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Z-pinches as intense x-ray sources for high energy density physics 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. These x rays are produced when an imploding cylindrical plasma, driven by the magnetic field pressure associated with very large axial currents, stagnates upon the cylindrical axis of symmetry. On the Saturn pulsed-power accelerator [R.B. Spielman, *et al.*, in *Proceedings of the 2nd International Conference on Dense Z pinches*, Laguna Beach, CA, 1989, edited by N.R. Pereira, J. Davis, and N. Rostoker (AIP, New York, 1989), p3.] at Sandia National Laboratories, for example, currents of 6 to 8 MA with a risetime of less than 50 ns are driven through cylindrically-symmetric loads (typically gas jets, arrays of wires, thin foils, or low density foams), producing implosions velocities as high as 100 cm/μs and x-ray energies as high as 500 kJ. The keV component of the resulting x-ray spectrum has been used for many years as a radiation source for material response studies. Alternatively, the x-ray output can be thermalized into a near-Planckian x-ray source by containing it within a large cylindrical radiation case (a hohlraum). These large volume (~6000 mm^3), long-lived (~20 ns) radiation sources have recently been used for ICF-relevant ablator physics experiments as well as astrophysical opacity and radiation-material interaction experiments. Hydromagnetic Rayleigh-Taylor instabilities and cylindrical load symmetry are critical, limiting factors in determining the assembled plasma densities and temperatures, and thus in the x-ray pulsewidths that can be produced on these accelerators. In recent experiments on the Saturn accelerator, these implosion nonuniformities have been minimized by using uniform-fill gas puff loads or by using wire arrays with as many a 192 wires. These techniques produced significant improvements in the pinched plasma quality, reproducibility, and x-ray output power. X-ray pulsewidths of less than 5 ns and peak powers of 75±10 TW have been achieved with arrays of 120 tungsten wires. These powers represent greater than a factor of three in power amplification over the electrical power of the Saturn accelerator, and are a record for x-ray powers in the laboratory. When the modification to enable z-pinch implosions on the Particle Beam Fusion Accelerator (PBFA II) [R.B. Spielman, *et al.*, in *Proc. of the 11th Intl. Conf. on High Power Particle Beams*, edited by P. Sunka, K. Jungwrith, and J. Ullschmied, Prague, Czech Republic, June, paper O-4-1 (1996, in publication).] is completed, x-ray energies in excess of 1.5 MJ at powers in excess of 150 TW should be reached. These intense x-ray sources offer the potential for performing many new basic physics and fusion-relevant experiments.

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DISCLAIMER

I. INTRODUCTION

The azimuthal magnetic field associated with the axial flow of a large current through a cylindrically symmetric plasma creates a magnetic field pressure (JXB force) that accelerates the plasma radially inward. In these "z-pinches" on today's pulsed-power accelerators, multi-megaamps flow through centimeter-scale-size plasmas, accelerating them to implosion velocities as high as 10^8 cm/s. The hot, dense plasma that is generated when this imploding plasma stagnates and thermalizes at the cylindrical axis of symmetry is an efficient source of radiation. The conversion of electrical energy stored in the capacitor banks of these large pulsed-power generators into radiation has been demonstrated to be as large as 15% (through the conversion process of electrical to magnetic to kinetic to internal to radiation energy)[1,2].

Historically these z-pinch implosions have been used to generate K-shell radiation [3-6] in order to study the response of materials to photons in the range of 1 to 5 keV. Recent work at Sandia National Laboratories has emphasized the generation of softer x-rays as a source for Inertial Confinement Fusion (ICF) and related indirect (i.e. x-ray) drive, radiation physics experiments[7-9].

Assembling a hot, dense plasma on the cylindrical axis of symmetry requires an optimization of both the axial and azimuthal implosion uniformity. This symmetry requirement, coupled with the additional requirement of low mass in order to match the current levels and pulse widths produced by existing pulsed-power accelerators, makes fabricating the ideal z-pinch load challenging. Typically, masses less than 500 mg/cm can be efficiently imploded on short-rise-time electrical generators such as the 20-TW Saturn accelerator [10] The 50-TW Particle Beam Fusion Accelerator modified to drive z-pinch loads (PBFA Z) [8], with currents of up to 20 MA in the load, will efficiently implode masses of several mg/cm . In previous experiments on Saturn and smaller accelerators, the high-symmetry, low-mass tradeoff has led to the choice of gas puffs, thin foils, metal vapor jets, and low-density foams.

