

The Observation of an Optimal Wire Number Range in Long Implosion Time Aluminum Z-pinches

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Abstract

Experiments performed on the 8 MA Saturn Accelerator to investigate the effects of interwire gap spacing on long implosion time aluminum Z-pinches have resulted in the observation of a regime of optimal wire number. The experimental series utilized 40 mm diameter arrays and varied the wire number from 32 wires to 282 wires, corresponding to interwire gaps of 3.9 mm to 0.4 mm, with all other parameters held fixed. Additional shots with 32 mm diameter loads performed corresponded to interwire gaps of 0.91 mm to 0.36 mm. Aluminum K-shell yields of > 60 kJ were consistently measured, and the pulsewidths and risetimes of the x-ray pulses showed trends of long, slow rising pulses for interwire gaps > 3 mm and short, fast rising pulses for interwire gaps greater than 0.7 mm, but less than 3 mm, results consistent with theory. For the smallest interwire gaps studied (< 0.7 mm), the trend again appeared to be towards longer, slower rising x-ray pulses. These results suggest a regime of wire number in which Z-pinch performance is optimized.

The study of Z-pinches has been a rich field the last several years with the advent of high current pulsed power generators such as Saturn [1] and Z [2]. Moreover, advances in the theoretical understanding of Z-pinch physics and in computational modeling capabilities have led to the application of Z-pinches to many problems, including astrophysics measurements, radiation effects material studies, and inertial confinement fusion. [3-5]

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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 large fast-rising current is passed through a cylindrical array of fine wires. The wires vaporize into a plasma that is accelerated to the axis by a growing Lorentz force ($J \times B$). The imploding plasma gains kinetic energy, which rapidly thermalizes when the material stagnates on axis. This process produces compressed plasmas with high temperatures and densities that radiate up to 250 TW of x-ray power. Traditionally, most wire array Z-pinch work has occurred with short pulse drivers (<100 ns current risetime). The reduced cost and complexity of long pulse drivers (>100 ns current risetime) have made them a desirable option for the future generators, including the 8 MA, 300 ns implosion time Decade Quad. [13] In order for the potential benefits to be realized, however, the physical phenomena, including instability growth, which differ between short and long pulse Z-pinchs need to be studied and understood, especially for wire arrays.

One of the first theoretical models of wire array dynamics, developed by Haines [14], defines a critical wire number, n_{crit} , representing the minimum number of wires necessary to ensure that the individual wire plasmas sufficiently expand and merge prior to implosion on the axis. Such merging is believed to be beneficial since it smoothes the initial perturbations resulting from discrete wire initiation and magnetic field effects that can lead to unstable z-pinch implosions. Specifically, $n_{crit} = \pi r_0 / v t_p$, where r_0 is the initial radius of the wire array, v is the expansion velocity of the wires, and t_p is the implosion time. For low wire number arrays, i.e., $n < n_{crit}$, the interwire gap (IWG) between adjacent wires is large. In this case, the wires, which explode and become plasma (or partially plasma), cannot expand far enough to fill the gaps prior to the stagnation on the axis. The array implodes as a set of discrete individual wires with azimuthal asymmetries. For smaller IWG, i.e., $n > n_{crit}$, the wires merge early compared to the implosion time and the array implodes as an annular plasma shell. Experimentally, it has been observed in the short pulse mode at the Saturn and Z facilities that the output power increases as the interwire gap decreases [6-8], a result consistent with this model. Based

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on Haines' model, and others [15], it is apparent that the dynamics of the wire explosion and plasma implosion can differ for short and long implosion time experiments. Specifically, the timescales available for wire explosion and expansion, and the influence of implosion velocity on the stagnation and thermalization, could have substantial effects. The Haines model, for example, would predict a decrease in the critical wire number for longer implosion times, assuming all other parameters are unchanged.

The first long pulse Z-pinch experiments with wire arrays were carried out at Saturn using tungsten wires with implosion times up to 250 ns.[16] The measured x-ray powers (> 20 TW) were comparable to those achieved with short implosion times, an encouraging result consistent with post-experiment calculations [17] and with Haines' wire array model.[14] These observations suggested that for longer implosion times, the wires have a longer time in which to merge prior to acceleration and stagnation. An inference from these results and subsequent modeling was that larger interwire gaps (spacing between adjacent wires) are feasible. To demonstrate conclusively that long implosion times could positively impact the performance of wire arrays and to test some of the wire array models, a systematic scan of wire number using 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 via spectroscopy, and the availability of good short pulse data for comparison. [18] Aluminum radiates in the K-shell at approximately 1.8 keV. The results presented here confirm the previous implication of improved wire merger for longer implosion times, with an observed critical interwire gap of ~ 3 mm for a 165 ns implosions. Previous short pulse (60 ns) experiments also utilizing Al wire arrays had shown a critical interwire gap of 1 mm.[18] In addition, for the first time, it was observed that the pulsewidth and risetime increased if too many wires were employed. These results identify a range of wire numbers in which Z-pinch performance is optimized. The experimental observations, and comparisons to a wire array model and simulations, are presented in this paper.

