Inertial Confinement Fusion with Light Ion Beams

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The Particle Beam Fusion Accelerator II (PBFA II) is presently under construction and is the only existing facility with the potential of igniting thermonuclear fuel in the laboratory. The accelerator will generate up to 5 megamperes of lithium ions at 30 million electron volts and will focus them onto an inertial confinement fusion (ICF) target after beam production and focusing have been optimized. Since its inception, the light ion approach to ICF has been considered the one that combines low cost, high risk, and high payoff. The beams are of such high density that their self-generated electric and magnetic fields were thought to prohibit high focal intensities. Recent advances in beam production and focusing demonstrate that these self-forces can be controlled to the degree required for ignition, break-even, and high gain experiments. ICF has been pursued primarily for its potential military applications. However, the high efficiency and cost-effectiveness of the light ion approach enhance its potential for commercial energy application as well.

THE ADVANTAGES OF FUSION HAVE BEEN SO COMPELLING and the technical challenge so demanding that fusion has been a major research project for the last four decades. The fusion of deuterium and tritium nuclei into a helium nucleus plus a neutron results in the release of approximately 1000 times more energy than that required to cause the reaction. The deuterium isotope is readily abundant, and the tritium isotope can be produced as a part of the fusion fuel cycle, so that the deuterium-tritium (DT) fuel for fusion appears to be virtually inexhaustible. In addition, making fusion work is so difficult that, if anything goes wrong with the reaction, the process simply stops. Inertial confinement fusion (ICF) has so little fuel mass available at any one time in the reaction chamber that there is no possibility of meltdown in case of an accident. The surrounding materials can be chosen so that the problem of long-lived nuclear waste is greatly reduced. However, the fusion reaction is so difficult to ignite that the only working examples we have are stars and thermonuclear weapons.

The outstanding problem in fusion research has been to heat the fuel to 10^8 Celsius degrees so that the nuclei can overcome the strong electrostatic repulsion and get close enough to fuse. In addition, the scattering cross section is much greater than the fusion cross section, so that the particles must collide many, many times before fusion can occur. Consequently, the reacting nuclei must be confined for a very long time or be at very high densities.

Until the late 1960's, magnetic confinement was the only approach being pursued. The invention of the laser in 1960 and its development as a high power source of focusable energy in subsequent years opened the way to ICF, the high density approach. In laser fusion, intense beams of light are focused onto the pellet and ablate away material from the outer surface. The action of the ablation is to drive a pusher, which spherically compresses and then heats the fuel to thermonuclear ignition. Lasers offer the great advantage of being able to focus to the very high power density required for fusion. However, the energy deposition process creates plasma instabilities, producing electrons that can preheat the fuel. Short wavelength lasers are an apparent solution to this problem, but their efficiency is low and their cost is high. Megajoules of energy are required to produce high gain for either military applications or for power production. Efficiency improvements and cost reductions are major obstacles to the commercialization of the short-wavelength laser as a fusion energy source.

While lasers were being developed for near-term experiments, the ICF program developed an alternate technology for a low-cost, high energy, efficient source of power with charged particle beams. The initial approach used electron beams, but that was abandoned in 1979 after the efficient production of light ions was accomplished (*1–3*).

The principal research topics for the light ion approach have been the generation of a sufficiently powerful electrical pulse, the transformation of that electrical pulse into particle beam energy, the focusing of the beam to a diameter of a few millimeters, and the transport of the beam to a target at some distance from the source. Substantial progress has been made in all these areas, and the perceived risk of the light ion approach has been greatly reduced during the last year.

Requirements for Inertial Confinement Fusion

The near-term applications of ICF are defense-oriented, and the long-term applications include energy production. All applications require the ignition of a small mass of thermonuclear fuel in the laboratory and the extension of that technology to high gain (the energy produced is 50 to 200 times that required to drive the target). The principal difference between near-term and long-term issues is that, for the latter, the shot rate needs to be increased to several times per second. In addition, cost-effectiveness, high efficiency, and system reliability become much more important for economic energy production. For the next 10 years, the objectives of the military program and the commercial program are essentially identical for light ion beam drivers.

