrogen plasma, one obtains from (4)

$$n\nabla T + 4T\nabla n = 0 \quad (5)$$

or

$$Tn^4 = \text{const.} \quad (6)$$

The Nernst current density is here directed azimutally and is

$$j_\mathrm{N} = \frac{3nkc}{2H}\frac{\mathrm{d}T}{\mathrm{d}r}. \quad (7)$$

Inserting $\mathbf{j}_\mathrm{N}$ into Maxwell's equation

$$\frac{4\pi}{c}\mathbf{j}_\mathrm{N} = \nabla \times \mathbf{H}, \quad (8)$$

one obtains with $\mathbf{H}$ directed along the z-axis

$$6\pi nk\frac{\mathrm{d}T}{\mathrm{d}r} = -H\frac{\mathrm{d}H}{\mathrm{d}r}. \quad (9)$$

With $Tn^4 = T_0 n_0{}^4$, where T_0 and n_0 are the temperature and number density at $r = 0$, (9) becomes

$$-H\mathrm{d}H = 6\pi n_0 k T_0^{1/4} T^{-1/4}\mathrm{d}T. \quad (10)$$

Integrating (10) from H_0, $T = 0$ at the cold wall made from U-238 to $H = 0$, $T = T_0$ at $r = 0$, one obtains

$$\frac{H_0^2}{8\pi} = 2n_0 k T_0. \quad (11)$$

The return current flows along the cold wall with the magnetic field of the Nernst current shielding the interior of the hot DT plasma from the magnetic field of the Nernst current.

As an example, let us take a sphere of solid DT with $n_0 = 5\cdot 10^{22}$ cm^{-3} and with a radius $r_0 = 0.1$ cm. To be heated to $T_0 = 10^8$ K, the ignition temperature of the DT reaction requires the input energy

$$E_\mathrm{in} = 2n_0 k T_0 (4\pi/3) r_0^3 = 6\cdot 10^{12}\ \text{erg} = 600\ \text{kJ}.$$

According to (11), the magnetic field at the outer plasma boundary at $r = r_0$ would be $H_0 = \sqrt{16\pi n_0 k T_0} \cong 2\cdot 10^8$ G, with a Nernst current $I_\mathrm{N} = 5 r_0 H_0 = 10^8$ A. To deflect and entrap the α-particles from the DT fusion reaction inside the sphere of radius $r = r_0 = 0.1$ cm requires that $r_\mathrm{L} \ll r_0$, where $r_\mathrm{L} = a/H$ with $a = 2.7\cdot 10^5$ Gcm is the Larmor radius of the α-particles. For $H = 2\cdot 10^8$ G, one has $r_\mathrm{L} \sim 3\cdot 10^{-3}$ cm, smaller than r_0 by more than two orders of magnitude. Finally, the electron Larmor frequency at $H = 2\cdot 10^8$ G is $\omega \cong 3.5\cdot 10^{15}$ s^{-1}, and $\tau \approx 6.7\cdot 10^{-14}$ s, hence $\omega\tau \approx 230 \gg 1$.

The return current is going in the opposite direction along the cold surface of the U-238 shell, where $\omega\tau \ll 1$, with no thermomagnetic EMF in the opposite direction. Accordingly, the magnetic lines of force are closed, forming a torus wound around the z-axis.

4. Autocatalytic Fusion-Fission-Fusion Reaction

The concept of the "autocatalytic" fusion-fission-fusion reaction previously proposed [10] is here presented in a simplified way [11, 12]. The DT thermonuclear reaction rate inside the U-238 shell is determined by the equation

$$\frac{\partial n}{\partial t} = \frac{n^2}{4}\langle\sigma v\rangle, \quad (12)$$

where $\langle\sigma v\rangle$ is the DT nuclear fusion reaction cross section σ multiplied with the particle velocity v and averaged over a Maxwellian. With the help of (12) one obtains for the neutron flux at the surface of the DT sphere of radius r_0

$$\Phi = \frac{1}{4\pi r_0^2}\int_0^{r_0}\frac{n^2}{4}\langle\sigma v\rangle 4\pi r^2 \mathrm{d}r. \quad (13)$$

Assuming that $n^2\langle\sigma v\rangle$ does not depend on r, one finds that

$$\Phi = \frac{n^2}{12}\langle\sigma v\rangle r_0. \quad (14)$$

The fission reaction path length of the neutrons in U-238 is Σ_f^{-1}, where $\Sigma_\mathrm{f} = n_\mathrm{f}\sigma_\mathrm{f}$ is the macroscopic fission cross section where σ_f is the fission reaction cross section and n_f the atomic number density. For metallic U-238 one has $n_\mathrm{f} \approx 4\cdot 10^{22}$ cm^{-3} and $\sigma_\mathrm{f} \approx 2\cdot 10^{-24}$ cm^2, hence $\Sigma_\mathrm{f}^{-1} \approx 8$ cm.

