Shock formation in Ne, Ar, Kr, and Xe on deuterium gas puff implosions

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Shock formation in Ne, Ar, Kr, and Xe on deuterium gas puff implosions

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1- and 2-D simulations of 1-cm radius, gas-puff liners of Ne, Ar, Kr, and Xe imploding onto a deuterium target are conducted using the discharge parameters for the Zebra (1 MA, 130 ns) driver using the resistive MHD code MACH2. This is an implementation of the Staged Z-pinch concept, in which the target is driven to high-energy-density first by shock compression launched by a diffused azimuthal magnetic field \((J \times B)\) force, and then by the adiabatic compression as the liner converges on axis. During the run-in phase, the initial shock heating preheats the deuterium plasma, with a subsequent stable, adiabatic compression heating the target to high energy density. Shock compression of the target coincides with the development of a \((J \times B)\) force at the target/liner interface. Stronger B-field transport and earlier shock compression increases with higher-Z liners, which results in an earlier shock arrival on axis. Delayed shock formation in lower-Z liners yields a relative increase in shock heating, however, the 2-D simulations show an increased target isolation from magneto-Rayleigh-Taylor instability penetration, suggesting that an optimal balance between these two effects is reached in an Ar or Kr liner, rather than with Xe. Published by AIP Publishing.

I. INTRODUCTION

A gas puff Z-pinch is a pulsed-power-driven compression system in which an annular gas liner compresses in response to a self-generated \((J \times B)\) force due to an axial current. Gas puff Z-pinchs have been successfully developed as sources of x-rays and neutrons.1 Another application is the thermonuclear fusion, in which an annular liner and a target of deuterium (D) or a mixture of deuterium-tritium (DT) is used. In magneto-inertial fusion, the target is compressed and confined by a combination of inertial and magnetic forces, e.g., an axial magnetic field and a radially-inward-driven liner. At peak compression, a sufficient target ion temperature (>few keV), ion density (>1023 cm\(^{-3}\)) and confinement time (>1 ns) create the conditions necessary for thermonuclear fusion.2,3 A sufficiently strong magnetic field can confine \(x\)-particles generated from D-T or D-He\(^3\) reactions, further heating the target.4–7 For example, 3.5 MeV \(x\)-particles in a 100-T field have a gyroradius of \(\sim 60\mu m\) and would be fully-confined in an order \(\sim 100\mu m\) target plasma.

In a typical inertially confined fusion implosion, a liner or shell adiabatically compresses the target to ignition temperatures. The compression ratio, \(CR = r_0/r_F = (T_F/T_0)^{3/4}\), is prohibitively high without some form of target preheat. As a limiting example, a 1 cm-radius, \(\sim 3\) eV target would require \(CR \sim 250\), or \(r_F \sim 40\mu m\) to reach \(T_F = 5\) keV—an order of magnitude greater than has ever been observed in experiment. If the target is preheated and compressed by other means to \(2\) mm and \(\sim 90\) eV, then \(CR \sim 20\) and \(r_F \sim 100\mu m\). One promising approach is laser preheating.8,9

Another, which will be the focus of this paper, is shock preheating.10

Shock preheating is a core concept of the Staged Z-pinch.10–12 In the Staged Z-pinch concept, a high-Z liner implodes on a low-Z target, with target compression occurring in stages. First, an azimuthal magnetic field diffuses through the liner to the target/liner interface. There a \((J \times B)\) force develops, launching one or more shocks that compress and heat the target. Behind the shock, the \((J \times B)\) force at the surface compresses the liner. Upon shock reflection off axis and collision with the interface, shock compression in the target transitions to adiabatic compression by the imploding liner, driving the target to peak compression. A faster-rise pulse has numerous advantages over a slower-rise pulse, e.g., a smaller liner length is required, and a higher final target density is achievable.8 The Zebra voltage driver at the University of Nevada, Reno, which delivers 1 MA in \(\sim 130\) ns, is suitable for the Staged Z-pinch and will serve as the driver for the results presented in this study, as well as for the current and future experimental campaigns.

