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> PROGRESS ON THE PARTICLE BEAM FUSION ACCELERATOR II FOR LIGHT ION FUSION

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Abstract

Particle Beam Fusion Accelerator II (PBFA II) at Sandia National Laboratories is the largest in the series of particle beam drivers and the first with the potential of achieving the necessary energy and power density required for igniting thermo-nuclear fuel in the laboratory. PBFA II is a series of experiments in pulsed power, power flow, ion sources, lithium ion beam generation, beam transport, beam focussing, radiation physics and implosion hydrodynamics. these challenging experiments are successfully completed, then thermonuclear fuel may be ignited in the laboratory for the first time. Because of the large number of research items in series, the risk is very high and the experiments will require many years of intensive effort. On December 15, 1985, PBFA II construction was completed and the accelerator was activated. Since that time, the pulsed power has been developed and major experiments in power flow and ion sources have been conducted. Preliminary experiments on beam generation have also been conducted. The accelerator is currently operating and providing one fully diagnosed experiment each week. The PBFA II program and the results to date with this technology will be presented.

PBFA II Introduction

Light ion beams [1] offer the possibility of a very efficient and low-cost driver for Inertial Confinement Fusion (ICF). The energy deposition is straightforward since the ions deposit their energy in a dense plasma that prevents microscopic instabilities from producing preheating electrons. The difficulty with light ions has been the focusability. In 1984, a proof-of-principle experiment on Proto I, at the same current density and charge density required for inertial fusion on the Particle Beam Fusion Accelerator II (PBFA II), showed that intense ion beams can be focused to the required divergence with the correct local physics [2]. In 1985, diode and accelerator technology was examined [3] on PBFA I at the same current and diode radius required for fusion on PBFA II.

PBFA II [4] is the latest of a series of particle beam generators designed and tested to provide a power source for driving ICF targets. It is the first one that has been designed as an intense ion accelerator and the first with the potential of igniting thermonuclear fuel. Since the lithium ions deposit their energy efficiently in a dense plasma which shields the beam ions from each other and remains very collisional, instabilities and the resulting preheat are precluded. Consequently, energy deposition is classical and benign. The principal uncertainties are the generation and focusing of a million joule (MJ)

ion beam to the required 100 TW/cm² power density, which requires a 5 kA/cm² Li⁺ ion source and a divergence of 10 to 15 mrad. Consequently, almost all of the work on the light ion approach to ICF has centered on the generation and focusing of light ion beams. The target implosion experiments performed with other ICF drivers are generally applicable to the targets for light ions also, so target issues have not been neglected by this strategy.

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PBFA II is shown schematically in Fig. 1. The accelerator was activated on December 11, 1985, with all components outside the target in place for testing. Preparing it for target experiments requires three steps: a series of "shakedown" shots to stress the accelerator and identify weaknesses, a series of experiments to optimize the pulsed power and to develop the plasma opening switch (POS), and a final series to develop the beam technologies. The first of these steps is completed and the second is underway. The major technical issues for each of the PBFA II sections will be presented and evaluated.



Artist's cutaway drawing of PBFA II. Fig. 1. Energy from the capacitors in the outer annulus is delivered to the target in the center through the multi-module power-conditioning network.

Energy Storage Section

The energy is stored in 36 Marx generators, large banks in which 60 capacitors are charged in parallel and discharged in series. The 36 modules store 13 MJ of energy and discharge into a pulse-forming section in 1 μs by firing 1080 spark gaps inside the generators. Reliability, prefire control, and system timing uncertainty or jitter were the major issues. Experience on the PBFA I predecessor to PBFA II indicated that these would be major problems. The solution [5] required the changing internal resistors to promote a smooth spark-gap-breakdown sequence in the first two rows of the Marx to make spark gap firing sequence repeatable and, therefore, low jitter. The stable firing sequence was subsequently verified with new photonic diagnostics [6]. The same system changes were adapted on PBFA I and the timing spread was reduced from ~70 to 120 ns to the 20 ns range, and prefires were virtually eliminated. The 36 PBFA II generators each have a reliability of > 0.9995, which corresponds to a single gap reliability of 0.99998, and a PBFA II verified timing spread of 20 to 40 ns. This spread is adequate and does not contribute to target asynchrony.

Pulse-Forming Section

The pulse-forming section [4] in the water-filled annulus of PBFA II compresses the electrical power pulse from the Marx generator by a factor of 8, synchronizes all 36 modules, inverts the electric field direction c for the succleuter o add field direction c voltages in series. and transforms the impodance to match that of the vacuum section.

