Magnetic Rayleigh-Taylor instability mitigation and efficient radiation production in gas puff Z-pinch implosions

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(Received 3 November 2006; accepted 20 November 2006; published online 26 April 2007)

Large radius Z-pinch plasmas are inherently susceptible to the magnetic Rayleigh-Taylor (RT) instability because of their relatively long acceleration path. This has been reflected in a significant reduction of the argon K-shell yield as was observed when the diameter of the load was increased from 2.5 to > 4 cm. Recently, an approach was demonstrated to overcome the challenge with a structured gas puff load that mitigates the RT instability, enhances the energy coupling, and leads to a high compression, high yield Z-pinch. The novel load consists of a “pusher,” outer region plasma that carries the current and couples energy from the driver, a “stabilizer,” inner region plasma that mitigates the RT growth, and a “radiator,” high-density center jet plasma that is heated and compressed to radiate. In 3.5-MA, 200-ns, 12-cm initial diameter implosions, the Ar K-shell yield has increased by a factor of 2, to 21 kJ, matching the yields obtained on the same accelerator with 100-ns, 2.5-cm-diam implosions. Further tests of such structured Ar gas load on ~6 MA, 200-ns accelerators have achieved >80 kJ. From laser diagnostics and measurements of the K-shell and extreme ultraviolet emission, initial gas distribution and implosion trajectories were obtained, illustrating the RT suppression and stabilization of the imploding plasma, and identifying the radiation source region in a structured gas puff load. Magnetohydrodynamic simulations, started from actual initial density profiles, reproduce many features of the measurements both qualitatively and quantitatively.

I. INTRODUCTION

Dense Z-pinch plasmas are intense, energy-efficient laboratory sources of x rays with photon energy ranging from hundreds of eV to several keV. For decades, it was widely believed that large-radius, long-time implosions would be inherently inferior to short implosions because of the longer acceleration path for Rayleigh-Taylor (RT) instability growth. This conventional wisdom has recently been overturned. Using a novel structured load, it has been demonstrated that 200-ns implosions from a 12-cm-diam gas puff load match the x-ray yield obtained with 100-ns implosions on the same electrical driver. This is an important milestone because successful long implosions provide better energy coupling between the driver and the load, reduce the output voltage requirement of the electrical driver, and facilitate the practicality and lower cost offered by slower pulsed power technology. Short-time implosions may also benefit from the structured load profiles described in this paper, and reestablish “conventional wisdom.” However, since their performance is degraded less than long-time implosions by the RT instability, there may be less room for improvement.

The expectation, based on earlier experiments, has been that the K-shell yield for any particular element decreases with implosion time, or equivalently, with the diameter of the load as a consequence of the RT instability. The linear growth rate of the RT instability is $\sqrt{gk}$, where $g = R_0/\tau^2$ is the acceleration of the load, $k$ is the RT wave number, $R_0$ is the load radius, and $\tau$ is the implosion time. The number of e-foldings during acceleration thus scales as $\sqrt{gk}\tau \approx \sqrt{kR_0}$, implying diminishing performance with increasing initial plasma radius or implosion time when $R_0$ and $\tau$ are scaled together. A second concern that leads to a similar expectation is based on implosion and radiation energetics. To strip the ions to a He-like state for producing K-shell photons, the kinetic energy, $m_i\nu^2/2$, must exceed a threshold energy, $E_I$, by a factor $\eta = m_i\nu^2/2E_I$ of 2 to 5, where $m_i$ is the ion mass and $\nu = R_0/\tau$ is the ion implosion velocity. For a given peak current, $I_m$, and implosion velocity, the total load mass $\mu = (I_m\tau/R_0)^2$ is constant. The K-shell yield, $Y_K$, scales as $Y_K \approx \pi R_0^2 \tau n_i^2 \tau$, where $R_f = a R_0$ is the pinch radius, $n_i = \mu/(\pi R_0^2 m_i)$ is the ion density at stagnation, and $\tau_\epsilon = R_f/\nu$ is the radiation or confinement time. Putting these together, and assuming that the RT instability can be finessed to maintain a constant compression ratio, $\alpha$, as $R_0$ and $\tau$ increase, the yield still scales as $Y_K \approx 1/R_0 \approx 1/\tau$.

