Draft 5/18/2000ss

Wire-Number Effects on High-Power Annular Z-Pinches and Some Characteristics at High Wire Number

T. W. L. Sanford

Sandia National Laboratories*, Albuquerque, NM 87185-1196

Characteristics of annular wire-array z-pinches as a function of wire number and at high wire number are reviewed. The data, taken primarily using aluminum wires on Saturn are comprehensive. The experiments have provided important insights into the features of wire-array dynamics critical for high x-ray power generation, and have initiated a renaissance in z-pinches when high numbers of wires are used. In this regime, for example, radiation environments characteristic of those encountered during the early pulses required for indirect-drive ICF ignition on the NIF have been produced in hohlraums driven by x-rays from a z-pinch, and are commented on here.

PACS numbers: 52.35.Py, 52.55.Ez, 52.70.Kz. 52.70.La

I. INTRODUCTION

The discovery in 1995 (Sanford et al. 1995, 1996a, 1996b), that the use of very large numbers of wires enables the generation of high x-ray power from annular wire-array z pinches, represents a breakthrough (Matzen 1997, and Yonas 1998) in controlling z-pinch instabilities and is a major step forward in load design for large pulsed-power generators (Quintenz et al. 1996, 1998; Cook 1997; Mehlhorn 1997; and Ramirez 1997). Combined with the conversion of the PBFA-II generator to a z-pinch driver (Spielman et al. 1996, 1997, 1998), the successful application of this breakthrough on Z (Sanford et al. 1998b) has reopened interest in the field of fast, dynamic z-pinches (Ryutov et al. 2000) as x-ray sources for fusion (Matzen 1999a, 1999b), as well as initiated a renewed study of z-pinches (Haines et al. 2000) for other high energy-density applications (Matzen 1997). At Sandia National Laboratories, for example, three hohlraum concepts that take advantage of the high x-ray powers generated with this new pulsed-power capability are under development to investigate the feasibility of z-pinches to drive ICF (inertial confinement fusion) targets (Cook 1998; Quintenz 1998; Matzen 1999a, 1999b; and Leeper et al., 1999). They are referred to as the *z-pinch driven* (Porter 1998 and Hammer et al. 1999), the *dynamic* (Nash et al. 1998, and Lash et al. 1999), and the *static-wall* hohlraums (Olson et al. 1999). To date, the large-volume *z-pinch driven* hohlraum has developed a temperature of 95±5 eV in a 17-mm diameter by 15-mm high hohlraum, when heated by

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

radiation generated external to a single pinch (Cuneo et al. 1999). The energy-efficient *dynamic hohlraum*, which uses radiation generated internal to a radially converging target heated by the imploding wire array, has developed temperatures ranging from 80 to 180 eV as the diameter of a 10-mm high hohlraum compresses from 5 to 1.6 mm (Leeper et al. 1999). And the *static-wall hohlraum*, which combines features from both concepts, has developed a temperature of 130±7 eV in a NIF (National Ignition Facility)-scale (6-mm diameter by 7-mm high) hohlraum (Sanford et al. 1999d), again when heated by x-rays from a single pinch (Fig. 15B to be discussed in Sec. IV).

The breakthrough experiments (Sanford et al. 1995, 1996a, 1996b) were done on the 10-MA Saturn generator (Bloomquist et al. 1987) with aluminum wires, where the wire number varied from 10 (or 13) to 136 (or 192) for 8.6 mm (or 12 mm) radii array loads, respectively (Fig. 1). At each radius (8.6 or 12 mm), the total mass was held constant (0.66 or 0.82 mg, respectively). Analyses of these experiments showed that a key parameter controlling the x-ray power emitted at stagnation was the interwire gap spacing. Decreasing the interwire gap from 6 to 0.4 mm (the limit of load construction capability) increased the total power by a factor of ~20 and the total energy by ~2, for either array radius. A dramatic increase in x-ray power occurred when the interwire gap spacing decreased below ~2 mm (Fig. 2). The onset of this rapid rise in power correlated with simultaneous discontinuities in the rate of change in other measurable quantities such as radiated pulse width (Fig. 3A), radial pinch convergence (Fig. 3B), total radiated energy (Fig. 3C), K-shell energy (Fig. 3D), pinch density (Fig. 3E), pinch temperature from K-shell emission (Fig. 3F), and instability observations (Fig. 4). The discontinuity in the Fig. 3 data correlated with a calculated transition from the implosion of individual self-pinching *wire plasmas* to that of a *plasma shell* having azimuthal variations that diminished with increased wire number (Sanford et al. 1996 b, 1996c). In this *plasma-shell* regime many features of the data were consistent with RMHC (radiation-magnito-hydrodynamic code) simulations (Hammer et al. 1996 and Peterson et al. 1996) that take into account the development of the magnetically-driven RT (Rayleigh-Taylor) instability in the rz plane, assuming an azimuthally symmetric *plasma shell*. The use of large wire numbers reduced the azimuthal asymmetry of the initial plasma, improved the shot-to-shot repeatability, and thus permitted, for the first time, details of wire array implosions to be meaningfully compared with such 2D simulations over the full span of x-ray emission (Sanford et al. 1997c). Moreover, 1D simulations which accounted for the finite shell thickness through the use of viscosity and conductivity multipliers could now be used to extract relevant parameters of the pinch at stagnation (Whitney et al. 1997).

Previous experiments using wire array z-pinch loads did not show significant improvement in performance when the wire number increased beyond 10-20 wires (Periera and Davis 1988 and Ramirez 1997). Twenty-four wires were generally considered adequate to provide sufficient azimuthal symmetry for z-pinch loads. Such loads (Spielman et al. 1993) were routinely used for radiation-effects studies at Sandia. These loads developed unstable axial pinches that exhibited poor reproducibility, and research was accordingly directed to developing implosions of the more azimuthally symmetric annular and solid gas-puffs loads (see papers in Periera et al. 1989 and Haines and Knight 1993). In early 1995 when bringing into operation a fast-framing pinhole camera (Ruggles et al. 1995) to examine the early implosion phase of a typical 24-wire aluminum array on Saturn, however, self pinching of the individual wires was clearly observed prior to the implosion of the array (see Figs. 7-9 in Sanford et al. 1999a and Fig. 7 to be discussed in Sec. IIB). This measured lack of a coherent plasma shell prior to the radial implosion of the array motivated the use of increased wire number. The data suggested

that perhaps these unstable pinches could be better stabilized if more wires were added in order to eliminate the self-pinching by the formation of a continuous *plasma shell* prior to array implosion (Sanford et al. 1995).

This paper reviews the experimental and theoretical understanding generated by the 1995 wire-number variation experiment (Sanford et al. 1995a, 1996a, 1996b, 1997a, 1997c, 1999a; Whitney et al. 1997; Nash et al. 1998) and characteristics measured in follow-on experiments in 1996 at high wire number (Sanford et al 1998c, 1998d). Since other limited summaries of these data have been published (Sanford et al. 1997b, 1998a, 1999b), features measured in the very high-number wire regime for the first time are highlighted and integrated into a coherent picture. Subsequent measurements made with tungsten wires on Saturn (Deeney et al. 1997) and Z (Sanford et al. 1998b) confirm the general increase in x-ray power with wire number. Discussion of these measurements is deferred to the original references.

Since the discovery, a considerable amount of research has been done to understand the dynamics of fast z pinches (Ryutov et al. 2000 and Haines et al. 2000). The first-principles Heuristic Model of Haines 1998, the numerical simulations of Chittenden et al. 1999, 2000 , and the measurements of Lebedev et al. 1998, 1999, 2000 and Sinars et al. 2000a, 2000b have significantly aided in elucidating the Saturn experiments. In this review paper, the insights from this research are incorporated into the discussion. Measurements made with one of the hohlraum concepts (Olson, et al. 1999) (and that which the author has been associated with) are used as an example of what has been achieved to heat ICF-relevant hohlraums (Kilkenney et al. 1999) to high temperatures in the high wire-number regime with tungsten wires on Z. Of relevance to this review, examination of the axial radiation driving this hohlraum configuration measured with an axial diagnostic package (Nash et al. 1999 and Hurst et al. 1999) shows that the addition of a low-density foam target on axis can reduce the effective size of the radial pinch by a factor of two, creating ~2 ns wide radiation pulses when viewed from the side. The size reduction permitted cylindrical hohlraums of ICF-relevant dimensions (4-mm diameter by 4-mm height) to be driven to the high temperature of 155±8 eV in a z-pinch (Sanford et al. 1999c, 2000a). Measurements made with this geometry suggest the presence of an azimuthal mode number in the axial emission for the first time in high-wire-number implosions that utilize a solid current-return can (Sanford et al. 2000c).

II. WIRE-NUMBER VARIATION

A. EXPERIMENTAL OBSERVATIONS
1. Emission Characteristics

As summarized in the introduction, decreasing the interwire gap in the 1995 experiments resulted in monotonic increases in total radiated power (Fig. 3A) and energy (Fig. 3C), and simultaneous decreases in the width of the x-ray pulse (Fig. 3A), similarly for both array radii. For gaps smaller than 2 ± 0.6 mm, the character of the x-ray emission qualitatively changed, from a broad, irregular radiation pulse at large gaps (Fig. 4A) to a narrow, evenly-shaped radiation pulse followed by a much weaker pulse at small gaps (Fig 4B). The weaker second radiation peak in Fig. 4B is consistent with a second radial implosion and corresponds to a pinch having a lower temperature relative to that of the first implosion (Sec. III). For gaps greater than ~ 2 mm, time-integrated images of the pinch (mainly showing the plasma at stagnation) exhibit the presence of kink (m = 1) as well as sausage (m = 0) instability (Fig. 4C). Time-dependent

images show significant precursor plasma stagnating on axis, generating soft x-ray emission tens of nanoseconds prior to the main implosion, in agreement with earlier and current (Lebedev et al. 1998, 1999, 2000) experiments. For gaps less than ~ 2 mm, in contrast, no kink instability occurs and only minimal precursor plasma forms (Fig. 4D). The changes in the temporal shape of the x-ray pulse (Figs. 4A and 4B) and in the spatial quality of the pinch (Figs. 4C and 4D) with gap occurred with corresponding quantitative transitions in the rates of change of the peak total x-ray power and its pulsewidth (Fig. 3A), the radial convergence (obtained from the average size of the K-shell emission region) (Fig. 3B), the emitted total x-ray energy (Fig. 1C), the emitted K-shell energy (Fig. 3D), and other measured x-ray characteristics above and below a gap of ~2 mm (Sanford et al. 1999a). Not enough data were taken at wide gap spacings, however, to ascertain how sharply this transition in x-ray behavior took place. For this reason, it is represented simply as a transition between two gap-dependent power laws as illustrated in Fig. 3, with the gap (G) exponents indicated.

