Optimal Wire-Number Range for High X-Ray Power in Long-Implosion-Time Aluminum Z Pinches

C. A. Coverdale, C. Deeney, and M. R. Douglas
Sandia National Laboratories, Albuquerque, New Mexico 87185

J. P. Apruzese, K. G. Whitney, J. W. Thornhill, and J. Davis
Naval Research Lab, Washington, D.C. 20375
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Experiments performed on the 8-MA Saturn accelerator to investigate the effects of interwire gap spacing on long-implosion-time Z pinches have resulted in the observation of a regime of optimal wire number. The experiments varied the wire number of 40 and 32 mm diam arrays, resulting in interwire gaps from 3.9 to 0.36 mm, with fixed mass and length. aluminum K-shell powers up to 3.4 TW were measured, with long, slow rising, lower power x-ray pulses for interwire gaps greater than 2.2 mm and less than 0.7 mm, and short, fast rising, higher power pulses for interwire gaps in the range 0.7–2.2 mm.

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The study of Z pinches has been a rich field the last several years with the advent of high current (>5 MA) pulsed power generators such as Saturn [1] and Z [2]. Moreover, advances in theoretical and computational modeling have led to the application of Z pinches to many problems, including astrophysics [3], radiation effects [4], and inertial confinement fusion [5]. Key to these applications was the development of high output power, fast x-ray pulses through the use of high wire number arrays and nested wire arrays [6–12].

In a wire array Z pinch, a multi-megaamp, fast-rising current is passed through a cylindrical array of <20 μm diam wires. Early in the current pulse, the wires vaporize into plasma that is accelerated to the axis by the $J \times B$ force. The imploding plasma gains kinetic energy and thermalizes when the material stagnates on axis. This produces compressed plasmas with high temperatures and densities that radiate multiterawatts of x-ray power. For example, Saturn (8 MA) produces up to 75 TW from tungsten and 30 TW from aluminum with a 60 ns implosion time [13,14]. Note that the K-shell power from the short pulse aluminum wire arrays on Saturn is approximately 4 TW [14].

Traditionally, most wire array Z-pinch work has occurred with short pulse drivers (<120 ns current rise time). The reduced cost and complexity of longer pulse drivers have made them a desirable option for future generators, including the 8 MA, 300 ns Decade Quad [15]. The physical phenomena which differ between short and long pulse Z pinches need to be studied and understood, however. With long pulse experiments, wire initiation may change due to the slower current rise time and current penetration, the additional expansion time prior to the implosion allows any precursor plasmas more time to reach the pinch axis, field penetration and instability growth may be altered, and higher load masses could lead to higher opacities.

The first long pulse Z-pinch experiments with wire arrays carried out at Saturn used tungsten wires with implosion times up to 250 ns [16]. Measurements from these experiments, and subsequent modeling [17], suggested that for longer implosion times, the wires have more time to merge prior to acceleration and stagnation, thereby allowing larger interwire gaps (spacing between adjacent wires) while not impacting x-ray output. To study this effect, a systematic scan of wire number using 40 mm diameter aluminum wire arrays was performed. Aluminum was chosen for several reasons, including the need for information relevant to K-shell scaling laws, the ability to diagnose plasma conditions, and the availability of short pulse data [14] for comparison. In the experimental series discussed in this paper, the wire number was varied from 32 to 282 wires, corresponding to interwire gaps (IWG) of 3.9 to 0.45 mm. The mass, length, and radius were held fixed. Additional experiments with 32 mm diam loads, at the same implosion time and length as the 40 mm diam arrays, corresponded to IWG of 0.9 to 0.36 mm.

Aluminum K-shell yields >60 kJ were measured at implosion times near 165 ns, with pulse widths of 7–11 ns and rise times <8 ns for IWG in the range 0.7–2.2 mm. Both rise times and pulse widths increased for IWG > 2.2 mm and IWG < 0.7 mm. These results confirm the previous implication that larger IWG are feasible with longer implosion times. In addition, for the first time, it was observed that the pulse width and rise time increased if too many wires were employed. The experimental observations, and comparisons to a wire array model and simulations, are presented in this paper.

The 8-MA Saturn generator, in its typical short pulse mode (50 ns current rise time), delivers a 20 TW pulse at the water-vacuum interface. An adjustment in pulse forming switching produces a long pulse mode for Saturn, producing a 5 TW, 230 ns electrical pulse, with 11.5 MA measured in a short circuit load. The x-ray output of wire array implosions is studied using several x-ray diagnostics. Aluminum K-shell yields (~1.8 keV) are measured using filtered photoconducting detectors (PCDs) and a filtered

TABLE I. Load parameters and measured output of the aluminum wire arrays. All yield and power measurements are ±15%. FWHM and rise time values are ±0.5 ns.