In this paper, we review and summarize the recent research that has extended previous work with cylindrical wire array loads to very large number of wires (up to 192). These experiments demonstrated record x-ray power generation in the laboratory. Furthermore, these x-ray sources can be placed within a high-Z radiation container (a hohlraum) to produce a Planckian, spatially uniform x-ray source that can be applied to research in radiation flow and symmetrization, shock wave physics, low temperature opacities, and accurately simulates (in temperature, time, and spatial scales) the capsule ablator physics during the critical low-temperature-drive phase of ignition and high yield ICF capsules[11]. We will briefly discuss the "dynamic" hohlraum concept, where the imploding plasma itself becomes the radiation container, thereby decreasing the hohlraum wall area and increasing the contained radiation flux. Our calculations show that the dynamic hohlraum concept is a promising candidate for driving ICF capsule implosions. Finally, we will present preliminary results from the initial z-pinch implosion experiments on PBFA Z.

II. AL WIRE ARRAY IMPLOSIONS

For many years a goal of Plasma Radiation Source (PRS) research has been to produce sources of high brightness, keV x rays. The x-ray emission at stagnation is a strong function of the plasma temperature ($\sim T^{1/2}$), density ($\sim n_e^2$), and material ($\sim Z^2$). The hydromagnetic Rayleigh-Taylor instability is the major disruptive mechanism that increases the thickness of the imploding plasma sheath and inhibits the efficient assembly of the hot, dense plasma on the cylindrical axis of symmetry. Data and modeling [3-6] suggest that azimuthal and axial asymmetries related to the discreteness of the individual wires within an array of wires is at least partially responsible for seeding the growth of the Rayleigh-Taylor instabilities. Since aluminum loads have been used extensively in previous experiments, has relevant K-shell emission features near 1.7 keV, and has both well-characterized equations of state and opacities that enable comparison of experiments with numerical simulations, we performed a series of Al wire array experiments that systematically studied the dynamics of wire array implosions as a function of wire number in two Saturn load geometries [7].

As described in Reference 7, the initial circumferential gap spacing between adjacent wires was varied from a maximum of ~6 mm to a minimum of ~0.4 mm. As shown in Figure 1, the peak x-ray emission power increased with a decrease in inter-wire gap spacing. For initial wire array radii of both 8.6 mm and 12 mm, the total x-ray power began to increase dramatically when the initial inter-wire gap spacing decreased below ~1.4 mm. For all of these experiments the total radiation output was nearly constant at ~300 kJ; the x-ray pulsewidths decreased as the power increased, becoming less than 4 ns at the highest x-ray powers.

The fact that this transition in x-ray-power occurs at ~1.4 mm is consistent with one-dimensional (1D) radiation calculations of a single wire expansion coupled with two-dimensional (2D) radiation hydrodynamics calculations of the wire array implosion. At an inter-wire spacing of approximately 1.5 mm, 1D calculations using the measured prepulse on Saturn as the input current drive predict that the expansion of the individual wires is large enough to merge with the expanding plasma from the adjacent wires prior to the time at which the annular sheath begins to implode. At larger inter-wire spacings, the increasing current of the main drive pulse recompresses the individual wires (self-pinch), and they implode as a collection of individual wires. With larger number of wires (smaller inter-wire spacing), the current/wire is too small to recompress the individual wire plasmas, the plasmas from adjacent wires merge, and the 2D calculations predict the implosion of an annular plasma sheath. We will attempt to confirm these theoretical predictions in future experiments on PBFA Z with x-ray backlighting of the imploding plasma.

III. W WIRE ARRAY IMPLOSIONS

To improve the thermal x-ray power output, we performed a series of experiments on Saturn using tungsten wire arrays[9]. Record x-ray powers of 75±10 TW of x-rays with a total x-ray energy output of nearly 500 kJ were produced with the optimal tungsten wire array configuration. This tungsten wire array data can be summarized by the results from two experimental series: a wire number scan at fixed mass and radius, and a wire array radius scan at fixed implosion time and inter-wire spacing.