In general, variations in the peak total power track the inverse of the measured pulsewidths (Fig. 3A), as would be expected if the total energy radiated during stagnation is slowly varying. The greater rate of dependence on gap of the pulsewidth and the peak power, for gaps greater than ~2 mm, reflects the greater disorganization of the implosion as seen by the lost double-pulse nature of the stagnation (Figs. 4A and 4B). The increased rate of decrease in power for large gaps relative to that for small gaps is consistent with the decrease in total radiated energy (Fig. 1D in Sanford et al. 1999b). This change in energy is approximately consistent with the change in the calculated kinetic energy (dotted lines in Fig. 3C) (and by inference the radiated energy), using the measured radial compression from the K-shell emission images (Fig. 3B). The larger-radius load permitted the delivery of ~23% more kinetic energy to the load for a fixed radial convergence of 10. In Fig. 3C, the measured total radiated energy is normalized to this calculated 0D kinetic energy, and increasing the kinetic energy of the smaller-radius load by 23% produces the universal curves of Figs. 3C and 3D, respectively. Normalizing the peak total radiated power by the total radiated energy (and scaling the results to the average of the peak power measured at the smallest gap measured) generates the universal curve of Fig. 2. In this form, the normalized power could also be described by the simple scaling:
$P(TW) \sim 18 * G(mm)^{-0.93 \pm 0.1}$ (Sanford et al. 1998a, 1999a).

2. Pinch Characteristics

Measurement of the slope of the optically thin, free-to-bound, x-ray emission determined the electron temperature of the hot core of the pinch (Sanford et al. 1997a and Sec. III). This temperature exhibited no variation with gap (dashed lines) and is only a function of the implosion kinematics (Fig. 3F). For large gaps, where the measured ion density was low (Fig. 3E), the temperature (solid lines) extracted from aluminum K-shell line ratios (Whitney et al. 1997) agreed with that extracted from the free-to-bound emission. As the gap decreased and the emitting ion density increased (Fig. 3D), however, the optical depth of the K-shell emission becomes significant, and the line ratio began to reflect the temperature on the outside surface of the emitting region, rather than an average over the region. The related K-shell yield was also suppressed as the ion density and corresponding opacity increased (Fig. 3D). The data taken at the smallest gap (0.4 mm) were generated from wires containing ~5% magnesium. Spectral analyses indicated that >15% of the yield was due to the smaller magnesium mass fraction, and the statistically higher yield in the small-radius load was due to reduced opacity for this element. The transition from a thin to thick plasma, as suggested by the data of Figs. 3D-3F, also approximately coincided with the previously discussed transition at ~2 mm (Figs. 2, and 3A-3C).

The difference between the core and surface temperature was indicative of a substantial temperature gradient within the emitting plasma (Fig. 3F). Remarkably, the enhanced plasma density at small gaps increased the temperature and density gradients and opacity effects, in such a way as to approximately maintain the average amount of mass participating in the K-shell emission at 11±3%, independent of gap (Sanford et al 1999a). These density and temperature measurements showed that the increase in K-shell power measured (and by inference the total power) was the result of systematically greater plasma compression (Fig. 3E) and was not the result of an increase in temperature (Fig. 3F).

B. INTERPRETATION
1. Initial Simulations

The apparent transition in x-ray emission and inferred pinch characteristics near the 2-mm gap was interpreted using the 2D-TIP RMHC (Marder 1973 and Marder et al. 1998) in xy geometry, using 1D-RMHC simulations of individual wire explosions from a cold start as input (Sanford et al. 1996a, 1996b). Calculations performed with these codes showed (in correspondence with the experimental data) that a change in the implosion topology occurred with increasing wire number. The calculated implosion made a transition from one topology composed of non-merging, self-pinching, individual *wire plasmas* to one characterized by the early formation and subsequent implosion of a *plasma shell*. The shell had density and current variations distributed azimuthally that correlated with the initial wire location and which decreased in amplitude with decreasing gap. For the resistivity model employed and for the measured current prepulse and wire sizes fielded, this transition was calculated to occur between wire numbers 20 to 80 (or between interwire gaps of about 3 to 1 mm, respectively) for the small-radius load. For wire number (N) greater than 80, the calculated individual wire plasmas in 1D never self-pinched, because the current per wire was too low. For N less than ~20, the current per wire was high enough that the calculated individual wire plasmas always self-pinched in 1D before stagnation occurred. For N~40 (interwire gap ~1.4 mm), the calculated wire plasmas in both 1D and 2D partially merged prior to significant radial motion of the array. In general, the TIP xy simulations suggested that the character of single wire plasmas calculated in 1D provided a qualitative indicator of the behavior of a wire plasma within an array, with regard to self-pinching or not in the xy plane.

2. Recent Simulations

These 1D and 2D simulations have been recently redone using an improved resistivity MHD model (Chittenden et al. 1997, 1999, 2000), called here MHD. In contrast to the earlier calculations, the newer ones indicate that the wire cores remain colder longer, with a greater fraction of the current flowing in the exterior low-density plasma (corona) before implosion occurs, in agreement with MAGPIE (Mitchel et al. 1996) experiments. Figure 5 plots the associated MHD electron-number density calculated in 1D at a radius of G/2 as a function of time (for such single-wire plasmas), assuming that the wire would be an element of the small-radius, 16, 24, 48, 64, or 136 wire arrays on Saturn (Sanford et al 1999b). Throughout the current prepulse (approximately a linear ramp from 0 to 100 kA in 100 ns prior to the main pulse), the density increases in all the wire-number configurations. The rapid increase in density at 0 ns is associated with the onset of the main current pulse. As in the earlier 1D simulations, for the higher wire-number configurations (N ≥ 64) the magnetic field is too weak to cause self pinching of the individual wire plasma, and the density continues to increase. For the lower wire-number

configuration ($N \leq 48$), the density continues to rise and then falls, as the wire plasma is swept up by the stronger field and then is returned to the wire axis. The transition between self pinching and continued expansion in 1D thus occurs between ~ 48 and ~ 64 wires. It is qualitatively consistent with the earlier simulations, and with simulations using Trac-II (Reisman 1998) and ALEGRA (Morse et al. 2000). The general agreement suggests that the break-point in topology as calculated in 1D is somewhat insensitive to the details of the particular resistivity model used (within the granularity of the wire numbers simulated).

2D MHD simulations (Chittenden et al. 2000) in the rz plane of a single wire (from a cold start) modify these results slightly, as shown in Figs. 6A and 6B for one of 24 wires and one of 64 wires, again for the small-radius load, 30 ns into the main current pulse. Such simulations show that the self-pinching occurs only in the necks of instabilities, and that the remainder of the corona hardly pinches at all. The sausage instabilities set in just when in 1D the magnetic field would be large enough to pinch the coronal plasma. As a result, there is continued expansion of the plasma in the bulges, while pinching occurs primarily in the necks, as shown by Beg et al. 1997 in single-wire experiments. Importantly, these 2D simulations show that due to the higher current per wire for wires in a lower wire-number array the instability development is greater, which leads to more self-pinching that in turn exacerbates the sausage development. In this case, the instability can reach sufficient nonlinear development that the wire core is penetrated (Fig. 6B) prior to implosion. Because at the start of the implosion the majority of the mass remains in the wire cores, there is a substantial difference in the amplitude of the sausage perturbation between the arrays in which the instability occurs only in the corona compared to arrays where the instability penetrates the core. In the MHD simulations, the transition in perturbation amplitude occurs between 32 and 48 wires (or between intergap spacings of 1.7 and 1.1 mm, respectively), and may help explain the difference in gap dependence between the two regimes (Chittenden et al. 2000). (This perturbation sets the seed for the development of the RT instability in rz and is thought to be responsible for the order-of-magnitude variation in measured power, as will be discussed shortly.)

Using MHD, Figs. 6C and 6D illustrate the modification to the single-wire density distributions, now in the xy plane, 41-ns into the main current pulse when the wires are placed in an annulus, for 16- and a 48-wire arrays, respectively. In MHD, again cold solid wires were used as the initial conditions. Both configurations exhibited the low-density corona being swept around the dense cores by the global magnetic field, which streams toward the axis (jetting), forming a precursor plasma stagnating on axis. With the 16-wire array, the plasmas have self-pinched, in agreement with the single-wire simulations. With the 48-wire array, the low-density regions have merged, but the higher density regions still retain the characteristically tear-drop shaped azimuthal asymmetry, again in qualitative agreement with the 1D simulations. The global field distorts the otherwise symmetrical expansion of the wire plasma into the characteristic tear-drop shape shown. Because hotter individual-wire plasma was calculated in the 1D simulations used as input to TIP, the earlier TIP simulations (Sanford et al 1996a, 1996b, and Marder et al. 1998) did not exhibit the tear-drop shape now calculated. The precursor plasma is now more pronounced, owing to the deeper radial penetration of the global magnetic field between wires with decreased wire number.

The earlier and more recent calculations of the transition are seen to be consistent with the motivating images mentioned in the introduction, where loads having gaps of 1.3 mm in the now-recognized transition region were recorded. Radial lineouts of some of these images are plotted in Fig. 7A, together with an image (Fig. 7B) taken 19 ns prior to peak radiated power

(Fig. 7C). In Fig. 7B for example, individual wire plasmas were observed to neck-off in the form of bright spots (similar to Mosher et al. 1992, Beg et al. 1997, Ruiz-Camacho et al. 1999, and Fig. 6A), and were suggestive of a sausage instability occurring in the individual wires 19-ns prior to peak radiated power. At this time, the array had only imploded a fraction of a mm radially (as shown by the dashed curve in Fig. 6A). Ten ns later, after the array had imploded an additional 1.5 mm, the observed plasma emission became a continuous distribution, with no evidence of individual wire structure, suggestive of plasma merger. At times earlier than 21 ns, the images indicated the presence of a diffuse plasma stagnating on axis, as illustrated in the top lineout of Fig. 7A. This plasma may be associated with the precursor plasma calculated in the xy simulations of Chittenden et al. 2000 (Fig. 6C and 6D), which arises from the sweeping in of the corona produced from the ablation of the exploding-wire surface by the global magnetic field.

