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INERTIAL-FUSION RESEACH BASED ON PULSED POWER

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ABSTRACT

PBFA-II, with design parameters of 3.5 MJ and 100 TW, is being configured to allow us to investigate either imploding foils or ion beams as inertial fusion drivers. The same accelerator can drive a foil with a magnetically insulated electromagnetic flow > 10^{12} W/cm^2 at 10 MV/cm and also power an ion diode at a source intensity of 10^{10} W/cm^2 and an accelerating potential ~ 10 MV. Our goal is to obtain 100 TW/cm^2 and 1 MJ on target for ignition studies.

Imploding foil data on Proto II has shown that the electromagnetic energy couples efficiently into foil kinetic energy increasing with I^2 up to the 60 kJ level at 5 MA. The Proto II foil implodes in 80 ns and stagnates in 10 ns, demonstrating relatively stable behavior. Modeling has shown that this behavior should continue at higher currents if the implosion time is less than 100 ns and that a current of 30 MA will be needed for achieving ignition conditions.

Proton diodes produce 1 TW/cm^2 at 1 MV, and experiments show that focusing is limited by beam divergence induced by magnetic deflections, instabilities in the magnetically insulated flow, or nonuniformities in the anode plasma. Further increases in beam intensity can be achieved with increases in the voltage and ion mass, as well as the use of beam bunching. Limited data indicates that beam brightness scales as V^2, and that the needed intensity will be achieved at ~ 10 MV. Heavier ions such as He or Li, will be required to obtain the needed stopping power. PBFA II will operate in the 2-16 MV range to accommodate various ion species, as well as foil, options. Experiments using both the Sandia Ampfion concept and the NRL pinch-reflex diode are being carried out on PBFA I with emphasis on establishing the scaling of the focused power density with voltage.

DISCLAIMER

INERTIAL FUSION RESEARCH BASED ON PULSED POWER

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INTRODUCTION

The central question in ICF today is to determine the minimum fuel mass for ignition. Once this point is reached, additional investments can be made to pursue the physics of breakeven and high gain needed for any applications. With both CO_2 and glass lasers the required levels of beam intensity can be obtained in a straightforward manner, and progress is being made in dealing with the energy coupling issues that have been dominant. Given success in efficient energy absorption, avoidance of preheat, and symmetric implosion of a small fuel mass with acceptable hydrodynamic stability, breakeven is still likely to require a 1 MJ, $\sim$ 100 TW laser.[1] Unfortunately, the cost of such a laser, likely to be at least several hundred million dollars based on today's technology, presents a serious barrier to this important step.

Pulsed power devices, developed initially as relativistic electron beam accelerators, have been converted with relatively minor modifications and negligible energy losses into light ion beam accelerators and imploding foil drivers. These devices can produce (although not on a high rep-rate basis) comparable output energies and power levels as lasers although at substantially lower cost. Thus, megajoule ignition or breakeven experiments are a realistic objective within present day funding constraints.

Sandia National Laboratories' PBFA II device will have sufficient flexibility to operate as either a multimegajoule foil implosion driver or as an ion accelerator. A single module of this 36 module accelerator is now being constructed, while parallel developmental activities are underway on several other facilities. Ion beam experiments are being carried out on Proto I and PBFA I at Sandia, the Lion Accelerator (a module of PBFA I) at Cornell, and on Gamble II at NRL. Imploding foil experiments are underway on Proto II. The goal of these experiments is to obtain scaling relationships that will permit design of the PBFA II output section to proceed. The present schedule is to establish a baseline power concentration approach in late 1983 and to begin operation of PBFA II in 1986.

The primary question under investigation is not that of energy deposition, as has been the case for lasers. The stopping power of light ions has been calculated, including the effects of bound and free electrons in the heated material.[2] Experimental confirmation of this classical deposition behavior has been obtained at 500 kA/cm^2 at Sandia[3] and at 50-250 kA/cm^2 at NRL.[4] Roughly a factor of ten higher current densities will be needed for ignition, thus there are still questions of possible streaming instabilities that might lead to anomalous effects. A review of linear stability theory of ions propagating through homogeneous media has shown no destructive effects[5], although being alert to such possible effects is prudent as higher current densities are reached. Calculations indicate that 3 MeV protons, 12 MeV helium, 30 MeV lithium, or 60 MeV carbon will provide the needed stopping power to carry out ignition experiments and these ion species are compatible with PBFA II. The emphasis of our program, then, is to demonstrate production and focusing of such a beam onto the target.

