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Coriolis force-assisted inertial confinement fusion

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Abstract

A fundamental problem for the realization of laser fusion through the implosion of a spherical target is Kidder's $E^{-1/6}$ law, where E is the energy needed for ignition, proportional to the 6th power of the ratio R/R_0, where R_0 and R are the initial and final implosion radii, respectively. This law implies that the ignition energy is very sensitive to the ratio R_0/R, or *vice versa*, the ratio R_0/R is very insensitive to the energy input, with R_0/R limited by the Rayleigh–Taylor instability. According to still classified data of the Centurion–Halite experiment at the Nevada Test Site, ignition would require an energy of $\mathrm{E} \simeq 50$ MJ, 25 times larger than the 2 MJ laser at the National Ignition Facility (NIF) reported in the New York Times. This means that even a tenfold increase from 2 to 20 MJ would only decrease the R/R_0 ratio by an insignificant factor of $10^{-1/6} \simeq 0.7$. To overcome this problem, it is proposed that the spherical target is replaced with a hollowed-out, rapidly rotating, cm-size ferromagnetic target, accelerated by a rotating traveling magnetic wave to a rotational velocity of ~1 km/s, at the limit of its tensile strength. In a rotating reference system, the general theory of relativity predicts the occurrence of negative gravitational field masses in the center of rotation, with their source located in the Coriolis force field. The density of this negative gravitational field mass can be larger than the magnitude of the positive mass density of a neutron star. The repulsive gravitational force causes the centrifugal force. For a magnetized plasma placed in the rapidly spinning, hollowed-out target chamber, this repulsive force can be balanced by the magnetic force generated by thermomagnetic currents of the Nernst effect. Such a configuration does not suffer from the Rayleigh–Taylor instability, but becomes a small magnetohydrodynamic generator, amplifying the magnetic field to values about equal to those of the Nernst effect, axially confining the plasma. By placing the spinning target in the center of a lithium vortex, the fusion neutrons absorbed in the vortex can breed tritium, and at the same time remove heat from the target chamber to sustain the Nernst effect. A hot spot is thereby produced in the target chamber, which launches a thermonuclear burn wave into a cylindrical deuterium–tritium configuration. With the stability of a rapidly rotating target greatly increased, and the range of 10 MeV electrons in the wall of the cm-size ferromagnetic target, an intense 10 MeV relativistic electron beam drawn from a 10 MJ Marx generator should be sufficient to implode the target for thermonuclear ignition.

Introduction

The idea of achieving a large thermonuclear gain with a laser or particle beam is to create a hot spot from which a thermonuclear burn wave is launched into still unignited thermonuclear material. It can be traced back to the ignition of large thermonuclear explosive devices where the hot spot is created by soft X rays from an exploding fission bomb (Teller–Ulam configuration). It has been proposed that the creation of a hot spot with a laser or particle beam could be achieved by the implosion of a hollow, or even solid, sphere made from frozen deuterium–tritium (DT). But as the Centurion–Halite experiment at the Nevada Test Site has shown, generating a hot spot in this way would require an energy of at least 50 MJ, much larger than the 2 MJ energy of the laser at the National Ignition Facility (NIF). As an analysis by Kidder (1998) has shown, even a tenfold increase in energy from 2 to 20 MJ would not be enough. The reason for this problem is the Rayleigh–Taylor instability. Because current lasers have difficulty achieving an output of 50 MJ, several alternative concepts have been explored. One promising approach is the ignition of a target with axial symmetry by a multi-mega-ampere GeV proton beam below the Alfvén limit (Winterberg, 2014*a*). This may find an interesting application for fusion micro-explosion nuclear rocket propulsion, using the entire spacecraft as a magnetically insulated GeV capacitor in the high vacuum of space (Winterberg, 2014*b*), but all these proposals would still be very expensive.

