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Larger Sized Wire Arrays on 1.5 MA Z-pinch Generator

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Abstract. Experiments on the UNR Zebra generator with Load Current Multiplier (LCM) allow for implosions of larger sized wire array loads than at standard current of 1 MA. Advantages of larger sized planar wire array implosions include enhanced energy coupling to plasmas, better diagnostic access to observable plasma regions, and more complex geometries of the wire loads. The experiments with larger sized wire arrays were performed on 1.5 MA Zebra with LCM (the anode-cathode gap was 1 cm, which is half the gap used in the standard mode). In particular, larger sized multi-planar wire arrays had two outer wire planes from mid-atomic-number wires to create a global magnetic field (gmf) and plasma flow between them. A modified central plane with a few Al wires at the edges was put in the middle between outer planes to influence gmf and to create Al plasma flow in the perpendicular direction (to the outer arrays plasma flow). Such modified plane has different number of empty slots: it was increased from 6 up to 10, hence increasing the gap inside the middle plane from 4.9 to 7.7 mm, respectively. Such load configuration allows for more independent study of the flows of L-shell mid-atomic-number plasma (between the outer planes) and K-shell Al plasma (which first fills the gap between the edge wires along the middle plane) and their radiation in space and time. We demonstrate that such configuration produces higher linear radiation yield and electron temperatures as well as advantages of better diagnostics access to observable plasma regions and how the load geometry (size of the gap in the middle plane) influences K-shell Al radiation. In particular, K-shell Al radiation was delayed compared to L-shell mid-atomic-number radiation when the gap in the middle plane was large enough (when the number of empty slots was increased up to ten).

MOTIVATION, EXPERIMENTAL DETAILS, AND RESULTS

Implosion dynamics and K -shell x-ray generation in large diameter nested stainless steel wire array Z pinches were studied in experiments at the Z-accelerator at Sandia National Laboratories [1, 2]. K-shell x-ray generation from mid-atomic-number wire Z-pinches requires appropriate rates and degrees of ionization evidenced at higher plasma temperatures. To achieve it, the implosion velocity must be increased, by using, for example, large diameter, lower mass loads on any given pulsed power generator. Then, obvious advantages of larger sized planar wire array implosions include enhanced energy coupling to plasmas and better diagnostic access to observable plasma regions. University-scale Z-pinch generators are able to produce plasmas with a broad range of temperatures, densities, and opacity properties and provide data that can be useful for scaling purposes as well as for more general applications at the higher current generators such as SNL-Z [3]. Experiments on the Zebra generator at standard current of 1 MA have demonstrated that planar wire arrays (PWA) are very efficient radiators and in particular muti-planar wire arrays can be very useful in studying radiation from two different wire materials in space and time [4]. Experiments on the Zebra generator with LCM (Load Current Multiplier, provides 1.5-1.7 MA) allow for implosions of larger sized wire array loads including PWAs than at standard current of 1 MA as well as new applications such as to ICF [5]. In this work modified multi-planar wire arrays are tested that consisted of two outer wire planes, each 4.9 mm width that were made of eight mid-atomic-number (Alumel with 95% of Ni) wires with the inter-row gap increased from 3 or 6 mm (usually used at 1 MA current) up to 9 mm. In addition, a central plane was located in the middle between the outer planes that had empty slots and a few Al wires at the edges. The schematic of the loads with 6, 8, and 10 empty slots is shown in Fig. 1. Also, the diameter of Al wires was 17.8 μm in the load with the minimum number of empty slots (6) and 10 μm in other loads (with 8 and 10 empty slots) which provided the initial ratio of Al to Alumel in the loads equal to 23.6% and 7.4%, respectively.

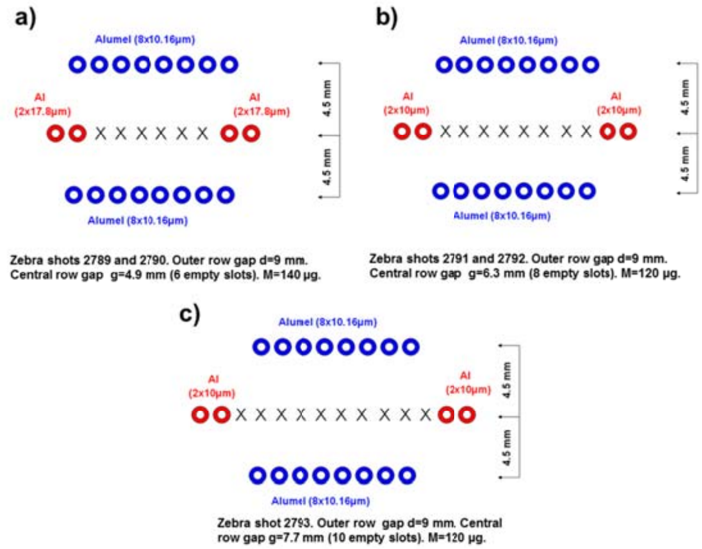

FIGURE 1. Schematics of the large sized planar wire array loads with the increased number of empty slots from 6 to 10 in the middle plane to change the K-shell Al plasma flow.