Isolation of the target from the outer liner surface is advantageous. The magneto-Rayleigh-Taylor (MRT) instability13,14 inevitably develops during the run-in phase, its name referring to the vacuum magnetic field outside the pinch that serves as the light fluid. Penetration of the MRT into the target disrupts its integrity and needs to be avoided. Various experimental configurations have been used in the past to mitigate the MRT instability growth, e.g., application of an axial magnetic field to induce the magnetic shear15–18 or preionization of the liner to reduce the initial density perturbations.19

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This work investigates the effect of the liner material in the Staged Z-pinch by comparing the shock formation in Ne, Ar, Kr, and Xe liner implosions using a deuterium fill. Recent simulations of the Staged Z-pinch concept\textsuperscript{13,19} suggest that stronger shocks and greater target preheat correlate with increasing liner atomic number.\textsuperscript{15} The effect of the liner material on instability development is also briefly investigated. For these initial studies, an MRT-mitigation mechanism is not used. The simulations are conducted using the resistive MHD code, MACH2,\textsuperscript{26} including a nonequilibrium radiation diffusion model.\textsuperscript{27} This model, while designed for optically thick plasmas, includes a flux limiter that extends the model to the optically thin regime. This will allow a transition between the optically-thin and optically-thick regimes, which will improve accuracy of the simulation, particularly at stagnation when the target may be optically thick.

The paper is organized as follows: in Section II, we describe the problem configuration and the MHD code used, in Section III, we discuss results from both 1-D and 2-D simulations, and in Section IV, a summary of our conclusions is presented.

II. SIMULATION CONFIGURATION

MACH2 is a 2 1/2-D, single-fluid, three-temperature code that solves the mass continuity, momentum, energy, magnetic field, and radiation diffusion equations. 2 1/2-D means that while the code carries all three components of spatial vector fields, it sets the spatial derivative of a scalar field to zero in one of the spatial directions. In cylindrical geometry, this means $\frac{\partial}{\partial \theta} \frac{\partial}{\partial \theta} = 0$. The equations solved by MACH2 are as follows:

Mass continuity

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}).$$  \hspace{1cm} (1a)

Momentum conservation

$$\rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{v} = \frac{(\mathbf{B} \cdot \nabla) \mathbf{B}}{\mu_0} - \nabla \left( \frac{B^2}{2\mu_0} + P \right).$$  \hspace{1cm} (1b)

Electron specific internal energy

$$\rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \right) e_e = -P_e (\nabla \cdot \mathbf{v}) + \eta J^2 + \nabla \cdot \left( \kappa_e \nabla T_e \right) - \Phi_{eR} - \rho \kappa_{ei} T_e - T_i \frac{T_e - T_i}{\tau_{ei}}.$$  \hspace{1cm} (1c)

Ion specific internal energy

$$\rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \right) e_i = -P_i (\nabla \cdot \mathbf{v}) + \nabla \cdot \left( \kappa_i \nabla T_i \right) + \rho \kappa_{ei} - T_e - T_i \frac{T_e - T_i}{\tau_{ei}}.$$  \hspace{1cm} (1d)

Magnetic induction

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times (\eta \mathbf{J}).$$  \hspace{1cm} (1e)

Radiation energy density

$$\frac{\partial \rho_{eR}}{\partial t} = -\mathbf{v} \cdot \nabla \rho_{eR} - \left( 1 + \frac{1}{3} \left( \frac{1}{1 + \rho_{ei}/d} \right) \right) u_R \nabla \cdot \mathbf{v} + \nabla \cdot \left( \frac{c^2_{\rho}}{3} \nabla u_{eR} \right) + \Phi_{eR},$$ \hspace{1cm} (1f)

where $P \equiv P_e + P_i$ is the total thermal pressure, $\epsilon_{ei}(i)$ is the electron (ion) specific internal energy, $\eta$ is the electrical resistivity, $\kappa_{ei}(i)$ is the electron (ion) thermal conductivity, $c_{\rho}$ is the electron specific heat, $\tau_{ei}$ is the electron-ion equilibration time, $u_R \equiv \frac{4\pi T^2_R}{k_B}$ is the radiation energy density, where $\sigma$ is the Stefan-Boltzmann constant, and $T_R$ the radiation temperature, $\Phi_{eR} \equiv 4\sigma P_{\rho e} (T_e^4 - T_i^4)$ is the radiation coupling term, $\rho_{ei} \equiv 1/\rho_{Z_{eo}}$ is a photon mean free path, $d$ is a scale length related to the transition from the optically thick to the optically thin regime,\textsuperscript{27} $\lambda_{ph(r)}$ is the Planck (Rosseland) mean opacity, and current density, $J$ is calculated from Ampere’s law.

