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MAGNETIC-GUN IGNITER FOR CONTROLLED THERMONUCLEAR FUSION*

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I INTRODUCTION

Major programs are underway at laboratories throughout the world attempting to ignite small pellets of deuterium and tritium (DT) to thermonuclear burn. Pellets weighing less than a gram, ignited once per second, could form the energy source for a gigawatt electric power plant. To ignite these pellets, it is generally believed to be necessary to deliver about 1 megajoule (MJ) of energy in a time period of about 10 ns into a volume of less than 1 cm^3. As of this writing, no device, other than a fission bomb, is capable of delivering this concentrated power. The future of controlled thermonuclear fusion using DT pellets depends on whether we can design and build a low-cost non-nuclear ignition system. Candidates for the igniter include lasers, electron beams and high-energy heavy-ion beams. In this paper we propose yet another igniter: a "dart" weighing about 0.1 gm, accelerated to 150 km/sec by the moving magnetic field of a delay line, a "magnetic gun."

One MJ is not a large amount of energy; it is, for example, the food energy contained in a small loaf of bread. The problem is to deliver this modest amount of energy in a very short time into a small volume, in the environment of a reactor vessel that must be designed to absorb the high power burst of the DT pellet. The delivery must be done in such a way that the apparatus will not be damaged by a blast equivalent to one ton of TNT; fragile mirrors or lenses cannot be close to the reaction region unless extremely fast and durable shutters are used. The advantage of using a

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line. In fact ~~it would be~~ quite reasonable to inject ~~the~~ darts into the delay lines at 1 km/sec using ~~chemical propulsion (e.g., an ordinary~~ or hot-gas gun). ~~The efficiency of the injector need not be high, since most of the energy is delivered to the dart in the high velocity phase.~~

~~We will now proceed with~~ a "conceptual design" for the magnetic gun is given in order to show that the various parameters required turn out to be reasonable (in an engineering sense). An engineering design will necessarily turn out to be far more complex; the purpose of the following calculations is merely to show that the basic idea* looks sufficiently good to warrant further work.

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*Traveling wave magnetic acceleration has been described in previous publications but apparently neglected. See, for example,
F. Winterberg, Journal of Nuclear Energy C8, 541 (1966);
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[Note: This edited version of page 148 appears before page 147 in the source document.]

"dart" is that the energy is naturally concentrated into a small volume. If the dart moves rapidly enough to contain the energy (a 0.1 gm dart at 150 km/sec) then it is also easy to deliver the energy in the required 10 ns simply by making the dart short (a few mm). Since no focussing is required, the hole in the reactor wall need be no larger than the diameter of the dart, and the pressure inside the reactor can be high without blocking the delivery of the energy in the bullet. Space charge forces, which cause problems for charged-particle beams, are non-existent. The magnetic gun which accelerates the dart can stand far back from the reactor, and be in no danger of damage from the DT fusion blast.

Thus the potential advantages of a magnetic gun igniter are many, particularly in the simplifications that might take place in the DT reactor design. The main advantages of lasers and particle accelerators are that they are "mature" technologies. Although devices similar to the magnetic gun have been proposed for many applications, including artillery and as a means of launching satellites into space, we know of no practical use that has been made of the concept.

The magnetic gun is the only means we know of to accelerate macroscopic pieces of matter to near-relativistic velocities. Electric fields won't work in a reasonable distance, for the electric field which can apply a pressure equivalent to that of a 10^5 gauss field is 10^5 statvolts/cm = 30×10^6 volts/cm, a field that cannot be sustained with known materials. Acceleration by means of rocket propulsion (or equivalently, spallation) is too inefficient for power production unless the exhaust velocity is 20% or more of the required dart velocity of 150 km/sec. We do not, however, rule out electric or chemical acceleration for injection into the delay line. In fact it would be quite reasonable to inject the darts into the delay lines at 1 km/sec using chemical propulsion (e.g., an ordinary or hot-gas gun). The efficiency of the injector need not be high, since most of the energy is delivered to the dart in the high velocity phase.