A similar situation arises for the imploding foil approach. Here we expect to be able to couple the electromagnetic energy from a pulsed power device directly to a foil at a power density > 10^{12} W/cm^2, using magnetic self-insulation in vacuum. The foil kinetic energy can be efficiently converted to thermal radiation during the plasma stagnation phase. The radiation is then used to ablatively implode a nearby spherical pellet. Again, the issue appears to be that of concentrating the output power rather than that of energy deposition.

In both cases we must demonstrate the required scaling of power concentration on Proto II and PBFA I at the ~ 10 TW, ~ 100 kJ level before proceeding to the study of ignition at the megajoule level on PBFA II. In preparation for these ignition experiments, we expect to carry out preliminary target experiments on Proto II and PBFA I. Techniques such as x-ray backlighting, neutron time of flight, and soft x-ray diagnostics are being prepared and utilized at low beam intensity levels on these devices. Long term target fabrication technology is being pursued at Los Alamos, and target design is being pursued in collaboration with the Lawrence Livermore Laboratory.

DISCUSSION

Our decision to change our emphasis from electron beams to light ions and imploding foils was made in 1979. Even though we had obtained experimental confirmation of enhanced magnetic stopping of electrons, our target design calculations indicated substantial energy penalties because of excessive preheat. The scaling of both the ion and foil approaches formed the basis for this program decision and substantial progress has continued since then. We now believe that the 100 TW, 35 ns PBFA II will permit ignition experiments. This optimism is based on an extrapolation of existing data on ion focusing and foil implosions.

Ion beam concentration will be carried out on PBFA II by the use of ballistic focusing. Although beam transport over distances of several meters is necessary for any repetitive pulse applications, it is not thought to be essential for demonstrating ignition. Thus, our immediate attention is being directed toward obtaining beams of sufficiently high intensity and low enough divergence to permit efficient convergence onto the target. All of the diodes being investigated utilize a magnetic field tangential to the anode in order to increase the path length for electron flow to the anode relative to that of the ions to the cathode. These magnetically insulated diodes thus have a substantially increased ion-to-electron current ratio, compared to electron diodes. These ion diodes differ in the specific method for applying the magnetic field and providing the plasma that supplies the ions.

A suitable diode must have a dense, stable, high purity, and spatially uniform anode plasma. The magnetic field must trap an electron cloud that can act as a virtual cathode to extract the ion beam at high current density. Finally, we must provide a plasma to charge and current-neutralize the beam during transit from the cathode to the target. The intensity on target will be given by the product of the beam bunching factor, the beam power brightness, β, and the fraction of the solid angle subtended by the diode surrounding the target. Time-of-flight bunching is an attractive option for these nonrelativistic particles. For example, a beam with a 0.5° divergence can be focused onto a 0.5 cm radius target from a distance of 50 cm. An example of beam bunching with this geometry is shown in Fig. 1 under different assumptions of PBFA II module jitter. It is not unreasonable for the diode to occupy one half of the solid angle so the beam power brightness, β, should be equal to the desired intensity.

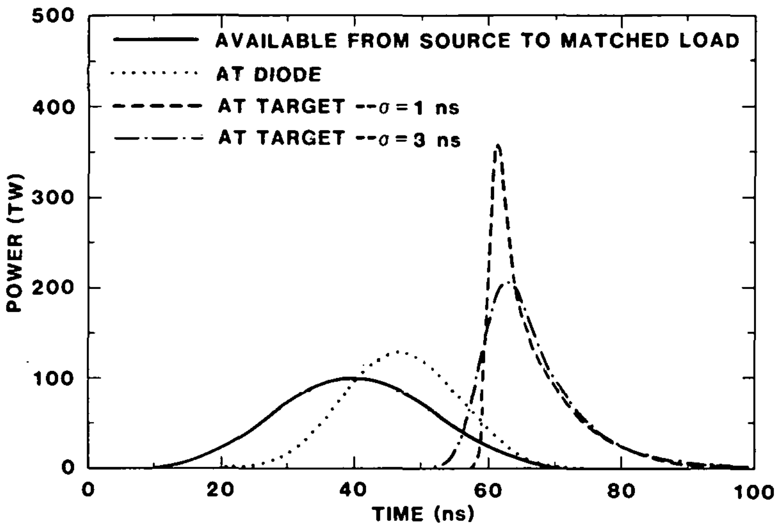

Fig. 1. Beam bunching with 3.75 MV H^+ or 15 MV He^+ from a 50 cm. Ampfion diode on PBFA II.

