Effect of Radial-Electric-Field Polarity on Wire-Array Z-Pinch Dynamics

S. N. Bland,[1] S. V. Lebedev,[1] J. P. Chittenden,[1] D. J. Ampleford,[1] S. C. Bott,[1] J. A. Gómez,[2] M. G. Haines,[1] G. N. Hall,[1] D. A. Hammer,[3] I. H. Mitchell,[2] and J. B. A. Palmer[1]

[1]Imperial College, Blackett Laboratory, Prince Consort Road, London SW7 2BZ, United Kingdom
[2]Pontificia Universidad Católica de Chile, Avenida Vicuña Mackenna 4860, Santiago, Chile
[3]Laboratory of Plasma Studies, Cornell University, Ithaca, New York, USA
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The formation of plasma in wire-array Z-pinch experiments was found to depend upon the polarity of the radial-electric field near the wires. Reversing the radial-electric field midway along the length of an array resulted in the ablation rate of one-half of the array being reduced by 50%, significantly delaying the start of its implosion and altering its acceleration towards the axis. The observed phenomena cannot be explained by the standard magnetohydrodynamic models of array behavior, suggesting that effects such as electron emission may be important, especially during wire initiation.

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The implosion of a wire-array Z pinch releases huge quantities of soft x-ray radiation—in the most powerful experiments on the 20 MA Z machine at Sandia National Laboratories, x-ray pulses of ~250 TW power with yields 1–2 MJ are regularly obtained [1–3]. Being able to produce such high powers and yields, wire-array Z pinches have naturally generated interest across the high energy density physics community. In particular, it has been suggested that they could provide a cheap, compact driver for high gain inertial confinement fusion (ICF) studies [4], perhaps even heralding the introduction of a usable fusion energy source.

In order to make efficient use of wire-array Z pinches in high energy density physics experiments, a better understanding of the implosion of an array is required and methods to control this implosion need to be developed. Recently it has been shown that the first 60%–80% of the evolution time of an array is dominated by the formation of core-corona plasma systems: the wires expand into relatively cold, dense, stationary "cores" (~0.1% solid density), which are gradually ablated into low density "coronal" plasma (electron density $\sim 10^{18}$ cm^{-3}) that flows towards the axis of the array [5,6]. Only when parts of the wire cores become fully ablated does the actual implosion of the array appear to begin, snowplowing up the coronal plasma as it accelerates inwards [7]. Thus the process of plasma formation in an array is thought to be extremely important in determining how the array implodes, yet neither this process nor its precise effects on implosion are well explored.

In this Letter we describe experiments in which the polarity of the radial-electric field was reversed midway along the wires of an array [8]. The implosion dynamics of both halves of the array were still dominated by wire ablation; however, the size of the wire cores and the ablation rate of the wires appeared to strongly depend upon polarity of the electric field—while displaying no obvious dependence on its strength. Surprisingly, in the half of the array with a positive polarity radial-electric field, the wire core size and ablation rate matched those of standard cylindrical array experiments (in which the electric field is always of negative polarity), while in the half of the array with a negative radial-electric field the core size was reduced by a factor >3 and the ablation rate by ~50%. Hence, although the two halves of the array were driven by the same current, the half of the array subject to a negative polarity radial-electric field had a delayed implosion, producing a separate, secondary x-ray pulse on stagnation on axis.

The experimental configuration is shown in Fig. 1(a). Arrays usually consisted of sixteen 13.2 μm Al wires on a diameter of 8 mm and were driven by the 1 MA, 240 ns rise-time current profile of the Magpie pulsed power facility [9]. Anode and cathode connections to the wires in each array were via "hollowed out" electrodes of diameter 16 mm and depth 30 mm. Close to the wires this electrode design was expected to produce the radial-electric-field