A promising alternative is to replace the small spherical target with a hollow cm-size double cone, made from a ferromagnet as shown in Figure 1 (Winterberg, 1977). If this target is brought into rapid rotation to an azimuthal velocity of 1 km/s, at the limit of its tensile strength of $\sim 10^{11}$ dyn/cm^2, then the general theory of relativity predicts in the co-rotating

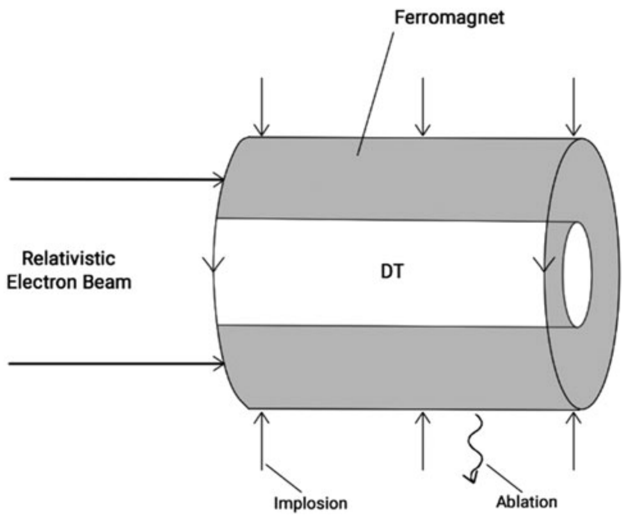

Fig. 1. The fusion fuel contained in the rapidly rotating cylinder, with a laser or particle beam heating and ablatively imploding the cylinder.

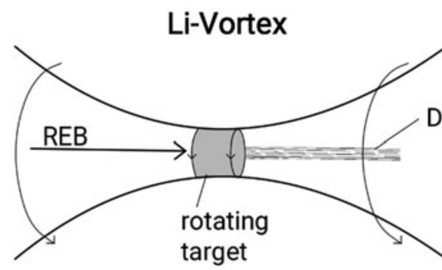

Fig. 2. The rapidly rotating cylinder is placed in a vortex with a laser or particle beam injected into one end of the vortex to heat and implode the cylinder using additional fuel.

reference frame, a large negative gravitational field mass in the center of the target by the Coriolis force-field. It gravitationally repels the DT plasma toward the inner wall of the target chamber, with a force equal to the centrifugal force. At the same time, the large temperature gradient in the radial outwards direction results in large electric currents by the thermomagnetic Nernst effect, leading to large magnetic fields radially confining the plasma. In addition, the Coriolis force leads to the establishment of a magnetohydrodynamic generator inside the target chamber with closed magnetic field lines, also axially confining the plasma.

Incorporating this configuration into a working thermonuclear inertial confinement fusion reactor, it is proposed to place the ferromagnetic target made up of a cylinder, filled with DT (Fig. 1), in the center of a liquid lithium vortex tube (Fig. 2), cooling its outer wall and generating tritium by the absorption of neutrons from the DT fusion. The DT is ignited by bombarding the ferromagnetic target with an intense relativistic beam injected into the vortex tube, imploding the target. The implosion leads to the creation of a hot spot from which a propagating thermonuclear burn wave can be launched into a long cylindrical second-stage target place through the other end of the vortex tube. The maximum rotational velocity is obtained from the inequality $\rho v^2 < \sigma$, $v \simeq \sqrt{\sigma/\rho}$, with $\sigma \simeq 10^{11}$ dyn/cm^2 is the tensile strength of a ferromagnet, and one obtains $v \simeq 1$ km/s.

The rotational acceleration of the target must be done by a rotating traveling magnetic wave acting as a small electric motor. After having reached the maximum rotational velocity, the target is ballistically injected into the vortex tube.

In this configuration, three physical principles miraculously work together: Einstein's general theory of relativity, the thermomagnetic Nernst effect, and Elsasser's dynamo theory.

But this is not all. Because of the greatly increased stability of a rapidly rotating target compared with a non-rotating one of spherical symmetry, the 50 MJ minimum ignition energy obtained by the Centurion–Halite experiment can conceivably be reduced to no more than 10 MJ, the value obtained in an early study of relativistic electron beam ignition (Winterberg, 1968). This is very important because the generation of a 10 MJ electron beam by a Marx generator is orders of magnitude less expensive than the generation of a laser beam of the same energy and power.

