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Temporal characteristics and radiative properties of uniform Mo and combined with Al triple planar wire arrays

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ABSTRACT

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.

1. 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} 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 >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 Ref. [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 2 describes experimental details and temporal characteristics of the TPWAs. Section 3 explores the radiative characteristics of the TPWAs. Section 4 concludes the paper.

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2. 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 ~67% Mo and ~33% Al (5056, 95% Al, 5% Mg) (Mo/Al/Mo), with Mo planes on the outside, and the third consisting of ~33% Mo and ~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 μm Be, >0.8 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 and 179 J, while the PCD energies for the 1.5 mm inter-planar gap loads radiated between 157 and 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 and 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. Fig. 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 Fig. 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

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.

Shot#	Material	Diameter (μm)	Linear mass (μg/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