In the simplest form of ICF, a source of energy is absorbed by an ablator (Fig. 1). As the ablator expands, the reaction accelerates the

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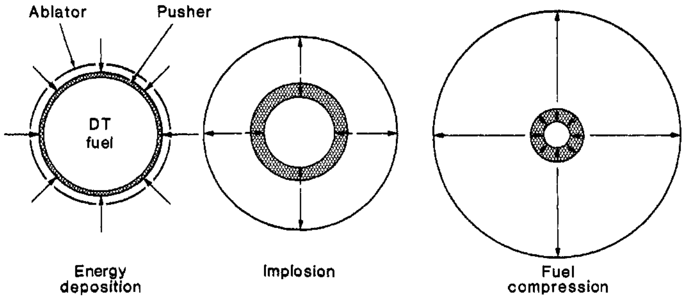

Fig. 1. Pellet implosion in one-dimensional ICF. Energy is rapidly deposited in the target ablator. The central fuel is compressed by a pusher that is driven inward by the reaction to mass ablation. The high-density fuel can then burn before the target disassembles.

pusher inward and compresses the fuel to a density of approximately 1000 times that of liquid DT. When the fuel has been compressed, a shock wave heats the small inner portion of the fuel to 10^8 Celsius degrees, and thermonuclear burning begins. The process may require several megajoules of energy and 10^{13} to 10^{15} watts of power (*4*). Producing much more energy than required for the reaction requires a carefully shaped power pulse.

The Particle Beam Fusion Accelerator II (PBFA II, Fig. 2) should be a low cost ($25 per joule), efficient (10 to 15 percent), 1- to 2-MJ (on target), 10^{14}-W facility for ignition of thermonuclear fuel in the laboratory. It began operation in December 1985.

Key Physics Issues

The potential advantages of the light ion approach include the low cost and high efficiency mentioned above as well as very low fuel preheat and favorable energy deposition. The advantages, however, are accompanied by considerable technical risk. The principal uncertainty has been whether or not the electromagnetic energy could be converted efficiently to an ion beam and whether that beam could be focused onto the target. Beam production and focusing take place in an ion diode as shown in Fig. 3. Electromagnetic energy from the pulsed power generator is fed through the vacuum-insulated transmission lines and creates a potential difference of many millions of volts between the anode and the cathode. The electrons would normally flow quickly to the anode and consume most of the energy of the device if they were not inhibited by an applied magnetic field from the field coil (Fig. 3). The magnetic field is sufficiently intense to inhibit the electrons from reaching the anode. More massive ions, however, can easily cross this magnetic field and continue to the target.

Because these intense beams of ions have millions of amperes of current, the number density of ions is large. This introduces new collective instabilities that may defocus the ion beam. These potentially damaging instabilities can grow quickly for these diodes, and most of the instabilities can reach saturation during the beam pulse. In view of this, the light ion approach to ICF was considered very high risk. However, the strength of these instabilities in saturation and, therefore, the effects of the instabilities on the ion focusing problem were not known.

In 1984, a crucial experiment (*5*) was performed on the Proto I accelerator at Sandia National Laboratories (SNL) that showed an improvement of a factor of 2 in focal spot size and demonstrated a beam divergence that was adequate for driving PBFA II targets. Since the beam current density, which is directly related to the charge density, is a principal source of the electron- and ion-driven instabilities in the diode, and since the Proto I experiment was performed at the same current density required for ignition experiments on PBFA II, it was considered (*6*) a proof-of-principle experiment of ion beam focusing. New diagnostics were applied to map the beam focusing from various parts of the anode. Johnson and colleagues (*5*) found that the beamlets from different heights on the anode were focusing at different times. The apparent cause of this astigmatic behavior was imperfect distribution of electron charge within the accelerating gap. By empirically shaping a nonspherical anode surface, all the ions from all portions of the anode were focused onto the same central spot at the same time. The full width at half-maximum of the beam focus spot was 1.3 mm from a 4.5-cm-radius diode. The divergence of 14.6 mrad included the steering error, the scattering from the cathode foil, and the intrinsic divergence from the ion production and acceleration process and was adequate for initial experiments on PBFA II. Large electron and