The equation of state variables were obtained from SESAME tables, opacity tables were interpolated from Post,\textsuperscript{26} isotropic electrical conductivity tables were generated using a Spitzer-Braginskii model,\textsuperscript{29} with the inclusion of a correction factor (~0.75) so that the Ar table agreed with one generated by M. Desjarlais. Tables of ionization level were generated via PrismSPECT simulations assuming local thermodynamic equilibrium (LTE), and an isotropic Spitzer-like thermal conductivity was used.

The current was calculated by modeling using the Zebra $(R = 1.9 \Omega, L = 69 \text{ nH})$ voltage driver as an RL circuit driven by a specified voltage waveform, $V_{Zebra}$, where $V_{Zebra}$ equals the summation of the inductive circuit voltage, $V_L = L_0 dI(l)/dt$, resistive circuit voltage $V_R = I(l)R$, and load voltage, which is calculated via the change in magnetic flux in the problem domain. Figure 1 shows a plot of the voltage waveforms for a typical run.

The simulation grid was Eulerian, with 50-\text{m axial and 100-\text{m radial resolution}. In an attempt to make the configuration realistic, both the target and liner were Gaussian distributions: the target with peak density $1.6 \times 10^{-6}$ g/cm$^3$ $(5.0 \times 10^{17}$ cm$^{-3}$) of FWHM 3.5 mm, extending from $r = 0$ to 7.0 mm; the liner with peak density $1.5 \times 10^{-2}$ g/cm$^3$ $(0.7-4.5 \times 10^{18}$ cm$^{-3}$) of FWHM $\sim 25$ \text{mm extending from r = 7.0 mm to 10.0 mm}. In 2-D simulations, a 1% random perturbation was
used to seed the instability growth. All temperatures were set at 3 eV to ensure preionization.

III. RESULTS

The implosion can be broadly divided into three phases: Ohmic heating, run-in, and stagnation. During the first, the target and liner remain stationary as the azimuthal field diffuses through the liner. The run-in phase begins as the $J \times B$ force drives both shock compression of the target and compression of the outer liner. The stagnation phase is characterized by the transition from shock compression to adiabatic compression as the liner converges on-axis.

The results presented here are from 1-D simulations unless stated otherwise.

A. Ohmic heating and shock formation

Shock formation in the target can be observed as a thermal pressure discontinuity that forms while the target is still stationary and develops into a shock front as the run-in phase begins. Whereas in a purely inertial implosion, shock formation and target acceleration is driven purely by thermal pressure, here the driver is a combination of thermal and magnetic pressures. It will be shown that the ratio of these two forces scales with the atomic number of the liner. Comparison between any two configurations reveals the same trend, so the limiting cases, i.e., Ne/D and Xe/D will be discussed.

First, consider the shock formation in the Xe/D configuration, as shown in Figure 2. At $t = 75$ ns, the outer surface of the liner has been compressed to $\sim 0.9$ cm, 1 mm from its initial position, whereas the target has expanded 250 $\mu$m. Magnetic and thermal pressure at the interface are 2.75 bar ($B_0 \sim 0.8$ T) and 0.24 bar, respectively, and a thermal pressure jump of 0.5–1.7 bar is seen in the target from 6.8 to 7.0 mm. The distance between the interface and pressure jump is $\sim 400 \mu$m.

At $t = 100$ ns, the interface has moved $\sim 1$ mm and has the velocity $\sim 4.85$ cm/µs. While a thermal pressure discontinuity has developed, the target plasma behind the front has heated such that this velocity remains subsonic—i.e., $c_s, \text{interface}(t = 75 \text{ ns}) \sim 3.4$ cm/µs ($T \sim 8$ eV), and $c_s, \text{interface}(t = 100 \text{ ns}) \sim 5.0$ cm/µs ($T \sim 15$ eV). Magnetic and thermal pressure at the interface are 14.32 bar ($B_0 \sim 1.9$ T) and 3.21 bar, respectively, and a thermal pressure jump of 2.9 to 13.5 bar is seen in the target from 5.7 to 5.9 mm.