We will now proceed with a "conceptual design" for the magnetic gun in order to show that the various parameters required turn out to be reasonable (in an engineering sense). An engineering design will necessarily turn out to be far more complex; the purpose of the following calculations is merely to show that the basic idea[*] looks sufficiently good to warrant further work.

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II CONCEPTUAL DESIGN

In the magnetic gun the dart is accelerated by magnetic pressure using either ferromagnetic or superconducting material for the part of the dart on which the magnetic field pulls or pushes. If the dart has an area A from which a magnetic field B is totally excluded as the dart is accelerated over a distance D, then the dart will gain kinetic energy

$$T = A \cdot D \cdot B^2/8\pi \quad .$$

For $T = 1$ MJ $= 10^{13}$ erg, $A = 0.13$ cm^2 (circle with radius $r = 2$ mm), and $B = 100$ kG, we find that the length of the accelerator is 2×10^5 cm $= 2$ km. For a ferromagnetic material the pressure would be reduced by a factor $\approx B_{sat}/B$. For $B = 100$ kG, and for gadolinium which has a saturation magnetic field $B_{sat} = 40$ kG, $D \approx 5$ km. These distances are not long, considering the simplicity and low cost of the accelerator design, and the acceleration length D can always be shortened, if necessary, by going to a higher B. It should be possible to keep the dart stably centered in the transverse directions, since it need not be stable in the acceleration direction. (Since the maximum dart speed is $\lesssim 10^{-3}$ of the velocity of light, the phase of the accelerating wave can be adjusted by sensing.the dart position in real time.)

If the mass of the dart is 0.1 gm, then the velocity of the dart is

$$v = \sqrt{2T/m} = 1.4 \times 10^7 \text{ cm/sec} = 140 \text{ km/sec}$$

which corresponds to an energy per nucleon of 100 eV. In order to deliver its energy in $\Delta t = 10$ ns, the length of the dart must be $v \cdot \Delta t = 1.4$ mm. If it is desirable to have a long precursor so that the DT pellet can be compressed adiabatically, then a thin spike can be added on the front of the dart. A typical dart might look in cross section something like that shown in Figure 1.

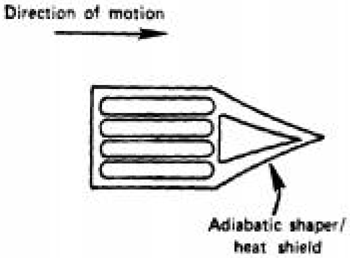

Figure 1

The simplest form of accelerator would be a lumped delay line. In order to get a rough idea of the currents, voltages, resistive losses, etc. which occur in such a machine, we make some estimates based on the simple-minded design shown schematically in Figure 2--a series of loops of radius 0.5 cm and length 1 cm, each connected to its own capacitor.

The current required for a magnetic field B at the center of a loop is

$$I \approx \frac{2Br}{\mu_o n} \quad .$$

For $B = 100$ kG $= 10$ T, $r = 0.005$ m, and $n = 1$, I will be 80,000 amps.

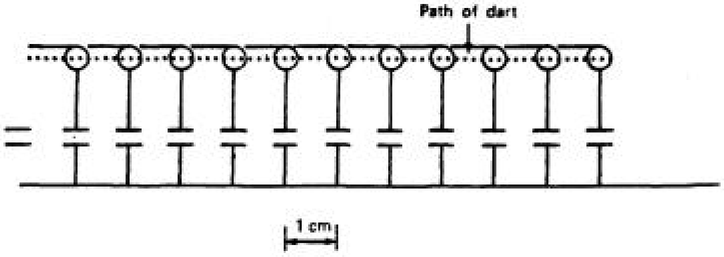

Figure 2 CONCEPTUAL DESIGN FOR THE MAGNETIC RIFLE

The inductance of each one turn loop is

$$L = \frac{\pi\mu_o r}{2} \approx 9 \times 10^{-9} \text{ henries}$$

giving a stored energy of

$$u = \tfrac{1}{2} LI^2 \approx 30 \text{ joules.}$$

The velocity of propagation down the line is

$$v = (LC)^{-\frac{1}{2}} \quad .$$

Taking $v = 1.5 \times 10^7$ cm/sec we find $C \approx 5 \times 10^{-7}$ farads. The impedance of the line is $Z = (L/C)^{\frac{1}{2}} \approx 0.13\ \Omega$, giving a peak voltage on the capacitor of about 10,000 volts.

