Observation of Shock-Front Separation in Multi-Ion-Species Collisional Plasma Shocks

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We observe shock-front separation and species-dependent shock widths in multi-ion-species collisional plasma shocks, which are produced by obliquely merging plasma jets of a He/Ar mixture (97% He and 3% Ar by initial number density) on the Plasma Liner Experiment [S. C. Hsu et al., IEEE Trans. Plasma Sci. 46, 1951 (2018)]. Visible plasma emission near the He-I 587.6-nm and Ar-II 476.5–514.5-nm lines are simultaneously recorded by splitting a single visible image of the shock into two different fast-framing cameras with different narrow bandpass filters (589 ± 5 nm for observing the He-I line and 500 ± 25 nm for the Ar-II lines). For conditions in these experiments (pre-shock ion and electron densities ≈ 5 × 10^{14} cm^{−3}, ion and electron temperatures of ≈ 2.2 eV, and relative plasma-merging speed of 22 km/s), the observationally inferred magnitude of He/Ar shock-front separation and the shock widths themselves are < 1 cm, which correspond to ~ 50 post-shock thermal ion–ion mean free paths. The experiments are in reasonable qualitative and quantitative agreement with results from 1D multi-fluid simulations using the CHICAGO code. Moreover, the experiment and simulation results are consistent with theoretical predictions that the lighter He ions diffuse farther ahead within the overall shock front than the heavier Ar ions.

I. INTRODUCTION

Supersonic flows generate shocks in astrophysics, aerodynamics, and high-energy-density (HED) plasma experiments. Compared to hydrodynamic shocks in neutral gases, collisional plasma shocks contain ion and electron species, arise due to Coulomb collisions, and are influenced by electromagnetic fields. A plasma shock front with multiple ion species contains additional structure compared to a single ion plasma shock. Prior experiments, simulations, and theoretical work explored multi-ion-species effects in the context of inertial confinement fusion (ICF), for which species separation in the fusion fuel potentially leads to neutron yield degradation. Interspecies ion separation and velocity separation were experimentally observed. Additional simulation and theoretical research on multi-ion-species plasmas examined how ion species diffusion causes species separation. The present research reports direct observations of the spatial profile of a multi-ion-species shock, showing shock-front separation and species-dependent shock widths in collisional plasma shocks. The experimental results agree with 1D multi-fluid simulations using the CHICAGO code. These experimental and simulation results are both consistent with ion species diffusion theory. This fundamental experimental data can be used to validate and benchmark numerical simulations of plasma environments with multi-ion-species collisional plasma shocks, especially in HED, magneto-inertial-fusion (MIF), and ICF experiments.

The organization of this paper is as follows: Sec. II provides background on the ion diffusion theory to which we compare our results. Sec. III describes the experimental setup of colliding plasma jets to generate a shock. Sec. IV presents results from the experimentally observed shock profiles, Sec. V overviews the relevant length scales in our experiments, Sec. VI discusses the agreement between the multi-fluid simulations and the experiments.

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II. BACKGROUND ON ION DIFFUSION THEORY

Theory and simulations about interspecies ion diffusion predict that lighter ions diffuse farther ahead within a collisional plasma shock (closer to the pre-shock region) than heavier ions.[11,12,14–18,24–28,30] Following Kagan and Tang,[24] in the center-of-mass frame of a multi-ion-species fluid element, the diffusion flux $\bar{f}_1$ of the lighter species 1 (in our case, He) equals the negative flux $\bar{f}_2$ of the heavier species 2 (in our case, Ar),

$$\bar{f}_1 = \rho_1 \bar{v}_{D_1} = -\bar{f}_2 = -\rho_2 \bar{v}_{D_2},$$

with mass densities $\rho_1$, $\rho_2$, and diffusion velocities $\bar{v}_{D_1}$, $\bar{v}_{D_2}$. The diffusion flux is related to the species mass concentration time evolution (continuity equation),

$$\rho \frac{\partial c_{m1}}{\partial t} + \rho \bar{u} \cdot \nabla c_{m1} + \nabla \cdot \bar{f}_1 = 0,$$

with total mass density $\rho$, species 1 mass concentration $c_{m_1} = \rho_1/\rho$, and bulk fluid velocity $\bar{u}$. The diffusion flux of the lighter species can be written as

$$\bar{f}_1 = -\rho D \nabla c_{m1} - \rho D \left( \frac{\kappa_P}{P_i} \nabla P_i \right) - \rho D \left( \frac{\kappa_T}{T_i} \nabla T_i + \frac{\kappa_{Te}}{T_e} \nabla T_e \right) - \rho D \left( \frac{e \kappa_e}{T_i} \nabla \Phi \right),$$

where the first term is the classical diffusion flux based on the mass concentration gradient, the second term is the barodiffusion flux based on the ion pressure gradient, the third term is the thermodiffusion flux based on the ion and electron temperature gradients, and the fourth term is the electrodiffusion flux based on the electric field (negative gradient of the electric potential). The new variables in Eq. (3) are the classical diffusion coefficient $D$, barodiffusion ratio $\kappa_P$, total ion pressure $P_i$, ion thermodiffusion ratio $\kappa_T$, electron thermodiffusion ratio $\kappa_{Te}$, ion temperature $T_i$ (approximating as equal for each species), electron temperature $T_e$, and electric potential $\Phi$.

