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POSSIBLE APPLICATION OF ELECTROMAGNETIC GUNS TO IMPACT FUSION*

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I. Introduction

The recent advances in macroparticle accelerators and especially the advances in electromagnetic gun technology have renewed interest in the concept of impact fusion that was first proposed in the early 1960s(Ref. 1). The Department of Energy initiated a review of impact fusion concepts in mid-1979. A team consisting of the University of Washington and the Los Alamos National Scientific Laboratory was selected to perform a technical analysis of and generate criteria for impact fusion. A major workshop on impact fusion was conducted in early July of 1979 by the UW/LASL team in Los Alamos, New Mexico(Ref. 2), and a final report has been issued(Ref. 3).

Like other inertial confinement fusion concepts, the major application of impact fusion would be to the generation of electric power. We shall review the possible applications of electromagnetic guns to impact fusion for electric power based upon the results of the above workshop and technical analysis.

II. Impact Fusion Concept

Impact fusion is the conversion of the kinetic energy of a fast moving, initially stationary macroparticle projectile into the internal energy of fusile material. The resulting internal energy of the fusile material is great enough to produce a fusile plasma that has a temperature, pressure, and density sufficiently high in at least one location to produce a thermonuclear reaction. This initial fusion reaction may be large enough to cause fusion ignition of a sizeable fraction of the fusile plasma. To produce a significant energy gain, a substantial fraction of the reacting fusile material must be consumed and converted to ash before the fusile mass disassembles and the thermonuclear burn is quenched. Since the inertia of the projectile prolongs the disassembly process, impact fusion is generically an inertial confinement fusion (ICF) concept.

The conversion of kinetic energy into internal energy is accomplished by colliding the macroparticle projectile with a stationary target or with another macroparticle projectile inside a reaction chamber. The necessary length of the macroparticle accelerator, perhaps hundreds of meters or more, precludes the use of many isotropically converging macroparticle beams. A two colliding projectile target system, at most, is considered feasible.

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To produce electric power, the energy released by the thermonuclear process is absorbed by the reaction chamber wall and transferred to a working fluid that in turn drives an electric generator. The debris is exhausted from the reaction chamber, and the process is repeated. As in other fusion power concepts, neutrons produced in the thermonuclear burn can be captured in a breeding blanket for fusion fission hybrid operation(Ref.4).

III. System Constraints

Bohachevsky, Booth, Krakowski, and Miller have shown that it is feasible to have an impact fusion power reactor that is capable of containing 100 gigajoule pulses with duty cycles as short as one pulse every ten seconds using about a ten meter radius fluid wall vessel(Ref.5,6,7). Williams, Booth, and Krakowski have shown that the minimum thermonuclear yield per pulse must be more than 1 gigajoule if the power plant is to be cost competitive with other forms of power generation even if the cost of the expended target system is as low as $1 per pulse(Ref. 8). This same system study showed that the ratio C of thermonuclear yield per pulse to projectile kinetic energy must not be less than about thirty if there is to be a reasonable recirculating power fraction in the plant. There are many problems, such as trajectory control and targeting, for which solutions have not yet been found.

IV. Target Interactions

In order to obtain a useful thermonuclear burn, one needs a plasma temperature of over 5 kilovolts, a plasma pressure of about 1000 megabars, and an ion density of the order of 3x 10^[illegible] ions per cc(Ref. 9). Using a model in which shock preheating is followed by uniform compression, Jarboe has shown that a planar target system leads to projectile velocity requirements that are about a factor of five higher than for a spherically converging target system(Ref. 10). In his calculations, Jarboe takes into account thermal conduction and bremsstrahlung radiation losses. Audenaerde has shown that the energy losses due to spherical-target compressibility are consistent with those assumed by Jarboe(Ref. 11).

The linear macroparticle velocity requirements for duplicating laser pellet compressions are higher by a factor of about six than for the case where macroparticle linear energy is converted to spherical target energy in a simple hydrodynamic sequence(Ref. 1[illegible]). Only a purely hydrodynamic spherically, or quasi-spherically, convergent target system seems feasible for impact fusion.

A major problem in impact fusion target design is the conversion of linear kinetic energy of the projectile into a spherically, or quasi-spherically, converging compression of the thermonuclear fuel without a severe loss in energy and assembly velocity. Although a definitive calculation has not yet been done, a maximum energy transfer from linear to spherical motion would seem to be about [illegible]0% with a small loss in velocity for two colliding macroparticles of equal masses and equal and opposite velocities. It is also necessary to avoid excessive target accuracy requirements for the macroparticles.

Starting with Jarboe's optimal spherical target system of an imploding shell with about 12 megajoules of energy moving spherically inward with a velocity of 1.3×10^7 cm/sec(Ref. 13), adding the assumption of 20% energy efficiency in going from linear to spherical motion with no loss in velocity, and assuming equal mass projectiles moving towards each other, one finds the mass, velocity, and energy of each projectile to be those given in Table I under the column "No Velocity Multiplier". The thermonuclear yield per pulse comes from applying the system requirement Q=30.

Velocity multiplication by colliding macroparticles of successively smaller masses has been proposed by Winterberg, among others, as a means of reducing the velocity requirements on impact fusion(Ref. 14). Assuming a macroparticle mass ratio of ten to one, one stage multiplication, and applying simple impact mechanics without any inelastic losses for velocity multiplication (which is most optimistic), one finds the results given in Table I under the heading "With Velocity Multiplier". Planer shock relations are used in these calculations for the preheat before the uniform compression. Christiansen(Ref. 15) discusses the possibility that spherical shock and wave focusing might reduce the macroparticle velocity requirements.