Against these expectations, the results reported for the 12-cm-diam load are remarkable not just in comparison with previous large diameter nozzle results (double the x-ray yield), but also in comparison with smaller diameter nozzles.
employed on Double-EAGLE,9 the K-shell yield reported here equals or exceeds the K-shell radiation produced at this current level in short pulse (~100 ns) experiments.8 This demonstrates that it is possible to remove the long implosion time penalty.

In this paper, we compare various initial load density profiles that produced either stable, high K-shell yield implosions or less stable, lower K-shell yield implosions in Sec. II. It follows with the numerical simulations of the implosion in Sec. III and diagnostic measurements and current scaling results of the highest yield profile at 3–6 MA current level in Sec. IV. In Sec. V, we summarize the results.

II. LOAD PROFILES

Figure 1 shows the Z-pinch load, which consists of three concentric gas puffs. At the cathode, the outer shell gas, (1), extends nominally from 5 to 6 cm in radius; the inner shell gas, (2), extends from 2 to 3 cm in radius; and the center jet gas, (3), is 0.5 cm in radius. Adjusting the pressures in each plenum changes the initial mass distribution of the load. The three independent plenums further provide the opportunity to seed a dopant (Cl, in the form of Freon12) to isolate the radiation produced by gas originating in a certain region, as presented later in Sec. IV.

We have investigated Z-pinch implosions with four distinctly different argon gas profiles, created by evacuating gas from some of the three plenums. The jet-inner-outer (JIO) profile has the gas in all three plenums; the inner-outer (IO) profile has the plenum for the center jet gas evacuated; the jet-outer (JO) profile has the plenum for the inner shell gas evacuated; the jet-inner (JI) profile has the plenum for the outer shell gas evacuated. Figure 2 shows the contour of the mass distribution (density times radius) as a function of radius r and axial position, z, for each of these profiles as determined by Planar Laser Induced Fluorescence (PLIF)10,11 The measurements were conducted under same condition as in Double-EAGLE. By rotating the PLIF diagnostic, Fig. 3 shows the density contour in the r-θ plane at a distance of 1.6 cm from the cathode. It demonstrates a high degree of azimuthal symmetry. More detailed descriptions of the profiles are provided in Ref. 7.

FIG. 1. (Color) Experimental setup. (1) Outer shell gas; (2) inner shell gas; (3) center jet gas; (4) anode screen; (5) current return posts.

FIG. 2. (Color) Contour plots of the mass times radius profile for the (a) JIO profile (22:3:1 psia), (b) IO profile (0:3:1 psia), (c) JO profile (20:0:2 psia), and (d) JI profile (22:4:8:0 psia).

III. NUMERICAL SIMULATIONS

To enhance our understanding of the Z-pinch process and the role of RT instabilities in the implosion of the four load profiles described above, we conducted numerical simulations of them for the Double-EAGLE experimental conditions. The specialized version of the Air Force two-dimensional magnetohydrodynamic (MHD) code, MACH2,12 employed in this work was derived from the base Air Force Research Laboratory code version (v0105a/b) by overlaying enhancements, including a specialized collisional-radiative equation of state (as described below), an alternative (more robust/accurate) finite-element magnetic field diffusion equation approximation technique, and OpenMP global parallel processing code speedup capabilities. Also included are the code error corrections and additional diagnostic capabilities developed and subsequently distributed by Numerex.
Radiation transition processes were treated in an optically thin regime according to the collisional-radiative equilibrium (CRE) model of Abdallah et al.,\textsuperscript{13} This model incorporates all argon ionic states and includes over 3000 bound electronic configurations. Electron-ion collision processes including excitation and de-excitation, ionization and three-body recombination, radiative and dielectronic recombination, and radiative and atomic processes including spontaneous and stimulated transitions, photoionization, photo-excitation, and autoionization are considered. The model is deemed applicable at strongly emitting densities for argon.