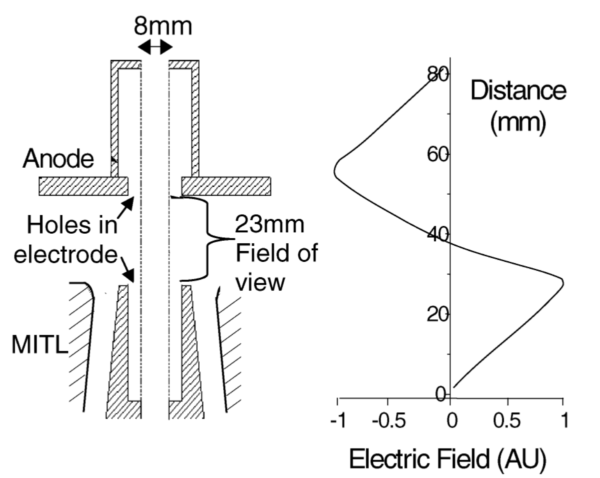

FIG. 1. Diagram of the array configuration and distribution of radial-electric-field strength along the wires inferred from calculations made using the 2D "Quickfield" e1ectrostatic field solver.

distribution shown in Fig. 1(b), with a maximum positive field adjacent to the hole in the cathode, a maximum negative field close to the hole in the anode, and a reversal in polarity halfway between these points. This is in contrast with standard wire-array Z-pinch configurations where direct connection of the wires to the anode and cathode, combined with pulsed power design, has always limited the radial-electric field to being of negative polarity.

The experimental results presented in this Letter show that despite being driven by the same current pulse, the halves of the array subject to opposite polarities of the radial-electric field evolve on significantly different time scales. This is evident from the very start of plasma formation in the array—laser probing images such as that shown in Fig. 2(a) [10] display a greater expansion of plasma along the wires in the half of the array with $E_r > 0$ as early as 19 ns after the start of the current pulse (at which time I is about 16 kA). Plasma formation proceeds with heterogeneous core-corona structures being established in both halves of the array [5,6]. Extreme ultraviolet (XUV) framing images [11]—Figs. 2(b) and 3(a)—show shadows of the wire cores backlit by emission from the coronal plasma. The low magnification image in Fig. 2(b) indicates that, although the size of the wire cores appears to be the same in each half of the array, there is a large difference in size of the cores between the two halves of the array. High magnification XUV images [Fig. 3(a)] show that the size of the cores in the half of the array with $E_r < 0$ is significantly smaller than in the half of the array with $E_r > 0$ (~ 100 μm; cf. ~300–350 μm). This difference in core size is also seen in hard x-ray radiography images of the array (3–5 KeV), which in standard aluminum wire-array experiments have shown a core size of ~300 μm [12]. Surprisingly, this is the same size as in the positive polarity half of our present experiments—even though in standard array experiments $E_r < 0$.

Further examination of the XUV image in Fig. 2 shows a higher level of emission from the coronal plasma in the top half of the array ($E_r < 0$). As observed in standard array experiments, the accumulation of coronal plasma on the axis of both halves of the array results in the formation of a precursor column [10]. However, optical streak photography indicates that the precursor column in the half of the array with $E_r < 0$ assembles on axis much earlier than in the other of the array: <75 ns after the start of the current pulse compared to ~90 ns (again this latter time is the same as in standard array experiments). The precursor column in the top half of the array is also significantly brighter, with its emission becoming observable on x-ray detectors filtered to view radiation >100 eV (see Fig. 4), suggesting a higher plasma temperature.

Differences between the two halves of the array remained up to and throughout the implosion. This is best illustrated by the XUV framing image in Fig. 3(b) and the laser probing image in Fig. 5(a), both of which depict a point in time when the top half of the array still consists of ablating wire cores, even though the half of the array with $E_r > 0$ has already started to implode. Figure 4 shows implosion trajectories of each half of the array measured using radial optical streak photography. The trajectories indicate that the implosion of the bottom half of the array starts at the same time (165 ns) as in standard array experiments while the implosion of the other half of the array is significantly delayed, starting at ~195 ns. The bottom half of the array stagnates on axis at ~200 ns and implodes along the same trajectory as observed in standard array experiments. The top half of the array stagnates on axis at ~230 ns, and it is interesting that the peak implosion velocity of this half of the array is 40–50 cm μs^{-1}, a factor

