Temporal Characteristics and Radiative Properties of Uniform Mo and Combined with Al Triple Planar Wire Arrays

M.E. Weller, A.S. Safronova, V.L. Kantsyrev, I. Shrestha, A. Stafford,
V.V. Shlyaptseva, E.E. Petkov

Physics Department, University of Nevada, Reno, NV 89557, USA

Results of the research with triple planar wire arrays (TPWAs) made of uniform Mo or from combined Mo and Al planes obtained on the University of Nevada, Reno (UNR) Zebra generator are presented. The combined loads consisted of either two Mo planes on the outside with Al in the center or two Al planes on the outside with Mo in the center. Different wire diameters of Mo and Al were used to keep the planes approximately the same mass. Also, the change of inter-planar gap was investigated: decreasing the inter-planar gap from 3.0 mm to 1.5 mm led to a higher yield of 25 kJ (up from 16 kJ), close to the highest yield from Mo double planar wire arrays. The question of how Mo and Al plasmas mix is raised and is examined and as a result it is demonstrated that L-shell Mo (~ 1000 eV) and K-shell Al (~ 400 eV) plasmas have very different electron temperatures. Additionally, time-gated K-shell Al and Mg plasma parameters were modeled, giving important information on the time-evolution of such plasmas. The future work on radiation from mixed higher and lower atomic number wire arrays is discussed.

PACS: 52.58Lq; 52.59.Qy; 32.30.Rj; 52.70.La

I. Introduction

Planar wire arrays (single and multi-planar) have previously shown to be very efficient x-ray radiators [1,2] on university scale z-pinch generators, such as the 1.7 MA Zebra generator at UNR. In 2007, a study [3] that involved mixing Mo and Al in single planar wire arrays (SPWAs) was accomplished and it was shown that L-shell Mo radiated mostly from random bright spots along the pinch, while K-shell Al radiated in a more column-like manner along the pinch. In continuation of this work on combined Mo and Al PWAs, single and double planar wire arrays of Mo were studied [4] and it was shown that Mo SPWAs produced very high T_e at > 1300 eV for heavier loads (150 μg) and moderately high electron density (n_e at $> 10^{21} \text{ cm}^{-3}$) for lighter loads (90 μg) with total radiated energies > 18 kJ. Mo double planar wire arrays (DPWAs), however, produced lower electron temperature (T_e at $>$

*Corresponding Author.

E-mail address: mweller@unr.edu (M.E. Weller)

1100 eV) but with higher total radiated energies > 21 kJ. These studies motivated research into applying new methods into understanding radiation from different materials in wire array plasmas, and recently in [5] a new method was suggested that involved multi-planar wire arrays, in particular triple planar wire arrays (TPWAs), which provide the initial space separation of different plasmas and the possibility of their observation. In that work, Cu and Al wires were employed in which K-shell Al and L-shell Cu radiated at very similar electron temperatures and plasma conditions. The next step then, which this paper focuses on, is to study wires using materials that radiate at much different electron temperatures to show more how different plasmas mix, which L-shell Mo and K-shell Al accomplish. Studying combined plasmas with different initial mass concentrations can also be used to study opacity effects, which is important when trying to identify plasma parameters. Therefore, this paper will concentrate on the radiative characteristics of Mo and mixed Mo and Al triple planar wire arrays (TPWAs), in particular how geometry and inter-planar gaps play a role in efficiency of energy conversion to x-rays, and also how placement and mass concentration of different Mo and Al wires influence overall radiation of K-shell Al and L-shell Mo, and how this affects opacity of the plasmas. Section II describes experimental details and temporal characteristics of the TPWAs. Section III explores the radiative characteristics of the TPWAs. Section IV concludes the paper.