Kidder's spherical implosion law and the law for the implosion of a rotating cylinder

Kidder's law is obtained as follows: For an implosion velocity v_{imp} (where for ignition $v_{\text{imp}} \sim 10^8$ cm/s), and M the mass of density ρ of an imploding spherical mass of radius R, the energy input E for ignition is

$$E = \frac{1}{2} \mathrm{M} V_{\text{imp}}^2 \simeq \rho R^3 \simeq \frac{(\rho R)^3}{\rho^2} \tag{1}$$

for thermonuclear burn in DT one has $\rho R \sim 1$ g/cm^2, hence

$$E \simeq \frac{1}{\rho^2} \tag{2}$$

but because

$$\frac{\rho}{\rho_0} = \left(\frac{R_0}{R}\right)^3 \tag{3}$$

where ρ and ρ_0 are the final and initial densities reached at R and R_0 the final and initial radii. Hence

$$E \simeq \left(\frac{R}{R_0}\right)^6 \tag{4}$$

or

$$\frac{R_0}{R} \simeq E^{-1/6} \tag{5}$$

which means that the ignition energy is very sensitive to the ratio R_0/R, or *vice versa*, the ratio R_0/R is very insensitive to the energy input and limited to the Rayleigh–Taylor instability.

Repeating the same analysis for a small cylinder of height h, one has

$$E = \frac{1}{2} M v^2 \tag{6}$$

or with $M \cong \rho R^2 h$,

$$E \simeq \rho R^2 h v^2 \tag{7}$$

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here we have

$$\frac{\rho}{\rho_0} = \left(\frac{R_0}{R}\right)^2 \tag{8}$$

but for a cylindrical implosion, one has

$$\frac{v}{v_0} = \frac{R_0}{R} \tag{9}$$

hence with $\rho R \cong 1$ g/cm^2

$$E = \frac{1}{\rho} h v^2 = \frac{h v_0^2}{\rho_0} \tag{10}$$

which unlike (5) does not depend on R_0/R.

The occurrence of the large negative mass densities in the general theory of relativity

While it is not possible to make a laboratory-size star, it is possible to reach a centrifugal field comparable to the gravitational field of a very dense star, with a density of the same order of magnitude as the density of a neutron star. It is the general theory of relativity (Landau and Lifshitz, 1951) in which the gravitational energy cannot be localized but is described by Einstein's energy-momentum pseudo tensor t^{ik}, where the energy and momentum are expressed by a sum of products of Christoffel symbols Γ^i_{kl}, which are the forces. In a non-inertial reference frame, these forces are generally different from zero even in the absence of gravity-producing masses. As it was shown by Hund (1948), for non-relativistic velocities these forces can be obtained by Newtonian mechanics.

In the rotating reference frame inside the rapidly rotating target chamber, the equation of motion for a test particle is given by:

$$m\frac{d\mathbf{v}}{dt} = m\mathbf{F} + m\frac{\mathbf{v}}{c} \times \mathbf{C} \tag{11}$$

where

$$\mathbf{F} = \omega^2 \mathbf{r} \tag{12}$$

is the centrifugal force, and:

$$\mathbf{C} = -2c\boldsymbol{\omega} \tag{13}$$

the Coriolis force, with $\boldsymbol{\omega}$ the angular velocity vector of rotation. If $\mathbf{F}$ is a gravitational acceleration produced by the mass distribution of density ρ as the source of Newton's law of gravity, one has:

$$\mathrm{div}\mathbf{F} = -4\pi G\rho \tag{14}$$

where G is Newton's constant. A centrifugal acceleration is also not free of sources, because of (12) one has

$$\mathrm{div}\mathbf{F} = 2\omega^2 \tag{15}$$

and hence the negative gravitational field mass density

$$\rho = -\frac{\omega^2}{2\pi G} \tag{16}$$

This negative mass is not fictitious and can be felt as the repulsive force in a merry-go-round. For $\omega = 0.6$/s (an example given by Hund), one has $\rho = -10^6$ g/cm^3, comparable to the positive mass density of a white dwarf star.

The mass density (16) represents a physical reality as the mass density of the electric field $\mathbf{E}$,

$$\rho_e = \frac{\mathbf{E}^2}{8\pi c^2} \tag{17}$$

While the mass density (17) is positive, because the equal sign charges repel each other, the mass density of a gravitational field $\mathbf{g}$ where equal sign masses attract each other, is negative and is

$$\rho_g = -\frac{\mathbf{g}^2}{8\pi G c^2} \tag{18}$$

Likewise the mass density of the Coriolis field (13) is

$$\rho = -\frac{\mathbf{C}^2}{8\pi G c^2} = -\frac{\omega^2}{2\pi G} \tag{19}$$

equal to the mass density given by (16). This means the centrifugal force is caused by the negative mass density of the Coriolis force field. By comparison, the negative mass density $-\mathbf{F}^2/8\pi G c^2$ of the centrifugal force field (12) is smaller by the order v^2/c^2.