All 36 modules must be synchronized within 15 to 20 ns for maximum accelerator power and sub-nanosecond asynchrony at the target. Modules are synchronized with a laser triggered gas switch. The strong coupling [7,8] between KrF laser light and SF6

insulating gas has been developed into a reliable, 5 MV, low prefire, low jitter, voltage insensitive switch technology [9] for PBFA II. The novel multistage switch design has series gaps arrayed along a central column and isolated from the segmented gasswitch housing. The laser trigger ensures low jitter. A new model [10] for gas switch breakdown has been developed and utilized to reduce prefires, jitter, and voltage sensitivity of high voltage gas switches. This gas switch is a key component of PBFA II and operates nominally at 5.2 MV, 0.9 us charge time, and with > 99.7% (from DEMON data) reliability against prefires. The r.m.s. jitter of the single prototype switch was 2 ns. However, the 36 switches in PBFA II have produced larger jitter, which varied between 5 and 10 ns over many accelerator shots. The switch is being redesigned to improve jitter and reliability.

The single 4 J, injection-locked KrF laser beam is divided into 36 beams which fire all 36 modules simultaneously. The laser itself had a misfire rate of 5% which has been improved to a rate of less than 0.2%. However, before this misfire improvement was made, a worst case accident occurred on the fifth "shakedown" shot and with the accelerator set to fire at full energy. A laser misfire could have been catastrophic if that fault mode had not been accommodated in the design. The energy left in the intermediate store might have destroyed the energystorage section, the storage capacitors, and the gas switches, and might have mixed the oil and water. The robust accelerator survived with only minor damage to the gas switches and useful data was obtained. Early tests of such fault modes are important in making a large pulsed-power system fully operational and

survival indicates the integrity of the design. The pulse-forming lines of PBFA II compress the energy into a 55 ns wide pulse by a two-staged, waterdielectric-switched, pulse-forming network. A doublebounce, charging scheme [11] was developed and adopted [4] for PBFA II to minimize the voltage on the lines. The pulse-forming section produces a 5.8 MJ, 100 TW, and 3.2 MV pulse from its 36 modules into the polarity-inverter-transformer combination.

Since a 30 MV pulse is desired to give the lithium ion optimum range in the target, the 36 modules are combined in a series-parallel combination to provide a 12 MV source for the vacuum section. The final voltage gain is accomplished by the POS [12,13] in vacuum. Each of the coaxial transmission lines of the pulse-forming section are split, with an 88% energy efficiency, into two parallel-plate transmission lines. The one further from the midplane of the accelerator has a cross-over network that inverts the electric field vectors. Parasitic losses from the inverter reduce the energy in that portion of the line to 80% of its initial value. The line without the inverter has no such loss, so approximately 120 kJ of energy is injected into the transformer. Measurements of the energy and power transport through the inverter agree with computed values [14].

Transformer Losses

Although approximately 4.6 MJ of energy is injected into the 36 transformers, only 76% is available at the output for the water section. The impedance transformation in each of the 72 parallel plate transformers is from 4.3 ohms input to 18 ohms output in a 2.2 m long linear taper. The severe impedance transformation over such a short distance is lousy. In addition, the electro-magnetic coupling between the various lines in the transformer causes destructive interference and reduces the output pulse. Finally, the parallel plate transmission lines have a relatively large ratio of line separation to width, so some of the current flows outside lines and is lost from the system. These effects are interdependent and the resulting losses are still present in PBFA II. Alternate transformer configurations are being investigated through 3-D computer simulations to reduce the parasitic losses. The potential for significantly increasing the PBFA II energy makes this research a high priority.

Vacuum Insulator Stack

The central vacuum section of PBFA II is 3.6 m in diameter and 4.8 m high. The 59 square meters of insulator are required to feed 100 TW of power in the baseline design. The insulator performed well in the "shakedown" shots and should accept the additional energy resulting from improvements in the transformer efficiency.

Magnetically Insulated Transmission Lines (MITLs)

The MITLs provide azimuthal smoothing of the wavefronts from the 9 modules feeding each level. This azimuthal smoothing is a key step in reducing the beam asynchrony at the target to the required subnanosecond level. In addition, these transmission lines provide the magnetically insulated storage inductor for the last stage of power compression and voltage gain. Since each half of the accelerator has 4 biconic MITLs added in series, electron loss at the junctions are potential energy losses. These losses are computed to be small because the POS provides the initial low impedance to keep the electron flow overly trapped.

The computed and measured current waveforms agree to within a few percent and indicate the monitoring system is adequate, the energy per module is as expected, and the MITLs are functioning to azimuthally and vertically smooth the wave as designed. More testing with optimal POS conduction and opening and normal module timing is required to fully test the MITL performance, but the shakedown tests are encouraging.

Plasma Opening Switch (POS)

The POS is a joint research and development project with the Naval Research Laboratory (NRL), the lead laboratory in the research. Substantial contributions have been made by individuals at Sandia National Laboratories (SNL) and at the Laboratory of Plasma Studies of Cornell University. Experiments and theoretical studies in many other institutions have added to the understanding of POS operation [15-17]. Nevertheless, that understanding is still incomplete and the POS is still a moderate risk component. The PBFA II POS could not be fully tested without PBFA II.

