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Z pinches as intense x-ray sources for Inertial Confinement Fusion applications

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ABSTRACT

Fast z-pinch implosions can convert more than 10% of the stored electrical energy in a pulsed-power accelerator into x-rays. On the Saturn pulsed-power accelerator at Sandia National Laboratories, currents of 6 to 8 MA with a risetime of less than 50 ns have been used to drive cylindrically-symmetric arrays of wires, producing x-ray energies greater than 400 kJ with x-ray pulsewidths less than 5 ns and peak x-ray powers of 75 ± 10 TW. Using similar loads, PBFA Z has produced >1.5 MJ and >150 TW of x-rays in the first four months of operation in the z-pinch mode. These x-ray energies and powers are records for laboratory x-ray production. The x-ray output can be thermalized into a near-Planckian x-ray source by containing it within a cylindrical radiation case (a hohlraum). These energetic, intense, large volume, long-lived hohlraum x-ray sources have recently been used for ICF-relevant ablator physics experiments and offer the potential for performing many new basic physics and fusion-relevant experiments.

1. INTRODUCTION

Sandia National Laboratories is investigating the feasibility of using a pulsed-power accelerator as a driver for Inertial Confinement Fusion (ICF) research. In order to achieve the US National ICF goal of a fusion yield in the range of 200-1000 MJ from radiation-driven (indirect drive) 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 ablator of the fusion capsule. Pulsed-power accelerators represent an efficient technology for producing these energy levels in the required pulsewidths.

Ion beam drivers are an attractive option for high yield ICF, since they offer the potential of both stand-off and repetitive operation for energy applications. The key physics issues in our high yield, ion-driven target designs [1] can be roughly divided into five categories: beam deposition, radiation production, radiation transport and symmetrization, radiation-

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hydrodynamics coupling, and capsule physics. The key issues in ion beam deposition (e.g. stopping power, range shortening, and preheat) and many key issues in production of x-rays by ion beams (e.g. the x-ray spectral distribution and the efficiency scaling with beam intensity) can be studied only with ion beam sources. Some of these issues have been addressed in proton and lithium beam experiments on PBFA II [2]. Most of the remaining issues are driver independent and can be addressed with any x-ray source of the appropriate intensity, duration, and scale size. Based on the recent successes in generating energetic, powerful x-ray sources on Saturn and PBFA Z, we are developing the capability to use these sources to address target issues such as x-ray transport and symmetrization in low density foams, radiation-hydrodynamic coupling, the response of ablator and capsule materials to the low temperature "foot" of the radiation drive, ablation stability and coupling efficiency in the presence of low density foams, internal pulse shaping, and capsule implosion dynamics.

In this paper we briefly describe our work to optimize the x-ray output from magnetic implosions on Saturn and PBFA Z. We also describe the configurations that utilize these energetic x-ray sources to study ICF target physics issues.

2. Z-PINCH-DRIVEN X-RAY SOURCE DEVELOPMENT

For many years the focus of research efforts in fast z-pinch implosions has centered on optimizing the energy and power output in the 1 to 5 keV spectral region [3-8] in order to provide an x-ray source for radiation-material interaction studies. In addition to this traditional application, recent work at Sandia National Laboratories has emphasized the generation of softer x rays that can be thermalized into a near-Planckian x-ray source by containing them within a large, high-Z-lined cylinder (a hohlraum). These large volume, long-lived near-Planckian radiation sources provide a well-characterized x-ray drive for ablator physics and radiation symmetrization experiments relevant to the Inertial Confinement Fusion (ICF) Program, as well as for astrophysical opacity and shock physics experiments. Since higher x-ray intensities and fluences enhance the utility of these z-pinch-driven x-ray sources for all of these applications,

our source development research has emphasized increasing the x-ray energy and power output. [9-11]

The goals of our recent z-pinch-driven x-ray source development research were to perform reproducible experiments that could be quantitatively compared to detailed numerical simulations, to study the x-ray power optimization, and to provide an x-ray source that can be reliably fielded in a hohlraum configuration. To meet these objectives, we have used wire array loads. An annular array of wires is an attractive load configuration for this research because the initial conditions (mass and radius) can be accurately determined, easily varied, and provide excellent initial axial uniformity.

Aluminum is a well-characterized material that is readily available in many different wire diameters and has been used extensively in previous z-pinch implosion experiments. For this reason we performed a series of aluminum wire array experiments on Saturn that systematically studied the dynamics of wire array implosions as a function of wire number for two different initial wire-array radii. In these experiments [9], the initial circumferential gap between adjacent wires was varied from a maximum of ~6 mm to a minimum of ~0.4 mm. For initial wire-array radii of both 8.6 mm and 12 mm, there was a dramatic increase in the peak x-ray emission power when the initial inter-wire gap was decreased below ~1.4 mm. This x-ray power increase was a result of both an increase in the emitted x-ray energy and a decrease in the x-ray pulse width full-width at half maximum (FWHM). Over this range of initial inter-wire gaps, the total radiated energy increased from ~175 to ~350 kJ for the small radius load and from ~240 to ~440 kJ for the large radius load. The x-ray FWHM decreased to less than 4 ns at the highest x-ray powers. These experiments with aluminum wire arrays conclusively demonstrated the necessity of using a very large number of wires within a wire array in order to optimize the x-ray energy and power output from z-pinch implosions, and represent a breakthrough in z-pinch implosion load configurations for large pulsed-power generators.

