PROGRESS IN THE PULSED POWER INERTIAL CONFINEMENT FUSION PROGRAM* SAND--96-0950C

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ABSTRACT

Pulsed power accelerators are being used in Inertial Confinement Fusion (ICF) research. In order to achieve our goal of a fusion yield in the range of 200 - 1000 MJ from radiation-driven fusion capsules, it is generally believed that ~10 MJ of driver energy must be deposited within the ICF target in order to deposit ~1 MJ of radiation energy in the fusion capsule. Pulsed power represents an efficient technology for producing both these energies and these radiation environments in the required short pulses (few tens of ns). Two possible approaches are being developed to utilize pulsed power accelerators in this effort: intense beams of light ions and z-pinches. This paper describes recent progress in both approaches. Over the past several years, experiments have successfully answered many questions critical to ion target design. Increasing the ion beam power and intensity are our next objectives. Last year, the Particle Beam Fusion Accelerator II (PBFA II) was modified to generate ion beams in a geometry that will be required for high yield applications. This modification has resulted in the production of the highest power ion beam to be accelerated from an extraction ion diode. We are also evaluating fast magnetically-driven implosions (z-pinches) as platforms for ICF ablator physics and EOS experiments. Z-pinch implosions driven by the 20 TW Saturn accelerator have efficiently produced high x-ray power (> 75 TW) and energy (> 400 kJ). Containing these x-ray sources within a hohlraum produces a unique large volume (> 6000 mm^3), long lived (>20 ns) radiation environment. In addition to studying fundamental ICF capsule physics, there are several concepts for driving ICF capsules with these x-ray sources. Progress in increasing the x-ray power on the Saturn accelerator and promise of further increases on the higher power PBFA II accelerator will be described.

1. INTRODUCTION

Sandia National Laboratories is investigating the feasibility of using a pulsed power accelerator as a driver for Inertial Confinement Fusion (ICF). High power accelerators have been used in ICF research for over 20 years to produce intense beams of light ions and energetic x-ray sources from fast magnetic implosions (z-pinches). In order to achieve the US National ICF program goal of a fusion yield in the range of 200 - 1000 MJ from radiation-driven fusion capsules, it is generally believed that ~10 MJ of driver energy must be deposited within the ICF target in order to deposit ~1 MJ of radiation energy in the fusion capsule. Pulsed power represents an efficient technology for producing both these energies and these radiation environments in the required short pulses (few tens of ns).

2. IONS FOR HIGH YIELD AND ION BEAM TARGET PHYSICS

Sandia National Laboratories is investigating the feasibility of obtaining high fusion yield for defense and energy applications using intense beams of light ions as a driver. This long term goal would be realized in a High Yield Facility (HYF). The fusion capsules in our ion-driven [1] ICF targets are indirectly driven by the radiation that is produced when the ion beam travels through a high-z radiation case and deposits the bulk of its energy in a low density foam that surrounds the fusion capsule. Capsule symmetry and ion diode requirements have led us to a spherically symmetric

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ion beam configuration, where the two steps of the ion beam drive consist of twenty and twelve beams that are spatially arranged on the vertices and faces, respectively, of a dodecahedron. During the first step (or "foot") of the HYF ion beam drive pulse, 24 MeV lithium ions at a flux of 5 TW/cm^2 produce temperatures approaching 100 eV. In 1993 a lithium ion beam from a radial ion diode was focused to ~1.4±0.4 TW/cm^2 and was used to heat a hohlraum to 58±4 eV on the PBFA-II accelerator. The key physics principles of an ion beam ICF target were demonstrated in these radial diode experiments including ion beam deposition, radiation conversion, tamping of the radiation case by the foam, optically thin foam, and radiation smoothing [2].