The time-dependent x-ray power for three different wire arrays (24, 40, and 70 wires), each with the same total initial mass at a radius of 6.25 mm, is shown in Figure 2. The peak radiated power increased from ~20 TW with 24 wires to ~40 TW with 70 wires. The inter-wire gap decreased from 1.6 mm to 0.56 mm for this wire number variation. The total radiated energy was 450 ± 40 kJ for all of the wire arrays, while the x-ray pulsewidth decreased from ~18 ns to ~8 ns. X-ray pinhole pictures show that the diameter of the emission region decreases with increasing wire number, consistent with a more stable implosion and higher density at stagnation[9].

Many experimenters have used the radius scaling technique to study the optimization of K- and L-shell radiators [5,6,12]. In order to hold the implosion time constant, the mass must decrease as the initial load radius is increased; in a constant current model, mR^2 ~constant for fixed current and implosion time. The experimental trends support the concept that higher velocity, lower mass implosions lead to higher temperature, lower density stagnations. This trend was tested for a high-Z, thermal radiator by driving implosions of tungsten wire arrays at initial radii of 3.5, 6.25, and 8.75 mm with 40, 70, and 120 wires, respectively (to maintain nearly constant inter-wire spacing). The time-dependent x-ray power output from this radius scan is shown in Figure 3. The implosion velocity increased from 28 to 65 cm/μs, while the initial total load mass decreased from 2018 to 450 μg/cm. The fastest implosions produced a 4 ns, 75 ± 10 TW x-ray pulse (uncertainty based on comparisons of different x-ray diagnostics), which is a power amplification of greater that a factor of 3 from the electrical power. The reproducibility of this high power x-ray pulse is illustrated in Figure 4.

These tungsten x-ray outputs have been modeled with a 2D (r-z) Eulerian radiation hydrodynamics code [13]. In these calculations, an initial random density perturbation is imposed on a 1-mm-thick plasma shell whose initial radius corresponds to the initial wire array radius. This annulus is imploded self-consistently by an equivalent circuit Saturn voltage waveform that is derived from a full circuit model of the Saturn accelerator. As shown in Figure 5, initial random density perturbations of 30% and 5% provide a good match to the power and pulsewidths of the low and high power experiments, respectively. In both calculations, the Rayleigh-Taylor instabilities are far into the non-linear regime by the time of stagnation. We note that while this agreement is promising and provides good insights into the behavior of these z-pinch implosions, much more work must be done in order to provide a general predictive capability.

IV. VACUUM HOHLRAUMS

In indirect drive ICF, high-power energy sources are used to heat high-Z radiation cavities (hohlraums), converting the driver energy into x-rays that implode the capsule. Lasers and ion beams 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 high-Z lined cylindrical container. When current flows into this closed configuration, the wire array implodes, producing x-rays at stagnation that are absorbed and re-emitted by the high-Z container, 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. In these closed systems at equilibrium, the x-ray power generated by the z-pinch stagnation (P_{pinch}) can be equated to the radiation power lost in heating the wall material: $P_{pinch} = \sigma T^4 A_{wall} (1-\alpha)$,w here T is the radiation temperature and α is the wall albedo, that is, the fraction of the incident x-ray energy that is re-emitted by the high-Z wall. The power enhancement due to the radiation case is given by $\sigma T^4/[P_{pinch}/A_{wall}] = 1/[1-\alpha]$. The albedo of high-Z walls can typically be ~0.8, implying that the radiation power enhancment in these hohlraums can be ~5. The use of laser-driven hohlraum "physics factories" was described in a recent review article by M. Rosen[14].

The side-on and end-on views of a typical z-pinch-driven vacuum hohlraum are shown in Figure 6. This configuration consists two small 6-mm-diameter by 9-mm-long 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 physics experiment to the z-pinch x-ray source. This configuration optimizes the spatial uniformity of a Planckian x-ray flux on the physics experiment. A measurement of the re-emission from the hohlraum wall is shown in Figure 7, 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 slightly lower temperature.

The principal applications of these z-pinch driven vacuum hohlraums to date has been to study ICF capsule ablator physics [11], Fe opacity at low densities (10^{-4} g/cc) and temperatures (20 eV) [15], and radiation flow. These 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.

