High Energy Density Physics 8 (2012) 184–189

Contents lists available at SciVerse ScienceDirect

High Energy Density Physics

journal homepage: www.elsevier.com/locate/hedp

# Radiative properties of mixed nested cylindrical wire arrays on Zebra at UNR

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ARTICLE INFO

*Article history:*
Received 5 March 2012
Accepted 5 March 2012
Available online 13 March 2012

*Keywords:*
Z-pinches
Plasma focus
Wire array
X-ray spectra
Radiative properties
Nested cylindrical wire arrays
Inertial confinement fusion

ABSTRACT

The dynamics of mixed nested cylindrical wire arrays were studied at the UNR Zebra generator with our existing theoretical and experimental tools to better understand the contributions of each array to the emitted radiation. In particular, experimental results of mixed brass (70% Cu, 30% Zn) and Al (5056, 5% Mg) nested cylindrical wire arrays are analyzed and compared. The loads used brass in the inner array and Al in the outer array, or alternately, Al in the inner array and brass in the outer array, with a mass ratio of 1:1 (outer to inner). Consequently, radiative properties of K-shell Al and Mg ions and L-shell Cu and Zn ions are compared as functions of the placements of the brass and Al wires on the inner and outer arrays. Results show that the placement of brass and Al, whether on the inner or outer array, dramatically affects the intensity of the X-ray emission. Specifically, the ratio of Cu L-shell to Al K-shell emissions changed from 4 when Al is in the outer array to 40 when brass is in the outer array, and the total radiated yield was highest when the brass was on the outer array (18 kJ, versus 15 kJ when brass is on the inner array). Each load was fielded twice to vary the timing of the time-gated imaging and spectral diagnostics. This provides a more complete understanding of the evolution of the plasma parameters over the X-ray pulse and highlights the importance of the time-gated diagnostics.

## 1. Introduction

Nested Cylindrical Wire Arrays (NCWAs) have been studied extensively at Sandia National Laboratories on the 20 MA, 100 ns rise time Z-machine and have demonstrated an increase in X-ray power and reduction of pulse width [1] as compared to single wire arrays, producing pulse shapes required for inertial confinement fusion [2,3]. An important issue for NCWAs is understanding how the inner and outer arrays radiate and implode. To this end, other experiments at lower current facilities [4,5] have sought to study the dynamics and radiative characteristics of nested arrays. In Ref. [4], tracer spectroscopy was utilized by switching Al (5056, 5% Mg) and pure Al (1100) between inner and outer arrays; it was shown that the outer array material reached the highest temperature plasma. It was shown in Ref. [5], using mixed Al (5056) and SS (304, 69% Fe, 19% Cr, 9% Ni) NCWAs on the 1 MA, 100 ns rise time COBRA generator at Cornell University [6], that the outer wire array radiates more intensely than the inner wire array. This was explained as the outer array having more kinetic energy than the inner array (due to its larger radius), though the complexity of nested arrays due to current switching and varying levels of inner-penetration of the outer array to the inner array makes this difficult to estimate [7,8]. In this paper, we present an extension of the work in Ref. [5] by comparing K-shell Al and other L-shell mid-Z's, specifically fielding mixed brass (70% Cu, 30% Zn) and Al (5056) NCWAs on the 1.7 MA, 100 ns rise time Zebra generator at UNR [9].

The outer and inner arrays were kept uniform with 8 wires of either brass (7.62 μm dia.) or Al (12.7 μm dia.) in the outer and inner arrays; the mass was the same (~30 μg/cm) for all the arrays. The 1:1 mass ratio (outer to inner) is different than many of the load configurations in previous nested array studies, where the ratio ranged from 2:1 to 4:1 (outer to inner) (see, for instance, Ref. [10,11]). The radius of the outer array was 13 mm, while the radius of the inner array was 6 mm, with interwire gaps of 5.1 and 2.4 mm, respectively. These gaps are relatively large compared to other work, but result from the desired mass loading of the arrays for optimal coupling to the Zebra generator and limitations on available wire sizes. For each experiment, the outer array was kept aligned with the inner array. Each load was fielded twice to vary the timing of the time-gated pinhole and X-ray spectrometers and

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doi:10.1016/j.hedp.2012.03.004

obtain a more complete understanding of the evolution of the plasma parameters. K-shell Al and Mg emissions and L-shell Cu and Zn emissions were studied extensively via spectroscopy to evaluate the emissions as a function of time and original placement of the materials in the array. An extensive diagnostic suite, which included more than ten different beam-lines, was fielded with the emphasis to study emissions from K-shell Al/Mg and L-shell Cu/Zn. These diagnostics are described throughout the text.

