PULSED POWER PARTICLE BEAM FUSION RESEARCH*

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Introduction

Sandia has the responsibility within the D.O.E. inertial confinement fusion (ICF) program for pursuing the pulsed power approach to particle beam ICF (PBICF). This program has evolved considerably since 1973, when it was based solely on the electron approach,[1] to the present program which has increasingly emphasized the application of the same technology to light ions. During that period substantial advances have been made in the Sandia program which has had vital contributions from the Naval Research Laboratory, Physics International Company, Cornell University, and Maxwell Laboratories. Inspite of the advances made thus far, there are still important barriers yet to be crossed and these will require considerably greater investments than made thus far. The dual goals of the Sandia program are as follows: first, the demonstration of pellet ignition with PBFA II (a 3.5 MJ, 100 TW accelerator) independent of such questions as repetitive pulse operation and economic practicality, and second, the development of the requisite practical technology to proceed to an ETF. The Sandia program has as its timetable to accomplish these two tasks by 1987.

The electron and light ion beam approaches represent a realistic potential for efficiencies of 20 to 40 percent with cost estimates for PBICF roughly a factor of 10 below that for other advanced drivers. The cost advantage for pulsed power will be decisive for small power plants but may be less important if one considers a single accelerator driving multiple reactor chambers in a multi-GW power plant. Another factor in determining which of the driver approaches will

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prove to be practical is the required driver energy to obtain an economically attractive value of pellet gain. Simple economics dictates a minimum acceptable gain-efficiency product of 10 ($\eta G = 10$). Preliminary estimates of the gain/driver energy relationship have been made and show that for conservatively designed targets, that the laser approach ($\eta = 5\%$) would require an energy storage capacity of more than 200 MJ and a combustion chamber capable of containing an explosive yield of 2000 MJ. The particle beam drivers ($\eta = 25\%$) would require only a few MJ energy store and a chamber designed for < 100 MJ yield explosions. This argument alone makes the reactor scenario based on the higher efficiency particle beam drivers an attractive option.

Discussion

A concept for a small particle beam fusion reactor has been developed which requires a gain 30 pellet with an energy input of 2 MJ.[2] Such energies are nominal for the projected particle beam drivers PBFA and Angara V, but this does not define the entire problem. Although pulsed power technology is clearly energy intensive, it does not necessarily meet the power concentration requirements. Without addressing specific target designs one can still generally define beam concentration requirements. It is widely agreed that a target ablator energy density $\gtrsim 10^7$ J/g and a spherical implosion velocity of $\sim 2 \times 10^7$ cm/sec are needed for ignition. Classical electron ranges of MeV electrons make the attainment of these energy densities extremely difficult. Nevertheless, such high energy density conditions have been closely approached as a result of strongly focused beams and magnetically enhanced electron deposition in experiments at the Kurchatov Institute.[3] These results together with those from experiments at Sandia can be explained based on a magnetic deposition enhancement factor $\chi = 2I/I_A$.[4] Scaling to MA beams and current density increases of roughly a factor of two should permit one to reach the required ablator energy density requirements. Successful pellet ignition may then be possible if specific target designs can deal with the non-negligible electron leakage and the bremsstrahlung radiation which penetrate the outer target layers.

Given such an acceptable target design, then a means is still required to deliver > 1 MJ of MeV electrons at several x 10^{13} W/cm^2. One approach to satisfy this requirement is to use an array of tens of extremely small diodes each delivering ∿ 1 TW and ∿ 100 kJ to a target.[5] If the power concentration factor as a result of beam self-focusing is ∿ 100, then the power density in the vacuum electromagnetic wave delivering energy to the cathode must be > 10^{11} W/cm^2. This implies an electric field in vacuum > 5 MV/cm. Self-magnetic insulation in vacuum transmission lines (MITL's)[6] has made such power densities a reality with the remaining challenge being the physical and engineering complexity of this approach.

