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Radiative properties of implosions of combined X-pinches and planar wire arrays composed from different wire materials on the UNR 1 MA Z-pinch generator

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Abstract

The radiation from implosions of X-pinches and planar wire arrays, which consist of alloyed Al and Mo wires, on the UNR 1MA ZEBRA generator was studied. Combined, planar-loop X-pinches are good surrogate sources for studying radiative properties of Z-pinch plasmas that can be of small size, high density and high temperature as are standard X-pinches. Further, the X-pinches consist of the wires from different materials and can also exhibit distinct radiation properties. In particular, combined X-pinches studied in this work used an Al 5056 (5% Mg) wire in the anode (cathode) loop and a Mo wire in the cathode (anode) loop. Combined planar wire arrays had from 10 to 15 wires arranged in one plane and consisted of the same two wire materials as used in the X-pinches. We find that planar wire arrays radiate significant peak power. Spatially-resolved and spatially integrated X-ray spectral data as well as time integrated pinhole X-ray images were analyzed. Non-LTE kinetic models were applied to study the axial gradients of electron temperatures and densities in these X-pinch and Z-pinch plasmas. Specifically, X-ray spectra of K-shell Al and Mg, and L-shell Mo were modeled. As a result, we discuss the dependence of the plasma spatial structure, temperature, density, and opacity. The importance of using different materials or alloys for Z-pinch plasma diagnostics is illustrated.

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Keywords: X-pinch; Planar wire array; X-ray spectra; Kinetic modeling

1. Introduction

High-z cylindrical wire arrays (such as tungsten wire arrays) have been studied extensively on the 20 MA SNL-Z generator at Sandia National Laboratories (SNL) since 1998 when it was shown that they could reach very high X-ray powers, ~200 TW, and X-ray energies, ~2 MJ [1]. Since then different wire materials (such as Al, Ti, Fe, Mo, W, etc.) as well as different load configurations (such as nested wire arrays) have been investigated at the SNL-Z facility to study implosion dynamics and radiation output for inertial confinement fusion (ICF) and other high-energy density applications (see, for example, Ref. [2] and the references therein). The radiative properties of the loads from two wire materials, Mo (mid-z) and Al (low-z) will be analyzed in this work. Aluminum wire arrays were studied on the various Z-pinch generators including Saturn and Z accelerators at SNL [3–6]. Al K-shell diagnostic in these experiments is challenging because of the opacity effect of the Al plasma and the need to perform sophisticated radiation transport modeling [5–6]. To study opacity issues and to produce opacity-free lines available for K-shell diagnostics, wires are used from the alloy Al 5056, which contains 95% Al and 5% Mg. Recently, radiative properties of Mo wire arrays have been spectroscopically investigated at the SNL-Z to study the axial, radial, and temporal gradients in the plasma [7,8].

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In the present work, two types of the wire loads have been studied, combined X-pinches and planar wire arrays (PWAs). Combined X-pinches are expected to be a good source for studying radiative properties of Z-pinch plasmas of very small sizes (100-μm-scale), high densities and temperatures as are usual for X-pinches but consist of the wires from different materials and hence may express different radiative properties [9,10]. Recently, combined X-pinches with Mo and W wires were studied for the first time and they have shown advantages in their applications for M-shell W diagnostics [11,12]. The combined X-pinches studied in this work had an Al 5056 (5% Mg) wire in the anode (cathode) loop and an Mo wire in a cathode (anode) loop [13]. PWAs are loads that have been shown to radiate the highest peak power and energy in sub-kiloelectron volt and kiloelectron volt of all loads at the 1 MA ZEBRA generator at UNR [14,15]. The combined Mo and Al PWAs had from 10 to 15 wires arranged in a plane where the Mo wires were replaced with two Al 5056 wires either on ends or in the center.

2. Experimental data and their interpretation

Experiments with X-pinches and wire arrays discussed in this paper were performed on Zebra generator with a current of 1 MA and a rise-time of 100 ns at UNR. X-pinches and planar wire arrays were composed of Al 5056 (5% Mg) and Mo wires arranged in the anode–cathode gap of 20 mm. In X-pinch experiments two wires were mounted at the angle of 31° to the central axis and the length of the wires was 23 mm. In planar wire array experiments, the Z-pinch load consisted of several wires (from 10 to 15) mounted in a single linear row with a 1 mm gap at the center of the discharge chamber. The masses of planar wire arrays studied here vary from 93 to 154 μg that was almost an order less than for X-pinches. In the combined Mo and Al planar wire arrays two wires of the primary Mo material (in array center or at periphery) were replaced by Al wires with the similar mass. The combined PWAs with two Al wires at periphery are denoted by Al/Mo/Al whereas with two Al wires at the center are denoted by Mo/Al/Mo. The wire length was 20 mm for all planar wire arrays. The list of the combined Mo and Al loads from X-pinch and PWA experiments analyzed is given in Table 1.