For descriptive purposes, the small wire-number region where the gap is greater than 2 mm was thus referred to as the *wire-plasma* regime, and the high wire-number region where the gap was less than 2 mm was called the *plasma-shell* regime, though significant azimuthal density variations within the shell could still exist in this regime. Direct evidence for such a transition in array-plasma character has recently been observed with aluminum-wire arrays (Lebedev et al. 2000) on MAGPIE. There, a qualitative change in implosion dynamics occurred when the interwire gap decreased from 1.6 to 0.8 mm. For gaps $\geq$ 1.6 mm, the wire cores remained in their initial position until ~80% of the implosion time had elapsed, whereupon they were accelerated to the axis by the sudden transfer of current to the residual cores. During this initial period, current was surmised to flow predominantly in the corona, with the corona continually swept towards the z axis by the global magnetic field as in Figs. 6C and 6D. In contrast, when the gap decreased from 1.6 to 0.8 mm, the measured array radius accurately tracked that of an 0D implosion model, which assumed that the array imploded as a hollow plasma cylinder accelerated by the global **JxB** force.

3. XY Simulations Suggest Mechanism for Energy Dependence

The TIP xy simulations (Marder et al. 1998) together with analytic wire modeling (Mosher 1994) showed that the wire plasmas (in contrast to the plasma of a shell) may accrue azimuthal velocity components during the implosion owing to deviations in the locations of the individual wires from those of a perfect annulus, wire-to-wire current nonuniformities, or the presence of the limited number of current return posts surrounding the array (Fig. 1), which could seed flute-mode instabilities. These velocity components in a *plasma-wire* implosion produced increased density asymmetries at stagnation relative to that of a *plasma-shell* implosion. The resulting difference in the calculated radial convergence between the implosion of a load in the *wire-plasma* regime relative to that of a load in the *plasma-shell* regime is illustrated in Figs. 8A and 8B, respectively, for a 10 current-return-post geometry as used in the Saturn experiments. In the Fig. 8 simulations, the variation in initial wire position arose from numerical noise. Such simulated asymmetries contributed to the reduction in both the compressibility of the stagnating plasma and the resulting radiated energy, both in qualitative agreement with the discontinuity observed in the radial convergence measurements (Fig. 3B) and in the energy channel (Fig. 3C). The increased jetting that also occurs in the *wire-plasma* regime with decreasing wire numbers (Chittenden et al. 2000), with its associated increase in axial plasma that softens the implosion, adds to the decreased convergence and radiated energy resulting from the increased sensitivity to azimuthal asymmetries.

7

4. RZ Simulations Suggest Mechanism for Power Dependence

The TIP simulations showed, however, that the xy variations could not account for the large change in measured pulse shape (Figs. 4A and 4B), for any wire number greater than ~10 or for any reasonable experimental wire or current deviation from azimuthal symmetry (Marder et al. 1998). The effect on the pulsewidth was typically less than an ns. In contrast, RMHC simulations in the rz plane, which assumed an azimuthally symmetric *plasma shell* with a random density distribution in the rz direction, suggested that the shape of the primary power pulse and the general change in peak power with gap were related to the evolution of the thickness of the plasma sheath due to rz motions and the growth of the RT instability. This thickness was calculated to scale linearly with the pulsewidth (Fig. 22 in Sanford et al. 1999a). The measured risetime of the total radiation pulse and the effective pulsewidth (defined as the total energy divided by the peak power--the inverse of the normalized power of Fig. 2) scale as the gap, over the entire gap range explored, showing no discontinuity near 2 mm. This data, together with the simulations, thus suggested a direct relation between the initial interwire gap and the resulting thickness of the imploding sheath (aside from the topology-change effects discussed).

5. Integrated 3D Model

The Heuristic Model (Haines 1998) integrates many of the above measured and simulated observations into four-phases: (1) individual wire expansion with sausage-instability development, (2) wire merger to form a conducting shell, (3) continued inward acceleration with RT instability development in the shell, and (4) pinch formation with equipartion of ion energy to electrons and subsequent radiation. In the model, sausage instabilities in single wires form the seed for the RT instability in the shell. The level of instabilities reached at the time of merger is greater in arrays of small wire numbers due to the increased current per wire and the longer time before merger occurs. The dependence of implosion quality on gap enters in the thickness of the initial annulus and a reduced average perturbation amplitude for larger wire numbers, in the extent of radial plasma jetting, and in slower energy equipartition between ions and electrons estimated for lower pinch densities. In the model, the geometrical connection between the array radius at which merger occurs and the trajectories of the wire plasmas up to this merger time lead to a nonlinear relation for these parameters and to a division of behavior above and below a critical interwire gap. The critical gap G_c is directly related to the 2-mm transition discussed. For $G > G_c$, the wires spend the bulk of their implosion time in a *wire-plasma* regime, and for $G < G_c$, the wire plasmas have merged, forming a *plasma shell* before significant motion of the array has occurred. For the small-radius Saturn geometry, $G_c = 1.6$ mm. This value is in agreement with the above numerical simulations and measurements. For this small-radius geometry, the model well described the measured risetime of the total radiated power pulse as a function of gap when assuming a linear relation between the plasma-shell thickness at stagnation and risetime (Fig. 8B in Sanford et al. 1999b).

III. CHARACTERISTICS AT HIGH WIRE NUMBER

A. INSTABILITIES AND THERMO-GRADIENTS MEASURED

The aluminum loads on Saturn in the *plasma-shell* regime with interwire spacing of less than ~ 0.6 mm exhibit both a strong first and weaker second radiation pulse (Figs. 4B and 9A) that correlate in time with a strong and then weak measured radial convergence (Fig. 9B), hotter and then cooler electron temperatures of the radiating core (Fig. 9C), and higher and then lower ion velocities of the emitting plasma (Fig. 9D), as expected for a double implosion (Sanford et al. 1997a, 1997b, 1997c). Off-axis images of the x-ray emission and radially resolved x-ray spectra indicate a coherent plasma shell (Fig. 10A) prior to first implosion (stagnation), a converged pinch at stagnation (Fig. 10B) composed of a hot core surrounded by a cooler halo (Sanford et al. 1997a and Nash et al. 1998), followed by expanding plasma (Fig. 10C). Fast-framing-pinhole camera images of the x-ray emission from the imploding shell a few nanoseconds prior to stagnation exhibit the classic bubble and spike structure associated with the RT instability. Axial lineouts at the leading edge of the shell (Fig. 10A) show, for example, the existence of a 1.1-mm wavelength that merges to form a 3.3-mm wavelength (Fig. 11A). RMHC simulations and Heuristic Model calculations of the wavelength agree with these magnitudes. At stagnation, axial lineouts (integrated over all radii) exhibit only ~10% RMS variations. After stagnation, a clear sausage instability develops (Fig. 11B), whose wavelength appears to be seeded by the long wavelength amplitude of the RT instability in the pre-stagnating shell (Fig. 11A). The sausage instability persists into and throughout the next implosion and shows no variation in axial position with time (Sanford et al. 1997a).

Figure 9C plots the spatially averaged temperature of the electrons in the core measured from the time-resolved slope of the optically-thin free-bound emission and a measure of the electron temperature in the halo from the ratio of the time-resolved, optically-thick hydrogen-like to helium-like line emissions. At peak convergence, the temperature of the halo (~ 0.4 keV) is estimated to be three to four times cooler than that of the core (~ 1.4 keV), again indicating the presence of strong temperature gradients (see also Fig. 3F at small gaps). While both line and continuum emissions are generated in the hot plasma core at the time of peak convergence, only the optically-thin continuum x-rays escape the plasma directly. The optically-thick line emission is absorbed and re-emitted from the cooler regions until the pinch expands and the plasma opacity declines. The high temperature inferred from the line analysis at times when the plasma is expanding and the core electrons are cooling (Fig. 9C) suggests a lag in recombination (Whitney et al. 1997). That is, the ionization state is likely no longer in equilibrium with the cooled electrons, but reflects instead the earlier state of the plasma when the electrons were hot and the plasma was in equilibrium. The core electrons cool too rapidly in this case for recombination processes to maintain ionization equilibrium.

B. 2D SIMULATIONS

In general, many of the features measured at the first implosion in this high-wire-number *plasma-shell* regime agree with RMHC simulations that take into account the dominant RT instability in the rz plane (Sanford et al 1997c). In these 2D simulations, the magnitude of a random-density seed used to initiate the instability is adjusted so that the width of the radiation pulse generated at stagnation agrees with that measured for a soft-energy channel, such as that shown in Fig. 9A for a three-temperature E (Eulerian)-RMHC (Peterson et al. 1996) simulation. These E-RMHC simulations provide insights into the underlying dynamics for a typical high-

wire-number *plasma-shell* implosion, which are not easily measured. Figure 12A, for example, shows that the mass-averaged radius basically tracks the current-averaged radius up to stagnation, diverging for times beyond peak radiated power. At the minimum mass-averaged radius of ~0.5 mm, E-RMHC indicates a pinched plasma column with a hot high-density core surrounded by a somewhat cooler and slightly lower-density region in qualitative agreement with that measured (Fig. 9C and 10B). The radiation pulse begins when the average radius is still between 3-5 mm (Fig. 12A), indicating a large spread in the plasma sheath thickness due to the instability growth. In the simulation, use of the nominal electron-photon coupling (denoted by E-RMHC:N in the figures) leads to the generation of slightly more radiation at the first compression than measured, and little internal energy is left over to initiate a significant re-expansion followed by a second radial compression as observed. Reducing the coupling (denoted by E-RMHC:R in the figures), however, can led to a second implosion in the simulation, as illustrated with the reduced-coupling simulation in Figs. 9A and 9B.

Figure 12B shows the associated energy partition in the Fig. 12A simulation using the nominal electron-photon coupling. The primary difference between this case and the case with the reduced electron-photon coupling (Figs. 9A and 9B) occurs in the internal energy, where the reduced coupling results in a higher internal energy. Both give similar radiation pulsewidths (Fig. 11 in Sanford et al. 1998c). The energy deposited in the plasma comes primarily from the Lorentz ($\mathbf{J} \times \mathbf{B}$) force and goes primarily to accelerating the plasma, increasing the kinetic energy. Early in the process when instabilities have not become important and there has been little plasma heating, the energy deposited by the Lorentz force and plasma radial kinetic energies are essentially equal. Later, the instability destroys the plasma shell, accelerating plasma to the axis where it stagnates, and the kinetic energy diverges significantly from that generated by the Lorentz force. When stagnation begins, the internal energy starts to rise and the plasma begins to radiate. At this time, most of the plasma extends over a significant radial region. Energy still flows into the load through the Poynting flux, and part of this flux continues to accelerate the plasma that has not stagnated. The radiation continues to rise as the main part of the plasma stagnates. Well after stagnation, the total radiated energy is nearly equal to that provided by the Lorentz force acting on the plasma (Fig. 12B). As plotted, the calculation shows only a small contribution from the Joule heating.