II. Experimental Details and Temporal Characteristics of Mo and Combined with Al TPWAs

The experimental details of the Mo and combined Mo and Al TPWAs are laid out in Table 1. All experiments contained six wires in each plane with an anode-cathode gap of 20 mm, and were carried out on the Zebra generator at 1.0 MA configuration (100 ns current rise, 150 kJ stored energy). The first set of experiments, shot numbers 1261, 1262, and 1263, were carried out with an inter-planar gap of 3.0 mm. The second set of experiments, shot numbers 1969, 1932, 1968, 1933, 1953, and 2166, were carried out with an inter-planar gap of 1.5 mm. The TPWAs can be characterized into three categories: the first consisting of uniform Mo (Mo/Mo/Mo), the second consisting of $\sim 67\%$ Mo and $\sim 33\%$ Al (5056, 95% Al, 5% Mg) (Mo/Al/Mo), with Mo planes on the outside, and the third consisting of $\sim 33\%$ Mo and $\sim 67\%$ Al (5056) (Al/Mo/Al), with Al planes on the outside. The wire thicknesses were adjusted to not only ensure that each plane had approximately the same mass, but that the load would implode at approximately 100 ns, or the maximum of the current, which allows maximum efficiency of x-ray radiation and total radiated energy output. Al 5056 alloy wires are utilized to help in countering opacity effects for K-shell Al as suggested in Ref. [6].

For the TPWAs with a 3.0 mm inter-planar gap, the total radiated energy for the Mo/Mo/Mo and Mo/Al/Mo loads were comparable at 16.2 and 16.9 kJ, respectively. The total radiated energy for Al/Mo/Al load, however, was less at 13.1 kJ. These energies are less than for the Mo DPWAs (> 21 kJ) previously studied in Ref [4] and it is important to note here that because of the open magnetic configuration of the TPWA the placement of the outer wires can significantly change the dynamics and efficiency of the implosion. In order to attain higher efficiency in total radiation output, experiments were carried out by changing the inter-planar gap from 3.0 mm to 1.5 mm. By doing so this makes the total outer-planar gap 3.0 mm, which is the same as the outer-planar gap of the Mo DPWAs with the highest total radiated energy that were previously studied. Looking back to Table 1, it can be seen that the TPWA loads with a 1.5 mm inter-planar gap have increased total radiated energy. The Mo/Mo/Mo loads radiated 25.5 kJ and 24.5 kJ, the Mo/Al/Mo loads radiated 22.2 kJ and 22.5 kJ, and the Al/Mo/Al loads radiated 23.1 kJ and 24.0 kJ of total energy, an increase of an average 1.6 times the previous values, and show good reproducibility to within 5%. Similar results from DPWAs were attained in Ref [2] where it was shown that when comparing inter-planar gaps between 1.5 mm and 6.0 mm, the maximum total radiated energy corresponded to the 1.5 mm inter-planar gap. A possible explanation is that when the initial plane separation is too far apart the load will be more difficult to implode. This will increase the implosion time and by doing so the implosion will not utilize the maximum of the current which may decrease the total radiated energy. Reducing the total mass can compensate for the larger gap; however this results in less mass that can radiate which may also decrease total radiated energy. Therefore there needs to be a balance between inter-planar gap and total mass. The results here indicate that for TPWAs the inter-planar gap of 1.5 mm provides optimal results, similar to Ref [2] with DPWAs. To compare radiated energy in the x-ray regime, a calibrated photoconduction diode (PCD) was filtered ($8\text{ }\mu\text{m Be}$, $> 0.8\text{ keV}$) to include both K-shell Al and L-shell Mo radiation. The PCD energies for the 3.0 mm inter-planar gap loads radiated between 102 – 179 J, while the PCD energies for the 1.5 mm inter-planar gap loads radiated between 157 – 349 J, depending on the Al concentration. Comparing loads with similar Al concentration and placement, there is an increase in PCD energy from roughly 1.5 – 2 times when going from a 3.0 mm to 1.5 mm interplanar gap, which agree with the increase in total radiated energy. The fraction of x-ray radiation within the PCD cutoff energy range to the total radiated energy is between 0.6 – 1.5 %, indicating a vast majority of the radiation comes from softer radiation. Additionally, it can be noted that PCD energy appears to increase with increasing Al concentration, possibly because it's easier to radiate into K-shell Al than into L-shell Mo. The remainder of the paper will focus on these loads with a 1.5 mm inter-planar gap, in particular shots 1969, 1968, and 1953 (their respective identical loads 1932, 1933, and 2166 will not be shown because their time-resolved and radiative characteristics were similar).