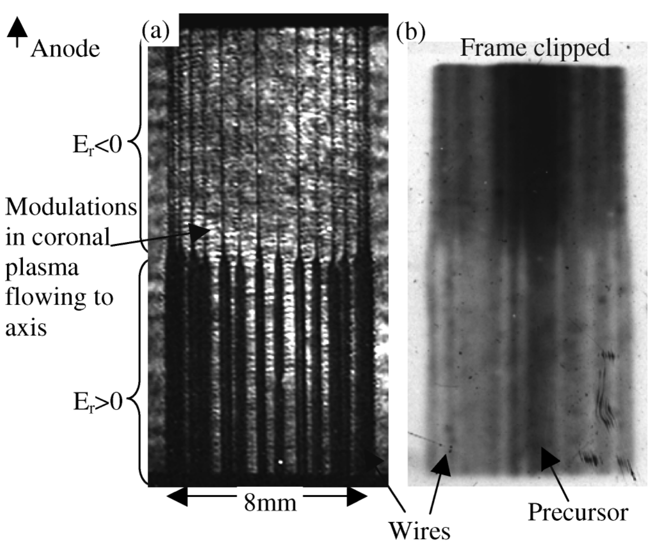

FIG. 2. (a) Laser probing image of the array taken 77 ns after the start of the current pulse, and (b) XUV framing image at 91 ns. Both images show a clear difference in plasma formation between the halves of the array. The laser probing image is sensitive to electron densities ~10^{18} cm^{-3} [10], while the XUV images display radiation of energy ~30 eV and above [11].

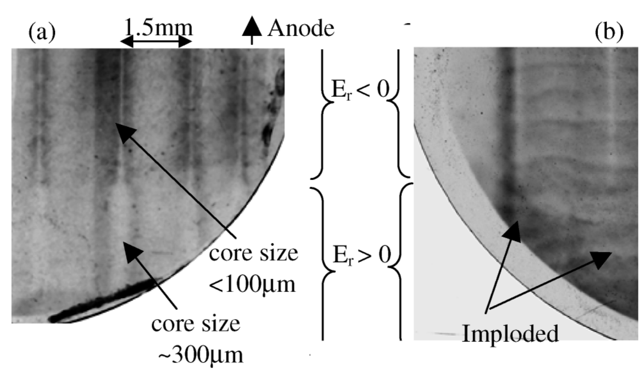

FIG. 3. High magnification XUV framing images at (a) 80 ns and (b) 170 ns, illustrating the relative size of the wire cores in the two halves of the array. By 170 ns, the bottom half of the array ($E_r > 0$) has started to implode, and wire cores are seen only in the top half.

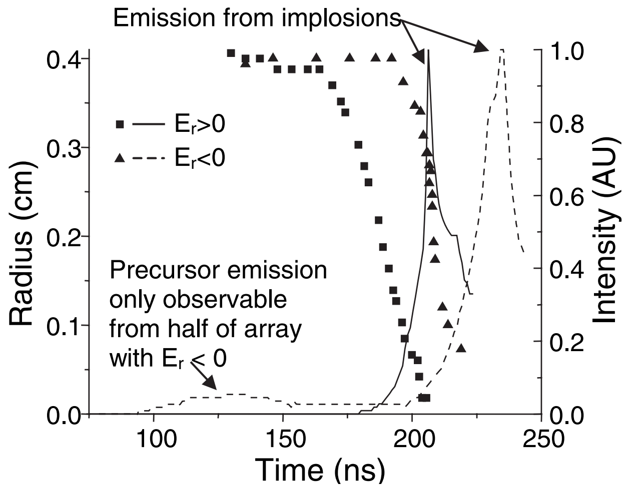

FIG. 4. Implosion trajectories and x-ray emission of the two halves of the array. Trajectories were measured from radial optical streaks. X-ray emission was monitored by collimated diamond photoconducting detectors filtered using 1.5 μm polycarbonate foils (transmission of 100–290 eV and >400 eV).

of 2–3 times higher than in standard array experiments. Stagnation of each half of the array produces a separate x-ray pulse.