In order to implode targets at the MJ level with ablation velocities of 2 x 10^7 cm/sec, we must deposit 20 MJ/g in a 10 ns pulse. With a particle particle range of 20 mg/cm^2, we require a beam intensity of 40 TW/cm^2. The beam brightness, $\beta = J_D V/\theta^2$, where J_D, V, and θ are the current density, accelerating potential, and divergence angle at the diode. An example of postulated PBFA II diode conditions would be $J_D = 10^3$ A/cm^2, V = 10^7V, $\theta = 0.5°$, giving a $\beta \sim 10^{14}$ W/cm^{2}Sr^2. Several diode types have already demonstrated local divergences of approximately one degree (Fig. 2) with protons at an operating voltage of ~ 1 MV. The most pressing issue is to therefore obtain data on scaling of the beam divergence angle with voltage and mass. If the divergence is due to simple magnetic deflection or irregularities in the anode plasma, then the needed level of brightness can be reached at 10^7V.

Scaling experiments are under way on PBFA I in the 1-2 MV range. In order to operate PBFA I as an ion accelerator we have reversed the polarity of half of the modules in the pulse forming section and connected the output vacuum transmission lines in series to achieve voltage doubling

SUMMARY OF ION DIODE DEVELOPMENT - MARCH, 1982

ACCELERATOR AND LABORATORY	DIODE TYPE	V (MV)	TOTAL DIODE POWER (TW)	J (kA/cm^2)	LOCAL DIVERGENCE θ (0)	$\beta = \frac{J\ V}{\theta^2}$
NEPTUNE CORNELL U.	APPLIED-B PLANAR	0.60-0.80	0.06	0.25	0.40	~4.00
PROTO I SANDIA	APPLIED-B RADIAL	0.80-1.40	1.00	3.00	1.00	9.00
PROTO II SANDIA	APPLIED-B PLASMA TRANSPORT	1.20	3.50	3.00	1.50	5.00
GAMBLE II NRL	PINCH REFLEX	1.20	1.00	25.00	3.00	12.00
PBFA I SANDIA	PINCH REFLEX	0.80	3.50	0.44	~1.00	~1.00
HYDRAMITE SANDIA	AMPFION	1.70	1.00	0.30	~1.00	~2.00
PBFA I SANDIA	AMPFION	0.75	3.50	0.34	~1.00	~1.00

Fig. 2. Summary of ion diode development as of March 1982.

with a negative extraction electrode. Experiments being carried out use a single barrel-shaped diode connected to this "current manifold." Both the Ampfion[6] and the pinch reflex[7] concepts are under study.

The Ampfion diode uses a self-excited, distributed field coil that provides a spatially uniform magnetic field for electron current suppression in the accelerating gap. This field coil (shown as a spiral winding in Fig. 3) limits the spatial extent of the magnetically nonneutralized region and consequently minimizes beam deflection. This applied field acting normal to the ion flow direction impedes the flow of electrons that provide current neutralization for force-free drift. At the multimegampere level, the self-magnetic deflection of a nonneutralized beam would prevent the required focusing. In Ampfion experiments on PBFA I employing a dielectric flashover plasma source, initial data at ~ .8 MV gave a beam brightness of ~ 10^{12} W/cm^2Sr^2. By injecting plasma into the drift region, excellent current neutralization was demonstrated. We now project that the intensity on target should be ~ 5 x 10^{12} W/cm^2 at the 2 MV level.

The pinch reflex diode has no field coils but relies on the combined self-magnetic field of the leakage electron and ion flow to limit

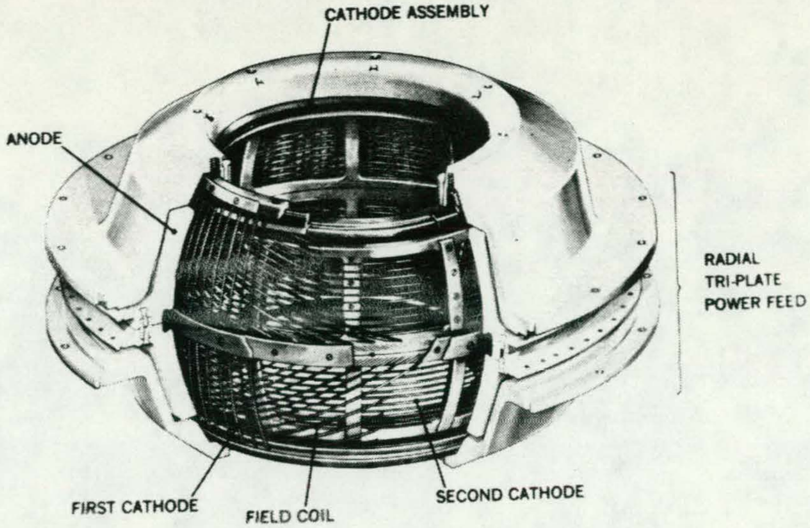

Fig. 3. The Ampfion diode under investigation on PBFA I.