The second step, or main HYF drive pulse, consists of 35 MeV lithium ions at a flux of just over 50 TW/cm^2, producing drive temperatures of approximately 250 eV. Generation, transport and focusing of a lithium to HYF target intensities presents a formidable challenge to the ion beam project. A major limitation in achieving higher lithium beam intensities with the radial ion diode on PBFA II was the parasitic load that limited the lithium beam power to about 6 TW [3]. Research on PBFA II and the SABRE accelerators in 1994 and 1995 identified the parasitic load as contaminant ions that are desorbed from the anode and ionized during the accelerator pulse. In 1995, the lithium beam generation efficiency was increased by a factor-of-three on the SABRE extraction diode by anode cleaning that included RF discharges and inductive anode heating [5] as shown in Fig. 1.

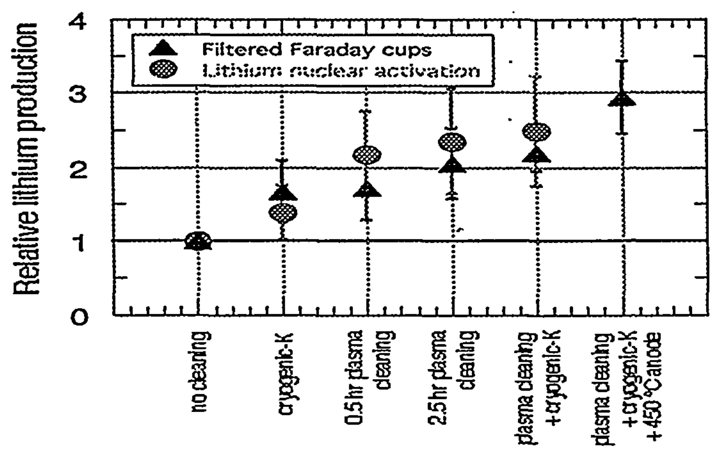

Fig. 1 SABRE heating and cleaning results.

2.1. PBFA-X

In 1996 Sandia's target physics research program moved to laser and Z-pinch drivers and the world's most powerful accelerator (PBFA II) was modified to generate ion beams in a geometry and at a power level that will allow the remaining key physics issues of light ion driven ICF to be resolved. This modification has resulted in the production of the highest power ion beam (4 TW lithium) to be accelerated from an extraction ion diode. A new modeling capability for generating uniform ion current density was developed and successfully tested on PBFA-X. We evaluated the application of SABRE cleaning techniques to ion diodes at PBFA power levels and demonstrated a dramatic increase in ion diode impedance using a LiF passive ion source. We achieved 15 MV and 0.3 MA lithium ion diode operation. Finally, we performed preliminary experiments using an active laser- produced ion source and achieved a 10 ns earlier production of ion current at a 25% higher ion power compared to a LiF ion source, yielding the 4 TW of lithium beam power. FY97 and FY98 ion beam experiments to explore the key research issues in ion beam generation, focusing, and transport physics will be primarily performed on the SABRE accelerator as well as the COBRA accelerator at Cornell University and the GAMBLE-II accelerator at the Naval Research Laboratory (NRL). Related experiments will be conducted in Germany, Japan. and Russia.

2.2. Key issues

The key ion beam issues to be resolved fall into two main areas: beam intensity and standoff. The ion beam intensity is determined by the total ion beam power and the ion beam divergence (FWHM of focus). Our 3-D electromagnetic particle-in- cell simulations of ion diodes suggest that the electromagnetic contribution to the ion beam divergence can be controlled by controlling the electron sheath through high magnetic fields or by physical limiters that keep electrons away from the anode[4]. Electron control is also important because cross field diffusion allows electrons to reach the anode which reduces power efficiency. The electron loss also heats the anode leading to thermal and stimulated desorption of monolayer surface contaminants that become ionized and generate a parasitic loss current of ions. RF discharge cleaning of the electrode surfaces can help suppress this parasitic current; the efficiency of lithium production has increased three-fold on the SABRE accelerator using these techniques[5] as shown previously in Fig. 1. Recent experiments on PBFA-X have shown a large increase in diode impedance using RF cleaning. Limiting the electron flux to the anode also reduces the parasitic current problem by limiting the anode temperature rise. However, limiting the electron flux to the anode means that a passive ion source, such as the thin film LiF lithium ion source, can not be used. Spectroscopic measurements of the electric field in the diode indicate the LiF requires an 8 MV/cm field to emit lithium and that the source divergence is ~17 mrad [6]. An active ion source where an independent energy source is used to prepare an anode plasma is required to allow both control of the electron distribution and reduce the source divergence to an acceptable level. Two-stage acceleration is attractive because acceleration at roughly constant emittance in the second stage reduces the total beam divergence and also increases the total efficiency of the diode-to-beam power coupling. In our conceptual designs, the power, voltage, impedance and divergence requirements placed on the HYF ion diode require the use of a two-stage ion diode.