The equation of state relating the ion and electron internal energies and the mean ionization state \( \bar{Z} = N_e / N_i \), where \( N_e \) and \( N_i \) are the electron and ion number densities, was derived from the CR-EMIT model of Parks, Katz, and Vik.\textsuperscript{14} All of the related data are tabulated over an electron temperature range of 1 eV \(-10\) keV, and an ion density range of \( 10^{16} - 10^{20} \) cm\(^{-3}\).

For the initial density distribution, we have incorporated a general PLIF density data preprocessing and importation facility. The right and left halves of the measured density (i.e., positive and negative radial position in Fig. 2) were averaged and then interpolated and smoothed onto the computational grid. The circuit model for Double-EAGLE was an open circuit voltage, \( V_{OC} \), driving a 0.4 \( \Omega \), 19 nH transmission line and the variable inductance of the imploding load. The \( V_{OC} \) waveform was produced self-consistently from the measured voltage just upstream (on the water side) of the water-vacuum interface.

Calculated density contours at the implosion times of 165 and 198 ns for three representative load configurations are shown in Fig. 4. Here, lack of axial uniformity and the presence of large-scale bubble and spike features in the absence of the inner shell are evident in the JO profile, consistent with the experiment results. The JO profile, with the outer shell absent, is substantially more stable, though it exhibits some nonuniform zipper features. The JIO profile clearly produces the most uniform implosion. Further comparison with experimental results is presented in Sec. IV.

### IV. EXPERIMENTAL MEASUREMENTS WITH FOUR LOAD PROFILES

#### A. Diagnostics

A suite of diagnostics was fielded on Double-EAGLE. The K-shell x-ray pulses were measured by XRDs and the total K-shell yield by tantalum calorimeters. Axially resolved pictures of the K-shell emission pulses were obtained from the zipper array,\textsuperscript{15} which views the pinch through a slot orthogonal to the pinch axis, providing axial resolution of \( \sim 3\) mm, but integrating radially and thus providing no resolution in that dimension. Charge-coupled device (CCD) based diagnostics provided immediate K-shell spectrum and pinhole x-ray images,\textsuperscript{16} which were analyzed using the collisional radiative equilibrium algorithm of Apruzese et al.,\textsuperscript{17} to determine the axially resolved electron temperature, ion density, and K-shell participating mass. A CCD-based extreme ultraviolet (XUV) transmission grating spectograph\textsuperscript{18,19} provided companion data at photon energies of \( 100 < E < 3000 \) eV. A laser shearing interferometer (LSI)\textsuperscript{20} was used to study the implosion dynamics.

#### B. Analysis of K-shell and XUV emission

The four load profiles of Fig. 2 were investigated on Double-EAGLE. In these shots, the current waveforms and implosion times, as shown in Fig. 5, were nearly identical. The K-shell x-ray pulse, however, are vastly different, ranging from a 21.2 kJ, 7.3 ns full width at half-maximum (FWHM) pulse with the JO profile to a 7.1 kJ, 29.1 ns FWHM pulse with the JO profile. The highest K-shell radiation power of 2.05 TW was achieved with the JI profile.

Z-pinch emission at both K-shell and XUV wavelengths varies with different gas loads. Here we present measurements and discuss the sources of these variations. Diagnostics of the K-shell (3 \(< E < 5\) keV) emitting mass are fairly well developed,\textsuperscript{15} but most of the load mass radiates at sub-keV photon energies. XUV emission provides information about this cooler mass.\textsuperscript{18} We have measured the radial emission profile either time-integrated as a function of photon energy or time-resolved in discrete energy bands. Also, we...
have measured the time history of the spectrum (with coarse energy resolution) emitted from a few-mm-long axial section of the pinch and integrated over radius. Finally, we have measured, for the first time, the axially resolved XUV spectrum and the axially resolved emission time history or “zipper” in discrete XUV energy bands.

