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PULSED POWER FUSION PROGRAM UPDATE*

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Abstract

The U. S. Department of Energy has supported a substantial research program in Inertial Confinement Fusion (ICF) since the early 1970's. Over the course of the ensuing 25 years, pulsed power approaches to inertial fusion have remained of interest primarily because of the high energy, efficiency, and relatively low cost of the technology when compared to the mainline ICF approach involving large glass lasers. These compelling advantages of pulsed power, however, have been tempered with the difficulty that has been encountered in concentrating the energy in space and time to create the high energy and power density required to achieve temperatures useful in indirect drive ICF. Since the Beams '96 meeting two years ago, the situation has changed dramatically and extremely high x-ray power (~290 TW) and energy (~1.8 MJ) have been produced in fast z-pinch implosions on the Z accelerator. These sources have been utilized to heat hohlraums to > 150 eV and have opened the door to important ICF capsule experiments.

Introduction

For more than two decades, scientists in laboratories around the world have been utilizing pulsed power drivers with very short (10's of nanoseconds) pulse lengths for Inertial Confinement Fusion (ICF) experiments. In the United States, this research has been sponsored by Defense Programs within the Department of Energy. During this period, the fundamental pulsed power components and accelerator architectures have evolved to a remarkable extent and today electrical pulses exceeding 50 TW are routinely obtained on the Z accelerator at Sandia National Laboratories. Many of the technological advances in pulsed power were driven by the demanding requirements placed upon accelerators by the needs of the fusion program. These requirements are driven by the goal of achieving up to 1 GJ of fusion yield from an ICF capsule for defense and energy applications. While the fusion yield goal has remained remarkably the same for the better part of two decades, the required driver energy, capsule symmetry, and capsule drive pulse shape have evolved considerably as the community

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has learned more about the coupling of driver energy into the capsule ablator and the capsule response to this energy deposition.

At the same time as the driver requirements were changing, the driver options for pulsed power were evolving as well. Early driver technologies included intense electron beams and z pinches. In the late 70's after the development of very intense electron beam diodes, a shift from electrons to ions was dictated by the more favorable deposition characteristics of the more massive ions. Z-pinch experiments continued to improve in radiated power and energy and were applied to other applications but funding from the ICF program was suspended in favor of ions. While advances in understanding in the physics of intense light ion beam were substantial, the record ion beam intensities that have been achieved (~5 TW/cm^2 - protons, ~3 TW/cm^2 - lithium) remain far below the requirements of ICF (~100 TW/cm^2).

By 1994 on the Saturn accelerator, z-pinch x-ray power and energy output had been increased to the level (~20 TW and ~400 kJ) that important ICF experiments could begin. The success of these experiments and the recent breakthroughs in z-pinch performance (~ 290 TW and 2MJ of x rays, >150 eV in a hohlraum) have led to another major shift in emphasis in pulsed power fusion. Beginning in 1999, the entire pulsed power fusion effort at Sandia will be directed toward developing z-pinch x-ray sources for ICF. This paper will describe the present status of the pulsed power fusion program at Sandia and the plans to further develop this promising path to fusion.

The long term goal of ICF research is the production of high yield. High yield in this context means thermonuclear yield of 200-1000 MJ. In 1994, glass laser technology was chosen to demonstrate ignition in the laboratory. The National Ignition Facility will be a large laser capable of delivering 1.8 MJ of 3ω (350 nm) light to a target. The 1.8 MJ of laser energy will result in ~ 100 - 150 kJ of x-ray energy absorbed in the capsule. The predicted thermonuclear yield with this absorbed x-ray energy is 2 - 20 MJ. Ignition demonstration on the NIF would be a major step forward toward obtaining high yield in the laboratory. However, a high-yield target is expected to require approximately 1-2 MJ of x-rays absorbed in the capsule ablator with radiation symmetry on the surface of the capsule of better than 1%. In order to achieve this radiation symmetry, a large case-to-capsule radius ratio is needed. Consequently, a driver will be required with approximately 10 MJ of x-ray energy, prohibitively expensive using laser technology. In addition, the x-ray power pulse incident on the capsule must have an appropriate time variation (shaped pulse) to keep the DT fuel on a low adiabat during compression. Furthermore, any energy application of ICF will require a repetitive pulse capability (4 Hz). Pulsed-power-driven ICF offers an attractive alternative with affordable, high energy, high efficiency drivers and the potential for repetitive pulse operation.