Load radius (mm)	Wire number	Wire diam (μm)	Interwire gap (mm)	K-shell yield (kJ)	K-shell rise time (ns)	K-shell FWHM (ns)	K-shell power (TW)	Total FWHM (ns)	Total power (TW)	Pinch diam (mm)
40	32	30.5	3.9	60.6	14.5	29	1.3	27.6	20	5.4
40	56	22.9	2.2	66.1	6.5	10.5	2.5	13.6	33	2.6
40	70	20.3	1.8	52.2	5.5	11	1.7	13.8	22	3.5
40	126	15.2	1.0	60.4	4	8.5	2.6	9.4	42	2.4
40	180	12.7	0.7	62.9	5	7	3.4	9.6	52	1.8
40	282	10.2	0.45	60.4	8.5	14.2	2.4	12.9	44	2.8
32	110	20.3	0.9	61.6	5.3	18	1.9	22	31	
32	194	15.2	0.52	52.3	6.8	12.6	1.9	14	16	
32	280	12.7	0.36	61.6	9.2	15	1.8	14	28	3.8

gold bolometer [18]. The total radiated yield is obtained with a bare nickel bolometer. Time-resolved power estimates are obtained from an array of filtered carbon cathode x-ray diodes (XRDs) [19]. Spectral information is gathered using time-integrated and time-resolved crystal spectrometers. Spatial properties of the Z pinch are studied with an x-ray pinhole camera.

Experiments using 40 mm diameter Al wire arrays had shown a peak K shell yield of 65 kJ with a load mass per unit length of 620 μg/cm, with an implosion time near 165 ns [20,21]. Using this mass, a set of experiments was designed that varied the interwire gap from 3.9 to 0.45 mm, as shown in Table I. Note that the individual wire diameter decreased with decreasing IWG, a consequence of holding the load mass fixed. Decreasing the IWG below 0.45 mm was not possible with 40 mm diam arrays due to limited available wire sizes, so to study smaller IWG, experiments were also performed using 32 mm diam arrays. For these experiments, the implosion time was still ~165 ns, corresponding to an initial load mass per unit length of 960 μg/cm, and the wire number was varied from 110 to 280 (IWG of 0.9 to 0.26 mm).

Shown in Fig. 1 are the current waveforms and total power waveforms for three of the arrays used in this experiment. The load currents were similar for the shots, but the total power waveforms show distinct differences with increasing wire number. As observed in experiments with short implosion times [6,14], the K shell and total powers increased with increased wire number (decreased IWG). Variations of greater than a factor of 2 were observed in the K-shell power (and total power) over the range of interwire gaps studied (see Table I). The measured K-shell energy, however, remained in the range of 55–65 kJ, ±9 kJ. The powers and yields are similar to those observed in the short pulse mode. Note that a decrease in the K-shell and total powers is observed at the smallest IWG with both the 40 and 32 mm diam wire arrays, an effect not previously seen in short or long pulse experiments [6–8,14,16].

Two-dimensional radiation magnetohydrodynamic (MHD) modeling and analyses of pinhole images show that the rise time of the x-ray pulse is a good metric of the pinch quality [22]. While power (K-shell or total) is an often cited quantity, it is not necessarily representative of the x-ray rise time. X-ray rise times are not very sensitive to energy coupling issues, whereas powers, particularly K-shell powers, are very sensitive to radiating mass fractions and opacities. Total x-ray rise times for this experiment are plotted in Fig. 2. The rise times are short for IWG up to 1.8 mm (~5 ns), then show a slight increase for IWG $>$ 2 mm, and a substantial increase, to 24 ns, for an IWG of 3.9 mm. The rise times for IWG $<$ 0.7 mm also show an increase, up to 9 ns, which correlates with a power decrease. Rise times for the K-shell x rays, listed in Table I, show a similar trend. The pinch diameters measured from axially averaged time-integrated pinhole images, summarized in Table I, are consistent with the trends of the rise times, including an increase in diameter at the smallest IWG. The 32 mm diam data, plotted in Fig. 2, confirms the increase in rise time at the small IWG seen with the 40 mm data.

