PROGRESS IN LIGHT ION FUSION*

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Abstract

Advances in ion beam theory, diagnostics, and experiments in the past two years have enabled efficient generation of intense proton beams on PBFA II, and focusing of the beam power to 5.4 TW/cm² averaged over the surface of a 6-mm-diameter target. Improvements in the ion diode magnetic field uniformity and strength produced a proton beam with good azimuthal symmetry. The beam characteristics were diagnosed using conical targets in concert with inner-shell excitation x-ray cameras and ion pinhole cameras. Asymmetry was measured to be less than 15 percent, a level adequate for beginning ion deposition experiments. Initial studies of the beam/target interaction have begun with focused proton beams. Planar, conical, and cylindrical targets have been used in the experiments. These tests have provided information on ion beam power density, uniformity, and energy deposition. Substantial improvements in power density beyond the present level require a more magnetically stiff ion beam (higher voltage and mass) and lower ion divergence. Most of our effort has been concentrated on lithium. Thin-film-based lithium sources have produced more than 150 kJ of lithium energy above 6 MV. For the first 15 ns of the ion beam pulse, multiple diagnostics show a pure lithium beam. At peak lithium power, the efficiency of conversion of electrical power to ion power exceeds 70%. The time-resolved divergence of the ion beam, about 35 mrad, is still too large. Particle-in-cell simulations using the three-dimensional code QUICKSILVER have been used to pursue a fundamental understanding of ion beam divergence. The simulations are indicating that control of the electron density distribution in the diode is a major factor in constraining the diode to operate in a low divergence mode. Future applications of pulsed power based particle accelerators have been explored through conceptual studies. A conceptual design of a Laboratory Microfusion Facility driven by light ion beams has incorporated line induction voltage adding, transit-time ion bunching, pulse shaping, and long-distance transport. The Light Ion Beam Reactor Assessment (LIBRA) design effort has shown that a light ion driven energy producer can offer competitive electricity costs.

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I. INTRODUCTION

Pulsed power technology offers an efficient, low-cost, and potentially repetitive means for generating intense light ion beams for Inertial Confinement Fusion (ICF). The technology produces a beam that couples well to matter and is scalable to very high power levels. Considerable progress in developing this technology for ICF has been made on PBFA II (the Particle Beam Fusion Accelerator II) within the last two years. Advances in ion beam theory, diagnostics, and experiments have enabled efficient generation of intense proton beams on PBFA II, and focusing of the beam power to 5.4 TW/cm² averaged over a 6-mm-diameter target [1]. At the present operating level of PBFA II (Marx generators charged to about 9 MJ, or 3/4 of the nominal 12 MJ possible at $^+/_-$ 95 kV), this experimental achievement approaches the theoretical limit with the measured 17 mrad energy-resolved divergence and a 50% source purity for protons. Target experiments have been started with the intense proton beams, since the range of protons at 4-5 MeV is equivalent to that of lithium at 30 MeV.

II. PAST AND PRESENT CHALLENGE

Pulsed power based particle accelerators have been under development as ICF drivers since 1972. Several major obstacles foreseen at that time have been overcome since, allowing greater emphasis to be placed on the remaining challenges. At the time, each of these might have been viewed as a fatal flaw (as opponents occasionally argued), and the field of research terminated. Fortunately, it was not. Initially, scaling accelerators up in size was seen as a major obstacle (ca. 1972). The solution to this problem came in the form of multi-modular designs (ca. 1975). Later, synchronization of the independent modules was seen as the major problem. This problem was solved by development of low-jitter electrically triggered gas-insulated switches (ca. 1976). When the laser approach to ICF ran into the hot electron problem and electrons no longer appeared to have acceptable energy deposition properties, ion diodes were conceived (ca. 1976). For a while, it appeared that it might be impossible to generate an ion beam with high efficiency on a large accelerator, but this was eventually done using an applied-B ion diode (ca. 1979). The assertion that ion beams could never be focused was disproven on Proto I in 1984. Concerns that multimodular pulsed power accelerators at high voltage (> 2MV) could not be synchronized were laid to rest with successful low-jitter operation of a laser-triggered multistage gas-insulated switch on PBFA II in 1987. Proton beams were subsequently focused to >5 TW/cm^2 on PBFA II in 1989. Concerns that the environment of a pulsed power accelerator precluded high-quality target diagnostics from being fielded successfully have diminished since the first beam/target interaction series on PBFA II in 1989. Speculation that a higher-Z ion beam could never be generated efficiently by a pulsed power accelerator or have high purity was disproven in August 1990. At present, concerns are expressed that lithium beams will never focus on PBFA II and that ion beams will never be used for implosions. Fortunately, good critics are invaluable. From the present criticism, one can see that the greatest challenges lying ahead now are (1) reduction of ion divergence, and (2) design and execution of ion-driven target experiments. This is the main direction of the light ion program.