Progress in Z-pinch Development

Recent progress in x-ray generation using z pinches has been remarkable and has prompted a major shift in Sandia's ICF program. Z pinches are now seen to provide the fastest route to demonstration of high yield in the laboratory. Pulsed power accelerators have been used for many years to drive magnetic implosions (z-pinches). The load in these implosions has varied from cylindrical arrays of wires arranged at constant radius, to gas puffs and low density foams. These loads have historically coupled extremely well to pulsed power accelerators with resulting high electrical-to-kinetic energy efficiency. In the application as an x-ray source, the kinetic energy in the imploding system is converted into x-rays when the imploding plasma stagnates on axis or on a cylindrical cylinder. Z-pinches have historically been efficient at coupling electrical energy into kinetic energy in the implosion system, but the x-ray power available from these z-pinches has been limited to less than 20 TW. Beginning in the summer of 1995, however, breakthroughs in load fabrication (which allowed in excess of 190 5 μg/cm Al and W wires to be mounted forming a 1 - 2 cm diameter cylindrical array) and improved understanding of load behavior have resulted in dramatic improvements in x-ray power available from these sources. By early 1996, the x-ray power available from a tungsten load exceeded 85 TW, by far the most power ever generated in a laboratory device. Remarkably, the energy in x-rays remained nearly constant at 400 - 500 kJ as the power increased. These results were obtained on the Saturn accelerator. Such high power and energy x-rays sources have major applications in the ICF program.

While the breakthrough experiments were being conducted on Saturn, a major modification to the Particle-Beam Fusion Accelerator (PBFA II) was underway. The intent of the modification was to allow z-pinch experiments at higher currents than possible on Saturn to validate the scaling of x-ray power and energy with z-pinch current. The modified accelerator configuration was called PBFA-Z and later shortened to Z. Ambitious goals set for Z during design included delivering 18 MA to the pinch, producing 1.5 MJ and 150 TW of x-ray energy and power, and using this x-ray source, heating a vacuum hohlraum to > 100 eV and a dynamic hohlraum to > 120 eV. The first radiation producing experiment on Z was conducted in October of 1996 and within the first month of operation, the current, energy and power milestones were met. The x-ray power available from a z-pinch implosion is limited by the Rayleigh-Taylor instability. Mitigating the effects of this instability can greatly increase the total radiated power. Progress in this area has also been significant with a major advance occurring when nested wire arrays were employed. Analysis and computer simulations suggested that if one wire array were imploded onto another wire array at smaller radius, the growth of the R-T instability could be reduced. Experiments which optimized the mass ratio between he inner and outer arrays resulted in a 50% increase in radiated power. Today, the x-ray output of Z has climbed to 290 TW and 1.8 MJ. The energy and power scaling has been confirmed ($E,P \propto I^2$). Figure 1 shows the agreement in radiated energy scaling with z-pinch current over two decades in x-ray energy. Figure 2 plots the x-ray power increases as a function of year illustrating the very rapid progress of the past two years.

