PARTICLE BEAM INTERACTIONS WITH PLASMAS
AND THEIR APPLICATION TO INERTIAL FUSION*

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Introduction

As of 1973, E. A. Merts and his colleagues in Albuquerque, New Mexico started a branch of pulse power technology which is capable of producing extremely powerful electrical pulses. Pulse power generators can produce pulses with 1-10 and several hundred kilovolts. Major programs at Los Alamos Institute in New Mexico and at the laboratories, some with smaller programs at about 10 other laboratories throughout the world, are investigating the application of this technology to inertial confinement fusion. Generators producing 10-100 megajoules per pulse are planned for the early 1980's at Los Alamos and Sandia. The pulse power generators have two principle advantages over lasers: they are efficient (50% to 60%) and inexpensive (\$100,000).

The first pulse power approach to inertial fusion used electron beams to ablate the surface of a spherically imploding target.^{1,2} More recently, the use of light ion beams to implode spherical targets³⁻⁶ has been given serious consideration. At present, the main problem in these approaches is producing a high enough flux of energy to the surface of a target, particularly under conditions suitable for a power reactor. Energy beam fluxes of 10^9 W/cm^2 with electron beams⁷ and 6.2 TW/cm^2 with light ions⁸ have been achieved. To obtain ignition of a target with moderate gain (≈ 10) appears to require fluxes around 100 TW/cm^2 for ion beam implosions,

and several times higher for electron beam implosions. With improved understanding of the twin problems of symmetry and stability of implosions, it may be possible to reduce these requirements by an order of magnitude.⁹ The estimation of these requirements for particle beam fusion, the first section of this paper summarizes some of the basic principles of fusion target implosions, and the particle beam characteristics required to ignite the targets. The second and third sections deal with the interaction of light ion beams and of electron beams with fusion target plasmas.

Target Requirements

In its simplest form an inertial fusion target consists of three functional parts: the fuel, the pusher, and the ablator. The energy of the particle beam is deposited in the ablator, heating it to several hundred electron volts. (The momentum transfer from the particle beam to the target is generally insignificant.) The pressure produced in the ablator causes it to explode and to drive the pusher towards the fuel and consequently heats it to the ignition point. Ignition of the fuel can usually be achieved with an implosion velocity of $20 \text{ cm}/\mu\text{s}$; however, variations in target design may change this by a factor of two or more. Finally, the imploded pusher acts as a taper, confining the fuel while it burns.

The thermonuclear reaction rate per unit mass of fuel is proportional to the density ρ , while the

time for the fuel to disassemble is proportional to the fuel radius r_f . For unconfined fuel this is essentially an acoustic transit time, while for fuel confined by a denser pusher, the confinement time is increased in proportion to the pusher density. The quantity r_f is thus a measure of the fraction of the fuel burned.¹⁰ Generally, a value of $r_f \approx 1/\rho_p a^2$ is required for significant burning of the fuel.¹¹ The range of the alpha particle produced in the DT reaction is $\sim 10^{-4}$ cm at fusion temperatures, so that the condition for further heating of the fuel by the alpha particles is also generally met at the same time. The first criterion for burned fuel may be written in a hybrid form. With large densities or small compressed radius, lower fuel mass is required to meet the r_f condition, and hence less energy is required to ignite the fuel.

In order to achieve high compressions, the fuel must retain some resemblance to a sphere during the implosion process. The compression is thus limited by the symmetry of energy deposition in the ablator. Generally, a greater degree of symmetry is required for higher compression ratios. A radial convergence ratio around 10, producing a volume compression ratio of 1000 is generally considered to be achievable. The compression is also limited by the growth of hydrodynamic instabilities (e.g., Rayleigh-Taylor). Our understanding of the behavior of these instabilities and their effects on target behavior is rather incomplete. Nevertheless, a relatively simple analysis shows that the number of exponentiations of degrading instabilities during the inward acceleration of the pusher is approximately $(2\pi/r\Delta r)^{1/2}$, where r is the initial pusher radius and Δr is its thickness around the time of peak acceleration.¹² It seems to be generally accepted that a value of $r/\Delta r < 20$ results in reasonably stable implosions, although details of

target design and fabrication may change this limit up or down by a factor of a couple.