Table I

	No Velocity Multiplier	With Velocity Multiplier
Mass of each Projectile	3.6 g	36 g
Velocity of Each Projectile	1.3×10^{7} cm/sec	7.2×10^{6} cm/sec
Kinetic Energy of Each Projectile	30 MJ	91 MJ
Thermonuclear yield per pulse	1.8 GJ	5.4 GJ

Providing all the assumptions used in arriving at Table I are approximately correct, there is a set of projectile kinetic energy requirements that is consistent with the above reactor system requirements. Both cases in Table I have thermonuclear yields which are greater than the minimum economic yield and less than the vessel containment limit.

V. Accelerator Systems

Three electromagnetic accelerator systems that might meet the projectile velocity requirements are the rail gun accelerator, the travelling magnetic wave accelerator, and the laser driven ablative accelerator. Tidman and Goldstein have also proposed a plasma impulse accelerator(Ref. 16).

The segmented rail gun as analyzed by Hawke(Ref. 17) and by Muller, Garwin, and Richter (Ref. 18) seems to offer the most promise of being developed into an impact fusion accelerator. Using the information in References 17 and 18, one finds the entries in Table II for the rail gun.

Harris and others have shown that the physics limitation of the travelling magnetic wave accelerator is the current density in the Type II superconductor in the projectile of not more than 5×10^{9} amps/sq.meter(Ref. 19). He further concludes that magnetic fields of 10 Tesla at the high velocity end of the accelerator can not be achieved because of the energy-density limit of capacitors and the inductance of switches and current feeds. The length of the accelerator is therefore much longer and the efficiency much less than those given in the Impact Fusion Workshop. Knox and others have analyzed the electrical engineering aspects of the travelling wave accelerator and shown that there is little possibility of recovering the energy stored in the magnetic field of the driver coils because the technology does not exist for high voltage, high current, fast opening switches at acceptable accelerator lengths(Ref. 20). The frequency requirements for the high velocity stages coupled with the irreducible inductance requirements of the accelerator coils and feeds dictate a capacitor voltage greater than 100 kV. The plasma impulse accelerator will probably also have the same high voltage and switching difficulties as the travelling magnetic wave accelerator.

Acceleration of macroparticles to the required velocities and energies by laser driven ablation is possible in principle. The efficiency of conversion of laser energy to projectile kinetic energy can be as high as 20%(Ref. 21); but with maximum CO_2 long-pulse laser generation efficiencies of about 25%, the overall efficiency is less than or equal to 5%. This results in excessive energy requirements for the laser. None of the difficult problems of beam blocking, focal spot tracking or projectile stability have been considered by the proponents.

Some of the laser ablative accelerator techniques appear quite capable of accelerating fractional gram particles to velocities of the order of 10^6 cm/sec. This could be quite useful for magnetic fusion reactor refueling and equation of state studies.

[illegible]

Accelerator Type	Predicted Efficiency[2]	Predicted Length[3]	Present Demonstrated Velocity (Need > 1.3 x 10^7 cm/sec)	Comments
Rail Gun	[illegible]	[illegible] km	[illegible] x 10^5 cm/sec ([illegible])	Easily delivers 10-100MJ. Simple electrical technology: inductive storage and/or rotating machinery and capacitors. Relatively low voltage(~1kv). Much experimental data with gram size macroparticles. Efficiency can be increased by going to segmented rail gun and recovering the stored magnetic field energy.
Travelling Magnetic Wave	[illegible]	[illegible] km	Very low	Little present prospect of raising efficiency even at this length because the technology does not exist for the needed high voltage(~150kv). high current, fast opening switches.
Laser Driven Ablative	[illegible]	[illegible]	Theoretical only	Excessive laser energy requirements. Need for macroparticle feedback stabilization and light transmission through ablated plasma are problems.
Plasma Impulse	[illegible]	[illegible]	Theoretical only	Feasibility of acceleration principle could be shown in a one or two stage experiment. Will have same electrical engineering problems as travelling magnetic wave accelerator.

[1] The scale of the accelerator lengths rule out many beam reactor concepts that involve spherically converging beams of macroparticles. This table considers two macroparticles moving towards each other with equal and opposite velocities. Two accelerators are required.

[2] The accelerator efficiency is the ratio of the projectile payload kinetic energy to the accelerator input energy. No account is taken of energy that might be recovered from the stored magnetic field. The reactor system requirements are not defined enough to establish a firm lower bound on the required efficiency, but [illegible] is presently indicated by system studies(Ref. [illegible]).

[3] The accelerator length scales as the square of the terminal velocity if one assumes constant acceleration.

[4] The [illegible] length is set by the yield strength of macroparticle materials at constant acceleration.

VI. Conclusions

There are several distinct advantages of impact fusion over the more conventional inertial confinement fusion concepts. One advantage is the relative ease of inserting a small macroparticle into a reactor vessel cavity as compared with laser or charged particle beam transport. Impact fusion has no analogue to the last optical surface of laser inertial fusion or the last electrode of ion or electron beam fusion that could be destroyed during the thermonuclear burn. Impact fusion can achieve the necessary high yields, of the order of a few gigajoules, which are difficult to achieve with lasers except at unrealistically high target gains. The efficiency of macroparticle accelerators can be considerably higher than laser efficiencies. The needed macroparticle accelerator technology is nearer to realization than laser technology. The rail gun accelerator is well adapted to the delivery of some 10–100 megajoules of energy to the fusion target and the electrical technology involved is relatively simple--inductive storage and/or rotating machinery and capacitors.

The rail gun has the potential of developing into an impact fusion macroparticle accelerator, and it is the most promising electrical accelerating system since its efficiency can be high, its length relatively short, and there is a considerable body of experimental work. The next step in rail gun development would be to increase the velocity by a factor of three or four using three to five gram pellets. The final goal of rail gun research and development would then be to increase the velocity by another factor of five to six to obtain impact fusion parameters.

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