Laser Original**The Electromagnetic Rocket Gun Impact Fusion Driver****Friedwardt Winterberg***

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A macroparticle accelerator to be used as an impact fusion driver is discussed and which can accelerate a small projectile to ~ 200 km/sec over a distance of a few 100 meters. The driver which we have named electro-magnetic rocket gun, accelerates a small rocket-like projectile by a travelling magnetic wave. The rocket propellant not only serves as a sink to absorb the heat produced in the projectile by resistive energy losses, but at the same time is also the source of additional thrust through the heating of the propellant to high temperatures by the travelling magnetic wave. The total thrust on the projectile is the sum of the magnetic and recoil forces. In comparison to a rocket, the efficiency is here much larger, with the momentum transferred to the gun barrel of the gun rather than to a tenuous jet.

1. Introduction

The most simple, and also probably the first driver ever proposed for inertial confinement fusion is a fast moving projectile. This original concept to inertial confinement fusion, published by the author about 20 years ago, is also known under the name of impact fusion¹⁾.

As explained in Fig. 1, a projectile P coming from the left at high velocity strikes a fusion fuel embedded in a conical cavity of an anvil. Upon impact, the fusion fuel is first shock-heated to high temperatures, followed by an almost adiabatic compression and heating until ignition with subsequent thermonuclear burn. The conical implosion configuration ensures fast compression, minimizing the impact velocity needed to overcome the bremsstrahlungs losses.

A theoretical analysis of this configuration, showed that the minimum velocity required would be ~ 200 km/sec²⁾.

The advantage of impact fusion over other inertial confinement concepts is that it permits a

much smaller target compression (less than 100 fold) compared to a ~ 1000 fold compression needed with beam drivers. The reason for the substantial reduction in target compression is that in impact fusion the target is strongly tamped by the high velocity projectile, whereas in beam induced inertial fusion the target must be compressed ablatively. Another important advantage of impact fusion is its potential for a large stand-off distance between the reactor wall and the microexplosion.

To reach the high velocities of ~ 200 km/sec required for impact fusion, it was originally proposed to accelerate small superconducting projectiles by travelling magnetic waves^{2,3)}. The problem with this approach is that to reach ~ 200 km/sec, the accelerator would have to be more than 10 km long. Much shorter accelerator lengths would be possible if ordinary conductors, rather than superconductors, could be used, because for ordinary conductors the upper value of the magnetic field strength and which determines the maximum acceleration, depends on

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Fig. 1. Impact fusion concept and sequence of events. Projectile P strikes anvil A holding thermonuclear fuel F in conical cavity. The configurations **a-d**, show: Fig. 1a, moment before impact, **b** shock heating, **c** isentropic compression up to ignition, and **d** thermonuclear burn.

the tensile strength of the conductor, and not as for superconductors, is given by a critical field strength. The only reason superconductors were chosen is that they have no resistive energy losses, which for a projectile made up of an ordinary conductor would result in its vaporization long before it has reached a high velocity.

To take advantage of the maximum magnetic body force which can act only on a conducting metallic projectile, but to avoid the problem of its burning up by resistive heating, we propose a novel accelerator concept which we have named electromagnetic rocket gun, and where the projectile to be accelerated by the magnetic forces is a rocket. As in a rocket, where the propellant cools the rocket and thereby prevents it from burning up, the same happens here, except that the heat is produced by resistive energy losses, not by a chemical reaction. In addition to serve as a heat sink, the propellant of the electromagnetic rocket gun itself is also resistively heated by the magnetic field pushing against the projectile. This results in a large exhaust velocity of the propellant adding to the thrust of the magnetic body force pushing the projectile. Unlike a rocket, the propellant receives its energy externally. For a given magnetic field strength the resistive heating rate goes up in proportion to the projectile velocity and by which the exhaust velocity also goes up

with the projectile velocity. Unlike in a rocket, the recoil momentum is absorbed through the magnetic force field by the gun barrel rather than the exhaust. Because of both of these effects, first the increase in the exhaust velocity with the projectile velocity, and second the momentum transfer to the massive gun barrel, the acceleration is much more efficient than for a rocket where the exhaust velocity is constant with the recoil momentum going into a tenuous jet.