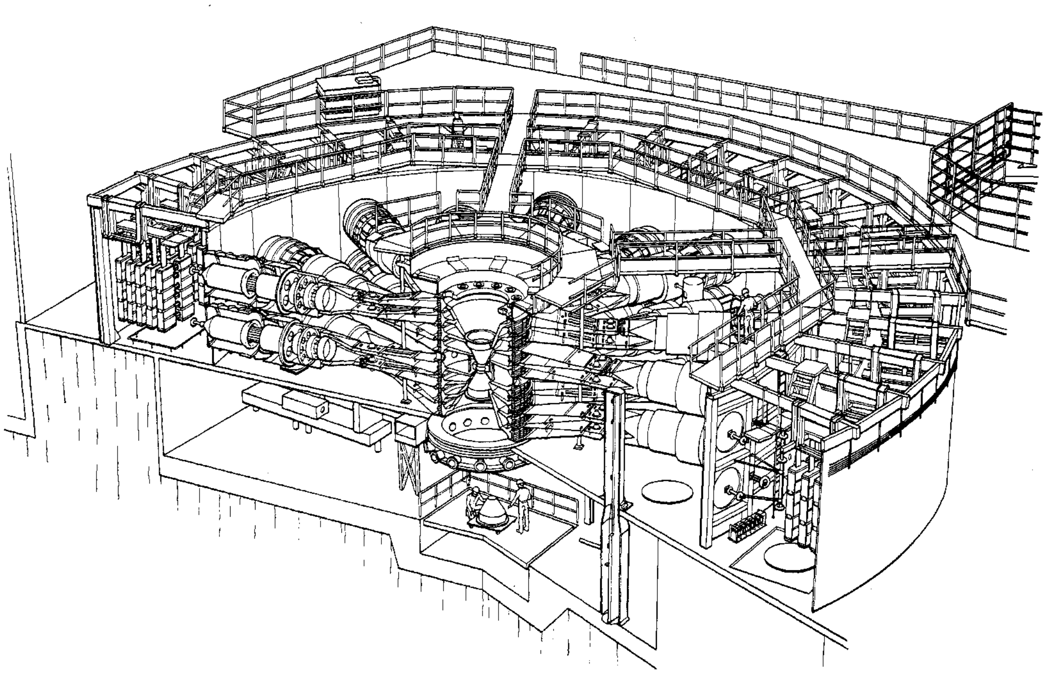

Fig. 2. Artist's cutaway drawing of PBFA II. Energy from the capacitors in the outer annulus is delivered to the target in the center through the multimodule power-conditioning network.

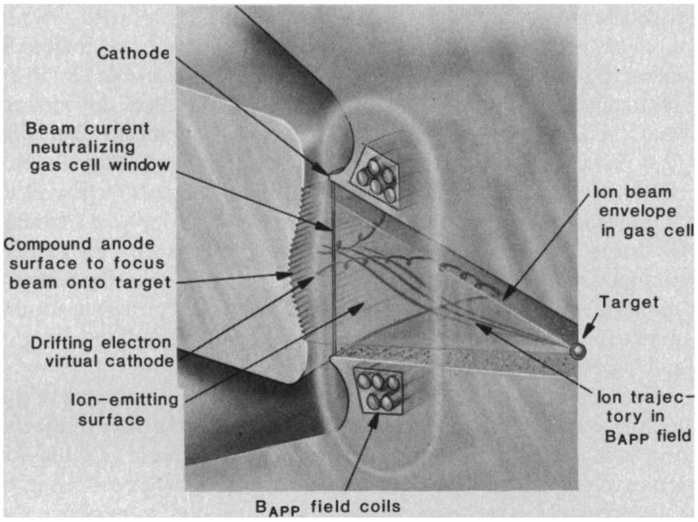

Fig. 3. The ion diode, which converts electromagnetic energy into ion beam energy and focuses it onto the central target.

ion current densities in the applied B (B_{APP}) diode did not spoil the focus of intense beams.

The proof-of-principle experiment on Proto I was extended to the higher total current and the larger diode size required for PBFA II on the PBFA I accelerator at SNL. PBFA I had initially been built for electron beam fusion experiments and was first operated in June 1980. By the time the accelerator was built, however, we had learned to produce intense ion beams, and the favorable energy deposition with intense ion beams had led to the switch from electrons to ions. PBFA I was therefore converted (at some cost in efficiency) to the world's largest ion beam accelerator, generating 2 MV and producing the current of 5 MA required for PBFA II. The diagnostics that were so successfully used on Proto I were extended to PBFA I, and the technology was further developed: a new method of neutralizing the ion charge and current was devised. Thin plastic filaments were placed near the edge of the cathode and inside the transport cell, where the applied magnetic field lines returned (Fig. 4). Electrons from the filaments controlled the steering of the ion beam and provided charge and partial current neutralization. Since this diode did not have a gas cell, the ion beam was not scattered on its way to the target. In March 1985, the PBFA I scaling experiments were successful at the current, diode radius, and the source current density required for PBFA II. The measured power density on target was 1.5 TW cm^{-2}, with protons making up approximately 22 percent of the diode charge (*7*).