This paper is divided into three sections: Section 2 focuses on time-integrated data, such as the time-integrated spatially resolved spectra; Section 3 focuses on time-gated data, such as time-gated spatially integrated spectra; Section 4 focuses on the wire ablation dynamics model (WADM) calculations; and Section 5 presents a discussion of the results and conclusions.

## 2. Time-integrated L-shell Cu and Zn and K-shell Al and Mg: data, modeling, and analysis

Table 1 lists the mixed NCWAs discussed in this paper. Shots 1790 and 1791 were performed with brass in the inner array and Al in the outer array and will be referred to as the Al-on-brass array. Shots 1792 and 1793 were the opposite configuration, with Al in the inner array and brass in the outer array and will be referred to as the brass-on-Al array. In all cases, the linear mass of the Al and brass alloys were kept approximately the same with 27 μg/cm for Al and 31 μg/cm for brass. The pinch length was 20 mm for all cases. A bare nickel bolometer was used to measure the total radiated energy, while a photoconducting diode (PCD) is used to derive energy >0.8 keV. The PCD was filtered using an 8 μm Be filter (>0.8 keV, 0.5 ns resolution), measuring only the hottest part of plasmas in the experiments, which is approximately the region in which K-shell Al and Mg and L-shell Cu and Zn radiate. It is interesting to note that when brass is in the outer array, the total energy, $E_{\mathrm{tot}}$, measured is higher than when brass is on the inner array, that is, $E_{\mathrm{tot}}$(brass-on-Al) ≈ 18 kJ and $E_{\mathrm{tot}}$(Al-on-brass) ≈ 15 kJ. PCD energy, $E_{\mathrm{PCD}}$, is also listed, with $E_{\mathrm{PCD}}$(brass-on-Al) ≈ 0.39 kJ and $E_{\mathrm{PCD}}$(Al-on-brass) ≈ 0.36 kJ. It has been shown [12] that for similar configurations the brass wire arrays radiate more total energy than Al wire arrays, which suggests in this case that the outer array contributes more to the total radiation than the inner array. Implosion times are also listed and are all between 110 and 120 ns. Zero time refers to the start of the current rise. In general, load parameters, such as wire diameter, are chosen to give an estimated implosion time of around peak current (100 ns).

Fig. 1 shows time-integrated spatially resolved (TISR) spectra and pinhole (TIPH) images of shots 1790 (Al-on-brass) and 1793 (brass-on-Al). The spectra were taken with a potassium hydrogen phthalate (KAP) (2d = 26.63 Å) convex crystal spectrometer while the pinhole images were filtered to study emissions >1.0 keV. Both diagnostics are axially resolved to study variations along the length of the pinch from anode to cathode. The spectra obtained on the other identical shots provided similar results to those shown here. Diagnostically important K-shell Al and Mg and L-shell Cu and Zn lines are indicated in Fig. 1 (see Ref. [13,14] for more information). The Al-on-brass array produces optically thick K-shell Al and relatively optically thin L-shell Zn and Cu, with well-defined column like structures for both. This is strengthened by the corresponding pinhole image that shows only a few bright spots along the axis. Conversely, the brass-on-Al array produces almost optically thin K-shell Al and more optically thicker L-shell Zn and Cu, with radiation that is more defined by the respective bright spot formations seen from the pinhole image. In general, the optical thickness, or opacity effects, will be seen first in lines with higher radiative decay rates (Al1 and Al2 for K-shell Al and Cu 3C for L-shell Cu, for example), provided that a large enough ion density or plasma thickness exists. Therefore, when the material is on the outer array, the respective lines have higher opacity, which is an indicator of more intense radiation in those lines. These results agree with previous observations of mixed NCWA loads which indicate that the outer array contributes more to the radiated energy than in the inner array; this is discussed further in the final paragraph of this section.