2. Description of the Accelerator

The principle of the electromagnetic rocket gun is shown in Fig. 2. A conducting metallic projectile P, being hollowed out except for its payload section PL, is placed in front of a travelling magnetic wave. The hollowed out part of the projectile is filled with some propellant F, preferably solid hydrogen. Hydrogen is preferred as a propellant because its radiation losses are low at the temperatures produced. The projectile is placed in front of a travelling magnetic wave, generated by the field coils MC. The rising magnetic field at the head of the travelling magnetic wave induces surface currents in the back part of the hollowed out projectile. The dissipation of the currents produces heat by which the solid hydrogen propellant is slowly

Fig. 2. Electromagnetic rocket gun principle. P part of the projectile holding the propellant F which vaporizes and together with the propellant becomes part of the jet J. PL projectile payload, MC magnetic field coils, H magnetic lines of force.

vaporized. The vaporized hydrogen thereafter enters the region behind the projectile where the magnetic field rapidly rises. In entering this region, the hydrogen gas is first shock-heated to high temperatures and becomes ionized. The rising magnetic field further compresses and heats the hydrogen plasma, until it has reached the position of the travelling magnetic wave where the field strength has reached its maximum value, and where the magnetic field has the shape of a magnetic mirror. In passing through the magnetic mirror the hot hydrogen plasma is ejected as a jet J with high speed. The projectile is accelerated because of both the magnetic pressure force and the recoil force of the jet. During its acceleration the projectile loses mass and it therefore behaves in part like a rocket. But because the projectile is also accelerated by the magnetic pressure force, it also acts in part like a projectile fired by a magnetic gun. In addition to the propellant, the metallic encasement holding the propellant too, is slowly ablated and ejected, thereby also contributing to the recoil-produced thrust. Both, the high conductivity of the encasement and of the plasma, ensures that the magnetic pressure by the travelling wave can exert its full force on the projectile.

To prevent the projectile from touching the wall, and which would result in disastrous black

body radiation losses, it must be made from some ferromagnetic material. By magnetic feedback control it can then be steered to stay away from the wall. Because the plasma jet can be much longer than the projectile, the length of the travelling magnetic wave can be made much longer too. The time needed to turn on the magnetic field can therefore become comparatively long. By a proper choice of the thickness and conductivity of the metal encasing the propellant one can arrange that the Joule heat produced in the encasement by the travelling magnetic wave gives the right evaporation rate of the propellant.

3. The Acceleration Physics

The magnetic body force density f acting on the projectile is given (in electrostatic units) by

$$f = -\frac{1}{4\pi} \mathbf{H} \times \text{curl} \mathbf{H} \quad (3.1)$$

With the vector identity $\mathbf{H} \times \text{curl} \mathbf{H} = (1/2) \nabla H^2 - (\mathbf{H} \cdot \nabla) \mathbf{H}$, and because in our configuration $\nabla |\mathbf{H}|$ is perpendicular to the direction of $\mathbf{H}$, making $(\mathbf{H} \cdot \nabla) \mathbf{H} = 0$, we have

$$f = -\nabla (H^2/8\pi). \quad (3.2)$$

In eq. (3.2) $H^2/8\pi$ is the usual expression of the magnetic pressure in the Maxwell stress tensor.

The maximum magnetic force F_H acting on

the rear side of the projectile having the cross section A is given by

$$F_H = AH^2/8\pi. \quad (3.3)$$

After the vaporized and preheated propellant has left the rearside of the projectile, it is, like in a theta pinch, shock-heated in entering the region occupied by the strong magnetic field. Because the magnetic field is very strong the propellant becomes a plasma. If the atomic number density of the plasma is n , and if all the magnetic energy, with an energy density $H^2/8\pi$, is converted into heat, one has

$$3nkT = H^2/8\pi, \quad (3.4)$$

valid for a singly ionized plasma, for example a fully ionized hydrogen plasma.

After it is heated to the temperature given by eq. (3.4), the plasma becomes a jet. The jet is radially confined, both by the magnetic field and the wall of the gun barrel.

