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Spectroscopic Study of Al Wire Array Stagnation on Z

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Abstract. The spatial structure and dynamics of a stagnating Al wire array plasma are studied on the Z machine. Radially- and time-resolved spectrometers are employed to study K-shell line emission from Al and a 5% alloyed Mg dopant. The stagnating plasma is modeled as separate concentric radial zones, and collisional-radiative modeling with radiation transport calculations are used to constrain the temperatures and densities in these regions, accounting for K-shell line opacity and Doppler effects. At early times (on the foot of the x-ray pulse), an imploding shell is observed with >50 cm/μs velocity inferred from Doppler splitting. At these times, a dense plasma core forms on axis, bearing 1-2% of the total mass with ~2 keV electron temperature.

Keywords: Wire array z pinch, K-shell x-ray spectra, collisional-radiative, radiation transport
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INTRODUCTION

Spectroscopic study of K-shell x-ray emission can offer great insight into z-pinch stagnation dynamics. The spatial structure of plasma temperature, density, and velocity are encoded within line ratios and shapes. Decoding the spectra requires consideration of the complex interplay of plasma gradients, opacity, and Doppler effects. Together, these effects can shift, broaden, split, or attenuate line emission, challenging the interpretation of spectral features.

Here we report on ongoing analysis of a 40 mm diameter, 1.5 mg/cm nested Al (5% Mg) wire array implosion from the 20 MA, 100 ns Z machine [1]. Radially resolved K-shell spectra were recorded with 1 ns time resolution as shown in Fig. 1(a) using elliptical mica crystal spectrometers [2]. Al and Mg line emission was observed from large radius at early times, with satellite lines and continuum becoming more pronounced near stagnation. Spectra were recorded from the foot of the x-ray pulse through peak K-shell power [Fig. 2(a)], although we focus on the earliest frames here.

The approach that we pursue is to generate synthetic spectra from a model to be compared with the experimental data, iterating on the modeled plasma parameters to achieve a reasonable fit. The model approximates plasma gradients by including a set of concentric shells, with ion density, electron temperature, radial velocity, and an

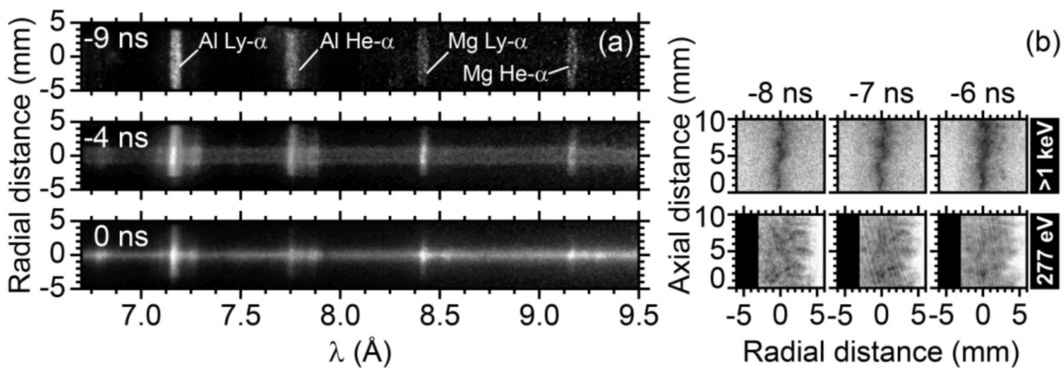

FIGURE 1. (a) Radially-resolved, 1-ns-gated K-shell spectra from shot Z1520. (b) >1 keV broadband K-shell imaging and 277 eV monochromatic imaging. Timing is relative to peak K-shell power.

isotropized velocity component specified in each shell. To simplify the model, only enough zones are defined [Fig. 3(a)] as required to explain key spectral features as will be discussed. The core radius R_1 is based on the core size observed in >1 keV pinhole imaging in Fig. 1(b). The presence of plasma outside of this core is evidenced by 277 eV imaging and by line emission from large radius in Fig. 1(a). We define an intermediate layer R_2-R_3 based on the radial extent observed in the Mg He-α line, which displays Doppler splitting. We also take a halo of plasma extending to the effective current radius R_4 from a circuit inductance analysis [3], found for tungsten wire arrays to be indicative of the outer edge of the radiographed mass profile [4].