The rest of this section goes over the experimental results of the temporal dynamics of the

TPWAs with a 1.5 mm inter-planar gap in order to better understand how the different configurations implode and also how K-shell Al radiates in time. Figure 1 shows signals, current, and time-gated pinhole (TGPH) images from Mo/Mo/Mo (1969). The signals include a 5 μm Kimfoil filtered x-ray diode (XRD, > 0.2 keV) and a calibrated PCD, as mentioned earlier. Briefly, the TGPH utilized a microchannel plate consisting of six gates with 6 ns spacing between gates and 3 ns frame duration, allowing two images of energies > 1.0 keV and > 3.0 keV. The XRD signal indicates a sharp rise just before the implosion at 94 ns, followed by a series of bursts after the main pinch lasting for approximately 40 ns. The PCD signals show interesting results where, similar to the XRD signals, there are a series of bursts and the start and the end is virtually identical to the timing of the XRD. The TGPH images indicate many random bright spot formations for both > 1.0 and > 3.0 keV images, which correlate well with the random burst nature of the XRD and PCD signals. The bright spot formations have been shown in other wire array configurations [7-10] to correlate with Rayleigh Taylor instabilities which are seeded by the development of quasi-periodic gaps in the wire cores at the start of the implosion phase, that may occur also in these experiments.

Next in Figure 2 are the signals and time-gated spectrometer (TGSP) images from Mo/Al/Mo (1968). The TGSP [11] was implemented to understand how K-shell Al and Mg radiate in time and utilized a potassium hydrogen phthalate (KAP) crystal ($2d = 26.63$ Å) which allowed for viewing of wavelengths between 6.2 and 11.0 Å, wide enough to cover most of K-shell Al and Mg spectra. Bio-max MS Kodak x-ray film was implemented in this work. The spacing between gates was 5 ns, while the microchannel plate was gated to last for 3 ns. The XRD and PCD signals look very similar to that of Mo/Mo/Mo, with an implosion time of 95 ns and many burst formations after the main implosion. Looking to the TGSP, spectra were collected starting at 79 ns after current rise, or 16 ns before the main implosion. Frame 2 in Figure 2(b) indicates the presence of background, perhaps bremsstrahlung radiation or recombination, however very weak K-shell Al radiation, and corresponds to a spike in PCD signal. This may indicate that L-shell Mo, from the outer planes, is radiating just slightly before K-shell Al, from the inner plane, however without time resolution of L-shell Mo itself this is purely speculation and points to the importance of understanding time evolution of L-shell Mo. Frame 3, which corresponds to a “valley” in the PCD signal and little background, shows definitive appearance of K-shell Al, with an estimated T_e of 425 eV. Plasma parameters are estimated using a non-LTE kinetic model of K-shell Al and Mg (for information of the model and labeling of important diagnostic lines, see Ref. [12]). The ratio of Al2 ($\text{Ly}\alpha: 2p^2P_{1/2,3/2} \rightarrow 1s^2S_{1/2}$) to Al1 ($\text{He}\alpha: 1s2p^1P_1 \rightarrow 1s^2^1S_0$) is used to estimate T_e with an uncertainty of $\pm 10\%$. Usually, the electron density is estimated by the ratio of Al1 and inter-combination line Al1' (IC: $1s2p^3P_1 - 1s^2^1S_0$) with an estimated uncertainty within an order of magnitude, however here the intensity of the Al1' is too low and the electron density 10^{20} cm^{-3} is used (electron densities on the order of $10^{19} -$

10^{20} cm^{-3} are common for university scale generators, see for example Ref [13,14]). Frame 4, 5 ns later, which corresponds just before the main implosion and re-emergence of background, shows a K-shell Al T_e of 430 eV. Frame 5, which corresponds to just after the main implosion, shows very intense background and a maximum of K-shell Al T_e of 450 eV. The final frame 6 corresponds to another “valley” in the PCD signal and significant reduction of background, along with reduction of K-shell Al T_e with an estimation of 350 eV. It’s important to note in this analysis that K-shell Al radiated relatively optically thin, with no presence of K-shell Mg. This is likely do to the Al wires being in the inner plane and also starting out with a low percentage of initial mass (35%).