The details of experiments and diagnostics on Zebra can be found in Refs. [9,14,15]. Briefly, time integrated X-ray pinhole images were recorded with the resolution of 220 μm with two different sets of filters that cover the region $\lambda < 10.3$ Å and at $\lambda < 4.4$ Å. In general, we find that in softer X-rays (at $\lambda < 10.3$ Å) the emission region is much larger in size (mm-scale) than in harder X-rays. The source becomes more compact, usually with one or a few distinct hot spots (100-μm-scale) in harder X-rays (at $\lambda < 4.4$ Å) and continues to decrease slightly in size with decreasing wavelength for all experiments. All X-ray spatially-resolved spectra considered in this paper were axially resolved spectra recorded through the 0.5 mm slit on the BIOMAX film by a convex crystal spectrometer with a KAP crystal ($2d = 26.63$ Å) [9,14,15]. This crystal collects both L-shell Mo (3.5–5.3 Å) and K-shell Al and Mg (6.5–9.2 Å). In particular, the strongest and most diagnostically important K-shell lines of Al and Mg are the He-like lines (He-α lines, Al1 and Mg1, respectively; the He-β and He-γ lines, Al3 and Al4, respectively) and H-like lines (Ly-α lines, Al2 and Mg2, respectively). The strongest and most diagnostically important L-shell Mo spectral features are Ne-like lines (3A–3G), F-like (F1) and Na-like (Na1 and Na2) spectral features. The observance of the Al1 and Mg1 lines that are stronger than Al2 and Mg2 would indicate a plasma with the moderate electron temperature T_e of 300–500 eV whereas the observance of the intense L-shell Mo radiation would indicate much hotter plasmas of $T_e \sim 800$–1300 eV. It is more likely that the L-shell Mo may be radiated from the "hottest core" of hot spots or from the cluster of hot spots whereas K-shell Al and Mg lines radiate from the "cooler periphery" of hot spots or the cluster of hot spots, or by a cooler plasma column. So, the softer X-ray image (at $\lambda < 10.3$ Å) is relevant to the K-shell Al and Mg radiation whereas the harder image (at $\lambda < 4.4$ Å) corresponds to the L-shell Mo radiation.

3. Analysis of the spatially-resolved spectra

In Figs. 1–4, we present X-ray axially resolved spectra from the lineouts of the spatially-resolved spectra. Specifically, Fig. 1 shows the Mo/Al X-pinch spectra from six lineouts taken at 17.4 mm (N1), 14.4 mm (N2), 9.2 mm (N3), 8.2 mm (N4), 6.4 mm (N5), and 4.6 mm (N6) from the anode. The first two lineouts closer to the cathode do not have any L-shell Mo radiation but do have the K-shell Al and Mg radiation proving that the Al radiating region almost reached the cathode. The spectrum N1 does not show H-like Mg2 line and has a less intense H-like Al2 line than the spectrum N2, so it radiates from the cooler plasma region. The next three lineouts, N3, N4, and N5 are radiated from the cluster of hot spots at the X-pinch cross point and have strong L-shell Mo radiation. These also show strong Al lines with narrower

Table 1
Configuration, number of wires, composition, wire diameters and masses of X-pinch and Planar Wire Array loads analyzed in this work

Shot No.	Type of load	No. of wires	Wire composition	Wire ϕ (μm)	Mass of load (μg)	Al mass (%)
466	X-pinch	2	Mo/Al	50/99	931	50.5
467	X-pinch	2	Al/Mo	99/50	931	50.5
769	Planar	10	Al/Mo/Al	15/7.62/15	93	20.1
802	Planar	15	Al/Mo/Al	15/7.62/15	140	13.4
803	Planar	14	Mo/Al/Mo	7.9/15/7.9	139	13.5
805	Planar	14	Mo/Al/Mo	7.9/19.8/7.9	154	21.2