For the highly-symmetric arrays being discussed here, x-ray images reveal a well-defined circular emission ring on the cathode surface (Fig. 13). The elliptical shape of the rings in the figure reflects the distortion introduced by the 35° viewing angle (Fig. 1). Between -9 and -7 ns in Fig. 13, the rings move inward at an average rate of about 0.45 mm/ns, increasing to about 0.53 mm/ns between -7 and -4 ns. These measured velocities are similar to the 0D-calculated implosion velocities of the array at the corresponding times, and the radii of the rings correlate with both the peaks of the mass and current profiles calculated by an E-RMHC simulation (see distributions shown below images of Fig. 13). The rings are thus conjectured to be from radiating plasma produced by either electron-current flow into the imploding plasma shell or an associated ion heating of the cathode surface.

In the Fig. 13 simulation, the radially-converging plasma precursor from instability bubble regions begins to stagnate on axis about 9 ns prior to peak emission, reaching electron temperatures of about 1 keV. This precursor becomes detectable in x-ray imaging just at this time (Fig. 13A). The Fig. 13 images indicate that the precursor emission expands axially to fill the entire 20-mm anode-cathode gap by the time peak x-ray emission occurs. Lagrangian-RMHC simulations (Hammer et al. 1996) that account for camera response and viewing angle show that

the interaction of the stagnated precursor plasma with that of the inward moving shell generates the appearance of a hot inward-moving, luminescent, cylindrical shell (Sanford et al. 1997c) like that imaged in Fig. 13. These data, combined with the above conjecture, suggest that a large fraction of the imploding mass is outside the emitting region and is either too cold or too diffuse to generate measurable x-rays.

These observations are also consistent with 1D-RMHC analyses (Whitney et al. 1997) that required a cool shell of plasma to implode onto a small amount of precursor plasma to explain the total to K-shell power ratio. In this model, the cool outer shell of plasma is needed to explain the greater than 4-to-1 power ratio measured, and it is also consistent with the spectral analysis (Sanford et al. 1996a, Whitney et al. 1997) which found that only 20% of the mass contributes to the K-shell radiation at the time of peak power. Moreover, the experimentally observed size of the K-shell emission region is smaller than the calculated mass-averaged plasma size (Figs. 9B and 13C), consistent with this low-mass fraction contributing to the K-shell emission.

C. MEASURED AND SIMULATED VARIATION WITH ARRAY MASS AND RADIUS

Following the 1995 wire-number scan, two additional series of Saturn aluminum-wire experiments were conducted in the high-wire-number, *plasma-shell* regime. These experiments were designed to better understand the conditions that optimize the total radiated power in this regime (Sanford et al. 1997b). In the first series, the radius was held fixed at 12 mm and the mass was varied over the range 0.42 to 3.4 mg (Sanford et al. 1998c). This series showed that when the mass of the array (which used ~ 192 wires) was reduced from above 1.9 to below 1.3 mg, a factor of two decrease in pulsewidth occurred (Fig. 14A), with an associated doubling of the peak total radiated power (Fig. 14B). In the second series, the array mass was held fixed near a value which maximized the peak power from the first series, and the array radius was varied (Sanford et al. 1998d). This series showed that when the radius increased from 8.6 to 20 mm, for a mass of 0.6 mg in 136 wires, the total radiated pulsewidth (Fig. 14C) increased from only ~ 4 to ~ 7 ns and the associated peak total radiated power (Fig. 14D) remained relatively unchanged with radius.

Within the uncertainty of the electron-photon coupling approximation, the E-RMHC pulsewidths and total radiated peak power reasonably followed the measured trends (Fig. 14), using only a single value of a density perturbation seed set by the comparison in Fig. 9A. Moreover, the simulations showed that over the mass- and radius-range measured, which spanned an implosion time of 40 to 90 ns, the shape of the simulated total-radiated-power pulse tracked the initial pulse measured. The implosion time of the simulated pulse agreed with that measured, within a shot-to-shot variation of only 2 ns. This agreement suggested that $(100 \pm 7)\%$ of the initial mass was accelerated during the implosion, for these *plasma-shell* loads. The agreement in these comparisons that spanned an order-of-magnitude in load mass and almost a factor of three in array radius, and that use this single-value seed, provided credibility to the average hydrodynamics of the E-RMHC simulations. These simulations showed that the RT growth occured via a two-staged process, if only 2D effects were considered (Peterson et al. 1998a, 1998b). The results also suggested that because in the radius scan the gap varied from 0.4 to 0.96 mm and because the simulation does not know about the discrete azimuthal nature of the array, the fact that the single seed described all the data implied that other asymmetries may be beginning to dominate these *plasma-shell* implosions.

The E-RMHC simulations attributed the decrease in pulsewidth and associated doubling of the peak total power as mass decreased, to the faster implosion velocity of the plasma shell relative to the growth of the shell thickness. The data and modeling of the K-shell yields using either the Two-Level Model (Mosher et al. 1998) or a phenomenological model (Thornhill et al. 1996) showed the importance of maintaining sufficient kinetic energy per ion (that is, imploding sufficiently low-mass and high-velocity loads) if maximum yields are to be extracted. The E-RMHC simulations correlated the decrease in pulsewidth with radius to the faster decrease of the shell thickness relative to the decrease in shell velocity. Importantly, the data showed that the improved uniformity provided by the large number of wires in the initial array reduced the effects of the RT instability observed in small-wire-number, large-radius arrays (Deeney et al. 1991, 1998b), and permitted the generation of high radiation powers from large-radius arrays for the first time. Large-radius arrays are often desired in order to optimize the energy transfer to the load, to reduce the electrical stress on the pulse forming lines feeding the load, or to provide the desired x-ray radiation characteristics as in Z (Spielman et al. 1998). Little variation in K-shell yield was measured over the radial variation explored. In general, the variation in the measured K-shell yield with mass and radius were consistent with both the Two-Level Model and the phenomenological model with an *ad hoc* assumption on the radial convergence (Fig. 6B in Sanford et al. 1998c, Fig. 10G in Sanford et al. 1998d).

IV. OBSERVATIONS IN AXIAL GEOMETRY AT HIGH-WIRE NUMBER

Owing to the greater number of radiative transitions available in tungsten relative to aluminum, tungsten-wire loads are routinely used on Saturn and Z when maximum soft x-ray powers are desired. For this reason, the three z-pinch ICF concepts mentioned in the introduction all utilize the radiation generated from tungsten wires in the high-wire-number regime to heat high atomic-number hohlraums. The absorbed radiation in the hohlraum is thermalized into a near Planckian x-ray source that would be suitable for imploding an ICF capsule if sufficient radiation temperature were attained. The extension of the observations and modeling discussed above to such tungsten loads on Saturn and Z can be found in (Deeney et al. 1998b, 1998c, 1999), (Lebedev et al. 2000), (Peterson et al. 1998a, 1998b, 1999), (Ruiz-Camancho et al. 1999), (Sanford et al. 1998b), and (Spielman et al. 1997, 1998). Subsequent to the Saturn measurements, nesting of the arrays has been found to mitigate the RT development and has enabled additional power increases (40±20%) with tungsten wire implosions on Z (Deeney et al. 1998a). Like the extension to tungsten loads, the interested reader is here again directed to the original paper. Relevant to this review, however, is the reduction in radial size and associated azimuthal structure observed near stagnation that has recently been measured when nested tungsten arrays are imploded on foam targets. The measurements were made using the *static-wall-hohlraum* geometry (Fig. 15A). As such, they also serve as an example of the high temperatures that have been achieved in configurations needed for ICF studies with a z-pinch (Fig. 15B).

The measurements were motivated by the need to understand the dynamics of the axial radiation that heats the hohlraum. In the single-sided x-ray drive of Fig. 15B, the hohlraum is placed above a pulse-shaping target (PST) within an x-ray producing z-pinch. In the two-sided x-ray drive of Fig. 15C, the hohlraum is sandwiched between two PSTs. In either case, x-rays

produced in the PST enter the axial hohlraum through one or two REH (radiation-entrance-holes) and heat its walls. The x-rays are generated in the PST by the thermalization of the kinetic energy, acquired when a cylindrical plasma shell created by one or more wire arrays, collides with the PST. In this arrangement, the tungsten wires form an annular plasma radiation case (Sanford et al. 1998b) by the time they strike the PST. The high-atomic-number radiation case traps a fraction of the x-rays produced in the PST and radiation flows from the interior of the PST into the hohlraum, whose walls remain relatively static. A low-opacity foam fill is used in some of the PSTs so that as final stagnation is approached, the foam remains transparent to the x-rays, yet provides a backpressure on the imploding mass. The backpressure enables additional energy to be extracted as the magnetic field compresses the PST. Changing the PST varies the x-ray pulse and the associated heating of the hohlraum. The single-sided drive of Fig. 15B is that which has been tested to date and is associated with the measurements discussed here. The two-sided drive of Fig. 15C is presently under development. It should permit both hotter and more spatially symmetric radiation fields to be produced within the hohlraum, where a capsule could be positioned with appropriate shine shields.

The radiation entering the hohlraum is measured by diagnostics that view the source through the REH when the hohlraum is not present (Fig. 15A). Over the measured peak x-ray input powers P of 0.7 to 13 TW (obtained by varying the PST), the measured peak hohlraum temperature T scales as the Planckian relation $T \sim (P/A)^{1/4}$ (Fig. 16), and is in agreement with simple theoretical expectations (Sanford et al. 2000a). A is the surface area of the hohlraum. In Fig. 16, all the data except the highest temperature data of ~155 eV correspond to those measured with the NIF-scale hohlraum, which had a surface area of 153 mm^2 (Sanford et al. 1999d). In Fig. 16, the 85-eV drive simulates the ~10-ns foot pulse necessary for ICF ignition and propagation burn (Dittrich et al. 1998, Wilson et al. 1998) on the NIF (National Ignition Facility). The 120-eV and ~155 eV temperatures correspond to those needed in the associated first- and second-drive steps (Sanford et al. 2000c).

In the figure, the axial powers greater than a TW were achieved, in part, by removing the azimuthal asymmetries in the current return can and by using a nested array to mitigate the RT instability. The use of a low-density (14 mg/cc) CH-foam PST decreased the radial size of the pinch at stagnation from ~2 to ~1 mm and permitted the same axial power to be produced through a 4-mm diameter REH as was produced with a bare pinch through a 6-mm diameter REH (Fig. 17). The size reduction permitted the reduced-scale hohlraum to be heated with the same radiation power as that used to heat the NIF-scale hohlraum. Now, however, temperatures higher than those achievable in the NIF-scale hohlraum became possible because of the reduced surface area (Fig. 16). Such temperatures (~155 eV), especially when generated in a NIF-scale hohlraum heated by the symmetric drive geometry of Fig. 15C, offer the opportunity to study the implosion of D$_2$ filled capsules capable of generating thermonuclear neutrons (Sanford et al. 2000a). These studies would be useful for NIF-relevant neutron diagnostic development (Leeper et al. 1997) and capsule fabrication performance evaluations (Wilson et al. 2000).