Although this approach may be suitable for initial experiments, reactor applications will probably demand beam transport. It has been known for some time that a magnetized, high density plasma can be used for transporting high current beams and we proposed the use of a plasma discharge channel for beam confinement and control.[7] A cylindrical discharge is initiated in a neutral background gas along a fine wire or another source of preionization and the ohmically heated channel expands as the resultant shock wave propagates radially. This discharge leaves a reduced density, high conductivity channel in which the beam is confined by the discharge magnetic field. The inertia of the channel prevents the dynamic expansion of the beam-channel combination during the pulse. The energy lost by the beam through return current ohmic dissipation as well as the energy required to form the discharge channels of several meters in length (as needed for a reactor) restricts the beam power density to a few x 10^{12} W/cm^2.[8]

For single shot experiments with transport distances << 1 m, beam transport power densities > 10^{13} W/cm^2 are achievable, but for reactor application it is clear that further beam concentration is required at the target. Because of the large transverse velocity components of the transported electron beams, the degree of further beam concentration at the target is thought to be limited to a factor of three.[9] Experiments to test the assumptions and analysis of electron beam overlap have been recently completed. Thus far, six beams have been propagated and combined onto a 1 cm radius target from an initial radius of 46 cm with 90 percent transport efficiency, and overlap experiments for target radius < 1 cm are in agreement with theoretical predictions.[10] Unless further beam concentration methods are devised, the desired power densities are thought to be achievable only in experiments with inadequate transport distances for reactors. For this reason, the emphasis on ion beams has increased considerably.

Although if only classical deposition of MeV electrons prevailed, this would preclude use of electrons for ICF applications such is not the case for light ions. For MeV protons the needed energy density can be achieved at a current density of $\approx 10^7$ A/cm^2. If one uses the same plasma discharge approach, as outlined above for electrons, to transport an ion beam of constant area over a distance of a few meters, then considerable power concentration can be achieved near the target by beam overlap and bunching. The greater ability to overlap ion beams than electron beams (a factor of ten instead of three) is a result of the lower transverse energy of the ion beams since the discharge current necessary for ion beam confinement is far below the Alfven current. If we assume a factor of ten enhancement in current density at the target, then ion beams must reach the target region at a current density of $\sim 10^6$ A/cm^2. In addition, they need not be focused to, or transported at, this current density if they can be space-time compressed as they propagate toward the target. By employing a rising voltage pulse and by transport of the beam over a few meters, a power concentration factor of 5 is achievable, implying the need for a focused beam current density $J \approx 2 \times 10^5$ A/cm^2 at the injection point into the channel.

One approach to achieving such a high ion current density is to employ an external magnetic field to create an electron cloud that acts as a virtual cathode for efficient ion extraction. It has been shown that the ion beam current density at the anode of such a magnetically insulated (MI) diode can be more than 5 times that given by the Child-Langmuir law. Progress in scaling of MI diodes has been dramatic since the work began at Cornell University five years ago. During the last year, particularly rapid advances have been made in experiments with radially converging beams from annular MI diodes. This work by D. J. Johnson at Sandia, has resulted in an ion production efficiency of 80 percent and a focused current density which has increased from 25 kA/cm^2 as reported at Innsbruck[11] to 200 kA/cm^2 earlier this year[12] and is now approaching 10^6 A/cm^2.[13] In order to ballistically focus such a beam to achieve $J \approx 2 \times 10^5$ A/cm^2 with an acceptable transverse velocity component to permit channel transport and beam overlap, the annular geometry must be modified and effective beam divergence angle at the anode must be $\approx 1°$. Thus far, experiments with dielectric flashover anodes have shown divergence angles of 2° to 3° with a dependence of divergence on anode plasma roughness. It is clear that greater effort will be needed in development of anode plasma sources and a method for injecting a dense plasma into the diode may be needed to improve the source characteristics.

Another cause of beam divergence is ion trajectory deflection due to the external magnetic field which shuts off the electron flow in the diode, but also extends beyond the cathode into the ion drift region. This field prevents the current neutralizing flow of low energy electrons along the ion beam and results in a self-pinching of the high current ion beam in a region of space charge neutralization. Other diodes, which employ magnetic fields which are confined to the diode[14,15] may produce better controlled beams or it may be necessary to use slightly more massive ions such as helium or even carbon to further reduce self-field effects. Recent developments at NRL have shown that such self-magnetic field insulated diodes scale according to previous models from the 1.5 TW Gamble II to the 3 TW level on the Physics International Pithon accelerator. A 1.7 TW, 100 kJ ion beam has been produced using a "pinch-reflex" diode and further studies for application to PBFA are underway.[16]