At $t = 125$ ns, the interface has moved $\sim 1.5$ mm and has the velocity $\sim 8.0$ cm/µs, compared to a sound speed of 6.1 cm/µs, or a Mach number, $M \sim 1.3$. $M$ approaches 1 at the shock front, located at 4.1 mm. Magnetic and thermal pressure at the interface are 42.6 bar ($B_0 \sim 3.3$ T) and 17.2 bar, respectively, and a thermal pressure jump of 7.2 to $\sim 40$ bar is seen at the shock front. At this time, the shocked target has a temperature $\sim 21–22$ eV and the unshocked target has a temperature $\sim 4–7$ eV. The nonuniform target temperature is a consequence of a nonuniform initial target density.

As a limiting case, now consider shock formation in the Ne/D configuration, as shown in Figure 3. Compared with the Xe liner, at $t = 75$ ns, the Ne liner is wider (6.9–9.5 mm vs. 7.2–9.0 mm) and has a higher thermal pressure, particularly in the liner interior. As the initial mass of the liner was held constant across materials, $n_i$ decreases $\sim 6.5$-fold in Xe compared with Ne. At low temperatures, this difference is not made up by greater ionization in Xe. For example, at 10 eV, $Z_{Ne} \sim 4–6$ and $Z_{Xe} \sim 7–10$. Magnetic and thermal pressure at the interface are 0.09 bar ($B_0 \sim 0.15$ T) and 1.73 bar, respectively. This is an interface $\beta$ of 19, compared with 0.08 in the Xe liner.

Here we also note that the radiation effects do not appear to substantially affect the shock formation. Broadly speaking, at these temperatures ($< 10$ eV), increased radiation in high-Z (Kr, Xe) liners appears to be offset, perhaps by increased Ohmic heating from higher resistivity.

At $t = 100$ ns, the interface has moved $\sim 0.1$ mm and has the velocity 1.2 cm/µs, well below the interface $c_s$, $\sim 3.4$ cm/µs. The interface plasma $\beta$ remains above unity (1.24 vs. 0.22 in Xe), with interface magnetic pressure 2.68 bar ($B_0 \sim 0.8$ T) and thermal pressure 3.31 bar. At $t = 125$ ns,
the interface has moved 0.65 mm and has the velocity 5.1 cm/μs, compared with an interface \( c_S \) of \( \sim 4.3 \) cm/μs, or \( M \sim 1.2 \). This drops to \( M \sim 0.73 \) at the pressure jump, so at 125 ns, the shock has not fully developed. Magnetic and thermal pressure at the interface are 18.9 bar (\( B_0 \sim 2.2 \) T) and 5.2 bar, respectively, or \( \beta \sim 0.28 \).

From comparing these two cases, as well as a similar data from Ar/D and Kr/D runs, a trend in shock formation is apparent. With all parameters held constant and adjusting only the atomic number of the liner material, an acoustic shock in the target will be launched earlier in time as the atomic number is increased. With increasing \( Z \), an accelerated rate of magnetic field transport drives the interface \( \beta \) to sub-unity earlier in time. A shock develops at the interface as the thermal pressure of the target is unable to equalize the thermal and magnetic pressure of the liner.

### B. Run-in and shock evolution

In this configuration, the run-in phase spans \( \sim 100 \) ns to \( \sim 170 \) ns. Shock heating and compression of the target occurs ahead of the slower-moving liner. Following shock reflection off axis and subsequent collision with the interface, the target stagnates until an adiabatic compression by the liner drives the target to peak implosion.

A comparison of Alfvén (\( v_A \)), sound (\( c_S \)), and radial (\( |v_R| \)) speeds between configurations at a specified time provides information on multiple relevant parameters simultaneously. For example, \( c_S \) provides the target temperature, location of the shock front, and the target/liner interface; \( |v_R| \) is a useful parameter in and of itself, and with \( c_S \) provides shock strength; and \( v_A \) describes the target \( B_\theta \) profile, provides liner thickness and gives a qualitative density profile.