The importance of this achievement with respect to PBFA II can be best understood by the equation for the power density on target (P_t) as a function of the various parameters of the diode:

$$P_t = \left(\frac{JV}{\theta^2}\right)\left(\frac{\Omega}{4\pi}\right)f_1 f_2 \qquad (1)$$

This equation represents the ratio of the beam power that impacts a target of radius r to the target area $4\pi r^2$. The power on target is the current in the diode times the voltage V of the diode, which is the diode power, times the fraction f_1 of the diode current that is in focusable ion species times the fraction f_2 of the focusable ion species that actually impacts the target. A conservative estimate of f_2 is approximately 0.5. The fraction f_1 is measured by lithium activation to infer the total charge of protons compared to the electrical measurement of the charge in the diode above a certain threshold voltage for the reaction. The divergence θ of the ion beam is defined as the radius of the target divided by the radius of the diode for a target size in which f_2 is approximately 0.5. The solid angle Ω is that subtended by the anode as seen from the target and is equal to the area of the anode divided by the square of the diode radius. The ion current density J at the anode source is equal to the total diode current divided by the area of the anode. Consequently, the divergence can be inferred from measurements of (i) the power density on target, (ii) the fraction of diode charge in focusable ions measured from nuclear activation, (iii) the diode voltage, (iv) the diode current, and (v) the geometry of the experiment. The PBFA I experiment yielded a divergence of 13.5 mrad. When this result is applied to PBFA II at 30 MV, 90 percent beam purity, and a slightly larger solid angle of the diode, the projected power density on target is in excess of 100 TW cm^{-2}.

These results were all obtained with protons; PBFA II will use lithium ions. Other experiments (*8–10*) have indicated that the beam divergence is reduced as the ion mass is increased. Recent detailed spectroscopic measurements of the ion velocity during acceleration have been obtained at Cornell University for C^{2+} and Al^{2+} ions (*11*). The divergence was approximately 16 mrad in a diode that produces protons with a divergence of more than 30 mrad. In addition to demonstrating lower divergence with larger mass, the experiment showed that the velocity perturbation was acquired near the anode before traversing the electron swarm. Consequently, the improved anode sources being developed for PBFA II should result in even lower beam divergence.

The general scaling of beam brightness JV/θ^2, which is the maximum power density that could be achieved on target, with the voltage V (from all the different diodes) to approximately the 3.5 power, is shown in Fig. 5. Since the data were taken at nearly the

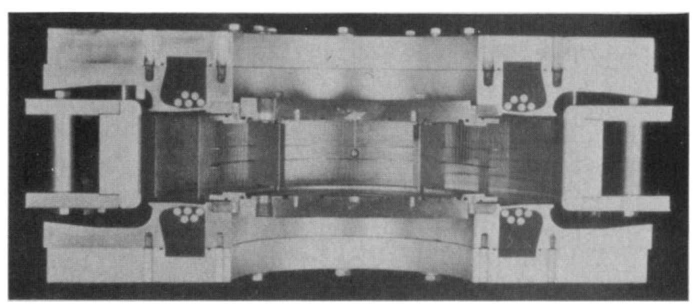

Fig. 4. Cross-sectional view of the PBFA I diode. In recent experiments, the gas cell has been replaced with a plastic mesh to supply electrons for neutralization.

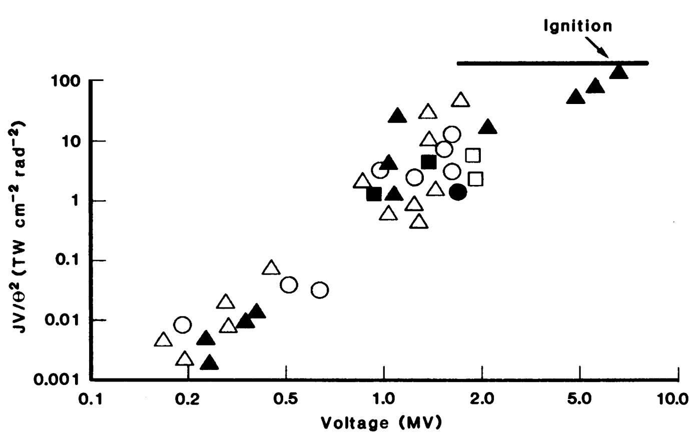

Fig. 5. JV/θ^2 plotted against V for all diodes, showing the favorable scaling with voltage for pinch-reflex diode (○), the Osaka B_{APP} diode (▲), U.S. B_{APP} diodes (△), and Ampfion/Hybrid diodes (□).