Standoff is required for high yield applications to protect the ion diode from the target blast. The baseline transport mode of our previous HYF study was an achromatic lens system that required an ion beam divergence of 6-8 mrad. Self-pinched ion beam transport is an attractive mode for all high yield and fusion energy applications and could relax the ion beam divergence requirements on the ion diode. The primary physics issue is whether gas breakdown will produce sufficient net currents to allow self-pinched experiments. A more complete description is found in a companion paper [7].

Success in establishing scaling laws and controlling solutions for these key issues on the SABRE, COBRA, and GAMBLE accelerators could lead to future high-power ion diode experiments on HERMES-III and eventually to an HYF module initiative.

2.3. Additional applications of ion beam technology

Near term applications of light ion beam technology are being developed in addition to the long term use of high intensity ion beams for high yield ICF. Low-power, large-area, repetitive ion beams are being generated by magnetically insulated ion diodes for use in advanced materials modifications including increased surface hardness, decreased surface roughness, and increased corrosion resistance [8]. Light ion beams are also being used at the Research Center in Karlsruhe, Germany to perform shock-wave physics experiments that can provide information on equation of state, the dynamics of beam interaction with condensed targets, and the properties of solids and plasmas a high-energy densities [9].

3. FAST MAGNETIC IMPLOSIONS

We are also evaluating fast magnetically-driven implosions (z pinches) as platforms for ICF capsule ablator physics, EOS, opacity, and capsule implosion experiments.

3.1. X-ray production with z-pinches

Z-pinch implosions are efficient sources of x-rays. On the 20 TW Saturn accelerator, for example, greater than 10% (> 400 kJ) of the electrical energy stored within the capacitor banks can be converted into x rays [10]. Maintaining cylindrical symmetry, i.e. perfect axial and azimuthal uniformity, in the initial load design is an important element in controlling the power generated by these sources . The additional requirement of low mass, typically less than 500 mg/cm for fast drivers such as Saturn, makes fabricating the ideal cylinder challenging. The high symmetry, low-mass tradeoff has led historically to the choice of gas puffs, low-density foams, or thin foils over cylindrical arrays of thin wires. Recent data [11] from aluminum wire array implosions on Saturn, where the gap between adjacent wires within the array was varied from 6 mm down to 0.4 mm, show a dramatic increase in x-ray power output below a circumferential gap spacing of 1.4 mm (Fig. 2). From 2D calculations of these implosions, this sharp increase in power corresponds to the transition where the imploding plasma behaves as a plasma sheath instead of an ensemble of individual imploding wires. We have applied this same concept to increase the power output from the z-pinch implosion of wire arrays containing high-Z elements. In Fig. 3 we show representative time-dependent x-ray power output from arrays of tungsten wires[12]. The 24, 40, and 70-wire arrays at an initial diameter of 12.5 mm result in peak x-ray powers of 20, 28, and 40 TW, respectively. Increasing the wire number to 120 at an initial diameter of 17.5 mm resulted in a peak x-ray power of ~80 TW, which represents a power gain of approximately four over Saturn's electrical power.

