K-shell and extreme ultraviolet spectroscopic signatures
of structured Ar puff Z-pinch loads with high K-shell x-ray yield

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I. INTRODUCTION

Structured 12-cm-diam Ar gas-puff loads have recently produced Z-pinch implosions with reduced Rayleigh-Taylor instability growth and increased K-shell x-ray yield [H. Sze, J. Banister, B. H. Failor, J. S. Levine, N. Qi, A. L. Velikovich, J. Davis, D. Lojewski, and P. Sincerny, Phys. Rev. Lett. 95, 105001 (2005)]. To better understand the dynamics of these loads, we have measured the extreme ultraviolet (XUV) emission resolved radially, spectrally, and axially. Radial measurements indicate a compressed diameter of ≈3 mm, consistent with the observed load inductance change and an imploded-mass consisting of a ≈1.5-mm-diam, hot, K-shell-emitting core and a cooler surrounding blanket. Spectral measurements indicate that, if the load is insufficiently heated, then radiation from the core will rapidly photoheat the outer blanket, producing a strong increase in XUV emission. Also, adding a massive center jet (≥20% of load mass) increases the rise and fall times of the XUV emission to ≥40 ns, consistent with a more adiabatic compression and heating of the load. Axial measurements show that, despite differences in the XUV and K-shell emission time histories, the K-shell x-ray yield is insensitive to axial variations in load mass. © 2007 American Institute of Physics. [DOI: 10.1063/1.2426919]
II. EXPERIMENTAL SETUP

The experimental configuration consists of an initial gas puff driven by a high-power, pulsed electrical generator. The gas puff nozzle has a center jet 0.5 cm in radius surrounded by two concentric annular shells, an inner shell 2–3 cm in radius and an outer shell 5–6 cm in radius. All three nozzle components have separate plenums, whose pressures can be independently varied to produce four basic configurations (the measured µg/cm, with an estimated uncertainty of 10%, at 2 cm from the nozzle is given in brackets for each configuration for the shots discussed below, the same load mass was used for all shots of the same configuration): “inner-outer” (with no center jet) [117], “jet-outer” [135], “jet-inner” [104], and “jet-inner-outer” [140]. Examples of the radial profiles of initial gas density are shown in Fig. 1; a complete discussion of the four different profiles has been given elsewhere previously.1,2 These density profiles were measured using laser-induced fluorescence of an acetone-seeded argon gas puff.7,8 The peak gas densities are in the $10^{16} - 10^{17}$ atoms/cm$^3$ range and the flow velocity of the gas is 650±20 m/s. Energy released by argon condensation increases the measured flow velocity above that expected for a gas at room temperature.8

The gas puff is positioned in the load region of a high-power, pulsed electrical generator. The cathode plane is formed by a high-transparency brass mesh located at the exit of the nozzle and the anode plane is formed by a web of Nichrome or aluminum wires located 3.8 cm from the cathode. The anode wires are attached to 12 posts located at a radius of 7.8 cm, which form the current return structure. Diagnostics view the argon Z-pinch emission through the gaps between the 12 posts. The pulse generator is fired ~500 µs after a breakdown signal from a spark gap located in the nozzle throat. Using a massive (i.e., nonimploding) load with constant inductance, the current rises to a peak of ~4 MA in ~200 ns.

Measurements from the Z-pinch experiment include the current flowing through the load and the radiation emitted both in the argon K-shell and the XUV. In addition, an active laser tracks the imploding plasma using shearing interferometry9 and laser wavefront analysis;10 the results of those measurements are discussed elsewhere.11 The load current is measured by a Rogowski coil mounted on the anode feed just outside the current return posts array. The time history of the spatially integrated K-shell emission was measured using filtered aluminum x-ray diodes (XRDs), while the axially resolved emission was imaged with a slit onto an array of filtered silicon photodiodes to provide time-resolved K-shell zipper12 data. The implosion time, defined as the time from the onset of current to the onset of K-shell emission, depends on the gas puff mass. The load current and XRD traces for a pair of shots that will be discussed in detail below are shown in Fig. 1(b). The time-integrated K-shell diagnostics include a set of Ta foil calorimeters for measuring the K-shell yield, a charge-coupled device (CCD) pinhole camera, and a CCD spectrograph.3 The spectrograph has a slit which spatially resolves the pinch emission in the axial direction. The XUV diagnostic also employs a slit to image the source emission either radially or axially, and a grating disperses the emission spectrally.5 Both the positive and negative first order spectra produced by the grating can be measured. A CCD camera captures the time-integrated, positive order spectrum in the range 0.1 keV < E < 1 keV as a function of radial or axial position. A photodiode array, which can be positioned anywhere in the 0.1 keV < E < 1 keV range of the negative order spectrum, records the time variation of either the radial or the axial emission profile corresponding to a relatively narrow spectral range (which corresponds to the 1 mm width of the array). When operating in the radially resolving mode, a grazing incidence