Despite the difference in the implosion trajectories of the two halves of the array, the implosion mechanism in each half of the array is the same, and equivalent to that observed in standard wire-array experiments [6,7,13]. XUV and laser probing images show that the implosion of each half of the array is initiated by the formation of gaps in the wire cores. These gaps are a result of a modulation in the ablation rate along the wires, which at early times manifests itself as modulations in the coronal plasma flow [5]—for example, in laser probing images such as Fig. 2(a), an axial perturbation of wavelength ~0.4 mm is seen in the plasma ablating from each wire. Even with the large difference in the size of the wire cores in the two halves of the array, the wavelength of this modulation appears to be the same and again is equal to that found in standard array experiments of the same array diameter. This indicates that the modulations may be related to the size of the current carrying region close to each wire core, not the core size itself. Implosion of the two halves of the array is shown in a sequence of XUV framing images in Fig. 5(b). After the formation of the gaps, both halves of the array implode as a current driven piston, snowplowing up coronal plasma as it accelerates towards the axis. However, the implosion of neither half of the array transports 100% of the arrays mass towards the axis—in the wake of each snowplowing a significant fraction of the array's mass is readily observed.

The separate evolution of the two halves of the array is consistent with the ablation rate of the wires with $E_r < 0$ being lower than that of wires with $E_r > 0$. A phenomenological "rocket" model [5] suggests that the rate of ablation of an array, dm/dt, varies as $I(t)^2/v_a$, where v_a is the velocity of the coronal plasma flowing from its wires. In standard array experiments end-on interferometry and other observations [7,10] have measured v_a as being $\sim$15 cm μs^{-1}. The start of implosion of the array then corresponds to the time when 50% of its mass is expected to have been ablated. In the present experiment, the implosion of the half of the array with $E_r > 0$ is comparable to that of a standard array, indicating the same ablation rate of its wires and the same coronal plasma velocity. To account for the 30 ns delay in the start of implosion of the half of the array with $E_r < 0$, meanwhile, requires the ablation rate of its wires to be reduced by a factor of $\sim$2, corresponding to a doubling in the coronal plasma velocity from 15 to $\sim$30 cm μs^{-1}.

This higher coronal plasma velocity is consistent with side-on laser interferometry measurements. The rate of ablation of the array can be equated with the mass flux of the plasma flow, $dm/dt \sim \rho v_a \sim I^2/v_a$. For both halves of the array driven by the same current, the product ρv^2 should therefore be the same. Assuming the same degree of ionization of the coronal plasma in each half of the array, the fringe shift on an interferogram should be proportional to ρ or $1/v_a{}^2$. Typically the fringe shift associated with

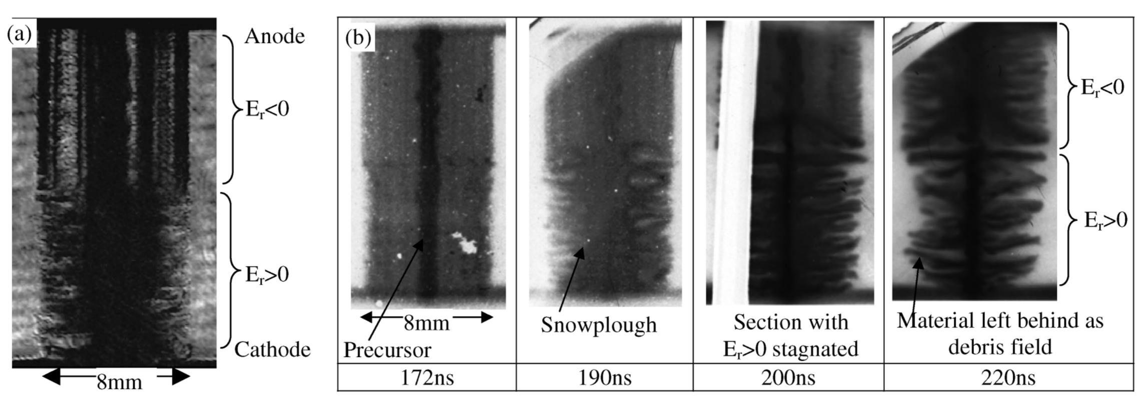

FIG. 5. (a) Laser probing image showing the effect of the difference in times at which the implosion of each half of the array started. (b) XUV framing sequence of the implosion of an array.