At temperatures and densities reached in the Saturn experiments [12], the x-ray power from aluminum wire array implosions is limited by the aluminum plasma emissivity. To improve the x-ray power output, we performed a series of experiments on Saturn using tungsten

wire arrays[11] to utilize the higher radiation emissivity of a higher-Z material. Similar tungsten wire array loads were used in the initial PBFA Z experiments. These tungsten wire array data can be summarized by the optimal x-ray energy and power output from both the Saturn and PBFA Z generators. In Figure 1 we show the time-dependent current that flows through a 1.75-cm-diameter array consisting of 120, 7.5- μ m-diameter tungsten wires and the resulting time-dependent x-ray power output. The x-ray pulse has a full-width-at-half-maximum (FWHM) of ~ 4 ns, with a peak power of ~ 80 TW. The total energy of the x-ray pulse is greater than 400 kJ. In Figure 2 we show a similar plot for the current and x-ray power produced on PBFA Z. For these experiments, the optimal x-ray output was achieved with a 4-cm-diameter array consisting of 240, 7.5- μ m-diameter tungsten wires. The x-ray pulse FWHM was ~ 8 ns, with a peak x-ray power of ~ 160 TW and a total radiated energy of ~ 1.6 MJ. These x-ray energies and power are world records for laboratory x-ray sources. Small increases in the x-ray energy and power may be achieved with further optimization of the power flow and load geometries on PBFA Z.

3. Z-PINCH VACUUM HOHLRAUMS

In indirect-drive ICF, high-power energy sources are used to heat high-Z-lined radiation cavities (hohlraums), converting the driver energy into x-rays that implode the capsule. Lasers [13] and ion beams [2] have been traditionally used as the energy sources that create the x rays within the hohlraums. To utilize the efficient z-pinch radiation sources discussed in the previous section as the energy source, a wire array is placed inside of a hohlraum. When current flows into this closed configuration, the wire array implodes, producing x rays at stagnation that are absorbed and re-emitted by the hohlraum wall, which also serves as the return current path. Enclosing the z-pinch radiation in a hohlraum both increases the x-ray intensity and improves its uniformity.

The side-on and end-on views of a typical z-pinch-driven vacuum hohlraum are shown in Figure 3. This configuration consists of two small 6-mm-diameter by 9-mm-long "physics" hohlraums attached to the cylindrical walls of a central 2-cm-diameter by 2-cm-tall z-pinch

hohlraum. The alignment of the smaller hohlraums is such that physics experiments can be attached to their walls in a manner such that there is no direct line-of-sight from the z-pinch x-ray source to the physics experiment. This configuration, which optimizes the spatial uniformity of a near-Planckian x-ray flux on the physics experiment, was designed with 2D radiation-hydrodynamics calculations [14]. A measurement of the re-emission from the hohlraum wall is shown in Figure 4, illustrating the Planckian nature of this radiation source. The temporal history of the x-ray flux in the smaller hohlraums is roughly the same as in the z-pinch hohlraum, but at a lower temperature. The time-dependent radiation spectrum in both the z-pinch vacuum hohlraum and the smaller physics hohlraums agrees very well with the predictions of the 2D radiation-hydrodynamics code.

To date, these z-pinch driven vacuum hohlraums have been used to study ICF capsule ablator physics [14], Fe opacity at low densities (10^{-4} g/cc) and temperatures (20 eV) [15], and radiation transport. These z-pinch hohlraums, which on Saturn reach 80-90 eV and on PBFA Z are projected to reach 120 eV, are particularly well-suited to experiments that require large energy, large spatial scales, and long time duration.

4. IMPLODING LINER HOHLRAUMS

Due to the large volume of the vacuum hohlraums described in the previous section, the temperatures are too low for many ICF capsule physics experiments, even though the z-pinch x-ray powers can be very high. In an effort to increase the radiation temperature in a z-pinch-driven hohlraum for these ICF-relevant capsule experiments, we are investigating the "imploding liner" hohlraum concept illustrated in Figure 5. In this concept, the radiation that is generated when the high-Z imploding plasma shell stagnates on an inner cylinder (a low-Z cylindrical shell or a low-Z, low-density foam) quickly permeates the low-Z central cylinder while being contained by the outer, cooler regions of the high-Z imploding plasma. If the albedo of the imploding plasma shell is equivalent to the albedo of a high-Z hohlraum wall, the increase in temperature within this imploding configuration is simply the 4th root of the decrease in wall

area. For example, if the imploding plasma stagnates at a radius that is $1/5$ of the radius of the vacuum hohlraum return-current wall, then the imploding liner hohlraum temperature will be 50% larger than the equivalent vacuum hohlraum temperature. Much of the early theoretical work on these hohlraums was performed during the initial design phases of PBFA II in 1980.