III. ICF TARGET REQUIREMENTS

For PBFA II to drive implosion targets effectively, it must provide an ion beam with adequate power, adequate power density, and proper range in the target. Adequate power (50-100 TW) on PBFA II requires use of an inductive store/plasma opening switch and full energy operation. Adequate power density (50-100 TW/cm^2) requires an ion beam with high magnetic stiffness. Proper range in the target (30-40 mg/cm^2) requires high voltage provided by the plasma opening switch (POS) and a magnetically stiff ion beam. In order to increase the power density for implosion target experiments while maintaining an adequately short ion range in the target, we are developing high voltage lithium ion beams. Our goal on PBFA II, shown in cross-section in Figure 1, is to provide 1 MJ of energy in a 30 MeV, 15 ns, 50-100 TW/cm^2 lithium ion beam to an ICF target for studying implosion hydrodynamics and investigating ignition scaling.

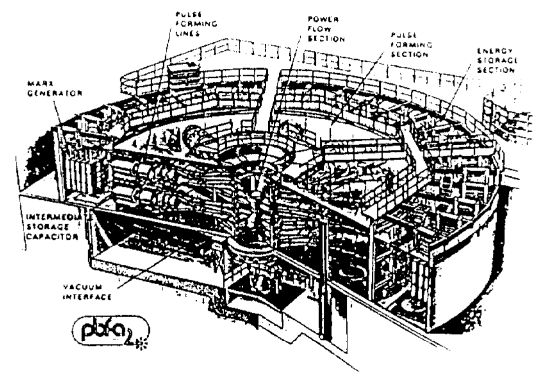

Figure 1. Cross-sectional drawing of PBFA II.

The key advantage in increasing the ion mass from protons to lithium is that the optimum range in the target is obtained at higher ion energy and, consequently, increased beam stiffness. High ion source species purity can be obtained with lithium, since singly ionized lithium has a helium-like closed electronic shell configuration. This results in a large difference between the first ionization potential (5.4 eV) and the second ionization potential (75.6 eV). In experiments on PBFA II using a lithium fluoride ion source, the purity at peak lithium power has been measured to be unity, within the uncertainty of the diagnostics. In going from protons to lithium on PBFA II, at constant ion beam divergence, we should be able to increase the ion beam focal power density to approximately 40-50 TW/cm^2, by increasing the ion source purity, by increasing the energy coupled to the diode, and by increasing the voltage and power using a plasma opening switch. We expect to be able to maintain a shot rate of one/day at the full energy level of PBFA II.

IV. TARGET EXPERIMENTS ON PBFA II

The configuration of the target experiments is shown in Figure 2. The ion beam, created at the 15 cm anode radius, is accelerated through the 1-2 cm anode-cathode gap, and passes through the 2 micron mylar gas cell window and into a few-torr Ar-filled propagation region. The beam is focused in the vertical direction from its initial 5-10 cm height to its 5-6 mm height at the target by bending in the self-magnetic field, bending in the applied magnetic field, and vertical shaping of the anode profile. Power feeds to the diode are symmetric about the diode midplane. Tungsten shields on the top and bottom of the diode attenuate bremsstrahlung by a factor of about 2500 for diagnostics contained within the shield cone. The upper diagnostics include multi-position x-ray pinhole cameras for observing inner shell excitation (e.g., K-, L-, or M-alpha) radiation from the target, an elliptic crystal spectrometer for obtaining x-ray spectra from the target, and a one-dimensional slit imaging magnetic spectrograph for obtaining Rutherford-scattered ion images, ion momenta, and ion power densities.

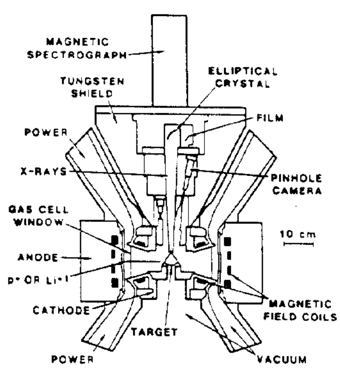

Figure 2. Configuration for target experiments on PBFA II showing upper diagnostics, upper shield, and diode.