In both the electron and ion approaches, we have described $\sim$ 1 TW beams either transported in plasma channels or delivered with clustered diodes to a target. A compact TW module has been developed using parallel plate water-insulated pulse forming lines and 72 modules delivering 3.5 MJ can be configured into an annular region at a distance of $\sim$ 10 m from the target.[17] Progress in development of MITL's has also been dramatic and they can be used to reliably transport the electromagnetic energy to within a fraction of a meter of the target. Energy transport over 7 m with efficiencies up to 90 percent has now been demonstrated.[6] Since ion diodes may require a positive output, an MITL geometry for either polarity has been developed,[6] and the matching of MITL's to ion diodes with efficient ion beam generation and extraction is underway. A four-module, 200 kJ, test bed for PBFA-II, as well as the 1 MJ, 36 module PBFA-I device will provide the basis for the upgrade of PBFA-I to take place in 1983.

We thus see that, in principle, the power density requirements for single shot pellet ignition can be met for either electrons or ions and that a reactor scenario can be outlined for light ions. For a reactor, plasma discharge channels $\gtrsim$ 2 m in length would have to be initiated using lasers and the energy storage, pulse forming sections and diodes would have to operate reliably at a rate of

10 Hz for 10^8 to 10^9 shots. The use of a background gas in which the discharge channels are formed also provides a method for shielding the reactor first wall from soft x-rays and debris at the expense of the formation of a blast wave. This wave attenuates rapidly as it expands but still applies a transient overpressure to the reactor structure. The required beam transport distance is then defined by the specific chamber wall structure design and the possible introduction of inhomogeneous chamber gasses to mitigate the overpressure transmitted to the beam injector region.[18]

Many of these concepts could be tested in an engineering test facility (ETF) which would repetitively ignite modest gain pellets. For instance, a 10 MW average power driver (1 MJ and 10 Hz) igniting gain 2.5 pellets could drive a 25 MW thermal output chamber allowing investigation of such questions as wall material damage, target delivery, pulse power component and diode lifetime, as well as a myriad of other practical questions. Before proceeding with such a step we must first accomplish the scientific demonstration of pellet ignition but we must also have available the appropriate repetitive pulse driver capable of reliable operation for at least 10^4 shots.

Sandia is beginning a fairly broad investigation of various aspects of high average power sources in order to establish the basis for a 100 kJ, 10 Hz module of an ETF. High voltage transformers, low loss Marx generators, gas dynamic spark gaps, and cold cathode diodes are being investigated.[19] Recent results are promising and one of the more encouraging results is the stable operation of a cold cathode diode for $\sim 10^5$ shots at electron current densities comparable to that projected for magnetically insulated ion diodes. These experiments indicate that although considerable effort is still needed in development of critical components there is reason to expect ultimate success.

The intent of this summary has been to highlight driver issues but it would be misleading to imply that the most serious issues are all related to production of the required beam conditions. Ultimately, the success of ICF will hinge upon achieving adequate symmetry of target irradiation and uniformity of target manufacture, as well as minimizing the potentially damaging effects of hydrodynamic instabilities. Our detailed understanding of these interrelated target implosion effects is incomplete with insufficient data to test the various theoretical treatments now in existence. Because of the larger size of allowable targets which we are able to irradiate with present and evolving sources it is now possible to study the dynamic target response to asymmetries and instabilities.[20] Although such nonlinear phenomena may be difficult to theoretically model in detail, the existence of a laboratory tool to explore their control should greatly ease our task.

Conclusion

Although substantial progress has been made in the last few years in developing the technology of intense particle beam drivers, there are still several unanswered questions which will determine their ultimate feasibility as fusion ignition systems. The questions of efficiency, cost, and single pulse scalability appear to have been answered affirmatively but repetitive pulse technology is still in its infancy. The allowable relatively low pellet gains and high available beam energies should greatly ease questions of pellet implosion physics. Insofar as beam-target coupling is concerned, ion deposition is thought to be understood and our measurements of enhanced electron deposition agree with theory. With the development of plasma discharges for intense beam transport and concentration it appears that light ion beams will be the preferred approach for reactors.

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