The jet produces a recoil force acting on the projectile which is given by

$$F_{\text{rec}} = -v \, dm/dt, \quad (3.5)$$

where v is the jet velocity relative to the projectile and dm/dt the mass ejected per unit time. If ρ is the density of the jet one has

$$dm/dt = -A\rho v, \quad (3.6)$$

and hence

$$F_{\text{rec}} = A\rho v^2. \quad (3.7)$$

If one neglects the electron mass against the ion mass one has

$$3nkT = \rho v^2 = H^2/8\pi, \quad (3.8)$$

and therefore

$$F_{\text{rec}} = AH^2/8\pi = F_H. \quad (3.9)$$

The total force F acting on the rear side of the projectile is the sum

$$F = F_H + F_{\text{rec}} = 2F_{\text{rec}}. \quad (3.10)$$

With the mass flow rate given by eq. (3.6) one

has

$$F = -2v \, dm/dt. \quad (3.11)$$

We now make the special assumption that in each moment during the acceleration of the projectile the jet velocity v is equal to the projectile velocity. This assumption can be satisfied by a properly programmed evaporation rate of the propellant. If the jet velocity is always equal to the projectile velocity, then, as seen from a frame at rest with the magnetic gun, the jet comes to rest and no kinetic energy is lost into the jet. Under this special mode of operation the efficiency of the rocket drive is always maximized.

The equation of motion of the projectile is now given by

$$m \, dv/dt = F = -2v \, dm/dt, \quad (3.12)$$

resulting in the differential equation

$$m \, dv = -2v \, dm. \quad (3.13)$$

By integration of eq. (3.13) we find

$$v/v_0 = (m_0/m)^2, \quad (3.14)$$

where m_0 is the initial projectile mass at the time $t=0$, and where $v=v_0$ is the initial projectile velocity. Comparing eq. (3.14) with the rocket equation $v=v_0 \ln(m_0/m)$, where v_0 is there the constant exhaust velocity, we see that with the electromagnetic rocket gun much higher velocities can be reached than with rockets. If, for example, $v_0=1$ km/sec and $m_0/m=10$, then $v=100$ km/sec is possible, whereas for a rocket $v \approx 2.3$ km/sec only. Of course, the electromagnetic rocket gun needs a gun barrel and the affordable length of this gun barrel sets a practical upper limit for the attainable velocity.

If we assume that the total force $F=AH^2/4\pi$, acting on the rocket-like projectile during its acceleration is constant, the equation of motion of the projectile can be integrated in closed form. We have

$$dv/dt = F/m = (F/m_0)(v/v_0)^2, \quad (3.15)$$

from which we obtain the first integral

$$v = v_0 [1 + (F/2m_0v_0)t]^2. \quad (3.16)$$

If z is the distance the projectile has moved down the magnetic gun barrel, with $z=0$, at $t=0$ and $v=v_0$, a second integral is obtained from eq. (3.16), after putting $v=dz/dt$:

$$z = (2/3)(m_0v_0^2/F)[(1 + (F/2m_0v_0)t)^3 - 1]. \quad (3.17)$$

Eliminating the time t from eqs. (3.16) and (3.17) gives us a relation in between v and the acceleration length z :

$$z = (2/3)(m_0v_0^2/F)[(v/v_0)^{3/2} - 1]. \quad (3.18)$$

The time dependence of the rocket mass, $m=m(t)$ is given by eq. (3.14) if we insert $v=v(t)$ given by eq. (3.16). The result is

$$m/m_0 = [1 + (F/2m_0v_0)t]^{-1}. \quad (3.19)$$

From eq. (3.19) we find for the rate the rocket loses mass:

$$dm/dt = -(F/2v_0)[1 + (F/2m_0v_0)t]^{-2}. \quad (3.20)$$

The power needed to drive the projectile is given by

$$P = Fv = A(H^2/4\pi)v, \quad (3.21)$$

and the propulsion efficiency is given by

$$\eta = \frac{(1/2)mv^2}{(1/2)m_0v_0^2 + \int_0^t P dt}. \quad (3.22)$$

With $P dt = Fv dt = -2v^2 dm$, we obtain from eq. (3.22):

$$\eta = 3/[4 - (m/m_0)^3]. \quad (3.23)$$

In the limit $m/m_0 \rightarrow 0$ one has $\eta \rightarrow 3/4 = 75\%$. For larger mass ratios, η is even larger. The electromagnetic rocket gun has a lower efficiency than a pure electromagnetic gun, but the price in a lower efficiency is well paid because it prevents the vaporization of the projectile.

4. The Maximum Possible Acceleration

The maximum possible acceleration is determined by the tensile strength of the driver coils, but also by the tensile strength of the projectile.

If the tensile strength of the coils is σ_s , equating the magnetic shear stress $H^2/4\pi$ with σ_s leads to $H = H_{\max} = \sqrt{4\pi\sigma_s}$. For $\sigma_s \simeq 10^{10}$ dyn/cm², which is typical for steel but also for other high tensile strength materials, one finds $H_{\max} \simeq 3 \times 10^5$ G. The same value of H follows for the projectile, if its tensile strength is equal to that of the coils.