Additional diagnostics are positioned beneath the accelerator inside another tungsten shield. The lower package includes both distant (3 m) and close-in diagnostics. The diagnostics mounted at about 3 meters from the target include on-axis x-ray pinhole cameras, a grazing incidence spectrometer, and a multichannel x-ray diode (XRD) detector array for obtaining energy cuts of the target x-ray spectrum. The close-in diagnostics include four more x-ray pinhole cameras, a streaked x-ray imaging camera, and a convex crystal spectrometer. The target configuration with a small titanium cone target mounted in the gas cell is shown in Figure 3.

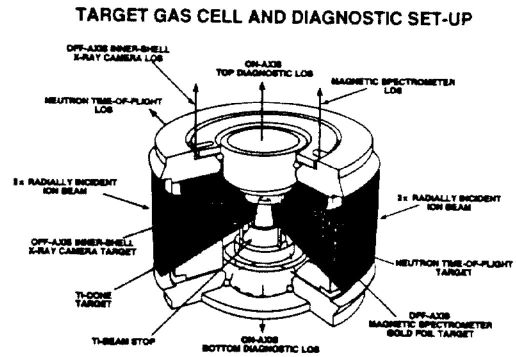

Figure 3. Configuration for target experiments showing small cone mounted in the gas cell.

Three series of target experiments have been completed on PBFA II so far [2,3,4]. The first series used large (15-20 mm midplane diameter) range-thick cones for development of target diagnostics. The second series used smaller cones (7.5-10 mm midplane diameter) for measurement of azimuthal beam uniformity and correlation of diagnostic data obtained at large radius with that obtained on the diode axis. The third series began the study of intense ion beam deposition in a low-density foam seeded with chlorine for x-ray imaging. In these series of experiments, we have made considerable progress on developing PBFA II as a target shooter and beginning to demonstrate the utility of light ions for targets by

- using large conical targets (CF_2) to develop and characterize target diagnostics, and to benchmark a CRE code,

- using planar Rutherford scattering targets and large conical K-alpha targets (Au) to cross-correlate on-axis and off-axis diagnostics,

- using small conical targets (Ti) and x-ray diagnostics to diagnose the stagnation of the range-thick target material on the axis,

- using large "apron" (conical) targets targets (Au) to directly measure the azimuthal uniformity of the ion beam passing through the foil on its way to the diode axis,

- using small conical targets (Al) to make the first-ever observation of K-alpha satellites (up to boron-like Al) in an ion beam heated target, and

- using chlorine-seeded carbon foam targets to diagnose ion beam deposition uniformity in low density foam, in preparation for integrated hohlraum experiments.

Future target experiments will concentrate upon diagnosis and improvement of ion beam deposition uniformity, measurement of the uniformity of the pressure pulse for driving implosion targets, and the hydrodynamics of target implosions. These target experiments will be more interesting if our development of lithium beams continues to be successful, and if we are able to reduce the divergence of the lithium beam.

V. LITHIUM SOURCE RESULTS

Our present efforts to develop a lithium ion source are focused on thin film-based approaches: (1) LiF, which uses a thin (10 micrometer) coating of lithium fluoride which is vacuum deposited on a stainless-steel anode, and (2) LEVIS [5], a laser-heated, laser-ionized source. In experiments on PBFA II with LiF and LEVIS, the lithium was accelerated as Li^{+1}. With the LiF source, comparison of measured lithium and total currents, using Faraday cups, showed lithium beam purity of unity at peak lithium power, within resolution of the diagnostics. Particle-in-cell simulations of the ion transport in the experiments, using actual voltage and current waveforms, indicate high lithium beam purity for the first 15ns of the beam pulse, and decreasing purity thereafter. We do not yet understand the decrease in beam purity with time. Optimization of the lithium source behavior for target experiments is the highest priority in our program.