Figure 6 shows the contours that provide the time history and axial profile of K-shell emission from the cathode/nozzle exit to the anode recorded by the 14-PIN-diodes zipper array. Also, shown in Fig. 6 are the K-shell pinhole images for the four mass profiles. The JIO pinch is straight and uniform, with a narrow radiating zone extending from 1 to 3 cm from the cathode [Fig. 6(a)]. The K-shell pinch diameter is about 1.5 mm. The JO pinch has no well-localized x-ray intensity contours, confirming that its implosion is distorted by the RT instability and fails to produce a tight pinch at stagnation, as seen in Fig. 6(c).

Next, assuming that all of the argon mass is heated sufficiently to radiate in the XUV energy band, the observed diameter should be the diameter of the total mass collected and compressed by the load current. In fact, the observed XUV radiating diameter ≈3 mm, which is twice the K-shell diameter, is indeed consistent with inductance estimates of the final load current radius.19

Figure 7 shows the temporal histories of the 200 eV [Fig. 7(a)] and 500 eV [Fig. 7(b)] XUV emissions of the four loads. The JI load had a much 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 [Fig. 7(c)].

It should be noted that the center jet plasma of the JIO profile is too close to the axis to gain a high velocity before stagnation. It is heated by the shock wave produced when the imploding outer plasma hits the center jet, and then adiabatically, as the stagnated plasma continues to converge. Simulations predict a long prepulse of sub-keV radiation to emerge as the density of the jet is increased, a key signature that indicates the shock wave is passing into the on-axis plasma.21 As shown in Fig. 7(d), such a prepulse in the XUV spectral range (260 < hν < 770 eV), ~20 ns earlier relative to the K-shell radiation peak than in the JIO profile, is indeed observed; also, the relatively slow emission rise time is characteristic of a quasidiabatic, or reversible, compression. In the IO profile, the rise time is much more rapid with a sharp jump (characteristic of a rapid, irreversible compression) at the time of peak K-shell emission. Thus, by adding a massive center jet, the dynamics of the implosion are changed dramatically and the compression and temperature increase of the plasma become more adiabatic.

Spectroscopic signatures of the K-shell images and spectra, K and XUV (∼500 eV) emission vs space and time (zip-
per) data, and XUV spectra of the JIO and JO profiles are shown in Fig. 8 for comparison. Except for the radiating radii, the features of the K-shell and the XUV emission of the JIO profile are quite similar in time and space. For the JO profile, the feature of the XUV emission resembles that of the JIO profile. The major difference is the absence of uniform K-shell radiation.