Each zone is treated with a time-dependent collisional-radiative kinetic model [5] which relates plasma conditions to ionization state, line emissivities and opacities. The plasma is coupled by solving the equation of radiative transfer through the series of zones, so that the plasma conditions and radiation field are self consistent. This radiative transfer calculation also produces a synthetic spectrum emerging from the edge of the plasma, taking into account opacity in each zone as well as Doppler shifts due to radial motion. Doppler broadening due to an isotropic velocity component which could result from finite ion temperature or gradients in the bulk velocity is also

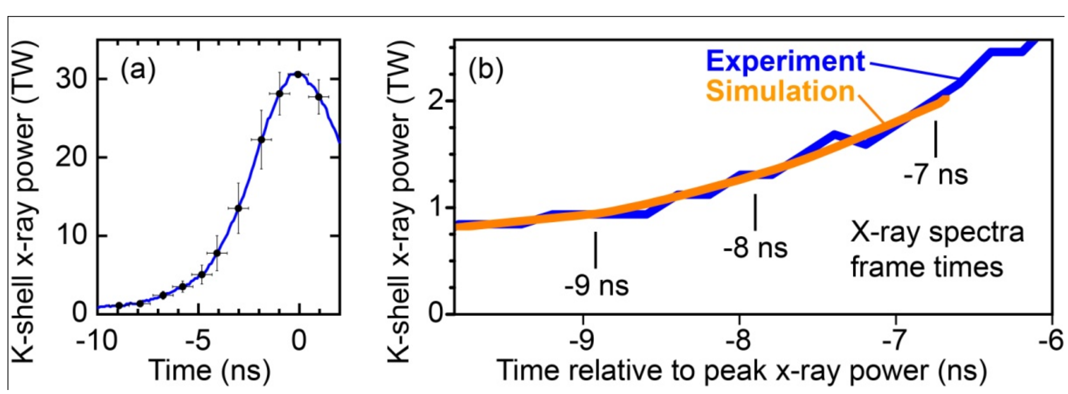

FIGURE 2. (a) Measured K-shell x-ray power (Z1520) with frame timing of spectral data. Error bars indicate ±0.5 ns timing error and associated error in power at that time (note also 30% absolute error). (b) Simulation matches the experimental K-shell power for the few frames at the foot of the x-ray pulse.

required in order to match measured line shapes.

ANALYSIS

We now describe the analysis of the spectrum at the foot of the x-ray pulse (-9 ns) as shown in Fig. 2(b). The Mg He-α line shows Doppler splitting when viewed along a chord passing through the axis [see Fig. 1(a) at -9 ns, and the Fig. 4(b) inset]. This indicates 50-60 cm/μs radial velocity in a shell-like region of emission (R_2-R_3). In contrast, the Mg Ly-α line does not show splitting, suggesting that the core plasma on axis emits this line. Approximately 2 keV electron temperature [Fig. 3(b)] is then required in the core in order to maintain a H-like Mg population with little He-like Mg. The inferred core density of $3x10^{19}$ cm^{-3} is constrained by the >1 keV power [Fig. 2(b)] and spectral features including continuum and satellite lines. Isotropized velocity comparable to the measured implosion velocity is required to broaden the Al lines to agree with the experimental data (Fig. 4).

The intermediate layers are of lower temperature [Fig. 3(b)] and density, constrained by matching the Mg lines (in particular generating Mg He-α preferentially in R_2-R_3) as well as introducing opacity in the Al lines that modifies the line shapes emitted from the core. Temperature drops to <100 eV in the halo, which is mostly He-like Al in the ground state and is required in the model in order to attenuate Al He-α emission to the levels seen in the experiment without perturbing the Al Ly-α line shape. The simulated and measured spectra are compared in Fig. 4 viewed along chords passing through intermediate region (a) and through the core on axis (b). Small differences in line shapes likely indicate that the simplified model has not completely captured gradients in the plasma, which may have finer variations or 3D structure.