Trends in implosion dynamics are typically reflected in the measured x-ray spectra. Temperatures and densities extracted from the time-integrated data [23] suggest electron temperatures of 600–1100 eV and ion densities of $>10^{19}$ cm^{-3}, similar to the short pulse mode. As plotted in Fig. 3, the temperatures are lower and the densities

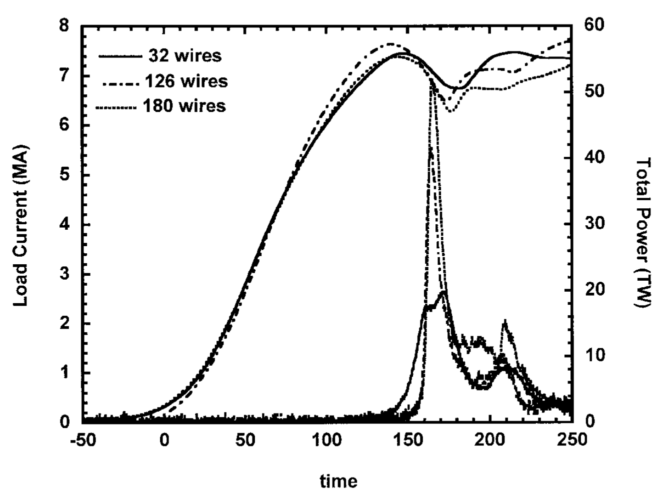

FIG. 1. Overlay of the load current waveforms, and total power waveforms for the 32 wire, 126 wire, and 180 wire arrays.

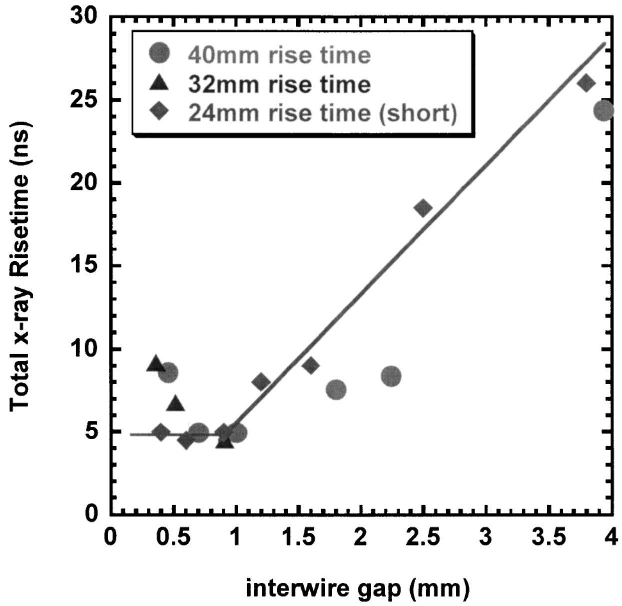

FIG. 2. The measured total x-ray rise times as a function of the interwire gap for 40 and 32 mm diam long pulse loads. The total x-ray rise times from 24 mm diam short pulse loads are included for comparison. The error bar is ±0.5 ns.

higher at both small and large IWG. The density increase is associated with a decrease in pinch diameter and the temperature decrease is associated with higher opacities and possibly radiative cooling. Detailed spectral analyses performed on the time-integrated data assume uniform temperature and density [23], but it is known that gradients exist in the imploded plasmas and these analyses are not yet complete.

To put the results presented here in perspective, the data can be compared with theoretical and computational models. One of the first theoretical models of wire array dynamics, developed by Haines [24], defines a critical wire number n_{crit}, which represents the minimum number of wires necessary to ensure that the individual wire plasmas sufficiently expand and merge prior to implosion on the axis. At merger, this model assumes that the statistical average of MHD perturbations on the individual wires acts as the seed for the Rayleigh-Taylor instability during the implosion. Merging due to high wire numbers is believed to be beneficial since it smooths the initial azimuthal perturbations resulting from discrete wire initiation and magnetic field effects that can lead to unstable Z-pinch implosions. For this paper, the focus is the evaluation of the critical wire number (or IWG). Specifically, $n_{\text{crit}} = \pi r_0 / v t_p$, where r_0 is the initial wire array radius, v is the wire expansion velocity, and t_p is the implosion time. For large IWG, i.e., $n < n_{\text{crit}}$, the wires cannot expand far enough to fill the IWG prior to the stagnation on the axis. For small IWG, i.e., $n > n_{\text{crit}}$, the wires merge early compared to the implosion time and the array implodes as an annular plasma shell. Haines' model, and others [25], suggest that the dynamics of the wire explosion and plasma implosion can differ for short and long implosion time experiments.

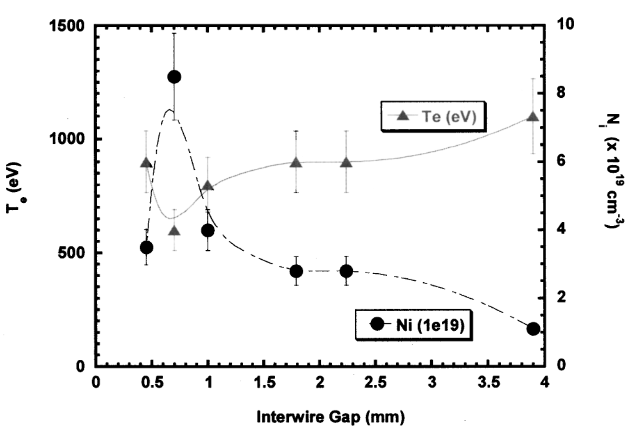

FIG. 3. Measured electron temperature and ion density as a function of interwire gap for the 40 mm diam wire arrays.