Let us compare the negative gravitational field mass density with the positive mass density, $\rho_N = 10^{14}$g/cm^3, of a neutron star. With $\omega \simeq v/R_0$, where $R_0 \simeq 1$ cm is the radius of the target chamber and $v \simeq 1$ km/s $= 10^5$cm/s, one finds that $\omega = 2.6 \times 10^5$/s and $\rho = -10^{17}$ g/cm^3, absolute three orders of magnitude larger than the mass density of a neutron star.

In the scientific literature little can be found about the fundamental importance of the Coriolis force in rotating plasmas. However, there are two references, one made by the author (Winterberg, 1963), to an experimental verification of Elsasser's dynamo theory in rotating liquid metals, and the work by Haverkort and de Blank (2012).

Nernst effect

In the proposed concept, the plasma is confined by the outwardly directed gravitational force of the negative mass of the Coriolis field, and by the inwardly directed magnetic force from the wall of the target chamber, by the Nernst effect.

With the temperature gradient ∇T from the cold wall into the hot plasma and B the magnetic field, the thermomagnetic current by the Nernst effect is for a hydrogen plasma given by Spitzer (1962):

$$\mathbf{j}_N = \frac{3knc}{2B^2}\mathbf{B} \times \nabla T \tag{20}$$

with the magnetic force density of the plasma:

$$\mathbf{f} = \frac{1}{c}\mathbf{j}_N \times \mathbf{B} = \frac{3nk}{2B^2}(\mathbf{B} \times \nabla T) \times \mathbf{B} \tag{21}$$

or with ∇T perpendicular and $\mathbf{B}$ parallel to the wall

$$\mathbf{f} = \frac{3}{2} nk\nabla T \tag{22}$$

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With the magnetohydrodynamic equilibrium condition

$$\nabla p = \mathbf{f} \tag{23}$$

where $p = 2nkT$, $\nabla p = 2nk\nabla T + 2kT\nabla n$, one has

$$2nk\nabla T + 2kT\nabla n = \frac{3}{2}nk\nabla T \tag{24}$$

which upon integration yields

$$Tn^4 = \text{const.} \tag{25}$$

In a cartesian x, y, z coordinate system with the cold wall at $z = 0$, and the magnetic field $\mathbf{B}$ into the x-direction, the Nernst current density $\mathbf{j}$ is in the y-direction, and is

$$\mathbf{j}_y = -\frac{3knc}{2\mathbf{B}}\frac{dT}{dz} \tag{26}$$

From Maxwell's equations $4\pi\mathbf{j}/c = \text{curl}\,\mathbf{B}$ one has

$$\mathbf{j}_y = \frac{c}{4\pi}\frac{d\boldsymbol{B}}{dz} \tag{27}$$

Eliminating $\mathbf{j}_y$ from (26) and (27) one obtains

$$2\mathbf{B}\frac{d\mathbf{B}}{dz} = -12\pi kn\frac{dT}{dz} \tag{28}$$

If in the plasma far away from the wall $n = n_0$, $T = T_0$, one has from (25)

$$n = \frac{n_0 T_0^{1/4}}{T^{1/4}} \tag{29}$$

Inserting this into (28) one finds

$$d\mathbf{B}^2 = -\frac{12\pi kn_0 T_0^{1/4}}{T^{1/4}}dT \tag{30}$$

With the boundary condition $B = B_0$ at $z = 0$ and $T = T_0$ at $z = \infty$, integration of (30) yields

$$\frac{\mathbf{B}_0^2}{8\pi} = 2n_0kT_0 \tag{31}$$

The meaning of (31) is that the magnetic pressure $\mathbf{B}_0^2/8\pi$ exerted on the plasma from the wall surface at $z = 0$ balances the plasma pressure $2n_0kT_0$ at $z = \infty$. With $n_0 = 10^{23}/\text{cm}^3$ and $T \simeq 10^8$ K, one finds that $B_0 \simeq 10^7$ Gauss.

With the Nernst effect, where according to (25) $Tn^4 = \text{constant}$, the bremsstrahlung losses going in proportion to $n^2\sqrt{T}$ (Spitzer, 1962) are constant across the entire plasma, which for $nT = \text{constant}$ would near the wall rise in proportion to $T^{-3/2}$. The reason are the large thermomagnetic currents set up in between the hot plasma and the cold wall of the target, leading to a large magnetic force repelling the hot plasma from the wall.