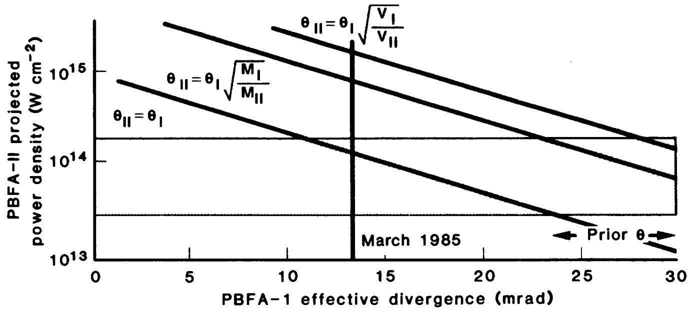

Fig. 6. The projected PBFA II power density shown as a function of the PBFA I divergence θ_I and various assumptions about the scaling of divergence between PBFA I and PBFA II (θ_{II}).

same anode-to-cathode spacing, the current density J should scale as $V^{1.5}$. The quantity JV scales as $V^{2.5}$, so that θ scales as the -0.5 power in V. If we scale the PBFA I results with protons and a voltage of 1.8 MV to PBFA II with lithium at 30 MV, three scaling relations are supported by some experiments and theory. The most conservative relation is the one that assumes that the divergence on PBFA II is no better than that on PBFA I. This assumption gives the lowest projected value for the power density on PBFA II as shown in Fig. 6. However, if we assume that the divergence improves because of either voltage or ion mass, the other two curves shown in Fig. 6 are projected. These power densities are much more than the minimum required for ignition or break-even experiments on PBFA II. The next major step in demonstrating a high power density on target clearly requires the larger voltage, the improved ion source purity, and the heavier ion of PBFA II.

Ion Source Development

The development of a high purity, preformed, uniform source of lithium ions has been a major technical challenge for the light ion fusion program. The singly charged lithium ion is desirable for many reasons. Its charge-to-mass ratio is small, so that magnetic bending in time-varying, self-magnetic fields of the diode is minimized. In addition, the low ionization potential of lithium neutrals to make the singly charged ion means that a high density ion plasma can be formed without significant contribution of the ion thermal velocity to the beam divergence. The large ionization energy of Li^+ to make Li^{2+} means that the population of Li^{2+} can be small, and preheat from the more energetic Li^{2+} particles should be negligible. Since approximately 10^{15} lithium ions per square centimeter must be supplied to the beam by the lithium source, and since depletion of the ion source should be a small perturbation on the plasma, a density of 10^{16} ions per square centimeter in a 1-mm-thick plasma has been defined as the goal for PBFA II. The uniformity must be excellent over an area of approximately 1000 cm^2, and the source of ions should be established before the main accelerator pulse arrives. These requirements place severe constraints on the lithium ion source. None of the usual sources met these requirements when the ion source was identified as a major research initiative in 1983.

Since that time, research and development has been carried out for many ion sources. At least three sources will probably be used on PBFA II, and the best performer will be chosen for the eventual target experiments.

The lowest risk approach features the resonant laser ionization of a preformed lithium vapor (Fig. 7). The vapor is formed with a boil-off vapor source obtained by flash-heating a metallic heater overcoated with the lithium-bearing material (lithium silver). In small-scale laboratory experiments (*12*), this source has produced directly measured lithium vapor densities of 3×10^{15} cm^{-3} and indirectly inferred lithium densities of up to 10^{17} cm^{-3} with a scale length of approximately 1 mm. This vapor source has been resonantly ionized with the laser ionization based on resonant saturation (LIBORS) (*13*) process, in which the low-energy photon from a dye laser is resonantly absorbed to form excited lithium neutrals. A few electrons formed by multiphoton ionization or a laser-induced Penning discharge can gain energy from inelastic collisions with the excited lithium neutrals. The energetic electrons can then ionize the neutrals and create a fully ionized lithium ion plasma. The process is ideally suited for the high densities required for the PBFA II application and is being developed for that mode.