![Graph](https://via.placeholder.com/150)

**FIG. 1.** (Color) (a) Relative gas puff areal density (density times radius) as a function of radius at a distance of 2 cm from the cathode/nozzle for inner-outer (I-O), jet-inner-outer (J-I-O), jet-outer (J-O), and jet-inner (J-I) configurations. The plotted radial I-O profile is for the L-3 communications nozzle, 120 µg/cm load mass, which should not differ significantly from the profile of the Alameda Applied Sciences Corporation (AASC) I-O nozzle, 117 µg/cm. The XUV radially resolved data shown in Figs. 2 and 3 were produced by the AASC I-O nozzle. The estimated load mass uncertainties are 10%. (b) Current (in MA) and K-shell power for shots 5862 (jet-inner-outer) and 5864 (jet-outer). The K-shell power waveforms were normalized to the same integral for ease of viewing; calorimeter measurements of K-shell x-ray yields were 20.2 kJ (with inner) and 6.4 kJ (no inner).
gold mirror is inserted between the pinch and the spectrometer to limit the axial extent of the pinch sampled to $\approx 3$ mm. A time-resolved spectrum with relatively coarse energy bins (10 channels between 0.1 and 1.1 keV) can be obtained while in this orientation by rotating the photodiode array $90^\circ$ and removing the radial imaging slit. A detailed discussion of the $K$-shell and XUV images and spectra is presented in the following sections.

XUV diagnostics using film to record the experimental data have been fielded in the past to provide time-resolved images$^{13}$ and spectra. Because the data we will describe here were recorded electronically, they are available for analysis immediately following a shot. In the radially resolving configuration this diagnostic will allow us to track the radius of the pinch mass that is compressed and heated but that does not get hot enough to radiate at $K$-shell wavelengths. The radius of the cooler mass is difficult to measure by other means, such as laser interferometry, because of the steep density gradients and inhomogeneities that result from the growth and saturation of fluid instabilities.$^{14}$ In the axially resolving configuration, the XUV profile can be directly compared with the $K$-shell images and spectra.

III. AXIALLY LOCALIZED MEASUREMENTS

The initial XUV measurements were made with a gold mirror inserted between the spectrometer and the Z-pinch to view only a $\approx 3$ mm axial section of the pinch. The first series of measurements were performed in the radially resolved configuration to determine the diameter of the XUV emission. Assuming that all of the Ar mass is heated sufficiently to radiate in this energy band, the observed diameter should be the diameter of the total mass collected and compressed by the load current. In fact, the observed diameter of $\approx 3$ mm is indeed consistent with inductance estimates of the final load current radius. The second series of measurements were performed in the time-resolved configuration; the radial slit was removed, so the spectra were all radially integrated. The time history and time-integrated signals for these spectral measurements depended strongly on the load type. In particular, the higher-gas-density loads had an earlier onset of XUV emission, produced a large increase of emission at the time of $K$-shell emission onset, and had a much higher time-integrated XUV signal. Descriptions of these measurements are given in the following sections.