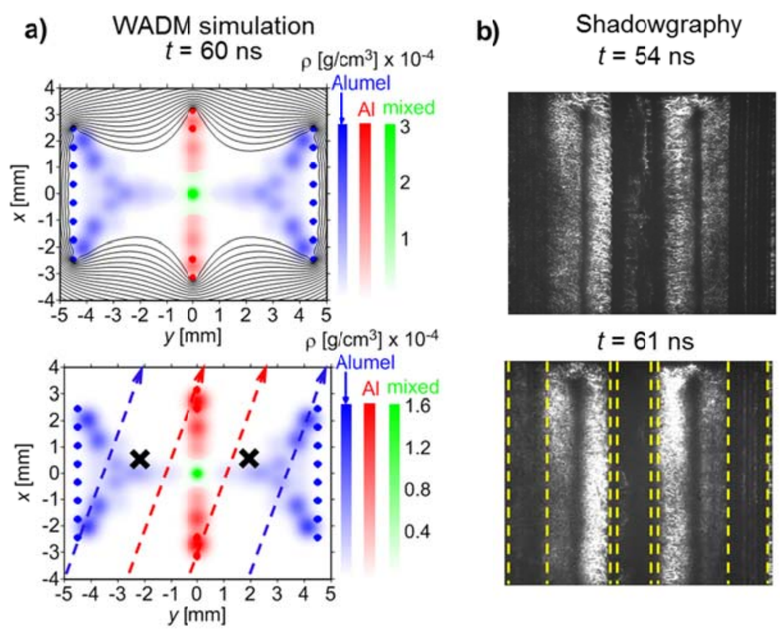

FIGURE 2. a) Wire Ablation Dynamics Model (WADM) simulations of the global magnetic field configurations and plasma mass density (ρ). The dotted arrow lines (bottom) indicate the direction of optical laser probing and crosses show the probable location of standing shocks. b) shadowgraphy images for the large sized planar wire array (Zebra shot 2790) recorded at 54 and 61 ns after the current start, respectively. Yellow dotted lines show the initial positions of wires.

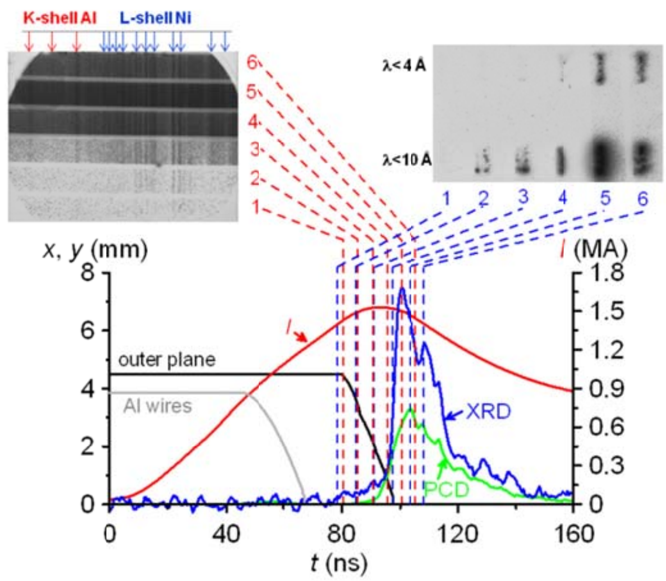

FIGURE 3. Alumel/Al/Alumel larger sized planar wire array (Zebra shot 2793): at the top, six-frame time gated X-ray spectra (left) and six-frame X-ray time-gated pinhole images filtered at two different wavelengths (right); in the middle, current *I*, XRD and PCD signals in arbitrary units, and the implosion trajectories of the outer Alumel planes and Al plane, calculated by the WADM.