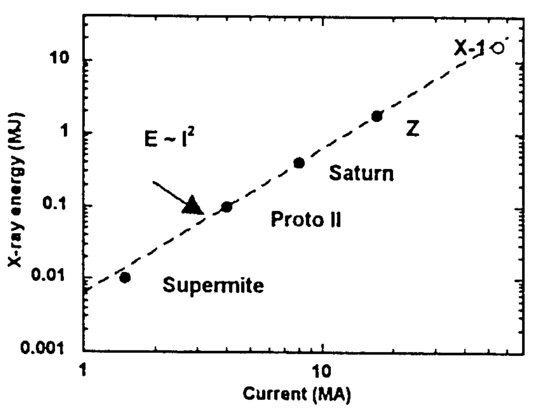

Figure 1. X-ray energy vs. z-pinch current

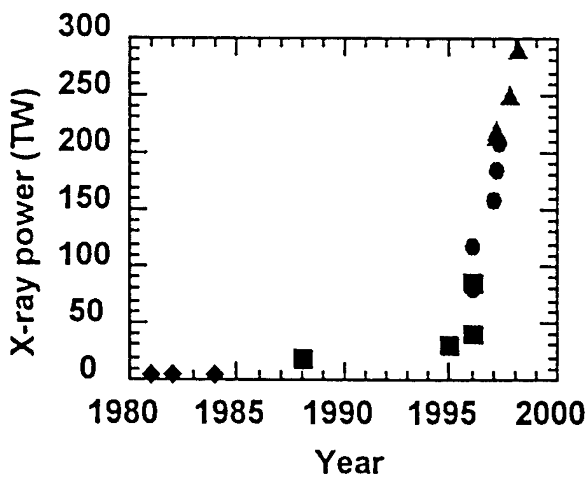

Figure 2. X-ray power vs. year

Hohlraum heating and target concepts

This high x-ray output has enabled experiments to begin to optimize the temperature in hohlraums. Progress in this area has also been rapid. 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 large (up to 2-cm diameter, 2-cm long) cylindrical hohlraums. This configuration is denoted a "static walled" or "vacuum" 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 five larger than the power generated by the z-pinch source itself. Measurements indicate the hohlraum temperature exceeds 150 eV when a 20 mm diameter 300-wire tungsten array implodes within a 10 mm long, 23 mm diameter hohlraum. The re-radiation of the z-pinch x-rays from the high-Z walls of the hohlraum effectively produces a Planckian radiation source. If the imploding array itself contains (re-radiates) radiation into the cylindrical region within the array, a dynamic hohlraum can be formed. Experiments in this configuration have shown that a dynamic hohlraum does indeed form and significant gains in radiation temperature have been achieved. In experiments on Z, a nested wire array was imploded onto a plastic annular target (2.5 mm radius, 3 mg). The peak temperature obtained while the hohlraum remained useful for driving a capsule experiment (imploding cylindrical shell remains open in x-ray image with radius greater than ~ 1 mm) was > 155 eV.

There are currently three generic z-pinch driven capsule configurations being considered as possible high yield targets. These concepts are shown in Figure 3. They include hohlraum concepts that range from the vacuum or static walled to the dynamic walled. The concepts explore variations in the level of conservatism in the z-pinch source characteristics versus drive temperature and source efficiency.

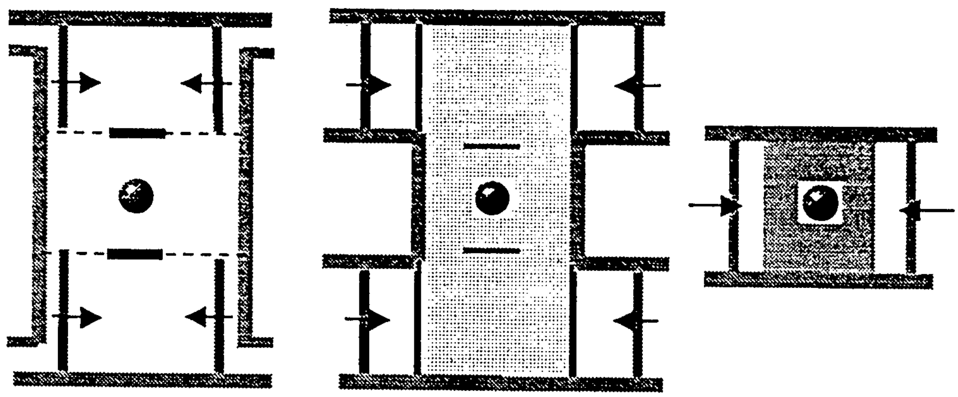

Figure 3. Three hohlraum/capsule concepts for high yield.

These high temperature hohlraum results enable the first capsule experiments which are scheduled to begin this summer. These first experiments with capsules will be employ internal dynamic hohlraums driven by nested wire arrays. Currently the internal dynamic hohlraum provides our highest radiation temperatures in an open volume while simultaneously producing a reasonably symmetric radiation drive. At the time of this writing, a 240 on 120 wire nested tungsten array of 3 mg total mass striking a 2.5 mg deuterated plastic cylinder of 5 mm diameter yields a first strike temperature of 80 eV which linearly ramps to 180 eV over roughly 7 ns. While the high-temperature of the internal dynamic hohlraum is preferred over external hohlraums, target designs are constrained by the time between first-strike and stagnation when the dynamic hohlraum is open.