The LIBORS process is the most complicated of all because of the multilayered anode surface, the high current pulsed power inside the anode that drives the heaters, the requirement for a few tens of joules of visible light from a dye laser, and perhaps the need for an x-ray–ultraviolet laser that generates several joules to produce the initial electrons. However, LIBORS offers the advantage of being able to produce and characterize, in the laboratory, the required lithium plasma independent of the accelerator development. The relatively low density, high current conditions in the plasma may lead to heating of the plasma and to electron impact ionization of the Li^+ ion to form the more penetrating Li^{2+} ion. Special target configurations may be necessary to avoid preheat, and these appear to be available with a modest penalty in the useful energy of the beam. In any case, the possibility of preheat due to Li^{2+} does not appear to be a major problem at this time. LIBORS seems to offer one low risk PBFA II ion source. Others are being developed to provide simpler, more robust, and repetitively operable sources.

PBFA II

PBFA II (Fig. 2) is the first superpower accelerator specifically designed for light ion fusion experiments. The requirements of high voltage and high power have led to a four-tiered, 36-module, pulsed power configuration. The reliability of these high voltage, high current components exceeds the previous state of the art by large factors. The PBFA II project has engendered many technological

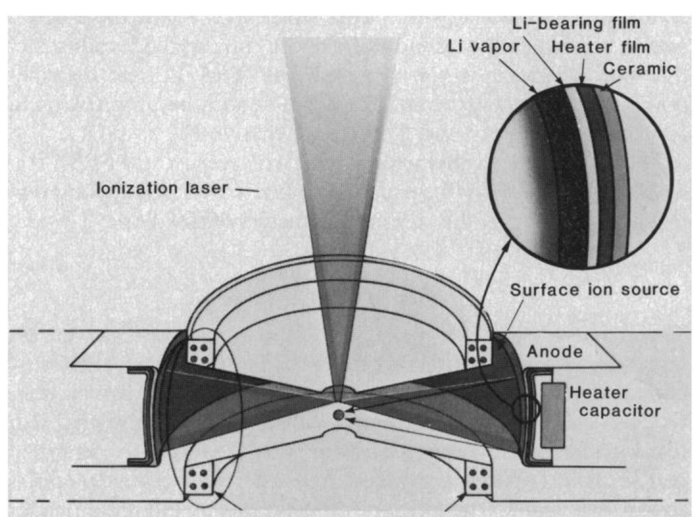

Fig. 7. The laser ionization based on resonant saturation (LIBORS) process, used to ionize a lithium vapor produced by the rapid heating of a lithium-bearing layer. The lithium plasma is one of the ion sources being developed for PBFA II.

advances during the past 15 years and represents a major experiment in accelerator physics.

The energy store of PBFA II consists of one Marx generator for each module. Each of these devices is composed of 60 100-kV capacitors with high energy density that are charged in parallel over 2 minutes and then switched into a series configuration when the accelerator is fired. The output pulse duration of the Marx generators is 1 μsec. The power pulse, conditioned in the 36 modules by successively charging and discharging the coaxial transmission lines in the water section, has a 50-nsec duration. All the modules are synchronized by a newly developed, laser-triggered, multistage gas switch. The power pulses from the 36 modules are added in parallel and series combinations to produce a single 130-TW power pulse at 15 MV. (A terawatt, 10^{12} watts, is about equivalent to the power in a lightning bolt or to the electrical generating capacity of the entire United States.) The power flows into the central vacuum chamber for a final stage of pulse compression and voltage amplification.

A new technology was developed for this final stage of pulse compression: the plasma erosion opening switch (*14–15*) just outside the ion diode in PBFA II (Fig. 8). Plasma is injected across the magnetically insulated transmission lines to short these lines during the first 55 nsec of the power pulse. During this time, the energy is stored magnetically in the vacuum region between the conductors of the magnetically insulated line. As the energy stored nears its maximum, the plasma opening switch develops an electron sheath near the cathode, and the plasma ions are eroded away to produce a pathway for the electromagnetic wave. The major uncertainty in the pulsed power aspect of PBFA II is the successful operation of the 30-MV plasma opening switch. Voltage gains of two to three have been observed at several laboratories (*15–18*) with a maximum voltage of up to 6 MV. Also, the required current of 5 MA at the required switch current density has been successfully tested on the PBFA I accelerator (*18*). The extension of this technology to 30 MV and 150 TW on PBFA II experiments will be the first major piece of new pulsed power physics to be achieved. The Naval Research Laboratory, one of the two major collaborators in the development of light ion beam fusion (along with Cornell University), is primarily responsible for developing the plasma erosion opening switch for PBFA II.