V. DYNAMIC 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 "dynamic" hohlraum concept illustrated in Figure 8. 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. The radiation is contained within the imploding high-Z shell until the radiation front reaches its outside surface. 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 return-current wall, then the dynamic 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 a dynamic hohlraum are illustrated in Figures 9 and 10. In the "double-ended" hohlraum shown in Figure 9, 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[16,17]. 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. In this configuration the ICF-relevant physics experiments are spatially isolated from the Rayleigh-Taylor instabilities in the imploding plasma shell.

A more efficient, but higher risk ICF capsule hohlraum configuration is illustrated in Figure 10. 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 and create a region in which the radiation mean-free-path is long, allowing uniform radiation drive at the ablation surface. Two-dimensional calculations predict that ignition-relevant ICF capsules could be studied in this dynamic hohlraum system if 40 MA of current could be driven through the high-Z imploding plasma.

This configurations are high risk, however, since the capsule symmetry is susceptible to both radiation asymmetries and hydrodynamic coupling that can occur due to the Rayleigh-Taylor instabilities in the imploding plasma. An initial experimental series on Saturn utilized the 120-wire tungsten arrays around a 3 mg/cm^3 silicon aerogel foam End-on and side-on radiation output measurements show the predicted delay in risetime of the radiation pulse, the predicted decrease in peak radiation output and pulsewidth in the side-on detectors, and an increase in the ratio of end-on to side-on radiation temperatures[18].

Preliminary x-ray measurements on PBFA Z

The installation of the modifications to PBFA II that enable z-pinch implosion experiments at the 16 to 20 MA level was completed in September, 1996. PBFA II in this z-pinch mode has been called PBFA Z, to distinguish this configuration from the mode that enables extraction ion diode experiments, called PBFA-X. The first radiation producing experiments were performed in October, 1996 with 2-cm long, 4-cm diameter, 120-wire tungsten arrays The initial wire array mass was slowly decreased to test the power flow on the accelerator at these high current levels. On the ninth x-ray producing shot, we measured ~17 MA near the load and 1.6 MJ of x-ray output in an 8-ns full-width-at-half-maximum pulse, with a peak x-ray power output in excess of 120 TW[19]. These results meet our design goal for x-ray energy and are over 80% of our 150 TW power goal. Both the energy and power are records for x-ray production in the laboratory. The x-ray energy exceeds the largest energies measure in high-explosive pulsed-power-driven plasma radiation sources at Los Alamos [20], and the x-ray power output exceeds the previous record set on Saturn [9]. Work to optimize this x-ray output, further quantify the x-ray and accelerator performance, and apply this intense x-ray source to both ICF and radiation physics experiments will be the near-term focus of the PBFA-Z experimental activities.

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REFERENCES

1. N.R. Pereira & J. Davis, J. Appl. Phys. 64, R1, (1988).

2. R.B. Spielman, M.K. Matzen, M.A. Palmer, P.B. Rand, T.W. Hussey & D.H. McDaniel, Appl. Phys. Lett. 47, 229, (1985).

3. K.G. Whitney, J.W. Thornhill, J.P. Apruzese, & J. Davis, J. Appl. Phys. 67, 1725, (1990).

4. J.W. Thornhil, K.G. Whitney, C. Deeney, and P.D. LePell, Phys. Plasmas 1, 321, (1994).

5. M. Gersten, W. Calrk, J.E. Rauch, G.M. Wilkinson, J. Katzenstein, R.D. Richardson, J. Davis, D. Duston, J.P. Apruzese, and R. Clark, Phys. Rev. A 33, 477, (1986).

6. C. Deeney, T. Nash, R.R. Prasad, L. Warren, K.G. Whitney, J.W. Thornhill, and M.C. Coulter, Phys. Rev. A 44, 6762, (1991).

7. T.W.L. Sanford, T.J. Nash, B.M. Marder, R.C. Mock, M.R. Douglas, R.B. Spielman, J.F. Seamen, J.S. McGurn, D.O. Jobe, T.L. Gilliland, M.F. Vargas, R. Humphreys, K.W. Struve, W.A. Stygar, J.H. Hammer, J.H. DeGroot, J.S. Eddleman, K.G. Whitney, J.W. Thornhill, P.E. Pulsifer, J.P. Apruzese, D. Mosher, Y. Maron, "Improved Azimuthal Symmetry Greatly Increases X-ray Power from Wire-Array Z-Pinches", in *Proc. of the 11th Intl. Conf. on High Power Particle Beams*, edited by P. Sunka, K. Jungwrith & J. Ullschmied, Prague, Czech Republic, June, (1996), paper O-4-2; Submitted to Phys. Rev. Lett. (1996).