The foam, like the inner shell of the nested array, appears to reduce the amplitude of the RT instability. Associated with the radial size reduction, the off-axis total radiated power pulse decreases by ~25% from 3.2 to 2.3 ns and the on-axis pulse from 5.2 to 4.0 ns. For either of the tight pinches plotted in Fig. 17, periodic azimuthal structure is evident in the fast-framing pinhole images of the radiation originating from the REH. The structure is consistent with mode numbers of 4-8 (Fig. 18). Preliminary MHD simulations (Roderick 2000) with an imposed 5% density variation having 6-fold symmetry on the outer array exhibit density variations with ~50%

excursions near stagnation similar to the emission variations observed (Sanford et al. 2000c). In the simulations, the initial variation is amplified due to radial convergence. The post-hole convolute structure on Z has a 12-fold azimuthal periodicity (Spielman et al. 1998). Calculations of the current at the load indicate, however, that any variation in the current flowing in the load would be less than 1% (Struve 2000). The origin of such azimuthal mode structures in the emission images, when using such highly symmetric loads, is not yet understood.

V SUMMARY

The 1995 Saturn experiments, where the wire number was systematically varied, demonstrated that a key parameter in significantly increasing radiation power and improving the quality of the pinch was the interwire gap spacing. The data show a dramatic increase in power below a gap of about 2±0.6 mm and associated transitions in other measured radiation and pinch parameters. When the gap decreased from 6 to 0.4 mm, the total radiated power increased by a factor of 20 and the energy by a factor of 2. The transition near 2 mm correlated with a transition in topology between that of individual *wire plasmas* at large gaps to that of a more uniform *plasma shell* at small gaps. Such a transition in topology has been recently confirmed in MAGPIE experiments (Lebedev et al. 2000). For gaps less than 2 mm, the total radiated energy showed no change. The measured decrease in total radiated energy for gaps greater than ~2 mm was qualitatively consistent with the increased sensitivity to azimuthal variations in the *wire plasma* regime and the recently calculated transition in perturbation amplitude resulting from the development of the $m=0$ instability in individual wires (Chittenden et al. 2000). The azimuthal variations lead to a reduced efficiency for converting kinetic energy to thermal energy at stagnation, and the greater perturbation amplitude leads to increased coronal jetting and a softer implosion.

The order-of-magnitude increase in the power and its inverse gap dependence when normalized by the total radiated energy (Fig. 2), however, cannot be explained by azimuthal asymmetries alone. RMHC simulations in the rz plane, in contrast, suggest that the measured change in peak x-ray power with gap (aside from the topology change effect) is related to the evolution of the thickness of a plasma shell due to the growth of axisymmetric RT instabilities. In general, many features of the data and simulations as a function of gap are well summarized by the four-phase Heuristic Model (Haines 1998). This model establishes the connection between the $m=0$ perturbation in the individual wire plasmas with the seed initiating the RT instability in the rz plane.

In the high wire-number *plasma-shell* regime, the data are well described by RMHC simulations in the rz plane, such as those of Hammer et al. 1996 and Peterson et al 1996, which includes the evolution of an RT instability in an axisymmetric implosion. In this regime, simple 1D K-shell models such as those of Mosher et al. 1998 and Thornhill et al. 1993, which assume an *ad hoc* radial convergence, agree with the measured K-shell yields as a function of mass and radius. Not yet included in any of the simulations, however, is an explanation of the azimuthal mode structure observed through a small REH (used for hohlraum heating in the *static-wall* configuration), when highly-symmetric nested-array loads stagnate on axis.

Application of such high-wire-number loads at large radii has led to the heating of ICF relevant hohlraums to high temperature. In the single-sided *static-wall-hohlraum* (Olson et al. 1999) configuration discussed here (Fig. 15B), temperatures of 130±7 eV and 155±8 eV have

been achieved in NIF-scale and reduced-scale hohlraums, respectively. Extrapolating this concept with a NIF-scale hohlraum, using a single-feed double-sided driver (Fig. 15C), to a 50-MA generator, could provide conditions suitable for studying capsule implosions driven at peak temperatures of 240-270 eV (Sanford et al 1999d). Such generators are characteristic of the next generation Z-pinch drivers being considered (Struve et al. 1999).

ACKNOWLEDGMENTS

REFERENCES

Beg, F.N., A.E. Dangor, P. Lee, M. Tatarakis, S.L. Niffikeer, and M.G. Haines. 1997. "Optical and x-ray observations of carbon and aluminum fibre Z-pinch plasmas," *Plasma Phys. Fusion* **39**, 1.

Bloomquist, D.D., R.M. Stinnett, D.H. McDaniel, *et al.* 1987. *Proc. 6th Int. IEEE Pulsed Power Conf.*, Arlington, VA, ed. P.J. Turchi and B.H. Bernstein (Institute of Electrical and Electronic Engineers, New York), p. 310.

Chittenden, J.P., R. Aliaga Rossel, S.V. Lebedev, I.H. Mitchell, M. Tatarakis, A.R. Bell, and M.G. Haines. 1997. "Two-dimensional magneto-hydrodynamic modeling of carbon fiber Z-pinch experiments," *Phys. Plasmas* **4**, 4309.

Chittenden, J.P., S.V. Lebedev, A.R. Bell, R. Aliaga-Rossel, S. N. Bland, and M. G. Haines. 1999. "Plasma formation and implosion structure in wire array z pinches" *Phys. Rev. Lett.* **83**, 100 (1999).

Chittenden, J.P., S.V. Lebedev, J. Ruiz-Camacho, F.N. Beg, S.N. Bland, C.A. Jennings, A.R. Bell, and M.G. Haines. 2000. "Plasma formation in metallic wire Z pinches," *Phys. Rev. E* **61**, 4370.

Cook, D.L. 1997. "New developments and applications of intense pulsed radiation sources at Sandia National Laboratories," *11th IEEE International Pulsed Power Conf. Baltimore, Ma, (June 29-July 2, 1997), Digest of Technical Papers*, Editors G. Cooperstein and I. Vitkovitsky, IEEE Cat. No. **97CH36127**, 25.

Cook, D.L., J.J. Ramirez, P.S. Raglin, G. E. Rocheau, M. K. Matzen, R. J. Leeper, J. L. Porter, R. E. Olson, D. H. McDaniel, R. B. Spielman, C. Deeney, and J. P. Quintenz. 1998. "X-1: The challenge of high fusion yield," In *12th International Conference on High-Power Particle Beams* (Haifa, Israel, June 7-12, 1998), 171.

Cuneo, M.E., R.A. Vesey, J.L. Porter, J.H. Hammer, L.E. Ruggles, W.W. Simpson, C.A. Hall, J.R. Asay, D.L. Hanson, T.J. Nash, G.A. Chandler, R.B. Spielman, J.F. Seamen, T.L. Gilliland. 1999. "Z-Pinch Driven Hohlraum Energetics and Load Development," *Bull Amer. Phys. Soc.* **44**, 40.

Deeney, C., T. Nash, R.R. Prasad, L. Warren, K.G. Whitney, J.W. Thornhill, and M.C. Coulter. 1991. "Role of the implosion kinetic energy in determining the kilovolt x-ray emission from aluminum-wire-array implosions," *Phys. Rev. A* **44**, 6762.

Deeney, C., T.J. Nash, R.B. Spielman, J.F. Seamen, G.C. 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.L. Fehl, D.H. McDaniel, D.L. Matzen, M.K. Peterson, W. Matuska, J.J. Roderick, and N.F. McFarlane. 1997. "Power

enhancement by increasing the initial array radius and wire number of tungsten Z pinches," *Phys. Rev. E.* **56**, 5945-5958.

Deeney, C., M.R. Douglas, R.B. Spielman, T.J. Nash, D.L. Peterson, P.L. Eplattenier, G.A. Chandler, J.F. Seamen, and K.W. Struve. 1998a. "Enhancement of X-Ray Power from a Z Pinch Using Nested-Wire Arrays," *Phys. Rev. Lett.* **81**, 4883.

Deeney, C., T.J. Nash, R.B. Spielman, J.F. Seamen, J.S. McGurn, D.O. Jobe, M.F. Vargus, T.L. Gilliland, R.C. Mock, K.W. Struve, K.G. Whitney, P.E. Pulsifer, J.P. Apruzese, J.W. Thornhill, and J. Davis. 1998b. "Improved large diameter wire array implosions from increased wire array symmetry and on-axis mass participation," *Phys. Plasmas* **5**, 2431.

Deeney, C., D.L. Peterson, R.B. Peterson, K.W. Struve, and G.A. Chandler. 1998c. "Optimization of power density by decreasing the length of tungsten wire array Z pinches," *Phys. Plasmas* **5**, 2605.

Deeney, C., C.A. Coverdale, M.R. Douglas, K.W. Struve, R.B. Spielman, W.A. Stygar, D.L. Peterson, N.F. Roderick, M.G. Haines, F.N. Beg, and J. Ruiz-Camacho. 1999. "Radiative properties of high wire number tungsten arrays with implosion times up to 250 ns," *Phys. Plasmas* **6**, 3576.

Derzon, M.S., G.O. Allshouse, G.A. Chandler, *et al.* 1997. *Bull. Am. Phys. Soc.* **42**, 1994.

Dittrich, T.R., S.W. Haan, M.M. Marinak, *et al.* 1998. "Reduced scale National Ignition Facility capsule design," *Phys. Plasmas* **5**, 3708.

Haines, M.G., and A. Knight, editors. 1993. *Dense z-Pinches 3rd International Conference*, London, UK, 1993, AIP Conference Proceedings 299, American Institute of Physics, New York 1994, L.C. Catalog Card No. 93-74569.

Haines, M.G. 1998. "A Heuristic Model of the Wire Array Z-Pinch", *IEEE Trans. Plasma Sci.* **26**, 1275.

Haines, M.G. 2000. "The past, present, and future of Z pinches," *Phys. Plasmas* **7**, 1672.

Hammer, J.H., J.L. Eddleman, P.T. Springer, M. Tabak, A. Toor, K.L. Wong, G.B. Zimmerman, C. Deeney, R. Humphreys, T.J. Nash, T.W.L. Sanford, R.B. Spielman, and J.S. De Groot. 1996. "Two-dimensional radiation-magnetohydrodynamic simulations of SATURN imploding Z pinches," *Phys. Plasmas* **3**, 2063.

Hurst, M.J., T.J. Nash, M.S. Derzon, J.W. Kellogg, J. Torres, J. McGurn, J. Seamens, D. Jobe, and S. Lazier. 1999. "Fielding of the axial diagnostic package at Z," *Rev. Sci. Instrum.* **70**, 468.