Two ICF capsule concepts that utilize the predicted increase in x-ray flux that is generated by an imploding liner hohlraum are illustrated in Figures 6 and 7. In the "double-ended" hohlraum shown in Figure 6, z-pinch implosions on each end of a hohlraum provide the x-ray drive in a configuration that is quite similar to the indirect-drive laser and heavy ion ICF hohlraum configurations [13,16]. Two-dimensional calculations predict that ~50% of the radiation generated by the imploding z-pinch hohlraum can be directed into the ICF capsule hohlraum, and the time-dependent radiation intensity within the ICF capsule hohlraum can be tuned by simple structural changes to the shape and density of the inner, low density cylinders. The symmetry of the x-ray flux at the capsule surface can be tuned by the placement and number of the symmetry shields within the ICF capsule hohlraum. Even though the ICF-relevant physics experiments in this configuration are spatially isolated from the Rayleigh-Taylor instabilities in the imploding plasma shell, the instabilities could affect the system performance by producing "holes" in the radiation case or by mixing high-Z materials into the low-density foam, preventing efficient radiation coupling into the ICF capsule hohlraum.

A more efficient, but higher risk ICF capsule hohlraum configuration is illustrated in Figure 7. In this configuration, the ICF-relevant capsule is placed at the center of the smaller low-density foam structure on the cylindrical symmetry axis of the z-pinch imploding plasma. The radiation produced when the imploding plasma strikes the low-density foam quickly penetrates the low-density material and begins to ablate the ICF capsule. The low-density foam and the material that is ablated from the ICF capsule isolate the capsule ablation surface from the hydrodynamics of the imploding plasma; this creates a region in which the radiation mean-free-path is long, allowing a uniform radiation drive at the ablation surface. Two-dimensional calculations predict that ignition-relevant ICF capsules could be studied in this imploding liner hohlraum system if 40 MA of current were driven through the high-Z imploding plasma. These

configurations are high risk, however, because the capsule symmetry is susceptible to both radiation asymmetries and the hydrodynamic coupling that can occur between the imploding z-pinch plasma and the imploding capsule.

CONCLUSIONS AND FUTURE PLANS

The production of x rays from magnetically-driven implosions has been demonstrated to be very efficient and to scale as predicted with the pulsed-power generator current to the current levels of PBFA Z. Initial experiments to thermalize these x-ray sources in large hohlraums and apply them to shock physics experiments have been successful. Future work will focus on continued optimization of the x-ray source, increasing the hohlraum temperature with imploding liner hohlraums, and applying these sources to key physics issues in radiation flow and symmetrization, radiation-driven ablation of ICF capsule materials, and ICF capsule implosion physics experiments.

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FIGURE CAPTIONS

Figure 1. The measured load current on Saturn and total x-ray power produced from a 1.75-cm-diameter array of 120, 7.5- μ m-diameter tungsten wires.

Figure 2. The measured load current on PBFA Z and total x-ray power produced from a 4-cm-diameter array of 240, 7.5- μ m-diameter tungsten wires..

Figure 3. Side-on and end-on views of the large z-pinch hohlraum (20-mm long by 20-mm diameter) and the smaller "physics" hohlraums (~6-mm diameter by 9-mm long). The smaller cylindrical object at the center of the side-on view and the small circle at the center of the end-on view represent the position of the radiating z-pinch plasma. Note that the smaller physics hohlraums are angled to ensure that the physics experiments mounted on their walls do not have a direct line-of-sight to the z-pinch x-ray source.

Figure 4. A comparison of the measured x-ray flux emitted from the wall of a vacuum hohlraum to an 82 eV Planckian spectrum (dashed line). The x-ray drive for this experiment was produced by a 40 wire, 30 TW z-pinch x-ray source, and the emission spectrum was measured with an eleven channel XRD array (solid line) and a 16-channel transmission grating spectrometer (data points shown as closed circles, •).

Figure 5. A radius-time plot from a one-dimensional calculation that illustrates the concept of the imploding liner hohlraum. The high-Z imploding liner, initially at 1-cm radius, serves as a container for the radiation that is produced when it stagnates on a low-density foam, initially at a radius of 0.5 cm. The dashed line intercepting the abscissa at ~110 ns shows the time-dependent position of the radiation wave propagating through the low density foam.

Figure 6. A schematic of a double-ended hohlraum configuration that utilizes the imploding liner hohlraum concept. Two z pinches at each end of a cylindrically symmetric hohlraum provide the radiation source for ICF-relevant capsule physics experiments.

Figure 7. A schematic of an internal ICF capsule configuration within an imploding liner hohlraum. This configuration optimizes the x-ray flux at the capsule at the risk of being susceptible to Rayleigh-Taylor instabilities in the imploding plasma and direct hydrodynamic coupling.

Figure 1, Matzen, IAEA TCM 3/97

Figure 2, Matzen, IAEA TCM 3/97

Side-on view

End-on view

Figure 3, Matzen, IAEA TCM 3/97

Figure 4, Matzen, IAEA TCM 3/97

Figure 5, Matzen, IAEA TCM 3/97

Figure 6, Matzen, IAEA TCM 3/97

Figure 7, Matzen, IAEA TCM 3/97