8. R.B. Spielman, S.F. Breeze, G.A. Chandler, C. Deeney, F. Long, T.H. Martin, M.K. Matzen, D.H. McDaniel, J.S. McGurn, T.J. Nash, L.E. Ruggles, T.W.L. Sanford, J.F. Seamen. W. A. Stygar, J.A. Torres, D.M. Zagar, D.L. Peterson, R.W. Shoup, K.W. Struve, M. Mostrom, P. Corcoran, and I. Smith, "PBFA Z: A 20-MA Driver for Z-Pinch Radiation Sources", in *Proc. of the 11th Intl. Conf. on High Power Particle Beams*, edited by P. Sunka, K. Jungwrith & J. Ullschmied, Prague, Czech Republic, June, (1996), paper O-4-1.

9. C. Deeney, T.J. Nash, R. B. Spielman, J.F. Seamen, G. Chandler, K. W. Struve, J.L. Porter, W.A. Stygar, J.S. McGurn, D.O. Jobe, T.L. Gilliland, J.A. Torres, M.F. Vargas, L.E. Ruggles, S. Breeze, R.C. Mock, M.R. Douglas, D. Fehl, D.H. McDaniel, and M.K. Matzen, "Power Enhancement by

Increasing Initial Array Radius and Wire Number of Tungsten Z Pinches", submitted to Phys. Rev. E (1996).

10. R.B. Spielman, "Saturn: a 10 MA Driver for Z-pinch Radiation Sources" in *Proceedings of the 2nd International Conference on Dense Z pinches*, Laguna Beach, CA, 1989, edited by N.R. Pereira, J. Davis, and N. Rostoker (AIP, New York, 1989), p3.
11. R.E. Olson, J.L. Porter, G. A. Chandler, D.L. Fehl, D.O. Jobe, R.J. Leeper, M.K. Matzen, J.S. McGurn, D.D. Noack, L.E. Ruggles, P. Sawyer, J.A. Torres, M. Vargas, D. M. Zagar, H.N. Kornblum, T.J. Orzechowski, D.W. Phillion, L.J. Suter, A.R. Thiessen, and R.J. Wallace, "ICF Ablator Physics Experiments on Saturn and Nova", submitted to Phys. Plasmas, this edition.
12. C. Deeney, T. Nash, P.D. LePell, K. Childers, M. Krishnan, K.G. Whitney, and J.W. Thornhill, J. Quant. Spectrosc. Radiat. Transfer **44**, 457, (1990).
13. D.L. Peterson, R.L. Bowers, J.H. Brownell, A.E. Greene, K.D. McLenithan, T.A. Oliphant, N.F. Roderick, and A.J. Scannapieco, Phys. Plasmas **3**, 368, (1996).
14. M. Rosen, Phy. Plasmas **3**, 1803 (1996).
15. P. Springer, K. Wong, "Measurements of low density LTE iron opacities", submitted to Phys. Rev. Lett. (1996)
16. J. D. Lindl, Phys. Plasmas 2, 3933 (1995).
17. D.D.M. Ho, J.A. Harte, and M. Tabak, Proc. 15th IAEA International Conf. Plasma Phys. Controlled Nuclear Fusion Research, Seville, Spain (1994).
18. T.J. Nash, M.S. Derzon, G.O. Allshouse, C. Deeney, J.F. Seamen, J.S. McGurn, D Jobe, T.L. Gilliland, J.J. MacFarlane, and P. Wang, Bull. Am. Phys. Soc. **41**, 1390 (1996).
19. R.B. Spielman, G.A. Chandler, C. Deeney, F. Long, T.H. Martin, M.K. Matzen, D.H. McDaniel, T.J. Nash, J. L. Porter, L.E. Ruggles, T.W.L. Sanford, J.F. Seamen. W. A. Stygar, S. P. Breeze, J.S. McGurn, J.A. Torres, D.M. Zagar, T.L. Gilliland, D. Jobe,, K.W. Struve, M. Mostrom, P. Corcoran, and I. Smith, and R.W. Shoup, Bull. Am. Phys. Soc. **41**, 1422 (1996).
20. C.A. Ekdahl, Los Alamos National Laboratory, private communication, November, 1996.