Kilkenney, J.D., T.P. Bernat, B.A. Hammel, *et al.* 1999. "Lawrence Livermore National Laboratory', activities to achieve ignition by x-ray drive on the National Ignition Facility", *Laser and Part. Beams* **17**, 159.

Lash, J.S., G.A. Chandler, G. Cooper, M.S. Derzon, M.R. Douglas, D. Hebron, R. Leeper, M.K. Matzen, T.A. Mehlhorn, T.J. Nash, C. Ruiz, S.A. Slutz, D.L. Peterson and R.E. Chrien. 1999. "The Prospects for High Yield ICF with a Z-pinch Driven Dynamic Hohlraum," *First International Conference on Inertial Fusion Sciences and Applications*, Bordeaux, France, September 12-17, 1999, proceedings to be published.

Lebedev, S.V., I.H. Mitchell, R. Aliaga-Rossel, S.N. Bland, J.P. Chittenden, A.E. Dangor, M.G. Haines. 1998. "Azimuthal structure and global instability in the implosion phase of wire array z-pinch experiments," *Phys. Rev. Lett.* **81**, 4152.

Lebedev, S.V., R. Aliaga-Rossel, S.N. Bland, J.P. Chittenden, A.E. Dangor, M.G. Haines, and I.H. Mitchell. 1999. "The dynamics of wire array Z-pinch implosions," *Phys. Plasmas* **6**, 2016.

Lebedev, S.V. Lebedev, F.N. Beg, S.N. Bland, J.P. Chittenden, A.E. Dangor, M.G. Haines, S.A. Pikuz, and T.A. Shelkovenko. 2000. "Effect of core-corona plasma structure on seeding of instabilities in wire array z-pinches," to be published in *Phys. Rev. Lett.*

Leeper, R.J., G.A. Chandler, G.W. Cooper, *et al.* 1997. "Target diagnostic system for the national ignition facility," *Rev. Sci. Instrum.* **68**, 868.

Leeper, R. J., T.E. Alberts, J.R. Asay, P.M. Baca, K.L. Baker, S. P. Breeze, G.A. Chandler, D.L. Cook, G.W. Cooper, C. Deeney, M.S. Derzon, M.R. Douglas, D.L. Fehl, T. Gilliland, D.E. Hebron, M.J. Hurst, D.O. Jobe, J.W. Kellogg, J.S. Lash, S.E. Lazier, M.K. Matzen, T.A. Mehlhorn, D.H. McDaniel, J.S. McGurn, A.R. Moats, R.C. Mock, D.J. Muron, T.J. Nash, R.E. Olson, J.L. Porter, J.P. Quintenz, P.V. Reyes, L. E. Ruggles, C.L. Ruiz, F.A. Schmidlapp, J.F. Seamen, R.B. Spielmen, T.W.L. Sanford, M.A. Stark, K.W. Struve, W.A. Stygar, D.R. Tibbetts-Russell, J.A. Torres, M. Vargas, T.C. Wagoner, C. Wakefield, J. H. Hammer, D.D. Ryutov, M. Tabak, S.C. Wilks, R.L. Bowers, K.K. McLenithan, and D.L. Peterson. 1999. "Z-pinch Driven Inertial Confinement Fusion Target Physics Research at Sandia National Laboratories," *Nuclear Fusion* **39**, 1283.

Marder, B.M. 1973. "GAP-A PIC-Type Fluid Code", *Math. of Comp.* **29**, 434.

Marder, B.M., T.W.L. Sanford, and G.O. Allshouse. 1998. "Numerical simulations of annular wire-array z-pinches in (x, y), (r, θ), and (r, z) geometries," *Physics of Plasmas* **5**, 2997.

Matzen. K.M. 1997. "Z pinches as intense x-ray sources for high-energy density physics applications," *Phys. Plasmas* **4**, 1519.

Matzen, K.M. 1999a. "Z-pinches as intense X-ray sources for inertial confinement fusion applications," *Fusion Engineering and Design* **44**, 287.

Matzen, K.M., C. Deeney, R.J. Leeper, J.L. Porter, R.B. Spielman, G. Chandler, M. Derzon, M. Douglas, D. Fehl, T. Nash, R. Olson, T.W.L. Sanford, J. Seamen, and W. Stygar. 1999b. "Fast Z-Pinches as a Dense Plasma, Intense X-ray Source for Plasma and Fusion Applications," *Plasma Physics and Controlled Fusion* **41**, A175-A184.

Mehlhorn, T.A. 1997. "Intense ion beams for inertial confinement fusion," *IEEE Trans. Plasma. Sci.* **25**, 1336.

Morse, R.L., and D.E. Carroll. 2000. "Magnetic screening of wires and other resistive sheath structure in the Sanford effect range with new conductivities," *Bull. Am. Phys. Soc.* **45**, 788.

Mosher, D., and D. Colombant. 1992. "Pinch Spot Formation in High Atomic Number z Discharges", *Phys. Rev. Lett.* **68**, 2600.

Mosher, D. 1994. "BEAMS'94," In *Proceedings of 10th International Conference on High power Particle Beams*, pp. 159-162. See National Technical Information Service document no. NTIS PB95-1443417. Copies may be ordered from the National Technical Information Service, Springfield, Virginia 22161.

Mosher, D., N. Qi, and M. Krishnan. 1998. "Two-level model for K-shell radiation scaling of the imploding z-pinch plasma radiation source," *IEEE Trans. Plasma Sci.* **26**, 1052.

Nash, T.J., T.W.L. Sanford, C. Deeney, R.B. Spielman, J. Seaman, J. McGurn, D.O. Jobe, R.C. Mock, T.L. Gilliland, J.P. Apruzese, and K.G. Whitney. 1998a. "High Temperature, Dense Cores in an Aluminum Wire Array Z-Pinches Observed by Spatially-Resolved Spectroscopy," *J. Quant. Spectrosc. Radiat. Transfer* **60** (1), 97-102.

Nash, T.J., M.S. Derzon, G.A. Chandler, *et al.* 1998b. "High Temperature Dynamic Hohlraums on the Pulsed Power Driver Z," submitted to *Phys. Plasmas* (Nov. 1998).

Nash, T.J., M.S. Derzon, G.A. Chandler, D. Fehl, R. Leeper, M. Hurst, D. Jobe, J. Torres, J. Seamens, S. Lazier, T. Gilliland, and J. McGurn. 1999. "Axial diagnostic package for Z," *Rev. Sci. Instrum.* **70**, 464.

Olson, R.E., G.A. Chandler, M.S. Derzon, D.E. Hebron, J.S. Lash, R.J. Leeper, T.J. Nash, G.E. Rochau, T.W.L. Sanford, N.B. Alexander, and C.R. Gibson. 1999. "Indirect-Drive ICF Target Concepts for the X-1 Z-Pinch Facility," *Fusion Technology* **35**, 260.

Periera, N.R., and J. Davis. 1988. "X rays from z-pinches on relativistic electron-beam generators," *J. Appl. Phys.* **64**, R1.

Periera, N.R., J. Davis, N. Rostoker, editors. 1989. *Dense z-Pinches 2nd International Conference*, Laguna Beach, CA, 1989), AIP Conference Proceedings 195, American Institute of Physics, New York 1994, L.C. Catalog Card No. 89-046212.

Peterson, D.L., R.L. Bowers, J.H. Brownell, A.E. Greene, K.D. McLenithan, T.A. Oliphant, N.F. Roderick, and A.J. Scannapieco. 1996. "Two-dimensional modeling of magnetically driven Rayleigh-Taylor instabilities in cylindrical Z pinches," *Phys. Plasmas* **3**, 368.

Peterson, D.L., R.L. Bowers, J.H. Brownell, C. Lund, W. Matuska, K. McLenithan, H. Oona, C. Deeney, M. Derzon, R.B. Spielman, T.J. Nash, G. Chandler, R.C. Mock, T.W. L. Sanford, M. K. Matzen, and N.F. Roderick. 1998a. "Application of 2-D Simulations to Hollow Z-Pinch Implosions,, *Dense Z-Pinches Fourth International Conference,* Vancouver, Canada, May 1997, edited by N.R. Pereira, J. Davis, and P.E. Pulsifer, published by The American Institute of Physics. **1-56396-610-7/97**, 201-210.

Peterson, D.L., R.L. Bowers, K.D. McLenithan, C. Deeney, G.A. Chandler, R.B. Spielman, M.K. Matzen, and N.F. Roderick. 1998b. "Characterization of energy flow and instability development in two-dimensional simulations of hollow z-pinches," *Phys. Plasmas* **5**, 3302.

Peterson, D.L., R.L. Bowers, W. Matuska, *et al.* 1999. "Insights and applications of two-dimensional simulations to Z-pinch experiments," *Phys. Plasmas* **6**, 2178.

Porter, J.L. 1997. *Am. Phys. Soc.* **44**, 1948.

Quintenz, J.P., R.G. Adams, J.E. Bailey, D.D. Bloomquist, G.A. Chandler, R.S. Coats, D.L. Cook, M.E. Cuneo, C. Deeney, M.S. Derzon, M.P. Desjarlais, R.J. Dukart, A.B. Filuk, T.A. Haill, D.L. Hanson, D.J. Johnson, M.L. Kiefer, R.J. Leeper, T.R. Lockner, B.M. Marder, M.K. Matzen, D.H. McDaniel, E.J. McGuire, T.A. Mehlhorn, C.W. Mendel, P.R. Menge, L.P. Mix, A.R. Moats, T.J. Nash, C.L. Olson, R.E. Olson, T.D. Pointon, J.L. Porter, T.J. Renk, S.E. Rosenthal, C.L. Ruiz, T.W.L. Sanford, J.F. Seamen, D.B. Seidel, S.A. Slutz, R.B. Spielman, W.A. Stygar, M.A. Sweeney, and G.C. Tisone, 1996. "Progress in Pulsed Power Fusion, BEAMS '96," In *Proceedings of the 11th International Conference on High-Power Particle Beams*, 146 (Prague, Czech Republic, June 10-14, 1996), edited by K. Jungwirth and J. Ullschmied, published by Academy of Sciences of the Czech Republic, Za Slovankou 3, 182 00 Prague 8, Czech Republic.