A variety of target designs have been suggested for electron,^{4,12-14} and ion-beam,^{15,16} drive. It appears that the energy and power requirements to drive these targets can be summarized by a set of relatively simple equations. The beam energy is converted to implanted kinetic energy with an efficiency ϵ , typically of order 2-3. Since the pusher is usually given more mass than the fuel, this can be written

$$E = 2\pi r_f^2 \rho_p v^2 \epsilon / 4\pi r_p$$

where r_f , r_p , and ϵ are the initial radius, time, mass, and density of the pusher, and v is its peak velocity. For unshaped pulses the pulse width is approximately r/v , and the beam power is given by

$$P = 2\pi r_f^2 \rho_p v^3 \epsilon / 4\pi r_p$$

When a shaped pulse is used, the width of the peak-beam pulse is somewhat shorter and the peak power somewhat higher. The flux of energy F on the target surface is just

$$F = 0.5 \epsilon^{-1} v^3 r_p^{-1} \Delta r$$

This last equation implies that flux or intensity requirements can be reduced by utilizing larger radius targets. However, this advantage is offset by the fact that the beam energy requirement increases as r^2 or faster. The energy, power, and flux requirements can all evidently be reduced by using a lower density pusher. Such a design has been proposed¹⁵ with reduced beam requirements, however the requirements were not reduced as much as one might expect because a higher implosion velocity and a shaped pulse were both required. The implosion velocity required for ignition can be reduced about three-fold by inducing a magnetic field of 10-100 kG in the fuel region to reduce thermal conduction.^{15,16,17} This type of target requires that the pusher ρ_p be higher at implosion time, which

radius that fit be initially three times higher than for the exploding magnetic targets. Consequently, the energy requirements are reduced by a factor of 9, and the power and flux requirements, about a factor of 3.

Most of the target designs have a pusher structure near 1 μm , for which the beam pulse length varies between 10 and 40 ns, depending on the target design. To produce gains of 1-100, these targets require ion beams of 1-10 MA , 100-500 TW, and 10^{14} 10^{15} cm^{-2} . The power and energy requirements for electron beam targets of similar design are roughly several times higher than for ions. At the present time, the lower limit on the ion beam requirements are thus about 10^6 J, 10^{14} W, and 10^{14} cm^{-2} . As the understanding of the stability and geometry of imploding improves, it may be possible to obtain higher compression ratios and thinner shells.¹²

For effective coupling of ablation energy into the target, the energy of the ablator mass should ideally be several times the pusher mass. This results in an ablator thickness of $0.1-0.2 \text{ g/cm}^2$ for the target designs discussed above which in turn implies the use of 0.1-10 MeV protons or 1/2-1 MeV electrons. For beams of ions other than protons, the target designs and therefore the beam requirements are essentially identical provided that ions are used that have the same range in the target plasma. For target designs different than those discussed above, particles with significantly different ranges are useful.

Interaction of Ion Beams with Target Plasmas

The ablator region of particle beam targets typically reach temperatures of several hundred electron volts and densities ranging from solid density down to a few orders of magnitude below solid density. Under these conditions, there should be no

beam instabilities, and the principal energy loss mechanisms are binary Coulomb collisions with the electrons and ions in the target plasma and excitation of plasma oscillations. Coulomb scattering from the target nuclei is generally a small effect. Consequently, the ion trajectories are nearly straight, which simplifies calculations of the energy deposition in the target.

Some initial target design calculations assumed that the stopping power of the target plasma is the same as for solid, solid-density material. More recently, the deposition models have been refined to include plasma effects which produce a strong density and temperature dependence of the stopping power.¹³⁻¹⁷ For typical target parameters, the plasma effects reduce the range of ion particles by 10-100% and the deposition profile is altered¹⁸ as is shown in Fig. 1. To compensate for this, the beam voltage can be increased by a factor of 2, with a corresponding reduction in the beam current requirements.

Fig. 1. Deposition profile of 10 MeV protons in solid density gold, with the gold at various temperatures.

Interaction of Electron Beams with Target Plasmas

The mechanisms responsible for energy loss by

the beam electrons in the target plasma are generally the same as for ion beams, binary coulomb collisions with the target electrons and ions, and excitation of plasma oscillations. In addition, some evidence of enhanced deposition due to beam-plasma instabilities has been reported.²³ In the ion beam, the spatial distribution of energy deposition in the target is affected by several additional factors. Electron beams produce a significant amount of bremsstrahlung, particularly in high-Z targets. This penetrates more deeply into the target, producing deleterious preheating of the powder.¹³ This can be offset somewhat by using low-Z absorbers.^{12,14}

The rate at which a beam of beam electrons in a beam deposits energy is dE/dx , where E is the current density and dE/dx is the stopping power of the target, typically 1 keV/cm. Hence the rate of energy deposition is proportional to the number density of beam electrons, mechanisms which increase the beam electron density by impedance or stagnating the flow of electrons can produce an enhancement of the energy deposition over the free streaming rate. There are three principle mechanisms which are known to stagnate the electron flow by altering the trajectories of individual electrons: (1) coulomb scattering in the target material, (2) electric fields, and (3) magnetic fields. The possibility of enhancing the energy deposition by appropriate electric and magnetic fields has been a fascination from the beginning of electron beam fusion research.² Enhanced deposition would generally produce higher temperatures in the deposition region, and in some cases would shorten the effective range over which energy is deposited. This would permit use of higher voltage electrons, which should be more readily focusable to high intensities.

Enhancement can be caused by fields which are

either inside or outside the target. With ion targets significant enhancement can only be achieved if the fields are inside the target and external fields can at best cause electrons which have scattered out of the target to return to it.