For the working of the Nernst effect one must have

$$\omega\tau \gg 1 \tag{32}$$

Where ω is the electron cyclotron frequency and τ is the electron–ion collision time. At high magnetic fields of the order $B \simeq 10^7$ G and temperatures of the order 10^8 K, with a particle number density $n \simeq 10^{23}/\text{cm}^3$, one has $\omega \simeq 10^{14}/\text{s}^1$, $\tau \simeq 10^{-9}$s (Spitzer, 1962) and hence $\omega\tau \simeq 10^5 \gg 1$.

Magnetohydrodynamic dynamo in the target chamber

A magnetohydrodynamic dynamo is ruled first by the equation (generalized Ohm's law in cgs units)

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{c^2}{4\pi\sigma}\nabla^2\mathbf{B} + \text{curl}\boldsymbol{v} \times \mathbf{B} \tag{33}$$

where σ is the electrical conductivity, second, by the Euler equation of motion with the magnetic body force $(1/c)\,\mathbf{j} \times \mathbf{B}$ where $\mathbf{j}$ is the electric current density, neglecting viscous forces, and is given by

$$\frac{\partial \mathbf{v}}{\partial t} = -\frac{1}{\rho}\nabla p - \frac{1}{2}\nabla\mathbf{v}^2 + \mathbf{v} \times \text{curl}\mathbf{v} + \frac{1}{\rho c}\mathbf{j} \times \mathbf{B} \tag{34}$$

in addition to the equation of continuity (mass conservation) and energy. For a uniform rotation, one can write

$$\mathbf{v} = \boldsymbol{\omega} \times \mathbf{r} \tag{35}$$

where $\boldsymbol{\omega} = (1/2)\text{curl}\mathbf{v}$ with $(4\pi/c)\mathbf{j} = \text{curl}\mathbf{B}$, one thus has for (34)

$$\frac{\partial \mathbf{v}}{\partial t} = -\frac{1}{\rho}\nabla p + \omega^2\mathbf{r} - 2\omega \times \mathbf{v} + \frac{1}{4\pi\rho}\mathbf{B} \times \text{curl}\mathbf{B} \tag{36}$$

Even without solving these equations, a general conclusion can already be drawn: For the buildup of the magnetic field by (33) one must have $\partial B/\partial t > 0$, which requires that the second term on the r.h.s of (33) is larger than the first term, or that the magnetic Reynolds number:

$$\text{Rem} = \frac{4\pi\sigma Rv}{c^2} > 1 \tag{37}$$

where $R \simeq 1$ cm is the radius of the target chamber and v the plasma velocity. Instead of (37) one can also write

$$v > \frac{c^2}{4\pi\sigma R} \tag{38}$$

or that

$$\sigma > \frac{c^2}{4\pi Rcv} \tag{39}$$

Setting $v = 10^5$ cm/s for the tangential velocity of the target chamber, one finds that $\sigma \gtrsim 2.5 \times 10^{13}$/s. On the other hand, the conductivity of a fully ionized plasma for $T \gtrsim 10^5$ K is

$$\sigma = 10^7 T^{3/2}/\text{s} \tag{40}$$

which means that for $T \gtrsim 10^5$ K, one has $\sigma \gtrsim 3 \times 10^{14}$/s, or that for $T \gtrsim 10^5$ K, σ is larger than the r.h.s. of (39).

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With the plasma accelerated by the magnetic forces to a velocity of the order $v \sim 10^8$ cm/s, (33) can be approximated extremely well by

$$\frac{\partial \mathbf{B}}{\partial t} = \text{curl}\, \mathbf{v} \times \mathbf{B} \tag{41}$$

The magnetohydrodynamic instabilities arise from the last term on the r.h.s. of (36), at the moment when the magnetic forces overwhelm the fluid stagnation pressure or when $B^2/8\pi \geq (1/2)\rho v^2$. For $(1/2)\rho v^2 \gg B^2/8\pi$, the magnetic lines of force align themselves with the streamlines of the fluid flow. Then, if likewise the electric current flow lines $\mathbf{j}$ align themselves with $\boldsymbol{\omega}$, one has $\mathbf{j}$ orthogonal to $\mathbf{B}$, and $\boldsymbol{\omega}$ orthogonal to $\mathbf{v}$. With $\boldsymbol{\omega} = (1/2)$ curl$\mathbf{v}$ and $\mathbf{j} = (c/4\pi)$curl$\mathbf{B}$ one can write for $(1/2)\rho v^2 \gg B^2/8\pi$, that