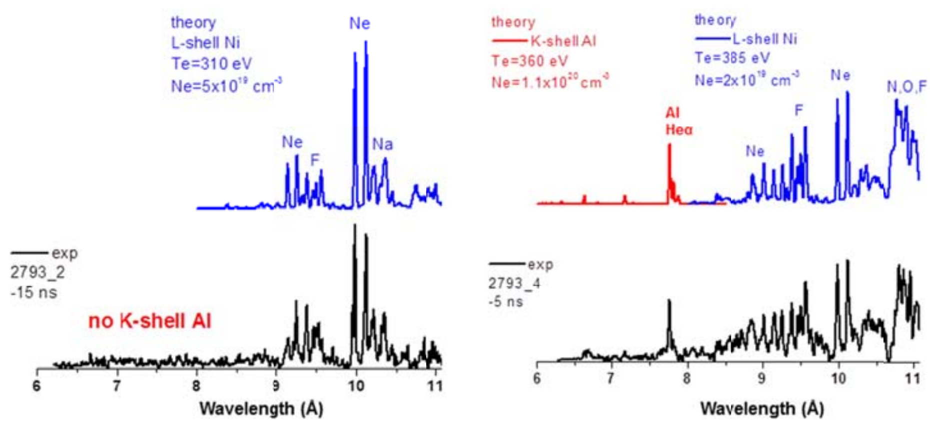

FIGURE 4. Alumel/Al/Alumel larger sized planar wire array (Zebra shot 2793). X-ray time-gated spectra (black) registered at different times with respect to the XRD peak, early at -15 ns (left) and then at -5 ns (right), fitted with theoretical calculations of L-shell Ni (blue) and K-shell Al (red).

A full set of diagnostics was implemented to study implosion and radiative properties of large arrays in a broad spectral range from few Å to few hundred Å using PCD, XRD, and EUV detectors, X-ray/EUV spectrometers and X-ray pinhole cameras (see [6] for more details of PWA experiments on Zebra). In addition, laser shadowgraphy was utilized. For example, Fig. 2 displays shadowgraphy images recorded at 54 and 61 ns after the current start in shot 2790 on Zebra together with Wire Ablation Dynamics Model [7] simulations of the global magnetic field configurations and plasma mass density ρ with probable location of standing shocks shown with crosses. Figure 2 illustrates that using PWAs and having them of larger size, provides better diagnostic access: for example, it allows for registration of the dynamic features such as standing shocks. Implosion and radiative properties of the large sized planar wire array with the maximum number of the empty slots in the middle plane produced in shot 2793 on Zebra with LCM are shown in Figs. 3 and 4.

DISCUSSION AND CONCLUSION

In the presented experiments, the current was about 1.5 MA, the implosion time was close to 100 ns, and the anode-cathode gap was 1 cm (which is half the gap used at the standard current). The total linear radiation yield measured with the calibrated bolometer was between 22.3 kJ/cm (Zebra shot 2789) and 30.8 kJ/cm (Zebra shot 2793) which is much higher than for the multi-PWAs of standard size (6mm between outer wires, ~10 kJ/cm) at 1 MA. Such larger sized multi-PWAs have a very complex ablation and implosion dynamics that is defined by the outer wire planes and the middle plane as shown by WADM simulations in Fig. 2a in blue and red, respectively. Though the ablation and implosion dynamics of outer planes should resemble a double PWA with a low aspect ratio (see, for example, [8]), the middle plane, even with only few wires at the edges, is changing this dynamics and prevents the penetration of the global magnetic field and allow formation of jets. It is manifested through the standing shocks in shadowgraphy images in Fig. 2b. Then, we can conclude that such a configuration may be beneficial for astrophysics.

When studying the combined wire arrays before, the time-gated X-ray spectra have always included radiation from both materials (see, for example, [4]) and even at early times as recorded in Zebra shots 2789-2791. If we will further increase the Al central gap (by putting more empty slots) then how it will influence precursor formation and K-shell Al radiation? The answer is provided in the analysis of the shot with a maximum number of empty slots (Zebra shot 2793, see Figs. 3 and 4). In Fig. 3, X-ray time-gated pinholes were recorded almost at the same time as time-gated spectra. The image of two columns (that likely represent the imploding outer planes) are seen as well as L-shell Ni as early as 15 ns before the PCD peak (at -15 ns) but no K-shell Al was detected at that time. From the third frame (at -10 ns), both L-shell Ni and K-shell Al were recorded. Though time-gated spectra seem to be the most intense and do not show changes on frames 4 (at -5 ns), 5 (at the XRD peak), and 6 (+5 ns), the pinhole images look somewhat different: as a uniform column at -5 ns to the most intense column at the PCD peak to the beginning of destruction of the column by instabilities at +5 ns after the peak. X-ray time-gated spectra are shown in Fig. 4 fitted with the theoretical modeling. On frame 2 at -15 ns, no K-shell Al lines and relatively cold L-shell Ni spectra (Na-like line structures of the same intensity as F-like ones) are observed. Frame 3 at -10 ns demonstrates appearance of Heα Al line which manifests relatively cold K-shell Al (< 300 eV). From frame 4 at -5 ns to frame 5 at the XRD peak, electron temperature Te of K-shell Al plasma increases from 360 eV to 450 eV (prominent H-like Lyα Al line, maximum Te) and so does of L-shell Ni plasmas reaching its maximum value among all considered shots (very intense N, O, F peak). In conclusion, by using a larger sized configuration of multi-PWAs with the increased number of empty slots, for the first time we were able to separate radiation from two different materials (at early time) and produce a test bed for new applications of magnetized Z-pinch plasma including astrophysics.

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