Shock preheating at any given time in the run-in phase is stronger as the liner atomic number increases. Consider, for example, Figure 4, which shows these speeds in each configuration at \( t = 140 \) ns. A shock has fully developed in the target in all four configurations, though there is a substantial difference in target and shock parameters. Target radius drops from 4.8 mm in the Ne/D configuration to 3.5 mm in Xe/D. Implosion velocity decreases slightly (11 to 10 cm/μs in Ne/D vs. Xe/D), whereas the shock sound speed increases from 6.3 to 6.7 cm/μs. While the increase in shock temperature (25 to 30 eV) is modest and the shocked target density is the same (\( 10^{18} \) cm\(^{-3} \)), shock width increases 2.5-fold, from 400 in Ne/D to 1000 μm in Xe/D. Downstream target density is also the same (\( \sim 3 \times 10^{17} \) cm\(^{-3} \)), suggesting a snowplow-like compression of the target.

At the target/liner interface, Alfvén velocity peaks and matches the implosion velocity. The drop-off in Alfvén speed to the left of the interface shows that the target is unmagnetized. Axial current density and the azimuthal magnetic field are highest at the outer surface of the liner, so the Alfvén speed profile to the right of the interface indicates the presence of a density gradient within the liner. The location of Alfvén speed divergence coincides with the outer surface of the liner. Its location does not vary significantly between the liner materials as the initial liner mass was the same in each configuration. However, the earlier target compression with an increasing atomic number results in a thicker liner through the run-in phase. This will affect the instability development in 2-D simulations.

### C. Shock reflection and target stagnation

Between 10–20 ns prior to peak implosion, the shock front in the target reaches the axis and reflects. Kinetic energy converts into thermal energy, radial velocity goes to zero and an acoustic wave propagates outward at a sound speed equal to the shock speed at reflection. In the Xe-compressed D, for example, Figure 5 shows that this speed is 13 cm/μs. Target preheating is completed upon the wave colliding with the interface. This can be visualized by plotting thermal pressure versus the radius and time, as in Figure 6. Note that these plots were reflected across \( z \equiv 0 \) to form a streak-like image. The shock front is the innermost pressure gradient, the inner band is the shocked target, and the outer band is the liner. Though time extends to \( t = 180 \) ns, the model is not valid after peak compression.

A comparison of the target states for each configuration with and without shock compression is presented in Table I. As is evident in Figure 6, the arrival of the reflected wave at
the interface occurs earlier in time with an increasing atomic number, ranging from $t = 165.5\,\text{ns}$ in the Xe/D configuration to $t = 169.8\,\text{ns}$ in the Ne/D configuration. This is consistent with the earlier shock formation and arrival on axis as $Z$ increases. The results of Table I suggest that, with this experimental configuration, the earlier shock formation appears to correspond with a lower degree of preheat. The initial hypothesis of increasing shock strength and preheating with increasing atomic number does not appear to be supported by the results presented here, suggesting that different physics are responsible for increased experimental performance with increasing atomic number. One consistent improvement, regardless of the liner material, is that the effective adiabatic compression ratio drops by an order of magnitude, if we assume the target is purely shock-compressed until shortly before peak implosion.

It is important to note that a) thus far, only 1-D physics have been considered, and b) the target preheat could be significantly increased with different experimental configurations. For example, the driver, liner, and target parameters could be modified such that the implosion velocity is several times higher. These results suggest those that would substantially increase the target preheat.

D. MRT instability evolution

Instability growth was qualitatively studied by conducting 2-D simulations, with an initial density perturbation of $\pm 1\%$ throughout the entire grid. We note that, in the results presented here, the same random number seed is used, and therefore the initial pseudorandom perturbation is identical across the four configurations.

The primary concern in the stability of Z-pinch implosions is the rapid growth of the MRT instability. The axial resolution was $100\,\mu\text{m}$, which sets a lower limit of the MRT wavelength, $\lambda_{\text{MRT}}$, to $200\,\mu\text{m}$. As the growth rate, $\gamma \propto \sqrt{g/\lambda_{\text{MRT}}}$, a change in resolution will affect the simulation results. Choosing a lower-resolution grid will artificially suppress the more-damaging shorter-wavelength instability growth, but using too high a resolution will give an unphysically large initial perturbation. In this work, no attempt was made to mitigate the instability growth.