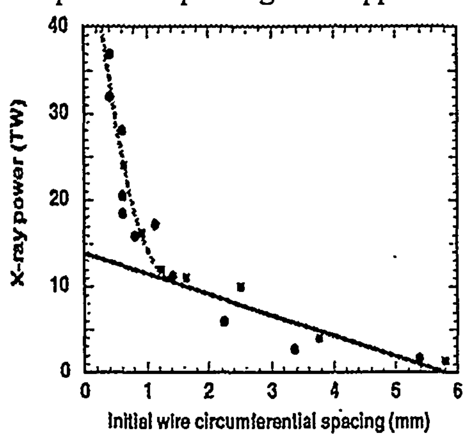

Fig. 2 X-ray power vs. wire spacing

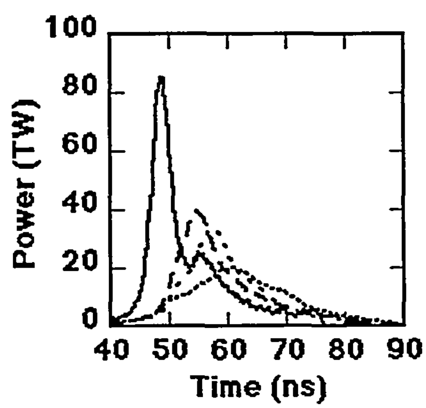

Fig. 3 X-ray power vs. wire number

3.2. Z-pinch heated hohlraums

To both increase the x-ray intensity and improve the x-ray spatial uniformity, we have enclosed these wire array z-pinch x-ray sources within a large, 2-cm diameter, 2-cm long cylindrical hohlraum. If we assume that 80% of the x-rays that are incident on the high-Z inner walls of this hohlraum are re-radiated back into the hohlraum volume, then a simple power balance predicts that the x-ray intensity inside this container will be a factor of four larger that the power generated by the z-pinch source itself. Measurements of the x-ray emission from the hohlraum walls at the time of peak power and the time-dependent hohlraum temperature produced by containing a 40-wire array within this hohlraum are shown in Fig. 4. Although the re-radiation of the z-pinch x-rays from the high-Z walls of the hohlraum effectively produces a Planckian radiation source, any ICF capsule-relevant physics package that is attached to the side of this hohlraum will also directly view the non-Planckian z-pinch source. To eliminate this direct line of sight to the z-pinch source, we have added two smaller cylindrical hohlraums (~ 6 mm in diameter by 10 mm in length) to the side of the z-pinch hohlraum. This geometry, as illustrated in Fig. 5, provides a spatially uniform, nearly-Planckian radiation source for capsule ablator physics and EOS experiments, and allows for simultaneous measurements in multiple hohlraums. In 3-mm-diameter samples attached to these smaller hohlraums, we have generated 1 Mbar shocks in aluminum that show spatial uniformity of ~ 1 eV/mm over the extent of the sample.