$$|\mathbf{v} \times \text{curl}\mathbf{v}| \gg \left|\frac{\mathbf{B} \times \text{curl}\mathbf{B}}{4\pi\rho}\right| \tag{42}$$

or

$$\mathbf{v} > \mathbf{v}_A \tag{43}$$

where

$$v_A = \frac{B}{\sqrt{4\pi\rho}} \tag{44}$$

is the Alfvén velocity. B will eventually reach the value $B = \sqrt{4\pi\rho}v$, where $v = v_A$. In approaching this magnetic field strength, the magnetic pressure forces begin to distort the fluid flow which becomes unstable. In a plasma this leads to the formation of unstable pinch current discharges, where $p = B^2/8\pi$. For a hydrogen plasma of temperature T and particle number density n this leads to the Bennett equation

$$B = \sqrt{16\pi nkT} \tag{45}$$

The pinch instability can be seen as the breakdown of the plasma into electric current filaments, determined by the $\mathbf{B} \times$ curl$\mathbf{B}$ term, whereas the $\mathbf{v} \times$ curl$\mathbf{v}$ term is responsible for the breakdown of the plasma in vortex filaments. But while the breakdown into current filaments is unstable, the opposite is true for the breakdown into vortex filaments. This can be seen as follows: Outside a linear pinch discharge one has curl$\mathbf{B} = 0$, and outside a linear vortex filament one has curl$\mathbf{v} = 0$. Because of curl$\mathbf{B} = 0$, the magnetic field strength gets larger with a decreasing distance from the center of curvature of magnetic field lines of force. For curl$\mathbf{v} = 0$, the same is true for the velocity of a vortex line. But whereas in the pinch discharge a larger magnetic field means a larger magnetic pressure, a larger fluid velocity means a smaller pressure by virtue of Bernoulli's theorem. Therefore, whereas a pinch column is unstable with regard to its bending, the opposite is true for a line vortex. This suggests that a pinch column places itself inside vortex tube.

What is true for the $m = 0$ kink pinch instability is also true for the $m = 0$ sausage instability by the conservation of circulation

$$Z = \oint \mathbf{v} \cdot d\mathbf{r} = \text{const.} \tag{46}$$

And because of the centrifugal force the vortex also stabilizes the plasma against the Rayleigh–Taylor instability.

In the proposed configuration, the plasma is radially confined between the convex centrifugal force in the target, and the concave centripetal magnetic force set up by the thermomagnetic current at the cold wall inside the target. According to Einstein's equivalence principle, the ions and electrons are affected by the centrifugal force in the same way as by the gravitational force in a star, having a stable configuration, but an instability may still arise in the thin boundary layer carrying the thermomagnetic current near the wall of the centrifuge. As Teller has pointed out in a private communication (1969), the instabilities of magnetic confinement configurations are likely to be absent in collision-dominated plasmas, or in plasmas where the mean free path λ is smaller than the linear dimension L of the magnetic confinement configuration. At the temperature T $[K]$ and particle density n, the mean free path is likely given by

$$\lambda = 10^4\, T^2/n \tag{47}$$

For $n \simeq 10^{18}/\text{cm}^3$ and $T \simeq 10^8$ K, one has $\lambda \simeq 10^{-2}$ cm $\ll R \simeq 1$ cm. This means that in this range of densities and temperature, the plasma is collision-stabilized.

In the past, rotating plasmas have been extensively studied by (Lehnert, 1971), but only for densities where the plasma is not "collision dominated." The proposed novel nuclear fusion concept is unique because it makes use of the self-exciting magnetohydrodynamic dynamo driven by the heat released from thermonuclear reactions in the fusion plasma. But it also has the potential to reach much larger magnetic fields for confinement and particle number densities than are otherwise possible.

This leaves open the question of how to remove heat from the target, even though this problem exists only for the 20% of fusion energy released in the target as charged particles, not for the 80% of the energy going into the kinetic energy of the neutrons, which can be slowed down outside the target over a much larger distance. One possible answer is to place the target in a supersonic potential gas vortex, for example, a vortex of helium gas, with the high velocity vortex core touching the outer surface of the target as a velocity of ~1 km/s, the tangential velocity of the target, with the vortex flow cooling the fusion target.