Capsule design and modeling are being carried out with the Lasnex lagrangian radiation hydrodynamics code. High-resolution capsule performance simulations are accomplished with 1-D calculations using experimentally obtained drive histories. Integrated 2-D simulations incorporating the tungsten wire impact on the dynamic hohlraum are used to address capsule drive symmetry. The current capsule design is a 1600 micron inner diameter sphere with a 30 micron thick polysytrene shell fabricated by General Atomics. For enhancing the fill gas lifetime, a permeation barrier consisting of approximately 4 microns of PVA and 0.6 microns of aluminum is coated on the shell. These capsules will be filled with 16-18 ATM of deuterium gas with an optional 0.1 ATM of a diagnostic dopant gas such as argon. Clean 1-D simulations predict a neutron yield of $\sim 3\times10^{10}$ for an undoped polystyrene shell while the yield increases to $\sim 1\times10^{11}$ with a 2.5% atomic fraction germanium doping.

Experimental diagnostics for this series can be divided into source diagnostics and capsule diagnostics. Characterization of the dynamic hohlraum environment will be determined through filtered XRDs both on- and off-axis, and filtered, time-resolved x-ray framing cameras. Capsule performance will be assessed through neutron time-of-flight, neutron activation and a filtered, time-resolved x-ray framing camera for imaging the imploding capsule emission. Careful characterization of the experiment is a necessity, as comparison of the capsule performance with simulation will provide the starting foundation for our high-yield dynamic hohlraum targets for the proposed X-1 facility.

X-1 is a proposed facility that would deliver ~ 60 MA to a z-pinch load. The scaling curves suggest that X-1 would be capable of producing ~16 MJ and > 1000 TW of x-ray energy and power and would be capable of heating hohlraums to > 250 eV. Simulations indicate that these conditions would allow capsule/hohlraum configurations to yield in excess of 200 MJ fusion output. X-1, if approved, could be built and high yield experiments begun by 2010.

Status of Light Ion Beam Development

Light ion beams have long offered the potential of capitalizing on the efficiency of pulsed power in applications for inertial fusion energy (IFE) by offering standoff and repetitive pulse operation. Progress in developing light ion beams for ICF has been substantial but many obstacles remain. The key physics principles of an ion beam ICF target were demonstrated in radial diode experiments including ion beam deposition, radiation conversion, tamping of the radiation case by an optically thin foam, and radiation smoothing. Utilizing light ion beams for IFE will require the development of extraction ion diodes with much higher beam brightness than has been demonstrated to date. Ion beam issues remaining 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. Simulations of ion diodes suggest that an 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. 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 substantially on the SABRE accelerator using these techniques. 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. Light lab experiments have determined the minimum laser fluence on the anode needed to produce a uniform plasma ion source. An experimental series that integrates all of these concepts at once (high magnetic field, active-laser-produced ion source, electron limiter, and improved anode conditioning) is in progress on the SABRE accelerator at Sandia.

Standoff is required for high yield applications to protect the ion diode from the target blast. The baseline transport mode of previous studies 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 both light and heavy ion fusion energy applications and could relax the ion beam divergence requirements on the ion diode. Self-pinched transport experiments are being conducted at the Naval Research Laboratories. Success in establishing scaling laws and controlling solutions for these key issues on the SABRE, COBRA, and GAMBLE accelerators could lead to future higher-power ion diode experiments and eventually to a repetitive high yield facility for energy production.

Conclusions

Pulsed power provides an economical source of x-ray energy and power for ICF research. Experiments on pulsed power accelerators have demonstrated that x-rays can be generated with high efficiency using fast z-pinches. Experiments are planned to continue to optimize these sources for application to ICF. The first capsule experiments on Z using a z-pinch x-ray source are planned for later this summer. These and similar capsule experiments will provide validation of computer models of capsule designs. Z-pinches represent the best means to generate high-energy, high-power x-ray environments for exploring pulsed power driven ignition and high-yield relevant capsule physics. In the far term if the remaining ion beam brightness and transport issues can be resolved, light-ion driven ICF could offer repetitive high yield for energy production. Sandia's pulsed power ICF program is focused upon exploiting the advantages of pulsed power in fusion research.

Acknowledgments

The authors would like to recognize the extraordinary contributions to this research made by George Allshouse and Alex Filuk both recently deceased. They have had a profound impact on our understanding of pulsed power fusion The pulsed power ICF program is an international effort. Important contributions to the field are being made by scientists and engineers from around the world. This presentation has emphasized activities at Sandia National Laboratories, however, the authors would like to acknowledge our many colleagues who have contributed to the recent progress. Many of these advances are presented elsewhere at this conference.

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