The maximum possible acceleration is not only determined by the tensile strength, but also by the length of the projectile. The acceleration a produces inside the projectile a pressure gradient, with the maximum pressure given by $P_{\max} = \rho al$, where ρ is the density of the projectile material and l its length. Equating $P_{\max}$ with σ_s leads to

$$a_{\max} = \sigma_s / l\rho. \quad (4.1)$$

5. Thermodynamic Considerations

The heat per unit volume generated in the projectile by resistive dissipation is

$$\varepsilon = j^2/\sigma, \quad (5.1)$$

where σ is the conductivity of the part of the projectile which carries the current. From Maxwell's equation $(4\pi/c)\mathbf{j} = \text{curl } \mathbf{H}$ we have

$$j = (c/4\pi)(H/l), \quad (5.2)$$

where l is a characteristic length and which by order of magnitude is equal to the length of the conducting projectile. We thus have

$$\varepsilon = \frac{c^2}{2\pi\sigma l^2} \frac{H^2}{8\pi}. \quad (5.3)$$

With the help of eq. (3.8) this can be also written as follows

$$\varepsilon = (c^2 / 2\pi\sigma)(\rho v^2 / l^2) . \quad (5.4)$$

The heating rate ε_p of the propellant of initial density ρ_0 is determined by the equation

$$\varepsilon_p = \rho_0 c_p \partial T / \partial t . \quad (5.5)$$

If T_0 is the vaporization temperature and v_0 the evaporation velocity one has

$$\partial T / \partial t \simeq v_0 T_0 / l_0 , \quad (5.6)$$

where l_0 is a characteristic length over which the propellant is heated. We thus can write for eq. (5.5):

$$\varepsilon_p \simeq \rho_0 v_0 c_p T_0 / l_0 . \quad (5.7)$$

Continuity requires that

$$\rho_0 v_0 = \rho v \quad (5.8)$$

and therefore also

$$\varepsilon_p \simeq \rho v c_p T_0 / l_0 . \quad (5.9)$$

To vaporize the propellant one must have $\varepsilon_p \simeq \varepsilon$. This leads to a condition for σ :

$$\sigma \simeq (c^2 / 2\pi c_p T_0)(l_0 v / l^2) . \quad (5.10)$$

Eq. (5.10) is the condition for the evaporation rate to match the final jet velocity v . Eq. (5.10) derived under the validity of eq. (5.8), therefore satisfies the assumption made following eq. (3.11), which was that the jet velocity is equal the projectile velocity.

Typically one has $c_p T_0 \sim 10^{19}$ erg/g, hence

$$\sigma \sim 10^{11} l_0 v / l^2 . \quad (5.11)$$

By order of magnitude $l_0 \sim l$ and hence

$$\sigma \sim 10^{11} v / l . \quad (5.12)$$

For example, if $v \sim 2 \times 10^7$ cm/sec and $l \sim 1$ cm, one would have $\sigma \sim 10^{16}$ sec⁻¹, and which is in line with the conductivity of a high tensile strength metal at cryogenic temperatures.

The final density and temperature of the jet are determined by eq. (3.8) with the result that

$$\rho = H^2 / 8\pi v^2 , \quad (5.13)$$

$$T = (A / 3R) v^2 . \quad (5.14)$$

6. An Example

As a typical example for impact fusion we choose $v = 200$ km/sec, $v_0 = 1$ km/sec and $m = 1$ g. At this velocity the kinetic energy of a 1 g projectile is 20 MJ. It then follows from eq. (3.14) that $m_0 \simeq 14$ g. For the initial length of the projectile we may assume $l \sim 10$ cm. With $\sigma_s \simeq 10^{10}$ dyn/cm² and $\rho \simeq 1$ g/cm³, we find from the above that $a = a_{\max} = 10^9$ dyn/cm². The corresponding magnetic field to reach $a_{\max}$ is $H_{\max} \simeq 350,000$ G. For a cross section $A = 3$ cm², one finds $F \simeq 10^{10}$ dyn. The length of the accelerator, given by eq. (3.18), is $z \simeq 260$ meter.

At $v = 2 \times 10^7$ cm/sec one computes from eq. (5.13) $\rho \simeq 10^{-5}$ g/cm³, or $n \simeq 10^{19}$ cm⁻³, and from eq. (5.14) $T \simeq 10^6$ °K.

References

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