The source of an internal electric field is the field established by the counterstreaming plasma current which internally neutralizes the beam current in the target.^{24,25} This return current heating may become significant at current densities around 10^9 A/cm², but not at the current densities achieved to date.

When the return current flows out, the magnetic field of the beam penetrates the target plasma and "magnetic stopping" of the beam electrons can occur.^{1,27} For magnetic stopping to be significant, the magnetic field must be large enough that the electron gyration frequency is larger than the collision frequency, and the magnetic field must have time to diffuse into the deposition region. There is concern that this is a result of a confinement of the electrons only in the outer, low density portion of the ablation plume, which results in low ablation pressures in thick targets.

During the last few years there has been considerable interest in targets which are thin compared to the electron's collisional range. Experiments have measured several-fold deposition enhancements in two somewhat different geometries.²⁵⁻²⁹ Rudakov and co-workers, using Trilon (0.5 MV, 0.12 kA, 2 MA/cm², 30 ns), first reported a ten-fold enhancement of the energy deposited in a 10 nm platinum foil, with half of the beam energy deposited in the foil,²⁵ heating it to 20-30 eV. The foil was mounted on the anode surface with a hole in the anode behind it as shown in Fig. 2. At the time of peak energy deposition, the foil had expanded to 0.5-1 mm and the magnetic

Fig. 2. Anode and foil target enhanced deposition experiment.

side of the foil, is at least partially due to the $E \times B$ drift velocity of the electrons through the foil plasma is controlled principally by gradient b drift. The drift velocity can be written as $v = 1/2 v_A$, where v_A is the Alfvén current, 1700 A/cm^2 , so that the deposition enhancement factor should be $1/2 v_A$, in approximate agreement with the experiment.²⁵

More recently, similar experiments have been conducted at other laboratories, and more extensive diagnostics have been used.^{27,28} These experiments reported enhancement factors around 5. More significant to the latest experiments²⁹ on Proto I (1.1 MW, 0.4 cm, 7 MA, 60° , 25 ns) measured the temperatures of both sides of the foil and found that while the diode side of the foil reached 29 eV, the rear surface only reached 7.6 eV. This is consistent with little or no enhancement of the rear surface deposition and is thought to be due to radial beam spreading in the foil interior where the magnetic field is weak. The rate of deposition on the front side of the foil was about 50 TW/g.

Even greater deposition enhancement has been

observed when thin targets are mounted inside the anode^{26,30} rather than in the anode plane. The first such experiment²⁶ used small nickel spheres mounted in the focused electron beam of Hydra (0.1 MW, 0.11 MA, 0.3 MA/cm^2 , 30 ns) as shown in Fig. 3. In addition to the magnetic field surrounding the target, the diode electric field is substantially altered by the presence of the target, and a potential well is formed around the sphere.

Fig. 3. Diode and target configuration for enhanced deposition experiment on Hydra.

Electrons passing through the target are deflected back towards the target by the surrounding electric and magnetic fields, increasing the electron density and hence the energy deposition in the target. Alternatively, the electric and magnetic fields around the target may be viewed as producing an $E \times B$ drift which opposes the gradient b drift, resulting in greater stagnation of the beam and hence greater deposition enhancement than would result from the magnetic drift alone. The deposition enhancement factor observed in these experiments was around 18. For these experiments, $1/v_A$ was about 3.7 and the enhancement was about $5 \cdot 1/v_A$, or two and a half times as much enhancement as for an anode-mounted foil. Since the current density on Hydra was much lower than on Triton or

Prad 1, the deposition rate was lower, about 8 TW/g .

More recently, experiments have been conducted on Mite (1.8 MV, 270 kA, 45 ns) with a thin gold foil mounted on a tungsten stalk.²⁹ The stalk extends across the diode into the interior of a hollow cathode as shown in Fig. 4. The presence of the stalk and gold foil at anode potential alters the electric fields and the electron flow even more than in the Hydra experiment. A substantial fraction of the electron current, $> 25\%$, reaches the foil as a result of both increased emission from the inside of the cathode and an $E \times B$ drift along the stalk toward the foil. In a 6 μm thick foil an energy deposition rate of 160 TW/g was observed which heated the foil to a temperature of 30-35 eV. The current density at the foil was not measured, however, it could not have been greater than 3.8 MA/cm^2 and was probably about 1 MA/cm^2 . Thus a deposition enhancement by a factor of 24 or more evidently resulted from the magnetic fields and the potential well surrounding the foil.

Fig. 4. Blade with gold foil mounted on stalk extended into hollow cathode for enhanced deposition experiment on Mite.

Conclusion

During the past few years, considerable progress has been achieved in focusing high power particle beams onto targets and understanding the

interaction of the beams with the targets. Pulse power generators are under construction and are expected to be capable of producing sufficient power and energy to ignite a fusion target. The challenge of the 1980's will be to demonstrate that this power can be sufficiently concentrated in the target and that the targets perform as predicted.

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