Assuming that the thickness of the U-238 shell is $\delta \ll \Sigma_\mathrm{f}^{-1}$, then only the fraction $\delta\Sigma_\mathrm{f} \ll 1$ of the neutrons passing through the shell will make a fission reaction. Because this fraction is small, the neutron flux over the shell remains approximately constant.

The energy released per unit volume in the time τ in the U-238 shell is

$$\varepsilon = \Sigma_f \Phi(\varepsilon_f + \varepsilon_0)\tau, \quad (15)$$

where ε_f is the fission energy released and ε_0 the kinetic energy of the neutrons released from the DT reaction. τ is the time of inertial confinement of the U-238 shell. By order of magnitude it is equal to

$$\tau \sim \delta/a, \quad (16)$$

where $a \approx \sqrt{p/\rho}$ is the velocity of sound in the hot U-238 shell of density ρ.

The justification of (15) can perhaps be better seen by writing it with the help of (16) as

$$\varepsilon = \Phi(\varepsilon_f + \varepsilon_0)\left(\frac{\delta}{L}\right)\frac{1}{a}, \quad (15a)$$

where $L = 1/\Sigma_f$ is the fission reaction path length in the shell, with the fraction (δ/L) of neutrons passing through the shell making a fission. Without the division by the velocity of sound, $a = \sqrt{p/\rho}$, (15a) would be the energy flux density in the shell.

Since by order of magnitude $p \approx \varepsilon$ one has

$$\tau = \delta\sqrt{\rho/\varepsilon} \quad (17)$$

and one obtains from (15)

$$\varepsilon = [\Sigma_f \Phi(\varepsilon_f + \varepsilon_0)\delta]^{2/3}\rho^{1/3}. \quad (18)$$

By inserting Φ from (14), this becomes

$$\varepsilon = \frac{1}{12^{2/3}}\left[\Sigma_f(\varepsilon_f + \varepsilon_0)\langle\sigma v\rangle n^2 r_0 \delta\right]^{2/3}\rho^{1/3}. \quad (19)$$

The shell begins to implode onto the DT if $\varepsilon > 2nkT$. With the help of (19), this condition can be written as

$$n(r_0\delta)^2 > \frac{(kT)^3}{\langle\sigma v\rangle^2}\frac{1152}{[\Sigma_f(\varepsilon_f + \varepsilon_0)]^2\rho}. \quad (20)$$

The right hand side of this equation is smallest for the minimum of $(kT)^3/\langle\sigma v\rangle^2$, which is at $kT \approx 15$ keV, where $(kT)^3/\langle\sigma v\rangle^2 \approx 2\cdot 10^8$ erg^{3}s^2/cm^6. We therefore have

$$n(r_0\delta)^2|_{\min} \approx 2\cdot 10^{11}[\Sigma_f(\varepsilon_f + \varepsilon_0)]^{-2}\rho^{-1} \text{ [cm]}. \quad (21)$$

For U-238 with $\Sigma_f \approx 0.8\cdot 10^{-1}$ cm^{-1}, $\varepsilon_f + \varepsilon_0 = 3\cdot 10^{-4}$ erg, $\rho = 18$ g/cm^3, and for $n = 5\cdot 10^{22}$ cm^{-3}, one finds that $r_0\delta|_{\min} \approx 2\cdot 10^{-2}$ cm^2; or for $r_0 = 0.1$ cm, that $\delta \approx 0.2$ cm.

We can now also compute the implosion velocity of the U-238 shell. For $kT_0 = 15$ keV $= 2.4\cdot 10^{-8}$ erg, the pressure in the DT plasma with $n = 5\cdot 10^{22}$ cm^{-3} is $p = 2nkT_0 = 2.4\cdot 10^{15}$ dyn/cm^2. For the autocatalytic implosion to take place, the pressure (i. e. energy density) in the U-238 shell must be at least that large. Therefore, with $\rho = 18$ g/cm^3 for U-238, the implosion velocity is $v_{\text{imp}} = \sqrt{p/\rho} \approx 10^7$ cm/s. And with $\delta = 0.2$ cm, the inertial confinement time is $\tau \approx 2\cdot 10^{-8}$ s. Therefore, $n\tau \approx 10^{15}$ cm^{-3} s, well about $n\tau \approx 10^{14}$ cm^{-3} s (Lawson criterion) to assure an exponential growth of the fusion-fission autocatalytic reaction.