Figure 3 shows the results of the K-shell Al and Mg spectra along with signals from the Al/Mo/Al configuration. Again the XRD and PCD signals show a sharp rise followed by random bursts. The TGPH images at $> 1.0 \text{ keV}$ in frames “c” “d” and “e”, which correspond to the middle of the main implosion, are very bright and likely saturated the film, which is a contrast to the TGPH images for the Mo/Mo/Mo array, which didn’t produce an oversaturation of the film. This is likely due to K-shell Al radiation from the outer planes, as will be shown in the next section when the time-integrated spatially resolved spectra are analyzed. Looking to the TGSP, similar to the previous Mo/Al/Mo case, the first frame 1 is taken before any PCD signal and no K-shell Al or Mg was measured. By frame 2, however, K-shell Al is measured, with very weak evidence of K-shell Mg and very little background on the film. The corresponding lineout indicates that K-shell Al lines Al1 and Al2 are optically thick. Frame 3 corresponds to a rapid rise in PCD signal, strong background on the film, and strong K-shell Al and Mg lines. Due to the high opacity of K-shell Al, K-shell Mg was modeled and had an estimated T_e of 300 eV. Frames 4-6 proceed to follow the PCD signal to just before to just after the main implosion, characterized by strong K-shell Al and Mg emissions, strong background, and modeled K-shell Mg T_e of 325, 350, and 310 eV, respectively. As previously for Mo/Al/Mo, the modeled T_e follows the PCD signal well.

III. Radiative Properties of Mo and Combined with Al TPWAs

This section will focus on the radiative properties of the TPWAs of Mo and combined with Al with a 1.5 mm inter-planar gap, in particular the time-integrated spatially resolved radiation, which will help in understanding axial gradients along the pinch for both K-shell Al and L-shell Mo plasmas, which is important in helping to understand plasma from different materials. Figure 4 shows the results of time-integrated spatially resolved pinhole and spectra from Mo/Mo/Mo, Mo/Al/Mo, and Al/Mo/Al. The spectra were taken with a KAP convex crystal spectrometer while the pinhole images were filtered to study L-shell Mo emissions $> 3.0 \text{ keV}$ and K-shell Al and Mg emission (along with L-shell Mo) $> 1.0 \text{ keV}$. Both diagnostics are axially resolved to study variations along the length of the pinch from anode