A. Radially resolved spectra

Time-integrated emission diameters were determined from radially resolved spectra recorded with a CCD camera and time-resolved emission diameters were obtained by placing a photodiode at an appropriate location (i.e., energy bin) in the spectral dispersion plane of the spectrometer. Figure 2(a) shows a time-integrated, radially resolved spectrum in which both the positive and negative orders can be seen. The spectrometer sampled an axial region $1.8-2.2$ cm from the cathode (nozzle exit) due to the limited length of the grazing incidence gold mirror described above. By integrating in radius and compensating for the grating and mirror responses,$^5$ the spectrum [shown in Fig. 2(b)] is obtained. There is reasonably good agreement between the spectral locations and amplitudes of the Ar $L$-shell emission bands predicted by calculations and those observed experimentally. To determine the dependence of the pinch emission diameter on photon energy, the spectrum was averaged over the energy bands indicated, and the resulting radial data were fitted to Gaussian profiles. The fitted FWHM diameters for two shots are shown plotted versus emission energy in Fig. 2(c). The diameters for the 280 eV and 520 eV bands are the largest and comparable, while the $K$-shell emission diameter is the smallest; the 720 eV emission diameter is intermediate to these two. For the discussion that follows we assume that the diameter of the 520 eV or 280 eV emission corresponds to the diameter of the total puff mass that is captured and compressed by the load current.

For the time-resolved measurement of the emission diameter, a photodiode array was brought into the 520 eV location in the spectral dispersion plane. The location of the photodiode array was confirmed by the shadow it cast on the CCD camera. An example of the time-resolved data is shown in Fig. 3. By fitting the radial profile at the time of peak emission, the diameters given in the table was obtained. For this series of nominally identical shots, the average values for the XUV and $K$-shell FWHM diameters were $2.8 \pm 0.7$ mm and $1.3 \pm 0.1$ mm, respectively. The XUV diameter agrees with the value found for the time-integrated measurement shown in Fig. 2(c), because the time-integrated image is dominated by the signal produced at the time of peak emission. These XUV FWHM values are consistent with inductance estimates of the minimum load current diameter. The measured change in inductance implies a convergence ratio of 40, which in turn implies a 3 mm final load current diameter for an initial diameter of 12 cm.

B. Time-resolved spectra

In order to better understand the interplay between XUV and $K$ emission, we reconfigured the spectrometer to obtain time-resolved spectra. By removing the radially resolving slit and rotating the photodiode array $90^\circ$, we obtained a time-resolved, radially averaged spectrum originating from a 3–4 mm axial length of the pinch. The energy resolution was relatively coarse, 10 bins in the range from...
Because some of the shots in the series were taken for a pinch length of only 2 cm (in contrast to the typical 3.8 cm), the spectrometer was aligned to an axial location 1 cm from the cathode nozzle exit.

During this test series, the 12-cm-diam, triple-plenum nozzle was run in three different load configurations: jet-outer, jet-inner-outer, and jet-inner. To maintain the same implosion time, the density of the gas puff was varied from relatively low for the jet-outer to relatively high for the jet-inner. As shown in Fig. 4, the K-shell emission images were very different from each other. The jet-outer load produced a diffuse radial profile with some narrow axial regions of intense emission (high density spots), while the jet-inner-outer emission was fairly uniform axially. The jet-inner load gave the smallest emission diameters and an axial profile that was strongly peaked near the cathode.

The XUV emission for the jet-inner load also differed

<table>
<thead>
<tr>
<th>Shot Number (all i-o loads)</th>
<th>XUV FWHM (mm)</th>
<th>K FWHM (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5421</td>
<td>3.5</td>
<td>1.2</td>
</tr>
<tr>
<td>5422</td>
<td>2.2</td>
<td>1.2</td>
</tr>
<tr>
<td>5423</td>
<td>2.8</td>
<td>1.3</td>
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<tr>
<td>5431</td>
<td>3.6</td>
<td>1.4</td>
</tr>
<tr>
<td>5432</td>
<td>2.1</td>
<td>1.5</td>
</tr>
<tr>
<td>Ave.</td>
<td>2.8 ±0.7</td>
<td>1.3 ±0.1</td>
</tr>
</tbody>
</table>

FIG. 3. Time-resolved radial profiles were obtained in the 520 eV energy bin. Time and radially resolved UV image shown was obtained from the photodiode array. The tabulated XUV diameters correspond to the time of peak XUV emission and a photon energy of ≈520 eV. K-shell diameters are from the time-integrated pinhole camera images at a distance of 1.8–2.2 cm from the cathode.