The 8-MA Saturn generator stores 5 MJ of electrical energy in 36 Marx banks. When delivered downline in its typical short pulse mode (50 ns current risetime), a 20 TW, 50 ns pulse is measured at the water-vacuum interface. An adjustment in pulse forming switching produces a long pulse mode for Saturn, which gives a 5 TW, 230 ns electrical pulse at the water-vacuum interface, with 11.5 MA measured in a short circuit load.

The x-ray output of the wire array implosions is studied using several x-ray diagnostics. Aluminum K-shell yields (~ 1.8 keV) are measured using four filtered photoconducting detectors (PCDs) and a filtered gold bolometer with near intrinsic resistivity. [19] A measurement of the total radiated yield is obtained with a bare nickel bolometer. Time-resolved power estimates for 0.18 – 1.5 keV x-rays are obtained from an array of filtered carbon cathode x-ray diodes (XRDs). [20] Spectral information is gathered using several spectrometers, both time-integrated and time-resolved. Spatial properties of the Z-pinch are measured with an x-ray pinhole camera.

Initial 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 $\mu\text{g}/\text{cm}$, which corresponded to an implosion time near 165 ns. [21,22] Using this optimal mass, a set of experiments was designed that varied the wire number from 32 wires to 282 wires, corresponding to interwire gaps of 3.9 mm to 0.45 mm, as shown in Table 1. Note that the individual wire diameter also decreased with decreasing interwire gap, a consequence of keeping all other parameters fixed. Decreasing the IWG below 0.45 mm was not possible with 40 mm diameter arrays due to limitations on the wire sizes available, so in order to pursue continued reductions in IWG, experiments were also performed using 32 mm diameter arrays. For these experiments, the implosion time was still held fixed at ~ 165 ns, corresponding to an initial load mass per unit length of ~ 960 $\mu\text{g}/\text{cm}$, and the wire number was varied from 110 to 280 (IWG of 0.9 mm to 0.36 mm).

Shown in figure 1 are the current waveforms, and resulting K-shell power waveforms for three of the arrays used in this experiment. The load currents were all near 7.5 MA for the wire arrays, but the K-shell power waveforms show distinct differences with

increasing wire number. As observed in experiments with short implosion times, 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. The measured K-shell energy, however, remained constant at 60-70 kJ. The powers and yields are at levels similar to those observed in the short pulse mode. Interestingly, a decrease in both the K-shell and total powers is observed at the smallest interwire gaps. The yields and powers are detailed in Table 1.

Two-dimensional radiation magnetohydrodynamic (MHD) modeling and analyses of pinhole images have indicated that the risetime of the x-ray pulse is a good metric of the pinch quality. Risetimes for this experiment are plotted in figure 2. The risetimes are short for $IWG < 2$ mm (~ 5 ns), then show a slight increase for $IWG > 2$ mm, and a substantial increase, to 15 ns for the K-shell and 24 ns for the total x-rays, for $IWG > 3$ mm. The risetimes for $IWG < 0.7$ mm also show an increase, up to 9 ns, which correlates with a power decrease. The pinch diameters, as measured from the time-integrated pinhole images, are summarized in Table 1 and are consistent with the trends in the risetimes seen in Figure 2, including an increase in diameter for the smallest IWG. The 32 mm diameter data, also plotted in Figure 2, confirms the increase in risetime at the small IWG seen with the 40 mm diameter data. It should be noted that the small IWG (high wire number) risetime increase observed in the long pulse experiments has not been previously seen in any other previous short or long pulse experiment. [6-8,16,18]

Trends in the implosion dynamics are reflected in the measured x-ray spectra.

Temperatures and densities extracted from this data suggest electron temperatures of 600-1100 eV and ion densities of $> 10^{19} \text{ cm}^{-3}$, levels similar to those obtained in the short pulse mode. As plotted in Figure 3, the temperatures decrease and the densities increase as the IWG decreases. The density increase is associated with a decrease in pinch diameter and the temperature decrease is associated with higher opacities and possibly radiative cooling. It is known that gradients exist in the imploded plasmas and more detailed spectral analyses will be performed. [23] As observed with other parameters in

this experiment, the trends in temperature and density reversed for the higher wire number arrays.