“a” to cathode “c”. Diagnostically important L-shell Mo lines (for more information on L-shell Mo and labeling of important diagnostic lines, along with the non-LTE kinetic model used to diagnose plasma parameters, see Ref. [15]), along with K-shell Al and K-shell Mg lines are indicated. The pure Mo/Mo/Mo load shows increased hard x-ray formation and less bright spot formation than the mixed loads. The mixed Mo/Al/Mo load produces optically thin K-shell Al radiation with no presence of K-shell Mg lines and radiates not in a column-like manner, but follows L-shell Mo radiation, which correlate with “bright” spot formations. The Al/Mo/Al load produces optically thick K-shell Al and has a strong presence of K-shell Mg and radiates more in a column-like manner than for the Mo/Al/Mo load, though there still appears to be an influence in K-shell Al and Mg electron temperatures wherever L-shell Mo along with “bright” spots in the film appear. For all cases, L-shell Mo radiates from many bright spots (approximately seven to ten). There are a few possible explanations to the clear change in opacity in K-shell Al lines, in particular Al_{II}, when moving from the Mo/Al/Mo to the Al/Mo/Al configuration. The first explanation, as is explained in Ref. [5] for TPWAs of Cu and Al, is that there is a current distribution between array planes, which is defined by the mutual inductance of these planes, which is affected by the load geometry rather than the specific properties of the wire materials. In short, the outer planes pick up more current than the inner planes. To illustrate this current distribution the Wire Ablation Dynamics Model (WADM [16]) was applied for configurations Mo/Al/Mo and Al/Mo/Al, and results are shown in Figure 5. At 45 ns, WADM clearly indicates most of the current is taken by the outer planes, with the inner wires of the middle plane showing little to no current. Earlier results of mixed Al and W cylindrical arrays were studied in [17] where it was shown that the Al wires imploded first, followed by the W wires, indicating an uneven current distribution due to a likely combination of inductance and resistance differences between the W and Al wires. So the current distribution is likely affected not only by placement, but also material. For more complicated loads, such as the recent star wire array configurations studied in [18], calculating and understanding current distribution is important in understanding implosion dynamics. Concerning the change in opacity in mixed arrays, similar results have been shown for Al and brass (30% Zn, 70% Cu) nested cylindrical wire arrays (Ref. [19]), where one cylindrical wire array was embedded in another cylindrical array. In this study, it was shown that switching the Al and brass wires from the inner array to the outer array dramatically affected the intensity and opacity of the K-shell Al and L-shell Zn and Cu radiation, despite having identical initial masses. The second explanation for the change in opacity could simply be due to smaller concentration of Al mass in the Mo/Al/Mo configuration compared to the Al/Mo/Al configuration.

Figure 6 shows the example of experimental lineouts (taken near the cathode in all cases) of the time-integrated spectra, as well as theoretical modeling of L-shell Mo and K-shell Al/Mg. This is to very clearly show how different mass concentrations and wire placement can effect radiation output and that

despite the fact that the mass of Al increased by twice and of Mo decreased by twice for Al/Mo/Al, the ratio of K-shell Al/L-shell Mo radiated energy went from 1 to 12, indicating that the outer planes are likely contributing more to the total radiation than the inner plane. Non-LTE kinetic modeling was successfully applied and despite substantially different mass and plane position of Mo for each shot, the electron temperatures and densities did not significantly change for L-shell Mo: electron temperatures were estimated to be between 950 and 1200 eV while electron densities were estimated to be between 10^{19} and 10^{20} cm⁻³. It's important to note that L-shell Mo radiated from many bright spots along the pinch, which itself indicates non-uniform plasma for L-shell Mo. The conclusion is that the bright spot formations and plasma parameters of L-shell Mo going from the Mo/Mo/Mo to Mo/Al/Mo to the Al/Mo/Al configurations do not substantially change. As for K-shell Al plasmas: electron temperatures were estimated to be between 370 and 500 eV while electron densities were estimated to be between 6×10^{19} and 5×10^{20} cm⁻³ for Mo/Al/Mo, indicating a very non-uniform implosion. For Al/Mo/Al, Mg plasma temperatures were estimated to be between 300 and 360 eV while electron densities were estimated to be between 9×10^{19} and 2×10^{20} cm⁻³, indicating a much more uniform implosion, yet cooler, than for Mo/Al/Mo. Results of electron temperature as a function of distance from anode from these experiments are shown in Figure 7 and show the significant difference between L-shell Mo and K-shell Al/Mg in T_e .

IV. Conclusions

Experiments and analysis of data for triple planar wire arrays of Mo and combined with Al at 3.0 mm inter-planar gap and with reduced 1.5 mm inter-planar gap was accomplished for the first time. The reduced gap size of TPWA's (3 mm to 1.5 mm) produced higher energy output (from ~ 16 kJ to ~ 25 kJ for pure Mo) for all configurations. Time-gated spectra modeling of K-shell Al and Mg followed PCD and XRD signals well for the Mo/Al/Mo and Al/Mo/Al configurations. The radiative properties of L-shell Mo and K-shell Al agree well with previous results from [3] with the investigation of mixed Mo and Al single planar wire arrays where L-shell Mo radiated from randomly generated bright spot formations between the anode and cathode. In Ref [5], Cu and Al TPWAs were tested and provide useful comparisons for the TPWAs discussed in this paper, specifically for opacity effects of mixed material plasmas. For the Mo/Al/Mo configuration, K-shell Al lines were optically thin and followed Mo L-shell radiation from bright spot pattern. This is likely due to initial placement on the inside of the array, which has less current distribution, and smaller initial Al concentration ($\sim 35\%$ total mass), which is a similar observation as in [5] when an Al plane is put in the middle of two Cu planes. For the Al/Mo/Al configuration, K-shell Al lines were optically thick and followed a column-like structure. This is likely