The inferred masses present in each zone are calculated and shown in Fig. 3(c) as fractions of the total initial wire array mass. Despite having the highest density, the core region bears only a few percent of the total mass at times corresponding to the foot of the x-ray pulse. Most of the inferred mass is present in the intermediate and halo regions, indicating the presence of a shell of material that is still imploding and likely contains most of the current. The hot core plasma observed may be the leading

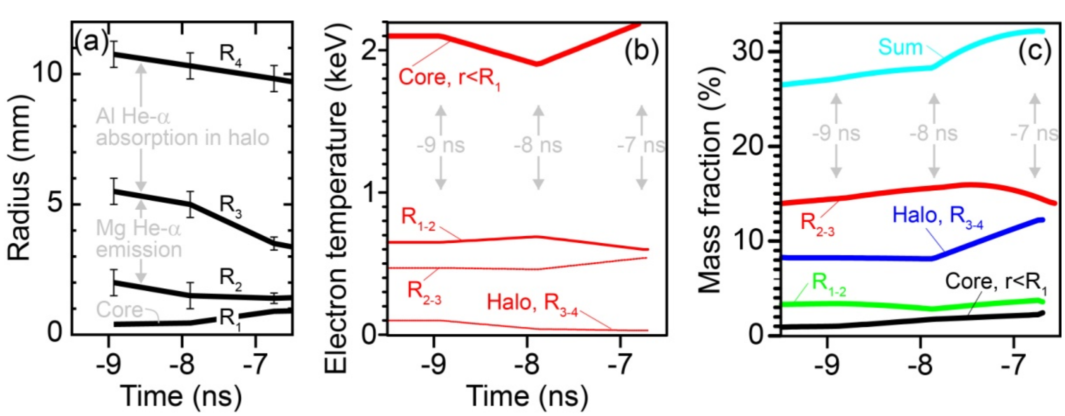

FIGURE 3. (a) Radial zones R_1-R_4used in the plasma model. Inferred electron temperature (b), and fraction of the total initial wire array mass (c) in each zone. Arrows indicate timing of gated spectra.

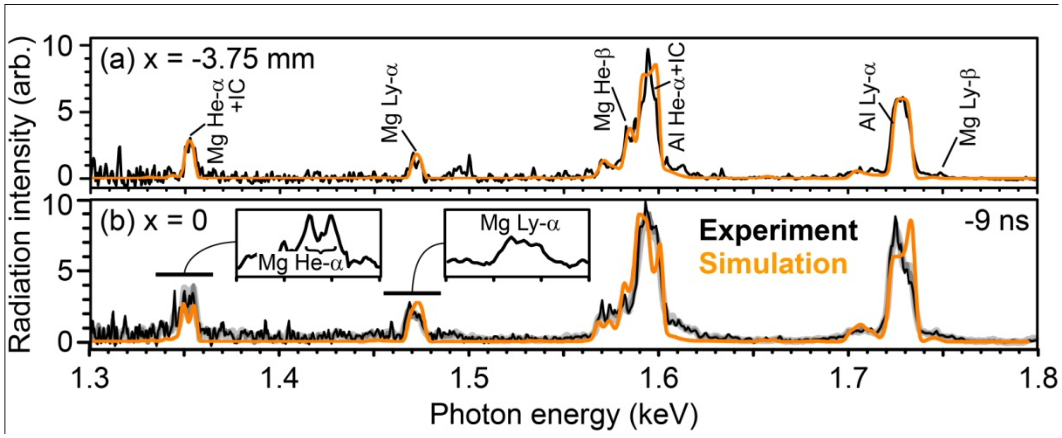

FIGURE 4. Comparison of experimental and modeled spectra at -9 ns relative to peak x-ray power along a chordal view through the intermediate zone (a) as well as through the core plasma on axis (b).

edge of this shell as it begins the process of stagnating on axis and generating K-shell x-rays. The model does not account for all of the mass; some trailing material could be too cold to participate in K-shell radiation generation and transfer.

DISCUSSION

Future work will extend this analysis to the later frames approaching peak K-shell x-ray power. We will also perform a sensitivity analysis in order to assign quantitative error bars to the plasma parameters inferred. Although we motivated the number and dimensions of concentric zones on physical observations, the model does not strictly give a unique solution. We believe, however, that this approach does offer valuable insight into spatial structure and radiative processes occurring during z-pinch stagnation. For example, we expect to be robust the inferences of a hot, low-mass initial core and of a cold halo absorbing He-like K-shell emission. A complementary approach that we also expect to provide insight is to compare simulated spectra from post-processing of MHD implosion models directly to the measured spectra.

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