the total electron current. Current neutralization is provided by a gas filled region separated from the vacuum diode by a thin foil. This diode has been extensively studied in the coaxial geometry at NRL and a barrel-shaped geometry is being jointly developed by Sandia and NRL for its use on PBFA I (Fig. 4). Preliminary experiments at 3.5 TW have shown a brightness of ~ 10^{12} W/cm^{2}Sr^2, based on local divergences of approximately one degree. If this divergence is maintained at higher power levels, this diode should also reach the 5 x 10^{12} W/cm^2 level on PBFA I.

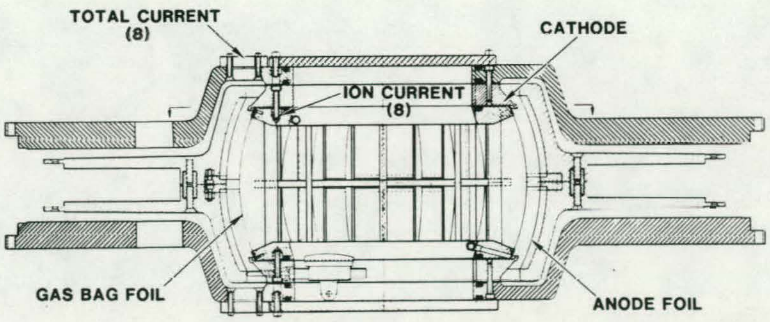

Fig. 4. Cross section of the pinch-reflex diode under study by NRL and Sandia on PBFA I.

Both the Ampfion and pinch-reflex diodes will be used to address the scaling of beam brightness with voltage and ion mass. Various effects such as plasma nonuniformity or self magnetic deflection are likely to be the cause of divergence and under various assumptions, beam brightness should increase rapidly with ion mass and with voltage as α with $0.5 \leq \alpha \leq 3$. The experiments on PBFA I should establish the crucial scaling laws.

Studies at Sandia and Cornell are aimed at producing several thousand cm^2 uniform plasma sources with plasma densities of $10^{13} - 10^{16}/cm^3$. Our studies with active devices such as plasma guns or arrays of capacitively driven plasma arcs, are emphasizing the production of adequate plasma purity, density, and uniformity. The simpler, passive dielectric flashover sources have been used in such diodes for several years, and recent data using lithium nitrate in a cathode heated to drive off impurities has produced 300 kA lithium beams with a proton impurity level of <10%.[8] Because of the rather high second ionization potential of lithium, we should also be able to obtain high charge state purity. If sufficient uniformity can be obtained over large areas, then the flashover source will be the most straightforward to use. Ion source development continues to be a high priority developmental area.

Fast-imploding-foil research has progressed rapidly since its inception at the AFWL in 1973.[9] As a result of an extensive series of scaling scaling experiments on Proto II over the last few years, we have found that the thermal x-ray output from the imploded plasma scales with the square of the current. The critical issue is the scaling of the thermalization time with current. A 10 ns radiation pulse has been produced with an 80 ns, 5 TW input pulse.[10] This behavior is consistent with limited growth of the hydromagnetic Rayleigh-Taylor instability. An estimate of the growth rate of the most rapidly growing perturbation, caused for instance by ripples in the foil, indicates that adequately stable implosions and short thermalization times will require drive times less than 500 ns and possibly less than 100 ns. Experiments are continuing on Proto II at the 10 TW, 10 MA level, using a low inductance diode that requires self-magnetic flashover inhibition of the vacuum interface to accomplish the needed level of power concentration. If these experiments are successful, then an additional factor of three higher current (30 MA) will be needed for ignition experiments on PBFA II.

PBFA II (Fig. 5) will consist of four tiers of modules with nine modules on each level. The pulse forming section will operate at a basic voltage level of 4 MV, but reconnection of the multiple modules will permit a wide range of operating conditions (from 2-16 MV). New technologies employed in PBFA II, including laser triggered switching and "double bounce" charging, are to be tested in a single module test bed before initiating final procurement of the modules. PBFA II may also use magnetic switching which would further reduce jitter, enhance shot-to-shot reproducibility, and simplify overall operation. A new laboratory building to house PBFA II is under construction and we plan to continue operation of PBFA I until PBFA II becomes operational in 1986.