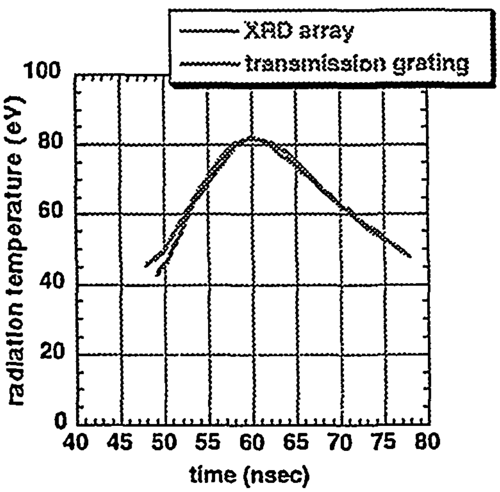

Fig. 4. Hohlraum temperature

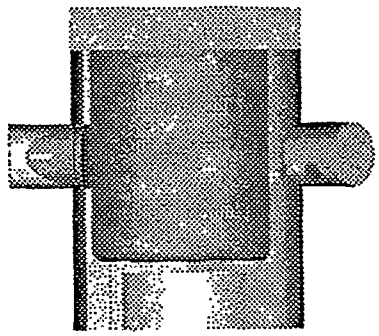

Fig. 5. Main and side hohlraum configuration

3.3. Z-pinch driven capsule implosions

A concept for efficiently using the energy of a z-pinch implosion to indirectly drive an ICF capsule is shown in Fig. 6, which illustrates this imploding hohlraum concept at the time when an imploding plasma shell is beginning to stagnate upon a cylinder of low density foam that contains an ICF capsule. The shock waves produced when this stagnation occurs heat the plasma, and create radiation fronts that propagate both into the foam and outward through the imploding plasma shell. In a high-Z material, the radiation front is subsonic and the imploding plasma shell can effectively contain the radiation produced by the stagnation. In a low-Z, low density foam, however, the radiation front is supersonic and quickly bathes the ICF capsule in a uniform radiation environment. In one-dimensional calculations, the time differential between the arrival of the radiation front and the shock front at the cylindrical axis of symmetry can exceed 10 ns. In addition, our two-dimensional calculations show that the ablation of the capsule itself isolates the imploding capsule ablation front from the imploding z-pinch plasma. This isolation allows the spherical ICF capsule to reach its peak compression with minimal asymmetric effects from the cylindrical symmetry of the imploding plasma shell. Key physics issues in this imploding hohlraum concept include the Rayleigh-Taylor instabilities in the imploding plasma, capsule preheat mechanisms, and the time-dependent radiation drive symmetry at the capsule ablation surface. In initial experiments on Saturn, we have tested this concept by imploding arrays of tungsten wires onto low density (3-6 mg/cm^3) aerogel foams. Comparisons of the end-on to side-on x-ray output are consistent with our calculations, and indicate the potential to both contain the radiation within the high-Z imploding plasma and produce a time-dependent radiation drive within the foam.

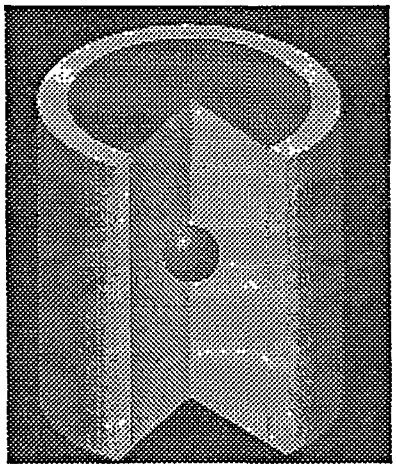

Fig. 6. Imploding hohlraum concept

3.4. PBFA-Z

The modifications that will enable PBFA II to drive imploding plasma loads [13] will be completed and tested in 1996. In this configuration, PBFA II can deliver up to 18 MA of current to a wire array load with a rise time of ~100 ns. With tungsten wire arrays, our calculations predict that PBFA will produce up to four times the energy (>1.5 MJ) and twice the power (>150 TW) of similar wire array configurations on Saturn. At these energy and power levels, the temperatures within the vacuum hohlraums should exceed 125 eV. Experiments to verify these predictions will begin this fall.

4. CONCULSIONS AND FUTURE PLANS

Experiments on pulsed power accelerators have demonstrated that x-rays can be generated with high efficiency using fast z-pinches and intense light ion beams can be focused and interact with matter to produce x-rays in a favorable way. Over the next few years, the scaling of these z-pinch results to higher x-ray energy and power will be attempted on PBFA-Z. If favorable results are obtained, the way will be clear to even higher energies and powers on follow-on accelerators. The key issues limiting the intensities of focused light ion beams will also be addressed. Favorable results in this area will allow consideration of a high yield facility based upon light ion beam driver technology.

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