due to initial placement on the outside of the array, which has more current distribution, and larger initial Al concentration ($\sim 70\%$ total mass). This is interesting to compare to the result from [5] when one Al plane was placed on the outside of a TPWA with two Cu planes, where K-shell Al radiated mostly optically thin, which may confirm that initial mass concentration of a material plays a role in the overall opacity features of the plasma. In addition to the much higher electron temperature of L-shell Mo, the size of the sources is much smaller while the sizes of the sources for K-shell Al and L-shell Cu were comparable.

This paper focused on reporting enhanced total radiated energy as a change in geometry type and exploring the details of the results. Future experiments should investigate more of the plasma physics, such as the dynamics of the implosion and instabilities reported, to understand more of this increased radiated energy. Furthermore, while experiments from this paper and Ref [5] were accomplished with comparable currents (1.0 MA), future experiments will also explore combined material TPWAs at higher currents, to understand how these results scale with current, utilizing the Load Current Multiplier [20] (1.7 MA) on the Zebra generator. Additionally, future experiments will focus on understanding the time-evolution of L-shell Mo by utilizing a new TGSP capable of attaining spectra in the proper x-ray wavelength range (4.0 – 5.5 Å).

Acknowledgements

This work was supported by NNSA under DOE Cooperative Agreements DE-NA0001984 and in part by DE-FC52-06NA27616.

We would like to thank all Nevada Terawatt Facility staff that helped in attaining experimental data. We would also like to thank former UNR team members Dr. Andrey Esaulov, Dr. Kenneth Williamson, and Dr. Glenn Osborn for their contributions.

References

- [1]. V.L. Kantsyrev, *et al.*, IEEE Transactions on Plasma Science **34** (2006) 2295.
- [2]. V.L. Kantsyrev, *et al.*, Physics of Plasmas **15** (2008) 030704.
- [3]. A.S. Safronova, *et al.*, High Energy Density Physics **3** (2007) 237.
- [4]. M.F. Yilmaz, *et al.*, Journal of Quantitative Spectroscopy and Radiative Transfer **109** (2008) 2877.
- [5]. A.S. Safronova, *et al.*, Physics of Plasmas **21** (2014) 031205.
- [6]. J.P. Apruzese, *et al.*, Physics of Plasmas **8** (2001) 3799.

- [7]. D.B. Sinars, *et al.*, Physics of Plasmas **12** (2005) 056303.
- [8]. G.N. Hall, *et al.*, Physics of Plasmas **13** (2006) 082701.
- [9]. S.N. Bland, *et al.*, Physics of Plasmas **14** (2007) 056315.
- [10]. V.V. Ivanov, *et al.*, Physics of Plasmas **20** (2013) 112703.
- [11]. V. Kantsyrev, *et al.*, Review of Scientific Instruments **72** (2001) 663.
- [12]. M.F. Yilmaz, *et al.*, High Energy Density Physics **8** (2012) 30.
- [13]. M.E. Weller, *et al.*, Physics of Plasmas **21** (2014) 031206.
- [14]. I.C. Blesner, *et al.*, Review of Scientific Instruments **80** (2009) 123505.
- [15]. A.S. Safronova, *et al.*, Physics of Plasmas **15** (2008) 033302.
- [16]. A.A. Esaulov, *et al.*, High Energy Density Physics **5** (2009) 166.
- [17]. S.N. Bland, *et al.*, AIP Conference Proceedings CP651 (2002) 83.
- [18]. V.V. Ivanov, *et al.*, Physics of Plasmas **17** (2010) 102702.
- [19]. M.E. Weller, *et al.*, High Energy Density Physics **8** (2012) 184.
- [20]. A.S. Chuvatin, *et al.*, Physical Review Special Topics – Accelerators and Beams **13** (2010) 010401.