Ignition

The ignition is achieved by a <50 MJ pulse of an intense relativistic electron beam as it was originally proposed by the author in his 1968 paper published in the Physical Review (Winterberg, 1968), except that here the beam stopping does not depend on the difficult to achieve two-stream instability, because for MeV electrons the stopping range is determined in the ferromagnetic mantle of the target, which implodes the target. This stopping range is given by (Winterberg, 2010):

$$\lambda \simeq \frac{1}{\rho}(0.543\, E - 0.16)\ \text{cm} \tag{48}$$

Where ρ is the target density in g/cm^3, and E is the electron energy in MeV. For $\rho \simeq 10$ g/cm^3 and $E \simeq 10$ MeV, one obtains $\lambda \simeq 1$ cm, about equal to the linear dimension of the target.

With $10\ \text{MJ} \simeq 10^{14}$ erg, deposited in a volume $V \simeq \pi R_0^2 h > 1\ \text{cm}^3$, the temperature given by $E \simeq nkT$, with

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$n \simeq 10^{23}$ particles/cm^3, is $T \simeq 10^6$ K. The threefold implosion of the DT from $R \simeq h \simeq 1$ to $R \simeq h \simeq 0.3$ cm increases its temperature by the factor of 100, from $T \simeq 10^6$ to $T \simeq 10^8$ K, meaning T would reach the ignition temperature of the DT reaction at $T \simeq 10^8$ K.

Conclusion

While the ignition of a large thermonuclear explosive device with a fission bomb trigger has been achieved more than 50 years ago, the non-fission ignition of thermonuclear micro-explosions is still awaiting its realization. The advent of powerful lasers raised the hope that this could be done by the spherical implosion of a small amount of DT with a powerful laser. However, experiments done at the Nevada Test Site (Centurion–Halite experiment) have shown that this would require a laser energy of about 50 MJ, 25 times more than the 2 MJ delivered by the laser of the NIF, currently the most powerful laser in the world. The analysis by Kidder (1998) has shown that even a tenfold increase of the laser energy from 2 to 20 MJ would be insufficient. The reason for this problem is the Rayleigh–Taylor instability of spherical implosions. The replacement of lasers by high-voltage pulse power technology for the generation of charged particle beams, proposed by the author in 1964–1968 (Winterberg, 1968), can reduce this problem, but so far has also failed to reach the ignition of a small thermonuclear target. In either case the idea is to create a hot spot, from which a thermonuclear detonation wave can be launched into still unburnt DT.

Because of the difficulty of creating a hot spot by the radial implosion of a DT sphere, it is proposed here to replace the sphere with a small, rapidly rotating conical target with the DT encased in a target made of ferromagnetic material. This target would have to be rotationally accelerated by an externally applied circular magnetic traveling wave to a velocity of 1 km/s at the limit of the tensile strength of the ferromagnetic material, about equal to 10^{11} dyn/cm^2.

The importance of such a configuration is a consequence of Einstein's general theory of relativity. In a reference system at rest with the rotating cylinder, it leads to a large, negative gravitational field mass from the Coriolis field. In such a configuration, a DT plasma is stably confined by the magnetic field of the thermomagnetic Nernst effect. In the presence of the strong Coriolis field, it acts as a powerful magnetohydrodynamic generator, axially confining the DT plasma. And because of the short stopping length of relativistic electrons in the ferromagnetic material, a 10 MJ intense relativistic electron beam can radially implode the rotating target, circumventing the Rayleigh–Taylor instability. With the DT plasma reaching ignition temperature, it can thus serve as a hot spot for the high gain release of fusion energy.

If experiments can establish the feasibility of this idea, it would imply the large-scale release of energy from nuclear fusion and lead to a breakthrough in developing a nuclear propulsion system without fission products for the manned exploration of the Solar System.

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Appendix

In Einstein's general theory of relativity, the motion of a test particle is given by the geodesic equation

$$\frac{d^2x^i}{ds^2} + \Gamma^i_{kl}\frac{dx^k}{ds}\frac{dx^l}{ds} = 0 \qquad (A.1)$$

where

$$ds^2 = g_{ik}dx^i dx^k \qquad (A.2)$$

In the limit of velocities small compared with the velocity of light, (A.1) is reduced to (11). It was shown by Hund (1948) that in this approximation the energy (mass) density of the Coriolis force field obtained from Einstein's energy-momentum pseudotensor must be equal to (19).

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