**Table 1**
List of considered shots and parameters for NCWAs. 1790 and 1791 have brass on the inner array and Al in the outer array, while 1792 and 1793 have Al on the inner array and brass on the outer array.

| Shot# | Wire material outer-on-inner | Diameter (μm) outer-on-inner | Total energy (kJ) | PCD energy (kJ) (>0.8 keV) | Implosion time (ns) |
|---|---|---|---|---|---|
| 1790 | Al-on-brass | 12.7-on-7.6 | 15.0 | 0.34 | 110 |
| 1791 | Al-on-brass | 12.7-on-7.6 | 14.5 | 0.37 | 112 |
| 1792 | Brass-on-Al | 7.6-on-12.7 | 17.5 | 0.38 | 111 |
| 1793 | Brass-on-Al | 7.6-on-12.7 | 17.5 | 0.39 | 118 |

Fig. 2 shows example lineouts of the TISR spectra overlaid with the non-LTE kinetic models of Cu, Zn, Al, and Mg [15] used to derive electron temperatures and densities ($T_e$ and $n_e$). The Cu and Zn models are used for L-shell radiation while the Al and Mg models are used for K-shell radiation. Generally speaking, the Al model is used to model lines that originate from high Rydberg states when the plasma is optically thin, in which case the 5% Mg in the alloy shows virtually no trace of lines. When Mg lines do appear in the spectra, Al is presumed optically thick, and thus the Mg model is used to estimate $T_e$ and $n_e$. The models average over a uniform plasma slab that is used to obtain an escape factor for each transition.

For the Al-on-brass array, the modeling shows that the L-shell Cu and Zn and K-shell Mg had similar electron temperatures, ranging from 320 to 370 eV. Electron density shows a different trend, however. The density for K-shell Mg remains relatively constant at $5 \times 10^{19}$ cm$^{-3}$ while L-shell Cu and Zn ranges from $5 \times 10^{19}$ cm$^{-3}$ near the anode to $5 \times 10^{18}$ cm$^{-3}$ near the cathode, a significant drop in density. For the brass-on-Al array, the electron temperatures for the L-shell Cu and Zn and K-shell Al are again similar, ranging from 310 eV to 380 eV, which is a slightly broader variation than observed for the Al-on-brass array. This variation is also evidenced in the respective pinhole images, which show non-uniformities in emissions for this same photon energy range. The electron densities for the brass-on-Al array range from $1.8 \times 10^{20}$ cm$^{-3}$ to $2 \times 10^{20}$ cm$^{-3}$ for K-shell Al while L-shell Cu and Zn varies from $1 \times 10^{19}$ cm$^{-3}$ near the anode to $5 \times 10^{18}$ cm$^{-3}$ near the cathode. As before, the Cu and Zn density is lower than the Al and Mg density, and decreases along the length of the pinch. For both configurations, the density from L-shell Cu and Zn is similar; however the K-shell Al and Mg density increases by a significant factor when the Al alloy is on the inner array compared to the outer array. Since the K-shell Al and Mg and L-shell Cu and Zn radiate at very similar electron temperatures, it is difficult to spot a clear trend on how $T_e$ changes as a function of initial placement of the alloys. This will be discussed further in Section 5.

While there is no obvious trend in $T_e$ with initial alloy placement, it is clear that the intensity of the radiation is dramatically affected by the initial position of the wires. Analysis of the intensity of spectral lines shows that the ratio of the L-shell Cu/Zn to K-shell Al/Mg increases from 4 to 40 when the configuration changes from Al-on-brass to brass-on-Al, while at the same time the energy derived from the PCD signal, $E_{\mathrm{PCD}}$, gives comparable values. This ratio was estimated by integrating the intensity of the K-shell Al/Mg and L-shell Cu/Zn taken from various lineouts of the spectra and averaged. This result is another indicator of the importance of the material on the outer array in determining the overall emissions from the plasma.