The B_{APP} ion diode in PBFA II was introduced at Cornell University (*3*) and further developed on Proto I (*5*) and PBFA I (*7*). However, the magnetic field geometry has been altered substantially to reduce the size of the capacitor banks for establishing the magnetic field for electron insulation at 30 MV. The multicoil design has been thoroughly explored with two-dimensional, fully electromagnetic, particle-in-cell computer simulations (*19*), but it has never been tested on any accelerator. The test of this diode will require the current, voltage, and power available only on PBFA II. The total current and the diode radius are the same as have been tested on PBFA I, but the addition of the high purity ion source, the new magnetic field configuration, and the very high voltage will significantly extend the regime of ion diode physics. These diode experiments will be the second major set of experiments to be conducted on PBFA II.

The first shot for PBFA II took place in December 1985 and tested the pulsed power, plasma opening switch, ion diode, and the first of several lithium ion sources. The optimization of the accelerator for its maximum energy and power output will require at least a year. The initial ion diode experiments will be done during this early optimization phase, but the major efforts on beam focusing will continue for at least another year. The goal of the program is to focus the high intensity lithium ion beam onto a target for converting power into x-rays, which would then drive a fuel-filled capsule. With this initial power and energy delivered to the target, several years will probably be needed to achieve ignition of thermonuclear fuel in the laboratory. A wide variety of target experiments will be conducted by investigators at SNL in collaboration with those from the other major institutions participating in the national ICF programs—Lawrence Livermore National Laboratory, Los Alamos National Laboratory, KMS Fusion, the University of Rochester Laboratory for Laser Energetics, and the Naval Research Laboratory. The goal of these experiments will be to show that a very small fuel mass required for both military and energy applications can be imploded satisfactorily, compressed to adequate density, and raised to sufficient temperature for igniting the thermonuclear fuel. Ignition will be a major advance in demonstrating the feasibility of ICF.

The Possibility of Going Beyond Ignition

PBFA II is designed for ignition and possibly break-even experiments. The power and energy of the single pulse from PBFA II should be adequate for achieving these goals if the implosion hydrodynamics is as modeled by the most sophisticated computer codes available. Producing much more energy than the accelerator consumes necessitates precise pulse shaping of the ion beam to provide carefully tailored density and temperature profiles within the target (*4*). These high gain targets can only be explored with pulse shaping.

A recent development in our understanding of ion diodes could potentially permit PBFA II to be retrofitted for pulse shaping and an initial venture into high gain physics. The PBFA II diode (Fig. 8) has the target centrally located. This type of diode is called a barrel diode, and the ions are generated from all the anode surfaces around the target. The explosive yield from a high gain target in the center of this diode would result in the destruction of a large part of the central accelerator. Clearly, another approach is required for high gain. In the late 1970's, the transport of intense ion beams through current-carrying channels (*20, 21*) was studied experimentally and theoretically and shown to be a feasible concept. This approach will