C. Laser shearing image analysis

Implosion dynamics were measured using LSI; details of this diagnostic method are reported in Ref. 20. Figure 9 shows the initial gas profile and a series of LSI images of the implosion plasma in the two extreme cases, the JIO and JO profiles. These images were captured on a sequence of nominally identical shots, one frame per shot. Looking first at the JIO profile [Figs. 9(a)–9(f)] with the current waveform in Fig. 5(a), we see that from time 0 to 45 ns, the drive current increased to 2 MA, and the plasma located beyond radius $r \sim 6$ cm started to implode and accelerate. By 80 ns, the current reached 3.3 MA, and the plasma swept through the outer zone ($r \sim 5$ – 6 cm) and decelerated as it swept up ~30% of the injected gas. The LSI image at $t=72$ ns [Fig. 9(c)] showed the cathode part of the plasma sheath, but the anode part was blocked by the shadow of the current posts at $r = 5.5$ cm. The wavelength of the unstable plasma sheath is estimated to be ~3 mm from the axial fringe oscillation periods near the inner edge of the area outlined in red. Next, until 110 ns, the plasma swept through a low-density region from $r=4.8$ to 4.2 cm. The LSI image at $t=122$ ns [Fig. 9(d)], which was before the plasma reached the outer edge of the inner plasma shell ($r \sim 4$ cm), shows the plasma became more unstable. The amplitudes grew and the wavelengths increased to ~7 mm near $z=2$ cm and ~9 mm near $z=3.5$ cm. From that point to 160 ns, the imploding plasma swept through high inner density and reached the inner edge of the inner gas shell at $r \sim 2$ cm. During this period, there are two very important observations. First, the LSI image at $t=148$ ns [Fig. 9(e)] shows clearly that the wavelength of the RT instabilities decreased to 2 – 3 mm. Second, the LSI measurements of the sheath position are consistent with a snowplow calculation, based on measured current and density profiles (see Fig. 15 and discussion thereof in Ref. 7), which
indicates that the inner gas shell stopped the acceleration so that the plasma imploded at an approximately constant velocity of $3.2 \times 10^7$ cm/s. Continuing, for $r > 180$ ns, the imploding plasma reached the center gas jet zone ($r < 2$ cm). The LSI image at $t = 192$ ns [Fig. 9(i)] shows a smooth, thin plasma sheath at $-1.2$ cm radius, which implies a stable implosion. Indeed, the argon K-shell x-ray yield was 21 kJ at a 3.2 MA current level, comparable to that achieved in 2.5-cm-diam gas loads with an approximately 100 ns implosion time.

For comparison, we now examine the JO profile [Figs. 9(g)–9(k)]. From 0 to 60 ns, as the current increased, the plasma sheath accelerated and swept up the mass ($\sim 3\%$ of the total) located at $r > 5.8$ cm, then decelerated up to 100 ns as it swept up $33\%$ more of the total mass while going through $r = 5.8 - 4.5$ cm. After that, the sheath resumed its acceleration. The LSI image at $t = 125$ ns [Fig. 9(i)] shows that the instability wavelength was $\sim 4$ mm, comparable to those obtained at $t = 122$ ns for the JO profile. In the absence of the inner gas shell, the imploding sheath accelerated continuously and the instability continued to grow. At $t = 146$ ns [Fig. 9(j)], the sheath is more unstable than in the previous image. The RT wavelength is hard to quantify precisely, but is on the order of 4 mm; the sheath thickness is also hard to define but clearly larger than at $t = 125$ ns. The RT instabilities have developed nonlinear, bubble, and spike features that are usually seen in fluid simulations of the instability.\cite{22, 23} At 200 ns, the LSI image [Fig. 9(k)] shows a highly unstable sheath; the nonuniform axial plasma profile showed a 1-cm-tall spike feature in the $z = 2 - 3$ cm region. At this time, the imploding plasma reached the center jet zone with very large RT amplitudes. Instead of a 3.8-cm-long uniform pinch, the x-ray pinhole camera image showed two localized radiating spots, 8 mm long and 4 mm in diameter centered at $z = 0.5$ and 2.5 cm, respectively. The argon K-shell x-ray yield was 5 kJ, about 25% of the 21 kJ achieved with the JO profile described above.

Thus, it is clearly demonstrated with the JO profile that (1) the imploding plasma from the outer zone was initially unstable; the plasma sheath was thick; plasma instabilities grew in amplitude and wavelengths; (2) the unstable plasma, sweeping through a higher mass inner zone, imploded at a constant velocity; it became less unstable with a thinner plasma sheath and shorter wavelength as compared with the JO profile; and (3) the plasma pinched on axis and maintained an axially uniform profile and achieved a compression ratio (initial radius/final pinch radius) of $>40$.