The dart at v = 150 km/sec passes through a single loop in about 70 nanoseconds. During a time somewhat longer than this, ohmic heating of the loop occurs, and energy is lost by this heating. The penetration depth (skin depth) of the current in the loop for the case described here is about 0.04 mm, and for a loop made of aluminum at room temperature 0.5 joule goes into heat. Since the dart gains 5 joules in passing through the loop, the heat loss is about 10% and the accelerator can be potentially very efficient even without subdividing the coil conductor, which could reduce the ohmic loss by a large factor.

It is reassuring to find such reasonable values for I, C, and V in this conceptual design, and also to find that an inexpensive coil material (solid aluminum) can be used.

In doing the delay line calculation, we have ignored the substantial loading of the dart. With only 30 joules stored in an L-C pair, and 5 joules being given to the dart at each stage, energy will have to be fed in to the system all along the path. It should be possible to do this by switching in already charged capacitors as the dart (and the pulse) passes down the line. Although such switching will initiate pulses traveling in both directions along the line, it is easy to see that most of the energy will be transformed into the pulse traveling in the original direction. Such switching should be easy to do since because of the relative slow speed of the pulse (1/2000 that of light) the position of the pellet can be used to trigger the next switch.

The cost of capacitors should be modest. At $0.10 per joule ($2 per capacitor), and assuming each L-C pair has a dedicated capacitor (i.e., the same capacitor is not reused at various points along the delay line) the cost is $400,000. Switch costs are probably higher and switch technology should be given some attention.

III VACUUM REQUIREMENTS

Vacuum is required along the beam line in order to limit the heating of the dart. For a ferromagnetic dart the temperature must remain below the Curie point during acceleration; for a superconducting dart the temperature must be kept well below the transition temperature. For a dart of area* A moving a distance D at velocity v (>>thermal velocities) through a gas of density ρ, the impact energy of the gas on the dart is

$$Q = \rho v^2 AD \quad .$$

For a pressure of 10^{-6} torr (easily obtainable), $\rho = 10^{-12}$ gm/cm^3, and the impact energy delivered to the dart is about one joule. This energy would be absorbed easily by a ferromagnetic material, but it would destroy superconductivity. If a superconductor must be used, a heat shield can be added to the front of the dart or the vacuum can be improved by the required factor $>10^4$.

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*Strictly speaking A is the "equivalent" area, equal to a drag coefficient C_D (0.1 to 0.5) times the true area.

IV ADDITIONAL CONSIDERATIONS

Certain serious matters have been ignored in the "conceptual" design in order to keep it simple. Dispersion in the lumped delay line was neglected; in a lumped delay line the energy in a pulse will not remain confined to a region as narrow as one L-C pair, but this hardly matters since the pulse travels only a few pairs before it is regenerated. Ordinary hard superconductors may not sustain a large enough current density for this application; "artifical" hard superconductors (lead in porous Vycor) may be required. In addition, there is a hystersis loss whenever the field on a hard superconductor changes and this may impose severe requirements on field uniformity in the accelerator.

Eddy-current heating of the gadolinium dart can cause a problem if the dart is not properly laminated. Coil designs are conceivable which will provide low field ripple in the moving frame. The mass of the pellet must be kept low, and yet its effect on the magnetic field must be such as to exert a maximum pressure. These, and other remaining problems strike us as difficult, but solvable.

V CONCLUSIONS

The idea of a magnetic gun for thermonuclear ignition is not obviously absurd, and it may hold several important advantages in comparison with the particle and light-beam igniters currently being considered. Many problems remain to be solved, but we think the idea is ripe for a serious attempt at an engineering design, perhaps in conjunction with small-scale experiments to discover the most practical way to build a larger scale experiment.