FIG. 4. (Color) (a) K-shell pinhole camera images for jet-outer (5558), jet-inner-outer (5556), and jet-inner (5560) shots. The color table is scaled to the peak value of each image. The smallest K-shell emitting diameter shot (jet-inner) has the highest XUV emission measured at $E \approx 200$ eV. (b) Axial profile of time integrated K-shell emission. Data points indicate the location of the XUV measurements and the value of the K-shell yield per unit length at that location.
strongly from the other loads, as shown in Fig. 5. For the jet-inner loads, the XUV emission was comparable to the other two loads up to the onset of K-shell emission. After that time, the XUV emission increased sharply, which is consistent with rapid photoheating of the cool outer blanket for jet-inner loads. This effect is seen most strongly in the 200 eV channel, but also in the 500 eV channel somewhat wider than the 520 eV channel described in the preceding section. Because the jet-inner load has the smallest initial radius, its initial jet mass density is the highest (30% higher than the jet-inner-outer loads), and it takes more time to heat and ionize. Integrating the traces in time, we see that the total signals in the 200 eV channel show a large increase for the jet-inner case, as shown in Fig. 5(c). The data indicate that the jet-inner-outer load produces strong K-shell emission with lower XUV emission than for jet-inner loads. Thus, jet-inner-outer loads are preferred for experiments that require high K-shell x-ray yields while minimizing XUV emission.

The time-resolved XUV measurements also shed light on the role of the center jet in the pinch dynamics. As shown in Fig. 5 for all load configurations with a center jet, the XUV emission starts 40–50 ns before the onset of K-shell emission. However, Fig. 6 indicates that the rise and fall of the XUV emission is more abrupt for a load without a central jet. Thus, the addition of a massive center jet appears to make the heating and cooling of the gas puff load more quasiadiabatic. In other words, the imploding plasma sheath formed from the inner and outer shells does compressive work on the center jet, rather than further shock heating the sheath itself as it stagnates on axis in the absence of a center jet.

In summary, these time-resolved XUV spectral measurements have shown that the addition of a massive jet increases the rise and fall times of the XUV emission, and that the XUV emission does not rapidly increase at the time of K-shell emission for efficient K-shell radiating loads.

IV. AXIALLY RESOLVED MEASUREMENTS

In this section we present new axially resolved XUV measurements and discuss the observed correlations between the XUV and K-shell emissions. These measurements extend those of Sec. III, which were made at a single axial location. The results we will discuss are from a series of four sequential shots, for which the peak load current was 3.40±0.15 MA and the implosion time (measured from the onset of current to onset of K-shell emission) was 207±9 ns. The first two shots (5862 and 5863) used the jet-inner-outer load configuration, while the last two shots (5864 and 5865) used the jet-outer load configuration (no inner shell). Figure 1 shows the radial gas profiles and current and K-shell XRD waveforms for two of the shots.

A. Measurements

The use of an inner shell increases both the K-shell and XUV emissions from the pinch. Figure 7 shows time- and space-resolved (“zipper”) data from all four shots; the color
scale for each image is normalized to its respective peak intensity. For one shot without an inner shell (5864) the K-shell emission is barely detectable above the noise. For the other three shots, we can plot the time histories that are offset from each other according to the axial location of the emission measured from the cathode; see Fig. 8. Although the no-inner-shell shot 5865 shows a small, intense spot close to the cathode, an integral over the entire axial length clearly shows an increase in both XUV and K-shell emission with the use of the inner shell. Finally, the time-integrated CCD pinhole camera and spectrograph data of Fig. 9 confirm the increase in emission when the inner shell is used.

We can further analyze the time-integrated data of Fig. 9 to produce the axial profiles shown in Fig. 10 for two shots with an inner shell (5862 and 5863) and one shot without it (5865). The axial profile of XUV emission [Fig. 10(a)] is obtained from the relative CCD camera signal of the axially resolved XUV spectrometer. The axial profile of the K-shell emission [Fig. 10(b)] is the sum of the He-α, intercombination (IC), and Ly-α lines from the time-integrated CCD spectrograph normalized to the calorimeter measurement. In gen-

FIG. 7. (Color) The K and XUV (~500 eV) emission vs space and time (zipper) data. The color scale is individually normalized to the peak intensity for each image. The peak and half-maximum points for K-shell emission are superimposed in black or white.