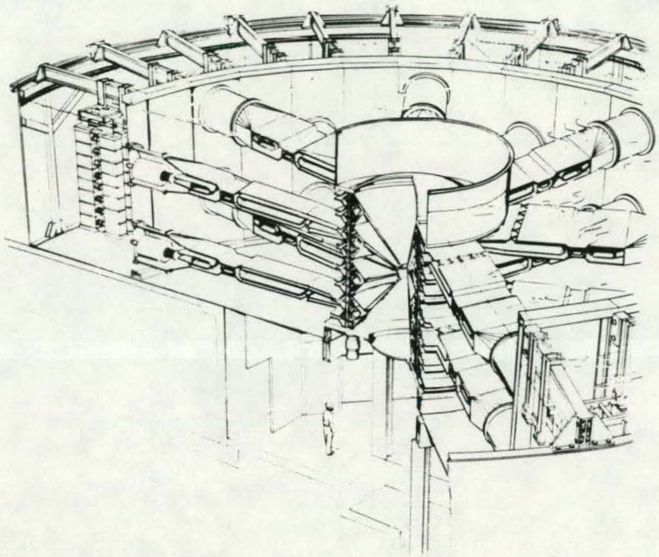

Fig. 5. Preliminary concept of PBFA II, in cutaway to show the 7 MV option with two ion diodes.

Both the ion and foil approaches to ignition described above will have an inherently low experimental data acquisition rate because of damage to nearby diode components. This situation would be undesireable for a high gain Target Development Facility (TDF) and would certainly prevent future energy applications. For these reasons, we have been studying methods for transporting beams over several meters in a background gas. The gas in the chamber would provide wall protection from x-rays and debris, and studies at the University of Wisconsin indicate that a wall structure can be designed to withstand the repetitive blast loading. The transport approach which has received the most attention is beam confinement in preformed current carrying plasma channels. Wire and laser initiated channels as well as wall-confined discharges have been studied at Sandia and NRL. This work has shown that beam brightness can be maintained over several meters given reasonable channel conditions. Other approaches which could considerably simplify reactor concepts would require beams of high brightness from either a high voltage single-stage or multiple-stage ion accelerators. Under suitable conditions it is conceivable to propagate a magnetically self-confined beam or even transport a beam ballistically. Minimal emphasis has been given until now to these long term issues, however they should emerge more clearly as the immediate questions of power concentration are answered.

CONCLUSION

Both light ions and imploding foils appear to be capable of creating the required drive conditions for ignition experiments on PBFA II. Scaling of these approaches on Proto II and PBFA I is providing the information necessary to proceed with the final design of PBFA II. Once the power concentration issues are resolved on PBFA II, we expect that the even more challenging problems of implosion hydrodynamics can be confronted with sufficient diagnostics to determine the feasibility of ignition. Beyond that we can envision further applications which will benefit from the low cost and high efficiency of the pulsed power approach.

REFERENCES

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[1]J. Holzrichter, "High Power Pulsed Lasers," J. of Fusion Energy, (1982).

[2]T. A. Mehlhorn, J. Appl. Phys. 52, 6522 (1981).

[3]M. M. Widner, T. A. Mehlhorn, F. C. Perry, E. J. T. Burns, and V. A. Farnsworth, Jr., "Light-Ion Energy Deposition and Implications for Inertial Confinement Targets," Comments in Plasma Phys. Vol. II, No. 4 (1982).

[4]F. C. Young, S. A. Goldstein, S. J. Stephanakis and D. Mosher, "Determination of Stopping of Deuterium Beams in a Plasma," 8th IEEE Int. Conf. on Plasma Science, Santa Fe, NM (1981).

[5]J. A. Swegle, Sandia National Laboratories, "Beam and Deposition Stability in Light Ion Fusion Targets," SAND-82-0072 (1982).

[6]C. W. Mendel, "Theory of Ampfion Class Ion Dioes," 4th Int. Topical Conf. on High Power Electron and Ion Beam Research and Technology, Palaiseau, France (1981).

[7]G. Cooperstein, R. A. Meger, D. Mosher, W. F. Oliphant, F. L. Sandel, S. J. Stephanakis, F. C. Young and H. U. Karow, "Light Ion Production of Focusing with Pinch-Reflex Diodes," ibid. Ref. 6.