Shot #	Material	Diameter (μm)	Linear Mass ($\mu\text{g/cm}$)	Al (%)	Total Radiated Energy (kJ)	PCD Energy (J)	Implosion Time (ns)
--------	----------	----------------------------	----------------------------------	--------	----------------------------	----------------	---------------------

1261	Mo/Mo/Mo	7.9/7.9/7.9	90	-	16.2	102	91
1262	Mo/Al/Mo	7.9/15.0/7.9	89	32	16.9	125	93
1263	Al/Mo/Al	15.0/7.9/15.0	87	65	13.1	179	97
1969	Mo/Mo/Mo	8.9/8.9/8.9	114	-	25.5	157	94
1932	Mo/Mo/Mo	8.9/8.9/8.9	114	-	24.5	158	99
1968	Mo/Al/Mo	8.9/17.8/8.9	116	35	22.2	220	95
1933	Mo/Al/Mo	8.9/17.8/8.9	116	35	22.5	274	97
1953	Al/Mo/Al	17.8/8.9/17.8	119	68	23.1	349	95
2166	Al/Mo/Al	17.8/8.9/17.8	119	68	24.0	301	97

TABLE 1. List of considered shots and parameters for Mo and combined Mo and Al TPWAs, with load characteristics, diameter of the wires, inter-planar gap, linear mass, percentage of Al in the load, PCD energy, and total radiated energy. The first three listed are loads with inter-planar gap of 3.0 mm. The last six are loads with inter-planar gap of 1.5 mm.

FIGURE 1. (a) PCD and XRD signals along with current (b) and time-gated pinhole images for Mo/Mo/Mo (1969). The pinhole timings are shown with gray boxes and are listed “a-f” and are filtered at > 1.0 keV and > 3.0 keV.

FIGURE 2. (a) PCD and XRD signals from Mo/Al/Mo along with current, timings from the time-gated spectrometer (labeled “1 – 6”), and K-shell Al electron temperatures. (b) Spectra from time-gated spectrometer and (c) lineouts taken from spectra in (b) along with synthetic spectra.

FIGURE 3. (a) PCD and XRD signals from Al/Mo/Al along with current, timings from the time-gated spectrometer (labeled “1 – 6”), and K-shell Al electron temperatures. (b) Time-gated pinhole images. The pinhole timings are shown with gray boxes and are listed “a-f” and are filtered at > 1.0 keV (top) and > 3.0 keV (bottom). (c) Spectra from time-gated spectrometer and (d) lineouts taken from spectra in (c) along with synthetic spectra.

FIGURE 4. (a) Time-integrated spatially resolved pinholes (left) and spectra (right) of Mo/Mo/Mo. (b) Time-integrated spatially resolved pinholes (left) and spectra (right) of Mo/Al/Mo. (c) Time-integrated spatially resolved pinholes (left) and spectra (right) of Al/Mo/Al.

FIGURE 5. Wire Ablation Dynamics Modeling for configurations Mo/Al/Mo and Al/Mo/Al. (a) The initial wire position for Mo/Al/Mo and (b) the current distribution at $t = 45$ ns. (c) The initial wire position for Al/Mo/Al and (d) the current distribution at $t = 45$ ns.

FIGURE 6. Lineouts in gray taken near the cathode from time-integrated spatially resolved spectra from Figure 4 of (a) Mo/Mo/Mo, (b) Mo/Al/Mo, and (c) Al/Mo/Al. Theoretical modeling is shown in black.

FIGURE 7. Modeled electron temperature as a function of distance from anode of L-shell Mo and K-shell Al/Mg from Zebra shots 1968 (Mo/Mo/Mo), 1969 (Mo/Al/Mo), and 1953 (Al/Mo/Al).