FIG. 8. (Color) Overlays of XUV (red) and K-shell (blue) emission at different distances from the cathode (nozzle exit) vary with load type. Shots 5862 and 5863 have an inner shell while shot 5865 does not. The relative vertical scale is the same for all three shots. Also, the K-shell data have been interpolated on the XUV spatial locations.
eral, the XUV emission is seen to extend further toward both the cathode and anode than the K-shell emission. This is consistent with cold material being injected into the plasma from solid material at those locations. The material would increase the density of the plasma and lower its temperature. Apparently the electron temperature near these solid surfaces is sufficient for XUV emission but not for the K-shell. Similar quenching of the K-shell emission near a solid surface has

![Image](image-url)

**FIG. 9.** (Color) CCD-based K-shell pinhole camera images and spectra and XUV spectra. The color scale is the same for all shots within each type of image or spectrum. The notch in the XUV spectrum at 280 eV is caused by a 2.1-μm-thick Kimfoil filter.

**FIG. 10.** (Color) Measured axial profiles for shots 5862 (black) and 5863 (red) with an inner shell and shot 5865 (green) with no inner shell. (a) XUV emission in the band centered at 510±40 eV given by the relative CCD camera signal, (b) K-shell emission in kJ/cm from the sum of He-α, intercombination (IC), and Ly-α lines measured by the CCD spectrograph and normalized to calorimeter measurement, (c) K-shell FWHM diameter measured by the CCD pinhole camera, and (d) ratio of Ar Ly-α to (He-α+IC line) measured by CCD spectrograph.
been seen in Ni wire array experiments.\textsuperscript{15} The axial profiles of the pinch diameter [Fig. 10(c)] and the Ly-\(\text{a}/(\text{He-}\text{a} +\text{IC})\) line ratio [Fig. 10(d)] can be found from the CCD data for the time-integrated \(K\)-shell pinhole camera and spectrometer, respectively.

The time-integrals of the \(K\)-shell and XUV zipper data from Fig. 7 are consistent with the radial integrals of CCD data from the pinhole images and spectral integrals of the CCD spectra of Fig. 9, although there is closer agreement within the CCD-based diagnostics of Fig. 9. There is an inconsistency very close to the cathode, which is especially apparent on shot 5865, where the CCD XUV spectrum (Fig. 9) shows an intense spot that is missing from the XUV zipper (Fig. 7). This is likely due to the fact that the XUV zipper line of sight to the pinch is obscured at that axial location, but it may also be the result of emission that occurs outside the time-integration window of the XUV zipper.

There are striking differences between jet-inner-outer and jet-inner shots, but there are also measurable differences between shots with the same load configuration, i.e., nozzle and gas puff plenum settings. For example, the two jet-inner shots (5864 and 5865) had comparable \(K\)-shell yields (6.4 and 4.9 kJ, respectively) and both shots had a region of intense emission at the cathode. However, the emission for shot 5864 also extended over a broad axial extent, while the emission for 5865 was limited to the cathode region (see Fig. 9). The measured \(K\)-shell yields for the two jet-inner-outer shots were very close (20.2 and 20.9 kJ, respectively), but the pinch diameters and line ratios showed clear differences, especially at locations further than 2 cm from the cathode (see Fig. 9). In that region the \(K\)-shell pinch diameter for shot 5863 increased above the value measured for shot 5862, while the line ratio for shot 5863 decreased. The following section discusses how these differences in the measured pinch parameters (e.g., diameter and line ratio) translate into differences in plasma conditions (e.g., density and temperature).