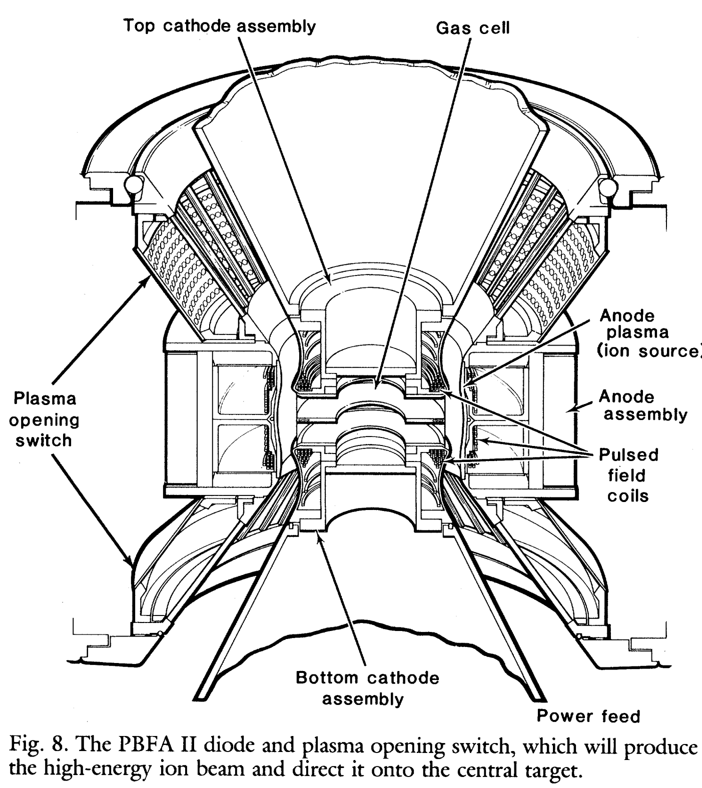

Fig. 8. The PBFA II diode and plasma opening switch, which will produce the high-energy ion beam and direct it onto the central target.

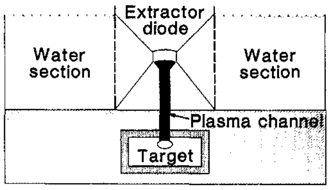

Fig. 9. Standoff and pulse shaping. The beam is bunched and debunched during transport through a current-carrying channel.

be necessary for a reactor application to produce standoff. The ion beam must be extracted from the diode, injected into the channel, and transported to the target.

Providing a focusable extractor ion diode had been a major unsolved problem for light ion fusion. Experiments (*22*) on this type of diode resulted in electron losses near the outer edge of the diode, nonuniform ion emission, and poor focusing. The electrons were not adequately controlled in this type of extraction diode. P. L. Dreike (while still at Cornell University), J. P. Quintenz, and S. A. Slutz (both of SNL) independently realized that the problem was to establish the proper magnetic field configuration within the diode. Slutz has modeled this analytically for a focusing extraction ion diode and has tested the model with a series of two-dimensional, fully self-consistent, relativistic, particle-in-cell, electromagnetic simulations (*23*). The simulations showed the electron loss pattern observed in earlier experiments unless the new coil geometry was incorporated. With the new coil geometry, the electrons are well behaved and the beam appears to be quite focusable. Experiments with this new coil configuration are being planned, and the extractor diode will be developed for the pulse shaping option on PBFA II.

This modification to the accelerator is shown schematically in Fig. 9. All levels of PBFA II could be added in series to power a single extractor ion diode. The ion beam would be injected into a current-carrying channel for transport to the target. The speed of the ions at each instant would be selected by carefully controlling the voltage, so that the beam could form the appropriate pulse shape by bunching and debunching on the way to the target. To handle the full power of PBFA II, the channel would probably have to be a wall-confined discharge and perhaps have a final focusing cell (*24*) at the output of the channel to produce the high power density onto the target. This technology was well developed at the end of the 1970's (*20, 21, 24*). Key technical issues include the voltage control on the ion diode and the modification of the PBFA II pulse-forming network to provide the correct pulse shape with appropriate means for fine tuning it.

Target experiments could proceed at the rate of two to four per week until the thermonuclear yields become very large. The target debris would be contained inside a target chamber that permits access for the beam and diagnostics but contains the radioactive by-products of the fusion reaction. The engineering and development of the target chamber is another major problem to be overcome for this concept.

With such a PBFA II retrofit, high gain target experiments to explore the critical issues of high gain targets could begin in 1991. If only a few hundred shots at less than 3 MJ are needed to develop high gain target physics and to demonstrate high gain target operation, PBFA II could be adequate for demonstrating the essential target physics required for ICF. If, however, the implosion hydrodynamics of small fuel masses is more difficult than expected, the research program will require several thousands of shots or more energy, and a new facility will be required.

The target development facility (TDF) (*25*) is proposed as a logical step beyond PBFA II. It is presently conceived as a 6- to 10-MJ facility that can test high gain, thermonuclear targets at a shot rate of up to ten per day. If PBFA II is successful in demonstrating some progress toward high gain even for a limited number of shots, the assurance that the TDF could be used to cover the range of power and energy necessary for full development of reliable, well-characterized, high gain targets at acceptably low cost would be enhanced considerably. In addition, the TDF could be used for the military applications of ICF, which include simulation of nuclear weapons effects by means of the x-rays and γ-rays from a small thermonuclear source and study of nuclear driven, directed energy weapons physics. The facility would be a full nuclear facility and therefore could meet this wide spectrum of ICF applications.

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