Quintenz, J.P., R.G. Adams, G. O. Allshouse, J.E. Bailey, D.D. Bloomquist, G.A. Chandler, R.S. Coats, D.L. Cook, M.E. Cuneo, C. Deeney, M.S. Derzon, M.P. Desjarlais, M. R. Douglas, D. L. Fehl, A.B. Filuk, T.A. Haill, D.L. Hanson, D.J. Johnson, M.L. Kiefer, J. S. Lash, R.J. Leeper, B.M. Marder, M.K. Matzen, D.H. McDaniel, E.J. McGuire, T.A. Mehlhorn, L. P. Mix, A.R. Moats, T.J. Nash, C.L. Olson, R.E. Olson, T.D. Pointon, J.L. Porter, C.L. Ruiz, T.W.L. Sanford, J.F. Seamen, D.B. Seidel, S.A. Slutz, R.B. Spielman, W.A. Stygar, M.A. Sweeney, R. A. Vesey, and D. F. Wenger, 1998. "Pulsed Power Fusion Program Update", "BEAMS'98" *12th International Conference on High-Power Particle Beams* (Haifa, Israel, June 7-12, 1998), 9.

Ramirez, J.J. 1997. "The X-1 Z-Pinch Driver," *IEEE Trans. Plasma Sci.* **25**, 155.

Reisman, D.B. 1998. *Ph.D. Dissertation*, University of California, Davis.

Roderick, N.F. 2000. Private communication.

Ruggles, L.E., R.E. Spielman, J.L. Porter, and S.P. Breeze. 1995. "Characterization of a high-speed x-ray imager," *Rev. Sci. Instrumen.* **66**, 712.

Ruiz-Camacho, J., F.N. Beg, A.E. Dangor, and M.G. Haines. 1999. "Z-pinch discharges in aluminum and tungsten wires," *Phys. Plasmas* **6**, 2579.

Ryutov, D.D., M.S. Derzon, M.K. Matzen. 2000. "The physics of fast Z pinches," *Rev. Modern Phys.* **72**, 167.

Sanford, T.W.L., T.J. Nash, B.M. Marder, R. Humphreys, C. Deeney, R.B. Spielman, J.F. Seamen, R.C. Mock, J.S. McGurn, D. Jobe, T.L. Gilliland, M. Vargas, K. Struve, W.A. Stygar, J.H. Hammer, J.L. Eddleman, J.S. De Groot, D. Mosher, K.G. Whitney, J.P. Apruzese, P. Pulsifer, Y. Maron. 1995. "Dynamics of Aluminum-Wire z-Pinch Implosions on Saturn," *Bull. Am. Phys. Soc.* **40**, 1846.

Sanford, T.W.L., G.O. Allshouse, B.M. Marder, T.J. Nash, R.C. Mock, M.R. Douglas, R.B. Spielman, J.F. Seamen, J.S. McGurn, D. Jobe, T.L. Gilliland, M. Vargas, K.W. Struve, W.A. Stygar, J.H. Hammer, J.S. De Groot, J.L. Eddleman, K.G. Whitney, J.W. Thornhill, P.E. Pulsifer, J.P. Apruzese, D. Mosher, D.L. Peterson, and Y. Maron. 1996a. "X-ray Power Increase from Symmetrized Wire-Array Z-pinch Implosions," *BEAMS '96, Proceedings of the 11th International Conference on High-Power Particle Beams*, 146 (Prague, Czech Republic, June 10-14, 1996), edited by K. Jungwirth and J. Ullschmied, published by Academy of Sciences of the Czech Republic, Za Slovankou 3, 182 00 Prague 8, Czech Republic.

Sanford, T.W.L., G.O. Allshouse, B.M. Marder, T.J. Nash, R.C. Mock, R.B. Spielman, J.F. Seamen, J.S. McGurn, D. Jobe, T.L. Gilliland, M. Vargas, K.W. Struve, W.A. Stygar, M.R. Douglas, M.K. Matzen, J.H. Hammer, J.S. De Groot, J.L. Eddleman, D.L. Peterson, D. Mosher, K.G. Whitney, J.W. Thornhill, P.E. Pulsifer, J.P. Apruzese, and Y. Maron. 1996b. "Improved Symmetry Greatly Increases X-ray Power from Wire-Array Z-Pinches," *Phys. Rev. Lett.* **77** (25), 5063.

Sanford, T.W.L., T.J. Nash, R.C. Mock, R.B. Spielman, J.F. Seamen, J.S. McGurn, D. Jobe, T.L. Gilliland, M. Vargas, K.G. Whitney, J.W. Thornhill, P.E. Pulsifer, and J.P. Apruzese. 1997a. "Time-Dependent Electron Temperature Diagnostics for High-Power, Aluminum Z-pinch Plasmas," *Rev. Sci. Instrum.* **68** (1), 852.

Sanford, T.W.L., R.C. Mock, B.M. Marder, T.J. Nash, R.B. Spielman, D.L. Peterson, N.F. Roderick, J.H. Hammer, J.S. De Groot, D. Mosher, K.G. Whitney, and J.P. Apruzese. 1997b. "Variation of High-Power Aluminum-Wire Array Z-Pinch Dynamics with Wire Number, Load Mass, and Array Radius," *Dense Z-Pinches Fourth International*

Conference, Vancouver, Canada, May 1997, edited by N.R. Pereira, J. Davis, and P.E. Pulsifer, published by The American Institute of Physics.

Sanford, T.W.L., T.J. Nash, R.C. Mock, R.B. Spielman, K.W. Struve, J.H. Hammer, J. S. De Groot, K. G. Whitney, and J. P. Apruzese. 1997c. "Dynamics of a High-Power Aluminum-Wire Array Z-Pinch Implosion," *Phys. Plasmas* **4**, 2188.

Sanford, T.W.L., R.C. Mock, B.M. Marder, M.P. Desjarlais, T.J. Nash, R.B. Spielman, D.L. Peterson, K.G. Whitney, J.P. Apruzese, P. E. Pulsifer, and D. Mosher. 1998a. "Wire Array Z-Pinch Insights for High X-ray Power Generation," "BEAMS'98" *12th International Conference on High-Power Particle Beams* (Haifa, Israel, June 7-12, 1998), 229.

Sanford, T.W.L., R.B. Spielman, G.O. Allshouse, G.A. Chandler, D.L. Fehl, W.A. Stygar, K.W. Struve, C. Deeney, T.J. Nash, J.F. Seamen, R.C. Mock, T.L. Gilliland, J.S. McGurn, and D.O. Jobe. 1998b. "Wire Number Doubling in High-Wire-Number Regime Increases Z-Accelerator X-ray Power," *IEEE Trans. Plasma Sci.* **26**, 1086.

Sanford, T.W.L., R.C. Mock, R.B. Spielman, D.L. Peterson, D. Mosher, and N.F. Roderick. 1998c. "Increased x-ray power generated from low-mass large-number aluminum-wire-array Z-pinch implosions," *Phy. Plasmas* **5**, 3737.

Sanford, T.W.L., R.C. Mock, R.B. Spielman, D.L. Peterson, D. Mosher, and N.F. Roderick. 1998d. "Symmetric aluminum-wire arrays generate high-quality Z pinches at large array radii," *Phys. Plasmas* **5**, 3755.

Sanford, T.W.L., R.C. Mock, T.J. Nash, K.G. Whitney, P.E. Pulsifer, J.P. Apruzese, D. Mosher, D.L. Peterson, and M.G. Haines. 1999a. "Systematic Trends in X-Ray Emission Characteristics of Variable-Wire-Number, Fixed-Mass, Aluminum-Array, Z-Pinch Implosions," *Phys. Plasmas* **6**, 1270.

Sanford, T.W.L., R.C. Mock, R.B. Spielman, M.G. Haines, J.P. Chittenden, K.G. Whitney, J.P. Apruzese, D.L. Peterson, J.B. Greenly, D.B. Sinars, D.B. Reisman, and D. Mosher. 1999b. "Wire Array Z-Pinch Insights for Enhanced X-Ray Production," *Phys. Plasmas* **6**, 2030.

Sanford, T.W.L., R.E. Olson, R.C. Mock, G. A. Chandler, D. E. Hebron, R. J. Leeper, T. J. Nash, L. E. Ruggles, W. W. Simpson, K. W. Struve, R. A. Vesey, R. L. Bowers, W. Matuska, D. L. Peterson, and R. R. Peterson. 1999c. "Z-Pinch Generated X-Rays In Static-Wall-Hohlraum Geometry Demonstrate Potential for Indirect-Drive ICF Studies," *First International Conference on Inertial Fusion Sciences and Applications*, Bordeaux, France, September 12-17, 1999, proceedings to be published.

Sanford, T.W.L., R.E. Olson, R. L. Bowers, G.A. Chandler, M. S. Derzon, D. H. Hebron, R. J. Leeper, R. C. Mock, T. J. Nash, D. L. Peterson, L. E. Ruggles, W. W. Simpson, K. W.

Struve, and R. A. Vesey. 1999d. "Z-Pinch Generated X-Rays Demonstrate Potential for Indirect-Drive ICF Experiments," *Phys. Rev. Lett.* **83**, 5511.

Sanford, T.W.L., R.E. Olson, R.A. Vesey, G.A. Chandler, D.E. Hebron, R.C. Mock, R.J. Leeper, T.J. Nash, C.L. Ruiz, L.E. Ruggles, W.W. Simpson, R.L. Bowers, W. Matuska, D.L. Peterson, and R.R. Peterson. 2000a. "Characteristics of ICF Relevant Hohlraums Driven by X-Rays from a Z-Pinch," to be published *Fusion Technology* (July 2000).

Sanford, T.W.L., R.E. Olson, R.C. Mock, G.A. Chandler, T.J. Nash, L.E. Ruggles, W.W. Simpson, K.W. Struve, R.L. Bowers, W. Matusk, and D.L. Peterson. 2000b. "Dynamics of z-pinch drive and hohlraum heating for 120-160 eV hohlraums," to be submitted to *Phys. Plasmas*.

Sanford, T.W.L., and N.F. Roderick. 2000c. "Azimuthal mode structure observed in high-wire-number z-pinches," to be submitted to *Phys. Plasmas*.

Spielman, R.B., J.S. De Groot, T.J. Nash, *et al.* 1993. *Dense z-Pinches 3rd International Conference*, London, UK, 1993, AIP Conference Proceedings 299, editors H. Haines and A. Knight, American Institute of Physics, New York 1994, L.C. Catalog Card No. 93-74569, 404-420.

Spielman, R.B., S.F. Breeze, C. Deeney, M.R. Douglas, F. Long, T.H. Martin, M.K. Matzen, D.H. McDaniel, J.S. McGurn, T.J. Nash, J.L. Porter, L.E. Ruggles, T.W.L. Sanford, J.F. Seamen, W.A. Stygar, J.A. Torres, D.M. Zagar, D.O. Jobe, D.L. Peterson, R.W. Shoup, K.W. Struve, M. Mostrom, P. Corcoran, and I. Smith. 1996. "PBFA Z: A 20-MA Z-pinch Driver for Plasma Radiation Sources," *BEAMS '96, Proceedings of the 11th International Conference on High-Power Particle Beams*, 150 (Prague, Czech Republic, June 10-14, 1996), edited by K. Jungwirth and J. Ullschmied, published by Academy of Sciences of the Czech Republic, Za Slovankou 3, 182 00 Prague 8, Czech Republic.