For the experimental parameters of this paper, the above wire merger model predicts a critical IWG of 4.5 mm. For the short pulse mode, the critical IWG is 1.5 mm. While the experiments show somewhat smaller critical IWGs for both the short and long pulse cases, 1 mm for short pulse and >2.2 mm for long pulse, the ratio is similar. However, Haines' heuristic model provides no explanation for the effect observed at small IWG (<0.7 mm).

Computational studies were performed [26] to further understand the experimental results. Detailed 1D ALE calculations of wire expansion using the experimental parameters studied wire merger. For these calculations, merger is defined as when 90% of the mass of the individual wires has expanded to one-half the IWG. Note that the exact physics of the merger and the correlation to implosion dynamics are still open issues. In addition, MACH2 [27] was used for 2D MHD calculations in the r-z plane. Initial random density perturbation levels, which seed the Rayleigh-Taylor instability (RT), were varied and the resulting calculated rise times were compared with the measured values to determine the perturbation necessary to match the experiment. This methodology is similar to that of Refs. [17,28].

Table II summarizes some of the calculated results. For the 126 and 180 wire number cases (IWG of 1.0 and 0.7 mm), the current per wire was low, but the wires expanded quickly and merged well before acceleration toward the axis, which occurs approximately 75 ns after the start of current. The 2D r-z modeling required low perturbation levels in order to reproduce the measured rise times. For an IWG of 1.8 mm, the wires merged immediately after the start of the acceleration, and a high perturbation level was necessary. For the largest IWG (>2 mm), the wires did not merge, and the 2D r-z modeling could never match the experiment. These results are consistent with the trends observed in the experimental data, including the IWG at which changes are observed in the x-ray output.

None of the computational modeling can explain the experimentally observed degradation of pinch parameters at

TABLE II. Highlights of the computational results. Merger times are based on the 1D ALE simulations; perturbation levels are listed for cases where 2D r-z modeling was appropriate.

Wire No.	Initial load diam (mm)	Interwire gap (mm)	0.5 × IWG (mm)	Merger time (ns)	Perturbation level (%)
180	40	0.70	0.35	30	1
126	40	1.00	0.50	35	1
70	40	1.80	0.90	0.85 mm at 75 ns	3
56	40	2.24	1.12	Never[a]	NA
32	40	3.93	1.96	Never	NA

[a]For this case, 2D r-θ modeling shows merger of the wires.

the smallest IWGs (<0.7 mm), however. Speculations for this degradation include nonuniform current paths, similar to the proposed mechanism for the poor quality of foil implosions, and wire initiation effects, such as low current per wire or early correlation of the RT instability [29–31]. Data from the MAGPIE generator [30] show that the dominant mode of the correlated coronal plasma instabilities of wavelength λ has $ka = 1$, where $k = 2\pi/\lambda$ and a = core radius. One hypothesis is that if the wire core size a is constant, then as the IWG is reduced, it becomes comparable to the wavelength of the instabilities (~0.5 mm for Al), leading to pronounced correlation and destructive RT. An alternate hypothesis is that the early wire merger that occurs with high wire number causes the implosion to be shell-like, mitigating any effects of a density profile ahead of the imploding mass. These hypotheses are speculations; detailed measurements with an x-ray backlighter, as well as 2D and 3D calculations, are necessary to identify the actual mechanisms responsible.

In summary, long pulse aluminum implosions on Saturn have shown an increase in x-ray power and decrease in pulse width and rise time with decreasing IWG, a result consistent with previous short pulse wire number studies. In addition, for the first time, a decrease in x-ray power and increase in pulse width and rise time was observed with very high wire number loads. Thus an optimal range of interwire gap of 0.7 to 2.2 mm, in which measured x-ray parameters were similar, was seen in the experiment. The critical IWG spacing was more than double for long pulse than short pulse experiments. Comparisons with theory and calculations confirm that in the long pulse mode, wire merger should occur for the larger IWG observed in the experiment. These observations confirm the speculations made in Ref. [16], i.e., longer implosion times give the wires more time to merge prior to acceleration, allowing larger IWG to produce high x-ray powers. However, the new observation of a degradation of Z-pinch parameters for IWG $<$ 0.7 mm challenges the previously held beliefs that continued improvements would be observed with continued decreases in IWG.

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