coronal plasma in the half of the array with $E_r < 0$ was 3 times less than in the half of the array with $E_r > 0$, corresponding to a $\sim$1.7 times difference in velocities, which is comparable to our estimates based upon the starting time of the implosions. The increased coronal plasma velocity is consistent with both the earlier formation and the higher level of emission of the precursor column in the half of the array with $E_r < 0$. Additionally, an increased coronal plasma velocity as well as the associated reduction in the ablation rate of the wires (and the density of the plasma near the wires) would have reduced the rate of mass accretion by the imploding snowplow piston in the half of the array with $E_r < 0$ allowing its snowplow to attain the observed higher velocity.

The reduced ablation rate or increased coronal plasma velocity in the half of the array with $E_r < 0$ could be due to the smaller size of the wire cores, as the energy flux arriving at the wire cores from the coronal plasma—the process most likely responsible for the ablation of the wire cores—will scale with the surface area of the cores. Single wire *Z*-pinch experiments appear to suggest that the expansion of a wire into the core-corona plasma system varies with the magnitude and polarity of the radial-electric field, becoming greater the more positive the field [14]. In our experiments the wire cores in the half of the array with $E_r < 0$ are, indeed, smaller than that in the half of the array $E_r > 0$. However, in contrast with single wire results, the size of the wire cores remains constant within each half of the array, even though the radial-electric field is expected to vary along the entire length of the wires. Moreover, the transition region between the two halves of the array is very small, <500 μm. These observations may indicate that the presence of the global magnetic field in the array has resulted in plasma formation depending only upon the polarity, not the magnitude, of the radial-electric field [15]. This view is supported by experiments in which the length of the hollowed out electrodes was adjusted, moving the axial position of the reversal in E_r. In these experiments the section of the array corresponding to $E_r < 0$ again demonstrated a reduced ablation rate and later implosion than the section of the array with $E_r > 0$, while the transition region between the two sections of the array remained sharp and positioned at $E_r = 0$.

The physical process responsible for plasma formation in our wire-array *Z*-pinch experiments is not yet known and will be examined in future experiments. It is possible that the separate evolution of the two halves of the array is simply a consequence of earlier plasma formation in the half of the array with $E_r < 0$. At the start of the current pulse, thermoelectric emission of electrons from the surface of the wires would be increased in the half of the array with $E_r < 0$, and suppressed in the half of the array with $E_r > 0$. Additionally, the $\mathbf{E}_r \wedge \mathbf{B}_{\text{global}}$ drift would confine any electrons to the half of the array in which they were emitted. Thus, a sheath of electrons could shunt a fraction of the current out of the wires in the half of the array with $E_r < 0$, reducing the energy deposited into the wires by Ohmic heating, and so limiting the expansion of the wires into core-corona plasma systems. Whatever process is responsible for plasma formation, it has to explain the most surprising result of our experiments: it is the behavior of the half of the array with $E_r > 0$ that matches that of a standard array where $E_r < 0$. The observed effect of the polarity of the radial-electric field does indicate that models of plasma formation in wire-array *Z* pinches may need to include the electric field—currently the majority of models are based purely on magnetohydrodynamics.

In conclusion, we found that the polarity of the radial-electric field at the wires of a wire-array *Z* pinch strongly affects the ablation rate of the array, significantly changing the time scale of its implosion. The general physical behavior of the array—the gradual ablation of wire cores into coronal plasma, followed by an implosion that snowplowed this coronal plasma to the axis—was, however, unchanged by polarity. It would be beneficial to explore using the radial-electric field to control plasma formation in experiments at larger facilities. In particular, the reduced ablation rate of the wires in an array could allow the total mass of the array to be decreased while keeping the implosion time constant. This could reduce the amount of material left behind by the implosion of the array, possibly increasing the current in the stagnated pinch on axis, and hence increasing x-ray emission [16]. Another potential use of the observed effect is to cause different sections of an array to implode at different times, introducing a new method of shaping the x-ray pulse for ICF and other high energy density physics experiments.

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