D. Identification of radiation source region

To identify the origin of the K-shell emitting ions, Cl ions ($2\%$ by partial pressure of CF$_2$Cl$_2$ in Ar) were introduced into each of the three plenums, one at a time, in a series of otherwise identical shots. Since Cl is only one atomic number lower than Ar, its K-shell radiation reflects the K-shell radiating Ar ions originating in the same plenum with it. For example, with the JO profile, the Cl K-shell line intensities (He-\(\alpha\), IC, ijk satellites, Ly-\(\alpha\)), normalized to the same Ar K-shell line intensities to eliminate the effect of small shot-to-shot variations, were in the ratio of 13:6:1 when introduced into the pinch through the jet, inner shell, and outer shell, respectively. It was thereby determined that 65% of the K-shell radiation was produced by gas originating in the central jet, 30% from the inner shell, and only 5% from the outer shell. The initial mass in the three regions $r < 1.5$ cm, 1.5 cm $< r < 4$ cm, and $r > 4$ cm were in the ratio of 1:2:2. The masses in these regions closely correspond to the central jet, inner shell, and outer shell masses, respectively, but, due to the radial spreading of the profiles (see Fig. 2), the correspondence is not exact.

The results for all four profiles are tabulated in Table I. In all cases, the gas introduced into the pinch from the innermost plenum (the jet in JIO, JO, and JI profiles; the inner shell in the IO profile) produced the bulk of the K-shell radiation. This is a clear indication that, although a snowplow model may provide a useful model of the run-in phase of the
implosion, the gas does not accrete into a thin shell of undifferentiated mass; instead, the initial ordering of the material is maintained as it is swept up.

E. Comparison with simulation results

Having seen that the qualitative structure of the implosions for the various profiles that was predicted by the numerical simulations was observed in practice, we can also compare the results quantitatively.

Table II compares the experimentally observed and numerically calculated peak current, implosion time, radiation pulse width, and K-shell yield for the four profiles. The agreement is good; not only is the relative ordering of the profiles reproduced, but the absolute values are also reproduced. The only significant difference between the measured and calculated results occurs for the JI profile. The simulation predicted a double pulse, caused by a delay between implosions at the cathode and anode ends, while we observed only the first (cathode end) implosion. Similar agreement with the K-shell yield was obtained in a scan of the center jet plenum pressure at fixed inner and outer shell plenum pressures as shown in Fig. 10. While the predicted yields are systematically somewhat high, the qualitative and quantitative agreement is good.

F. Current scaling experiments

A series of experiments were conducted to determine the K-shell yield scaling with load current. These included operation on Double-EAGLE at higher than typical Marx charge voltage, on Decade Quad, and on Saturn (configured in a 200 ns pulse mode). In the Decade Quad and Saturn experiments, the optimal 22:3:1 plenum pressure ratio was maintained, but the total mass was varied to obtain optimum K-shell yield. Figure 11 shows the Decade Quad and Saturn results versus implosion time, which have a very similar trend and optimized at 227 and 203 ns, respectively. Combining these optimal x-ray yields, Fig. 12 shows that the yield scales as current to the 2.1 power, exactly as would be expected in the “efficient” regime.