MRT growth is most significant at the end of the run-in phase, as the liner decelerates and stagnates. Broadly speaking, shorter-wavelength instabilities are the most damaging to the liner structure, so a thicker liner will provide a better isolation of the target from MRT instability penetration. As the average radial position and acceleration of the outer liner surface are independent of the liner material, the thickness of the liner depends on the location of the interface, or alternatively the time at which the shock is launched in the target. As discussed previously, magnetic field transport to the interface increases with $Z$, resulting in earlier target compression and shock formation. It is therefore expected that the Xe liner would be most stable, and that the Ne would be the least stable during the final 10–20 ns of compression.

This was observed in simulation, as shown in Figure 7, a qualitative display of MRT instability evolution from $t = 160\,\text{ns}$ to $t = 170\,\text{ns}$. Shortly after $170\,\text{ns}$, in all liners, the MRT instability penetrates through the liner and into the target, rendering the simulation unstable. Note, however, that shock preheating, which occurs prior to $170\,\text{ns}$, is unaffected by the MRT penetration in all four configurations. But clearly a
mitigation mechanism, such as an axial B-field, is necessary to maintain the liner integrity through peak implosion. While 1-D simulations suggested that a lower-Z liner material would provide stronger shock heating, 2-D simulations show that the MRT instability is more damaging to lower-Z liners. This suggests that there is an optimal liner material, possibly Kr (or between Ar and Kr), that would provide the proper combination of shock heating and target isolation from the MRT instability penetration. Reliable predictions of neutron yield were not available for this configuration, but such calculations will be included in future work.

IV. CONCLUSION

In this work, 1- and 2-D simulations of 1-cm gas liner on deuterium implosions were conducted using four different gases: Ne, Ar, Kr, and Xe. It was shown that the target shock-compression is driven by magnetic pressure transported through the liner to the liner/target interface. Magnetic field and current are transported to the interface earlier with higher-Z liners, launching the shock sooner in time. The earlier shock, while initially stronger, is ultimately weaker at the beginning of the liner stagnation, providing reduced shock heating - suggesting that a lower-Z material is more advantageous. It is shown that the chosen configuration with the Zebra driver shock heats the target to a few hundred eV and compresses the target to a few hundred microns, requiring the adiabatic compression to a sub-100 μm final radius to achieve ignition. 2-D simulations show that the MRT instability growth is more damaging to the lower-Z, thinner liners, suggesting the optimal liner material for the Staged Z-pinch is medium-Z, possibly Kr or between Ar and

<table>
<thead>
<tr>
<th>Liner</th>
<th>$P_{\text{thermal}}$ (kbar)</th>
<th>$T_{0,\text{shocked}}$ (eV)</th>
<th>$r_{0,\text{shocked}}$ (μm)</th>
<th>$T_f$ (eV)</th>
<th>$r_f$ (μm)</th>
<th>$r_{f,\text{shocked}}$ (μm)</th>
<th>CR (w/o shock)</th>
<th>CR (w/ shock)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ne</td>
<td>~12</td>
<td>220</td>
<td>500</td>
<td>5000</td>
<td>26.8</td>
<td>48.0</td>
<td>260</td>
<td>10.4</td>
</tr>
<tr>
<td>Ar</td>
<td>~10</td>
<td>175</td>
<td>550</td>
<td>5000</td>
<td>26.8</td>
<td>44.5</td>
<td>260</td>
<td>12.4</td>
</tr>
<tr>
<td>Kr</td>
<td>~5</td>
<td>130</td>
<td>600</td>
<td>5000</td>
<td>26.8</td>
<td>38.8</td>
<td>260</td>
<td>15.5</td>
</tr>
<tr>
<td>Xe</td>
<td>~4</td>
<td>125</td>
<td>700</td>
<td>5000</td>
<td>26.8</td>
<td>44.0</td>
<td>260</td>
<td>16</td>
</tr>
</tbody>
</table>

FIG. 7. Evolution of MRT instability from $t = 160$ ns (top) to $t = 170$ ns (bottom) in each configuration. From left to right: Ne/D, Ar/D, Kr/D, Xe/D. Axially-averaged $B_0$ lineouts are overlaid.
Kr. 2-D simulations also show that MRT instability penetration at peak compression is inevitable, necessitating the use of a mitigation mechanism in future work.

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