### B. Discussion

Given a set of measured \(K\)-shell plasma parameters, namely the pinch diameter, \(\text{La-}\text{a}/(\text{He-}\text{a} +\text{IC})\) line ratio, and emitted power, the plasma ion density, electron temperature, and \(K\)-shell-emitting mass can be estimated as a function of axial position.\textsuperscript{4,16} The pinch diameter is found directly from the CCD pinhole image and the line ratio is found from the CCD spectrum; see Fig. 10. Emitted power is found by dividing the \(K\)-emission profile (determined from either the pinhole image or the \(K\)-shell spectrum normalized to the Ta foil calorimeter yield) by the local radiated pulse width (found from the \(K\)-shell zipper data). The plasma conditions calculated in this manner for the three shots discussed above are shown in Fig. 11.

Without an inner shell, the \(K\)-shell performance of the pinch was not reproducible because of instability growth in the imploding plasma.\textsuperscript{11} Of the “no inner” shots, only 5865 was analyzed because the \(K\)-shell zipper data was in the noise for the other shot and a local pulse width could not be determined. For shot 5865, at locations greater than 1 cm from the cathode/nozzle the signals measured were at the noise level and the results plotted are strictly upper bounds. Within 1 cm of the cathode, the ion density [Fig. 11(a)] and \(K\)-shell-emitting mass [Fig. 11(b)] are comparable to that found for the shots with inner shells [Fig. 11(a)]. The peak electron temperature [Fig. 11(c)] is somewhat higher, 2.1 keV versus 1.9 keV. This increased temperature may be beneficial for some applications if it can be reproduced consistently.

For the two shots with an inner shell, measurements indicate that one load was more massive, i.e., the gas puff density was higher, than the other even though the gas puffs...
were set to be identical and the calorimeter measurements of the yield were nominally equivalent (20.2 kJ for shot 5862 and 20.9 kJ for shot 5863). Given that the implosion time scales as the square root of load mass, the measured implosion times of 216 ns and 209 ns for shots 5862 and 5863, respectively, would imply a 7% mass increase for shot 5862. A difference in load mass is possible, since two nozzles were being used alternately to reduce the facility shot turnaround time. A difference in manufacturing or nozzle erosion would produce a mass difference. There were no major differences in the electron temperature, $T_e$, profiles for these two shots. In both cases $T_e$ was highest, 1.9–2.0 keV, near the mid-plane of the pinch (i.e., 2 cm from the cathode/nozzle) and lowest near the wire mesh and wire grid defined the cathode and anode planes, respectively.

The time history of the XUV emission provides additional evidence for higher collected and compressed mass on shot 5862. Figure 8 shows differences between the two shots especially at axially locations more than 2 cm from the cathode, i.e., 2.05, 2.60, and 3.15 cm from the cathode. At these locations there is a sharp increase in the XUV after the initiation of K-shell emission for shot 5862, while for shot 5863 the XUV emission has already begun to decay and continues to do so during the time of K-shell emission. Comparing these XUV histories to those of Fig. 5, we find that shot 5862 is more similar to the higher-mass jet-inner load discussed previously. One possible explanation for a difference in the mass collected and compressed by the current would be a difference in the radial current flow, i.e., the way that electrons emitted from the nozzle, which is at the negative cathode potential, reach the current return posts, which are at ground (the anode potential). The closer to the nozzle the radial current flow connects to the current return posts, the greater will be the load mass that is collected and compressed by the current. Consistent with this picture, the radial current for 5862 connected to the return posts nearer to the cathode than did the radial current for 5863.

The axial profiles of plasma conditions in Fig. 11 suggest that the extra mass of shot 5862 lies in a cooler outer blanket. This explanation is consistent with a higher ion density, smaller K-shell emitting diameter, and lower K-shell-emitting mass that are seen for shot 5862. If the initial mass density is higher and the compression ratio is maintained, then a higher ion density will be achieved. For shot 5862 the ion density measured at locations more than 2 cm away from the cathode is about a factor of 2 higher compared to the 7% increase implied by simply scaling from the implosion time. To obtain the higher K-shell emitting ion density, there must be less heating of the gas on axis that would otherwise reduce the final compression. The smaller K-shell-radiating mass and K-shell diameter (Fig. 10[1]) at more than 2 cm from the cathode indicate that much of the mass here has not been sufficiently heated, i.e., that it lies in a cooler outer blanket.

In summary, the K-shell and XUV emissions are not reproducible either in magnitude or spatial distribution without the inner shell for stabilization. With an inner shell the emission profiles are much more similar, but there are some differences for two shots with the same nominal gas puff load.