A comparison of the short pulse and long pulse data clearly demonstrates that the longer wire initiation process has improved the pinch performance for the longer implosion time loads. Haines' heuristic wire merger model [14] predicts a critical interwire gap of 1.5 mm for the short pulse mode and 4.5 mm for the long pulse model. While the experiments show somewhat smaller critical IWG for both the short and long pulse cases, the ratio of the critical IWG is the same (approximately a factor of 3), and the experimental observations imply improved wire merger for longer implosion times. However, the heuristic model provides no explanation for the effect observed at small IWG (< 0.7 mm).

To better understand the results of the experiments and the effects of wire merger, detailed 1D ALE and 2D r-z MHD calculations were performed.[24] The calculations show a trend where conventional 2D r-z modeling is appropriate, and this trend is directly related to the merger of the wires. Table 2 summarizes some of the calculations. For the 126 and 180 wire number cases (small IWG), the current per wire was low, but the wires expanded quickly and merged well before acceleration toward the axis. For these cases, the 2D r-z modeling required low perturbation levels in order to reproduce the measured risetimes. (Note: the wire array is approximated by a thin shell, which is seeded with an initial perturbation meant to represent the true 3-D nature of the array initiation process. This perturbation produces instabilities which are believed to grow during the implosion phase.) For IWG ~ 2 mm, the wires merged immediately after the start of the acceleration, and a slightly higher perturbation level was necessary. For the largest IWG, the wires did not merge, and the 2D r-z modeling was not appropriate. These results are consistent with the trends observed in the experimental data, including the IWG at which changes are observed in the output. However, the computational model cannot explain the experimentally observed degradation of pinch parameters at the smallest IWGs (< 0.7 mm). Speculations for this degradation at small IWG include non-uniform current paths,

low current per wire effects, and wire initiation effects. Continuing theoretical and computational efforts are needed to explain why an optimal wire number exists.

In summary, long pulse implosions on Saturn have shown an increase in x-ray power and decrease in pulsewidth and risetime for $IWG > 0.7$ mm when the interwire gap spacing was decreased, a result consistent with previous short pulse wire number studies. A decrease in x-ray power and increase in pulsewidth and risetime were observed for the highest wire number loads, defining a range of optimal interwire gap (optimal wire number) of 0.7 mm to 3 mm. The changes in x-ray power and temporal character observed for $0.7 \text{ mm} < IWG < 3 \text{ mm}$ are consistent with wire merger models and calculations. This IWG spacing was a factor of three larger for the long pulse experiments: a clear indicator of improved wire merger with a longer implosion time. These observations confirm the speculations made in Reference 16. The additional observation of a degradation of Z-pinch output 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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Figure Captions

Figure 1: Overlay of the load current waveforms, and K-shell power waveforms for the 32 wire, 126 wire, and 180 wire arrays.

Figure 2: The measured total and K-shell x-ray risetimes as a function of interwire gap. The open symbols represent the 32 mm diameter load data.

Figure 3: Measured electron temperature and density as a function of interwire gap.

Table 1: Load parameters and measured output of the Aluminum wire arrays

Load radius (mm)	Wire number	Wire dia. (μm)	Interwire gap (mm)	K-shell Yield (kJ)	K-shell FWHM (ns)	K-shell power (TW)	Total FWHM (ns)	Total power (TW)	Pinch dia. (mm)
40	32	30.5	3.9	60.6	29	1.3	27.6	20	5.4
40	56	22.9	2.2	66.1	10.5	2.5	13.6	33	2.6
40	70	20.3	1.8	48	11	1.7	13.8	22	3.5
40	126	15.2	1.0	60.4	8.5	2.6	9.4	42	2.4
40	180	12.7	0.7	62.9	7	3.4	9.6	52	1.8
40	282	10.2	0.45	60.4	14.2	2.4	12.9	44	2.8
32	110	20.3	0.9	50.8		1.9		31	
32	194	15.2	0.52	40	12.6		14		
32	280	12.7	0.36	61.6	15	1.8	14	28	3.8

Table 2: 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. ** for this case, 2D r- θ modeling shows merger of the wires.

wire number	initial load dia. (mm)	intervire gap (mm)	0.5*TWG (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	0.85mmat 75ns	3
56	40	2.24	1.12	never **	NA
32	40	3.93	1.96	never	NA