<table>
<thead>
<tr>
<th>Load profile</th>
<th>K-Shell yield (kJ)</th>
<th>Jet</th>
<th>Inner shell</th>
<th>Outer shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>JIO</td>
<td>21.2</td>
<td>65%</td>
<td>30%</td>
<td>5%</td>
</tr>
<tr>
<td>IO</td>
<td>9.7</td>
<td></td>
<td>95%</td>
<td>5%</td>
</tr>
<tr>
<td>JO</td>
<td>7.1</td>
<td>&gt;95%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JI</td>
<td>14.6</td>
<td>75%</td>
<td>25%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nozzle type</th>
<th>Peak current (MA)</th>
<th>$t_{imp}$ (ns)</th>
<th>$t_{K}$ (ns)</th>
<th>K-Shell yield (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JIO</td>
<td>Measured</td>
<td>3.46</td>
<td>205</td>
<td>6.8</td>
</tr>
<tr>
<td>Calculated</td>
<td>3.53</td>
<td>225</td>
<td>5.6</td>
<td>21</td>
</tr>
<tr>
<td>IO</td>
<td>Measured</td>
<td>3.57</td>
<td>210</td>
<td>5.5</td>
</tr>
<tr>
<td>Calculated</td>
<td>3.83</td>
<td>215</td>
<td>4.8</td>
<td>14</td>
</tr>
<tr>
<td>JO</td>
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<td>202</td>
<td>30</td>
</tr>
<tr>
<td>Calculated</td>
<td>3.39</td>
<td>200</td>
<td>21</td>
<td>9</td>
</tr>
<tr>
<td>JI</td>
<td>Measured</td>
<td>3.37</td>
<td>200</td>
<td>3.5</td>
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<tr>
<td>Calculated</td>
<td>3.32</td>
<td>206</td>
<td>19$^a$</td>
<td>24$^a$</td>
</tr>
</tbody>
</table>

$^a$Composite pulse, formed by two narrower pulses

![Inner Shell @ 3 psia, Outer Shell @ 1 psia](image_url)

**FIG. 10.** (Color online) Comparison of the K-shell yield measured and predicted by simulation code for a scan of center jet pressure. The solid lines are parabolas, drawn as an aid to the eye.

![K-Shell Yield vs Implosion Time on Decade Quad and Saturn](image_url)

**FIG. 11.** (Color online) K-shell yield vs implosion time on Decade Quad and Saturn.
V. SUMMARY

In summary, the impact of our approach is the successful demonstration of how the imploding and radiating components of a gas-puff load can be and should be designed and optimized separately for their respective roles. This finding opens a new parameter space for load design and new opportunities for Z-pinch experiments. The “pusher-stabilizer-radiator” concept is not limited to long pulse drivers and opens a new parameter space for load design and new opportunities for Z-pinch experiments. The “pusher-stabilizer-radiator” concept is not limited to long pulse drivers and opens a new parameter space for load design and new opportunities for Z-pinch experiments. This suggests that either the conventional wisdom of decreased yield with larger diameter and long implosion Z-pinch has been overturned, or this new approach can lead us to even higher yields in short (~100 ns) implosions with new smaller-diameter (5 ~ 8 cm) nozzles, e.g., exceeding the 300 kJ Ar obtained with a 8-cm-diam double-shell nozzle at 15 MA.3 We demonstrated that in implosions driven by slower current pulses, the pusher does not necessarily have to start from larger radius [R_0 \propto \eta^{1/2} (\hbar \omega)^{2/3}] to maintain high η. Rather, the pusher can rapidly deliver the required thermal energy to the radiator via shock and quasiadiabatic compression, effectively amplifying η in the radiator, as in our jet-inner case. The post-shock heating of the radiator plasma takes a time \sim R_0/\nu, which is only about 3.5 ns in our experiments. Therefore, substantial energy could be coupled to the radiator plasma very quickly, at the rate as high as can be achieved in laser experiments on multi-keV x-ray generation. This makes it possible to strip a high-atomic-number K-shell radiator (Kr is of particular practical interest) down to its He-like state without severe energy losses through soft-x-ray line radiation cooling, which are inevitable with shell implosions. Therefore, the possibility of producing tens of kJ of Kr K-shell x rays at 13 keV on Z and 2R with appropriately designed gas-puff loads now appears more promising.

ACKNOWLEDGMENTS

The authors would like to recognize J. Apruzese and T. W. Thornhill for useful discussions and thank the L-3 Communications/Pulse Sciences Double-EAGLE, Arnold Engineering Development Center Decade Quad and Sandia National Laboratory Saturn crews for their professional performance of these experiments. This work was sponsored by the Defense Threat Reduction Agency.