A number of measurements, including the time history of the XUV emission, indicate that one of the loads was more massive than the other. The primary effect of the additional mass was to increase the XUV emission and reduce the K-shell emission at axial locations $\geq$ 3 cm from the cathode. For some applications, increased XUV emission is undesirable and it makes sense to run with a less massive load while maintaining the same level of K-shell emission. The reproducibility of the Z-pin$\pi$ K-shell x-ray yield appears to be fairly robust to small axial variations in the load mass—a very desirable characteristic for applications of this x-ray source.

V. CONCLUSION

The XUV measurements reported here have enhanced our understanding of gas puff Z-pin$\pi$ dynamics. From a series of shots taken on a 4 MA current generator, radial imaging of our 12-cm-diam gas puff loads indicates that the XUV emitting diameter is fairly constant at 2.8±0.7 mm for photon energies up to $\approx$600 eV. The measured diameter decreases at higher photon energies and has a value of 1.3±0.1 mm at argon K-shell energies ($\approx$3.2 keV). The 2.8-mm-diam for the compressed gas puff mass, corresponding to a compression ratio of $\approx$40, is consistent with the 3 mm minimum load current diameter value found from the change in load inductance. These measurements are consistent with the radiator-stabilizer-pusher model of the jet-inner-outer gas puff described by Sze et al.1 in which the jet mass is heated and radiates in the K-shell, while the inner and outer shells remain cooler and produce much less K-shell radiation. Indeed, measurements of Cl dopant K-shell emission reported by Levine et al.2 indicate that most of the Ar K-shell emission is produced by mass that originated in the center jet (65%), followed by the inner shell (30%) and the outer shell (5%). Given the load mass distribution (center jet 20%, inner 40%, and outer 40%), the relative K-shell yield per unit mass for the inner and outer were only 23% and 4%, respectively, compared to the center jet.

Time-resolved spectral measurements show that when the gas puff density is sufficiently high, the time history of the XUV emission changes dramatically. This behavior was seen for measurements made at a single axial location and at multiple axial locations simultaneously. For lower initial gas densities, the XUV emission rises over a period of $\approx$50 ns before K emission begins and then monotonically decreases in a reversible or quasiadiabatic fashion. For higher initial gas densities there is the same initial rise in emission, but, at the time K-shell emission begins, a rapid ($\approx$10 ns) rise in the XUV emission occurs due to rapid photoheating of the cooler outer blanket—an irreversible or nonadiabatic process. Total XUV emission is enhanced by a factor of up to 3. The changes in XUV behavior are correlated with changes in K-shell x-ray measurements. Axial locations with high XUV radiated powers typically have smaller K-shell emission diameters (consider the differences between shots 5862 and 5863 shown in Figs. 7, 8, and 10).

Axially resolved measurements reveal differences not only between load types (e.g., jet-inner-outer and jet-outer)
but also between shots with the same load configuration (e.g., both jet-inner-outer). We showed that two jet-inner-outer shots with nearly the same \(K\)-shell yield of \(\approx 20 \text{ kJ}\) had measurably different XUV signatures consistent with one shot having a slightly higher gas density. Interestingly, the plasma densities for the two shots agreed well up to a distance of \(\approx 2 \text{ cm}\) from the cathode, where laser shearing interferometry shows a change in slope of the sheath radius versus \(Z\).\(^1\) If there is radial current flow connecting to the sheath radius of the plasma densities for the two shots agreed well up to a distance of \(\approx 2 \text{ cm}\) from the cathode, where laser shearing interferometry shows a change in slope of the sheath radius versus \(Z\).\(^1\) If there is radial current flow connecting to the current return posts at a particular axial location, then, at larger axial distances from the nozzle/cathode, the compression of the gas will be modified. Despite the apparent differences in initial gas profiles, XUV time histories, and compressed densities, the \(K\)-shell output remarkably showed very little change.

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\(^11\)In this case “zipper” refers to nonsimultaneous \(K\)-emission at different axial locations. For example, the \(K\)-emission may occur first near the cathode and then move or “zipper” toward the anode.