5. Propagating Thermonuclear Burn from the Fission Assisted Fusion Hot Spot

Once a fast fission assisted hot spot is created, a propagating thermonuclear burn along a slender DT cylinder is possible with the aid of a large axial current along the cylinder [13] established here by the Nernst effect. As shown in Fig. 1, the efficiency of the burn can be further improved by precompressing the DT fuel cylinder with the soft X-rays coming from the hot spot and the rear of the burn wave. In this way a large thermonuclear yield seems possible, large in comparison to the small amount of energy released by the fast fission.

6. Conclusion

In fissionless fast ignition concepts the energy required for fast ignition is of the order $\sim 10^5$ J, to be delivered in $\sim 10^{-10}$ s by an expensive inefficient $\sim 10^{15}$ W laser. In addition, a $\sim 10^6$ J – 10^{14} W laser pulse is there required for compressing the target to thousand-fold solid density. By comparison, in the fission assisted fast ignition concept proposed here, the total energy is estimated to be about $6\cdot 10^5$ J, to be delivered in $2\cdot 10^{-8}$ s by a much less expensive $3\cdot 10^{13}$ W laser, with the target compression done "autocatalytically" by the coupling of the fusion with the fission process, and with no need to compress the target to thousand-fold solid density. With the relatively small fission reaction "fall-out", the proposed concept may have distinct advantages over pure fusion inertial confinement microexplosion concepts.

Finally, I may mention that the idea of a natural uranium shell surrounding a solid DT sphere with the DT ignited by a relativistic electron beam was proposed in 1971 [14] as a means for an efficient Orion-type nuclear microexplosion rocket propulsion system, but the concept was not further explored.

[1] M. Tabak, J. Hammer, M. E. Glinsky, W. L. Kruer, S. C. Wilkes, J. Woodworth, E. M. Campbell, and M. D. Perry, Phys. Plasmas **1**, 1626 (1994).
[2] J. Nuckolls, in: Laser Interaction and Related Plasma Phenomena (Eds. H. J. Schwarz and H. Hora), Plenum Press, New York 1974, Vol. 3B, p. 399ff.
[3] K. A. Brueckner, in: Laser Interaction and Related Plasma Phenomena (Eds. H. J. Schwarz and H. Hora), Plenum Press, New York 1974, Vol. 3B, p. 427ff.
[4] R. Martin, IEEE Trans. Nucl. Sci. **22**, 1763 (1975).
[5] A. W. Maschke, IEEE Trans. Nucl. Sci. **22**, 1825 (1975).
[6] T. W. L. Sanford, T. J. Nash, R. C. Mock, R. B. Spielman, K. W. Struve, J. H. Hammer, J. S. De Groot, K. G. Whitney, and J. P. Apruzese, Phys. Plasmas **4**, 2188 (1997).
[7] R. Kodama, P. A. Norreys, K. Mima, A. E. Dangor, R. G. Evans, H. Fujita, Y. Kitagawa, K. Krushelnick, T. Miyakoshi, N. Miyanaga, T. Norimatsu, S. J. Rose, T. Shozaki, K. Shigemori, A. Sunahara, M. Tampo, K. A. Tanaka, Y. Toyama, T. Yamanaka, and M. Zepf, Nature **412**, 798 (2001).
[8] R. Kodama and the Fast-Ignitor Consortium, Nature **418**, 933 (2002).
[9] L. Spitzer, Physics of Fully Ionized Plasmas, 2^{nd} ed., Interscience Publishers, John Wiley & Sons, New York 1962, p. 145.
[10] F. Winterberg, Atomkernenergie – Kerntechnik **44**, 145 (1984).
[11] F. Winterberg, Z. Naturforsch. **58a**, 612 (2003).
[12] F. Winterberg, Phys. Lett. A **336**, 188 (2005).
[13] F. Winterberg, Atomkernenergie – Kerntechnik **39**, 265 (1981).
[14] F. Winterberg, Raumfahrtforschung **15**, 208 (1971).