Early results are encouraging. The switch conducts for the designed current. However, in initial experiments it opened in approximately 30 ns instead of the 12-15 ns required. A problem was discovered in the azimuthal symmetry of the plasma. The plasma fill density varied by a factor of 4 max/min around the switch. The low density section would open first and shift current to the higher density sections. The switch would then become a three-dimensional device and opening would be delayed. The slope of average switch current versus plasma fluence indicates a $\pm 5\%$ uniform plasma would be adequate. Initial experiments indicate that, with improved uniformity, $\pm 25\%$ is adequate. The plasma uniformity is now being improved before further testing is done.

Recent experiments with a small cathode radius [18] or a series field coil in the cathode [19] have shown improved POS performance. These innovations offer possible improvements in the PBFA II POS. The voltage and power gain expected of the POS are essential for the PBFA II ignition experiments. However, the longer-term experiments with pulse shaping, beam extraction and beam transport will not require the POS. If the POS performance is found to be inadequate, the schedule for the pulse-shaping option will be accelerated.

Lithium Ion Source

In 1983, the development of a suitable lithium ion source was identified as a major priority for the light ion approach to ICF. Since that time, more than 20 proposed sources were evaluated and 5 were selected for development: a glow-discharge-cleaned LiF flashover source [20], an electro-hydrodynamicinstability driven liquid lithium source [21], an impact ionized Li gas gun approach [22], an approach [23] producing a Li vapor by flash heating a LiAg thin film with an electrical heater and ionizing the vapor through the LIBORS [24] process with a visible dye laser, and laser vaporization followed by singlephoton ionization with an ArF laser [25]. All 5 sources have shown encouraging results. The last 3 have shown evidence for lithium ion densities in

excess of the 10¹⁷ cm⁻³ specified by the design criteria. The first one has been fielded on PBFA II, but the lithium content of the ion beam was negligible at the 8 MV operating level achieved in the "shakedown" shots. The second source is being prepared for PBFA II testing during 1987. The rest are on hold because of hudget limitations. The number of promising sources is encouraging; only one has to work. Any of the 5 should be acceptable for the PBFA II experiments, but only the second can be readily extended to multi-shot or repetitive operation required by the ICF drivers following PBFA II.

Ion Beam Generation and Focusing

The PBFA II ion diode is shown in Fig. 2; it has the same radius as the PBFA I diode, but twice the height. The operating point is to be 30 MV and 5 MA compared to the 1.8 MV and 5 MA of PBFA I. The desired ion is lithium instead of the protons accelerated on PBFA I. The PBFA II diode features a much larger field coil in the anode and one in the mid-plane of the cathode. The new magnetic field geometry reduces the magnetic field energy required to insulate the electrons by a factor of 10, and

compensates for the Li⁺ canonical momentum change as

it strips to Li⁺⁺⁺ in the gas-cell membrane. The proton impurities that could preheat the target are excluded from the target region by their canonical momentum [26] in the PBFA II geometry. The diode was designed [27] with the MAGIC [28]

2-D, fully electromagnetic, PIC code merged with the accurate magnetic field profile computed with the TRIDIF code [29]. The insights gained from these computations have been generally encouraging. However, the ion current is significantly delayed, even with the ion-source space-charge limited at the beginning of the calculation. A new model [30] for the impedance of ion diodes has been advanced substantially since the last conference and the data from many ion diode experiments has been successfully explained with the electron lifetime (or, equivalently, the ion production efficiency) as the only free parameter. The Miller-Mendel [30] model suggests that new techniques for quickly establishing the electron charge - which determines the ion curren for a given geometry and voltage - in the acceleratin gap will be necessary to efficiently couple the ion diode to a 10 to 15 ns PBFA II pulse. In addition, techniques for controlling the electron lifetime after the desired ion current is reached will be required to maintain or preferably increase the diode voltage during the pulse. Until now, only limited attention has been given to electron control, such as the electron limiter [31] on the anode. There is a great need and opportunity for significant advances in ion diode physics through new ideas for electron control. The recent demonstration of electron retrapping in strong applied magnetic fields [19] may stimulate such new approaches.

Although the experiments in 1986 emphasized pulsed power development, many of the experiments had



Fig. 2. The PBFA II diode and plasma opening switch (POS), which will produce the high-energy ion beam and direct it onto the central target.

an ion diode. The coupling to the diode was poor when the plasma opening switch was used because the top and bottom switches have not been adequately simultaneous and because the diode impedance is too high for too long at the 8-9 MV of recent experiments. Experiments without the opening switch provide a longer pulse at 8 MV and permit the diode model in Ref. [30] to be tested in this regime. The model predictions agree well with the measured current and voltages, but no direct measurements of the total ion energy have been obtained. Key experiments in beam generation and focusing must await the implementation of a successful lithium ion source.

Acknowledgments

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