Spielman, R.B., C. Deeney, G.A. Chandler, M.R. Douglas, D.L. Fehl, M.K. Matzen, D.H. McDaniel, T.J. Nash, J.L. Porter, T.W.L. Sanford, J.F. Seamen, W.A. Stygar, K.W. Struve, S.P. Breeze, J.S. McGurn, J.A. Torres, D.M. Zagar, T.L. Gilliland, D.O. Jobe, J.L. McKenney, R.C. Mock, M. Vargas, and T. Wagoner. 1997. "PBFA Z: A 60-TW/5-MJ Z-Pinch Driver," *Dense Z-Pinches Fourth International Conference*, Vancouver, Canada, May 1997, edited by N.R. Pereira, J. Davis, and P.E. Pulsifer, published by The American Institute of Physics.

Spielman, R.B., C. Deeney, G.A. Chandler, M.R. Douglas, D.L. Fehl, M.K. Matzen, D.H. McDaniel, T.J. Nash, J.L. Porter, T.W.L. Sanford, J.F. Seamen, W.A. Stygar, K.W. Struve, S.P. Breeze, J.S. McGurn, J.A. Torres, D.M. Zagar, T.L. Gilliland, D.O. Jobe, J.L. McKenney, R.C. Mock, M. Vargas, T. Wagoner, and D.L. Peterson. 1998. "Tungsten wire-array Z-pinch experiments at 200 TW and 2 MJ," *Phys. Plasmas* **5**, 2105.

Struve, K.W., J.P. Corley, D.L. Johnson, D.H. McDaniel, R.B. Spielman, and W.A. Stygar. 1999. "ZX pulsed-power design" In *Proceedings of the 12th International Pulsed Power Conference* June 27-30, 1999 Monterey, CA., IEEE Cat. No. 99CH36358, 493.

Struve, K. W. 2000. Private communication.

Thornhill, J. W., K. G. Whitney, J. Davis, and J. P. Apruzese. (1996). "Investigation of K-shell Emission from Moderate-Z, Low-N (-Velocity) Z-Pinch Implosions", *J. Appl. Phys.* **80**, 710 and references therein.

Whitney, K.G., J.W. Thornhill, P.E. Pulsifer, J.P. Apruzese, T.W.L. Sanford, T.J. Nash, R.C. Mock, and R.B. Spielman. 1997. "Analyzing Time-Resolved Spectroscopic Data from an Azimuthally Symmetric, Aluminum-Wire Array, Z-Pinch Implosion," *Phys. Rev. E* **56**, 3540.

Wilson, D.C., P.A. Bradley, N.M. Hoffman, *et al.* 1998. "The development and advantages of beryllium capsules for the National Ignition Facility," *Phys. Plasmas* **5**, 1953.

Wilson, D.C., P.A. Bradley, S.R. Goldman, *et al.* 2000. "Developments in NIF Beryllium Capsule Design," to be published in *Fusion Technology* (July 2000).

Yonas, G. 1998. "Fusion and the Z Pinch," *Scientific American* **279**, 40.

FIGURE CAPTIONS

1. Schematic cross section of 1995 Saturn experiment.

2. Total radiated power normalized by the total radiated energy (scaled such that the normalized power agrees with that measured at the smallest gap versus initial interwire gap.

3. (A) Peak total radiated power (solid line) and pulsewidth (dashed line), (B) Radial convergence, (C) Total radiated energy normalized by calculated kinetic energy assuming a 10:1 convergence, (D) K-shell energy (8.6-mm data are scaled by 1.23), (E) Average ion densities inferred from time-integrated K-shell spectra , (F) Average electron temperature (Lines) inferred from time-integrated K-shell spectra and electron temperature (Free-Bound) inferred from measured free-bound continuum slope at time of peak power. ● and □ correspond to the 8.6-mm (small-radius) and 12-mm (large-radius) data, repectively.

4. Radiation pulseshapes in three energy channels normalized to the peak power measured in the lowest energy channel for the large-radius array where (A) G=5.5 mm and (B) G=0.4 mm. Time is measured from a linear extrapolation of the leading edge of the main current pulse to the abscissa. (C) and (D) are associated time-integrated x-ray images, respectively.

5. MHD electron-number density as a function of time at a radius corresponding to G/2, for an equivalent wire in a wire array having (A) 64 15-μm, and 136 10-μm diameter wires in the *plasma-shell* regime, and (B) 16 30-μm, 24 25-μm, 48 17.5-μm diameter wire in the *plasma-wire* regime, all for the small-radius array. Zero time corresponds to the start of the main current pulse.

6. MHD mass-density log contours calculated in the rz plane for a single aluminum wire, 30 ns into the main current pulse (A) for one of 24, 25-μm wires and (B) for one of 64, 15-μm wires, in the small-radius array. MHD mass-density log contours calculated in the xy plane, 35 ns into the main current pulse (D) for 16, 30-μm wire, and (E) a 48, 17.5-μm wire small-radius array.

7. (A) Lineouts of axially-integrated x-ray images as a function of time for a 1.3-mm interwire gap array. (B) Image at -19 ns. (C) Normalized total radiated power pulse. Zero time corresponds to peak radiated power. The wire array geometry was identical to that of the small-radius array, except 24 wires were mounted at a radius of only 5 mm.

8. TIP xy density contours for a small-radius load (having 10 current return posts) at stagnation for (A) a 10-wire array in the plasma-wire regime and (B) a 20-wire array in the plasma-shell regime.

9. Measured (A) x-ray power in indicated energy channels, (B) diameter of x-ray image radial lineouts averaged over z axis, (C) electron core temperaure from free-to-bound x-ray continuum and electron halo temperature from the ratio of He-like to H-like transitions, (D) ion velocity from K-shell line Doppler shifts, all for the small-radius load having interwire gaps of 0.6 mm. E-RMHC:R simulations of the measured power and diameter are compared in (A) and (B).

10. Radial lineouts integrated over z of x-ray images of a 0.6-mm-gap small-radius array taken (A) 3 before , (B) at, and (C) 4 ns after peak power.

11. Axial lineouts of x-ray images of a 0.6-mm-gap small-radius array (A) 3 ns before peak power, at a radius of 1.5 mm (Fig. 10A), and (B) 9 ns after peak power where the lineout is integrated over all radii.

12. (A) Mass-averaged radius (solid curve) and average-current (dashed curve) radius along with the radiation power (solid curve) for the E-RMHC:N simulation of a large-radius 0.84 mg implosion. (B) Associated energy flow.

13. Comparison of x-ray images [top] (sensitive to 0.2- to 0.3-keV and greater than 1-keV x rays) with E-RMHC:R simulations [bottom] of mass (solid curves) and current density (dashed curves), –9, –7, and –4 ns before peak power for a 1.3-mg large-radius array. Arrows correspond to RMS averages.

14. Measured and E-RMHC simulated (A) total-radiated-power pulsewidth and (B) total radiated peak power as a function of mass, for the ~192-wire, large-radius mass scan. Measured and E-RMHC simulated (C) total-radiated-power pulsewidth and (D) total radiated peak power as a function of array radius, for the ~136-wire, mass=0.6-mg radius scan.
15. Schematic of *static-wall* hohlraum geometry (A) without hohlraum, (B) for one-sided drive, and (C) for two-sided drive.

16. Measured *static-wall* hohlraum temperature as a function of measured on-axis x-ray power. The Planckian is normalized by a calculation at 13 TW. 153 mm^2 corresponds to the surface area of the 6mm x 7mm hohlraum.

17. Measured total radiation power and diameter (FWHM) of the x-ray emission from the REH of Fig. 15A as a function of time (A) for a bare pinch, and (B) for a 5-mm diameter, 14 mg/cc CH PST. The diameters and masses of the nested array used were 35 mm and 2 mg/cc, and 17.5 mm and 1 mg/cc, with wire numbers of 240 and 120, respectively .

18. Azimuthal lineout of x-ray images of the REH (A) associated with Fig. 17A at a radius of 1.5 mm and 2 ns before peak REH emission, and (B) associated with Fig. 17B at a radius of 0.4 mm and 2.5 ns before peak REH emission.

Experimental Arrangement on Saturn

Fig. 1

Fig. 2

Fig 3.

Fig. 4

A. Plasma Shell

N=136

64

B. Plasma Wire

48

16 24

Electron Number Density (1/m³)

Time (ns)

Fig. 5

A.

B.

C.

D.

Z Axis (mm)

Z Axis (mm)

Y Axis (mm)

Y Axis (mm)

R Axis (mm)

R Axis (mm)

X Axis (mm)

X Axis (mm)

Fig. 6

Fig. 7

A.

-26 ns

-19 ns

-7 ns

-1 ns

R

10⁻³ergs / cm²

R (mm)

B.

-19 ns

Z (mm)

R (mm)

C.

0.2-2 keV

Time (ns)

A.

B.

Y (mm)

X (mm)

X (mm)

Fig. 8

A.
Relative Power
XRD (0.25 keV)
PCD (2.5 keV)
E-RMHC:R
PCD (6.2 keV)

B.
FWHM (mm)
E-RMHC:R

C.
T_e (keV)
Core
Halo

D.
$\delta\lambda/\lambda$
T_i (keV)
V_{ion} (cm/μs)

Time (ns)

Fig. 9

A. -3 ns — Shot 2085

Intensity (axis: 0.0028, 0.0038, 0.0048; R axis: -4, -2, 0, 2, 4)

B. 0 ns

Relative Intensity (axis: 0, 0.5, 1; R axis: -4, -2, 0, 2, 4)

Core
FWHM = 0.62 mm

Halo
FWHM = 3.2 mm

C. 4 ns

Intensity (axis: 0, 0.02, 0.04; R axis: -4, -2, 0, 2, 4)

R (mm)

Fig 10

A.

λ = 3.2 mm Measurement
λ = 2.2 ±0.6 mm E-RMHC

λ = 1.1 mm Measurement
λ ~ 1.0 mm L/E-RMHC

B.

λ = 2.5 mm   Measurement
λ = 3.0 ±1.3 mm E-RMHC

Z (mm)

Fig. 11

Fig. 12

C. -4ns

ρ

J

Radius (mm)

B. -7ns

ρ

J

Radius (mm)

A. -9 ns

1

ρ

J

0

Radius (mm)

Fig 13

Fig 14

A.

Diagnostics

REH

Wires

PST

L_W

D_{PST}

D_{WI}

D_{WO}

K

A

B.

D_H

Hohlraum

L_H

Diagnostics

C.

Hohlraum

Capsule

Fig. 15

Fig 16

Fig. 17

Fig 18