VI. ION BEAM DIVERGENCE

Simulations using the three-dimensional electromagnetic particle-in-cell code QUICKSILVER have identified an early-time diocotron instability in the electron flow in the diode. Analytic calculations, which include a charge-neutral region in the diode following the beam acceleration gap, produce a calculated growth rate for the diocotron instability in good agreement with the simulations. In the QUICKSILVER simulations, the early-time diocotron instability evolves during the pulse to a low-frequency instability which couples energy to the ion beam on the ion beam "transit-time" timescale. When this enhanced coupling occurs, the ion divergence increases dramatically. A trend of decreasing ion beam divergence with decreasing ion current enhancement over the Child-Langmuir value is also found in the simulations. The simulations suggest a potential means to reduce ion divergence. By providing better control over the evolution of the electron density in the anode-cathode gap, the simulations show that the low divergence phase can be extended, avoiding the strong coupling between electromagnetic instabilities and the ion beam. Specific solutions include providing the electron control with an increased magnetic field (about 8 T), and using a protrusion from the anode (electron limiter) to limit electron density near the anode [6].

VII. ADVANCED DRIVER DEVELOPMENT

Progress on development of advanced light ion drivers for ICF (i.e., beyond PBFA II) is being made in conceptual studies and hardware prototypes. The light ion Laboratory Microfusion Facility (LMF), designed as a high yield simulator of nuclear weapon effects, is shown in Figure 4. As presently envisioned, it consists of 36 pulsed power modules. Twelve of these are rated at 20 MV and have electrical characteristics very similar to the Hermes III accelerator, shown in Figure 5, but they are operated in positive polarity. The remaining 24 modules are rated at 30 MV and 1.5 MA, a modest scale-up from the 20 MV, 0.7 MA level of Hermes III.

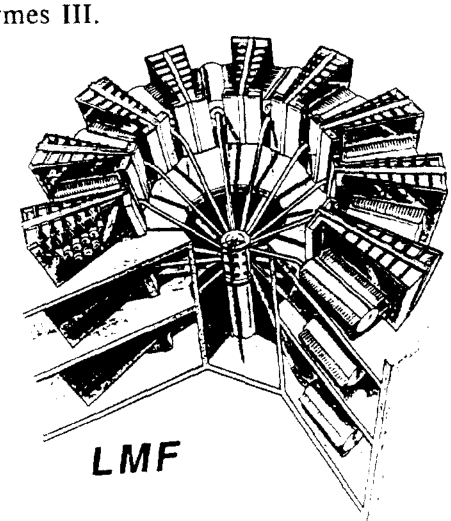

Figure 4. Light Ion Laboratory Microfusion Facility

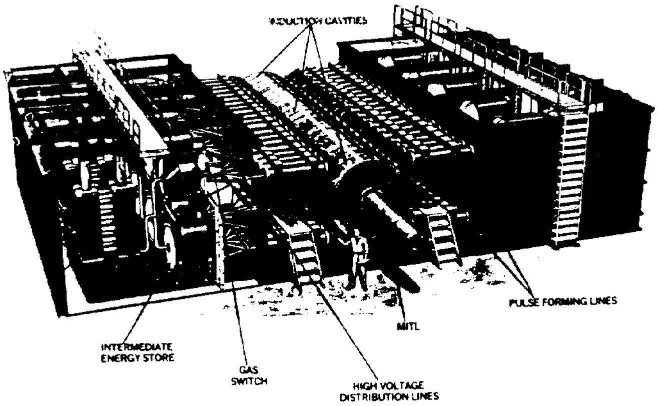

Figure 5. Hermes III Accelerator

Conceptual work on a light ion beam driven ICF reactor is being done jointly in the LIBRA (Light Ion Beam Reactor Assessment) study. The participants in the study include the Kernforschungszentrum Karlsruhe (KfK), the University of Wisconsin, Pulse Sciences Inc., and Sandia National Laboratories. Although the study is still in process, preliminary results from the 1000 MWe design show that light ion driven ICF can offer generation of electrical energy at a competitive electricity cost [7].

VI. SUMMARY

Advances in ion beam theory, diagnostics, and experiments in the past two years have produced a 5 TW/cm^2 proton beam. Target experiments using this beam have produced data on total proton energy, proton beam uniformity, and beam-target interaction physics. Experiments are being planned to measure ion beam deposition in heated material quantitatively. In parallel with these target experiments driven by intense proton beams, we are concentrating on development of a lithium ion beam. Two lithium sources have shown promising results, including production and acceleration of singly ionized lithium and high beam purity. The major challenge now lying ahead is that of increasing the amount of energy in the lithium beam and reducing the beam divergence. With success in these areas, we should be able to demonstrate a radiation-dominated hohlraum for providing beam smoothing at the implosion capsule, and begin implosion experiments driven by intense lithium beams. These achievements will demonstrate the utility of light ion beams for ICF.

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