Within a shock front, the gradients of pressure, temperature, and electric potential point in the direction from the pre-shock region toward the post-shock region.[2] Additionally, for the He/Ar mixture in our experimental shocks, the various diffusion fluxes have the same sign except for the relatively small electron thermodiffusion, as described in Sec. VII. We also assume no initial concentration separation. Therefore, in the center-of-mass frame, Eqs. (1) and (3) predict that the lighter species diffusion velocity $\bar{v}_{D_1}$ points in the direction from the post-shock region toward the pre-shock region, and the heavier species diffusion velocity $\bar{v}_{D_2}$ points in the opposite direction. In the present research, we directly observe the spatial profile of a plasma shock front containing a He/Ar mixture, offering the opportunity to validate models of multi-ion-species shock evolution based on the theory.

III. EXPERIMENTAL SETUP

In order to experimentally observe shock-front separation in multi-ion-species collisional plasma shocks, we form the shocks by merging two plasma jets, and we image the different species within the shock profiles using distinct narrow bandpass filters. In this section, we describe this experimental setup.
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FIG. 1. (Left) View 1: Projection of experimental setup, including approximate diagnostic views. Plasma guns mounted on the spherical vacuum chamber launch plasma jets toward the chamber center in the direction shown by the red dashed lines. (Right) View 2: Corresponding schematic with a 90° out-of-page rotation of View 1. Not to scale.

We experimentally create multi-ion-species plasma shocks by colliding plasma jets generated from plasma guns in a 2.7-m-diameter spherical vacuum chamber. Figure 1 depicts the experimental setup. Within the gun nozzle, a gas puff is pre-ionized into a plasma, and that plasma is accelerated by a 720 kA, 4.5 kV, 5 µs rise-time pulse. Initially, the gas puff atomic concentration, $c_a$, is 97% He and 3% Ar, corresponding to a mass concentration, $c_m$, of 76.4% He and 23.6% Ar. As the plasma jets propagate toward the chamber center, they expand in vacuum at approximately the sound speed. The two plasma jets merge at a half-angle of 11.6°, with speeds of 55 ± 5 km/s corresponding to 11 km/s in the direction normal to the shock and, therefore, a relative normal speed between the jets of $v_{rel} = 22$ km/s. Before the shock formation, individual jets have electron number densities $n_e \approx 5 \pm 1 \times 10^{14}$ cm$^{-3}$, electron and ion temperatures $T_e \approx T_i \approx 2.2^{+0.2}_{-0.5}$ eV, and inferred average ionization states $\bar{Z}$ of 0.73$^{+0.15}_{-0.67}$ for He and 1.15$^{+0.23}_{-0.16}$ for Ar. These parameters give pre-shock Mach numbers $M = v_{rel}/[\gamma(ZT_e + T_i)/m_i]^{1/2}$ of 1.7 for He ions, 5.1 for Ar ions, and an average $M = 1.8$, where we assume $\gamma = 5/3$ and a minimum ion $\bar{Z} = 1$. The jets have characteristic scale lengths of ~10 cm. Since the interspecies mean free path is much smaller than this overall characteristic length scale (see Sec. V), the He and Ar should act as a single fluid in the absence of gradients, i.e. pre-shock. The plasma parameters are measured with diagnostics including a photodiode array to infer jet velocity via time-of-flight, time-resolved interferometry for density, and emission spectroscopy for temperature and ionization states (data are compared with PRISMSPECT non-local-thermodynamic-equilibrium (non-LTE) atomic-modeling calculations, as used in earlier research). Figure 2 displays the experimental temperature and density diagnostic results. The density measurement uncertainty is based upon estimates of the path length. As listed in Table I, these pre-shock, experimentally inferred parameters are used to interpret the experimental observations and as input for simulations.

The shock profiles of the different ion species are imaged using a beam splitter to aim the plasma self-emission onto two intensified-charge-coupled-device (ICCD) cameras (10-ns exposure) with narrow bandpass filters. Singly ionized Ar-II line emission (near the Ar-II 476.5–514.5-nm lines) is observed with a 500 ± 25-nm filter, and neutral He-I line emission (near the He-I 587.6-nm line) is observed with a 589 ± 5-nm filter. A filter for singly ionized He-II line emission was not used due to the better ICCD camera sensitivity to visible compared to ultraviolet wavelengths and the presence of other stronger lines (Ar-II and/or He-I) near the visible He-II lines. Figure 3 illustrates how the distinct filters are sensitive to the different ion species, based on reference experiments using single-ion-species plasma jet merging. For the 100%-Ar jet merging, the bright region in the Ar-II filtered image correlates to an increase in singly ionized Ar emission. For the 100%-He jet collision,
IV. EXPERIMENTAL SHOCK PROFILE RESULTS

By imaging the experimental shocks, we can infer spatial separation of the ions within the shock profiles. Our spatially resolved shock profiles also allow us to observe different shock widths for the different species.

The top 4 rows in Fig. 2 show the time evolution of the merging of multi-ion-species plasma jets, observing the plasma self-emission using the Ar-II and He-I narrow bandpass.

dark bands in the He-I filtered image correlate to a reduction in neutral He emission and a corresponding increase in He ionization. Thus, using these filters, we can separately image the shock profiles of the different ion species.
TABLE I. Pre-shock and (simulation) post-shock parameters.

| Parameter               | Pre-shock | Post-shock |
|-------------------------|-----------|------------|
| Electron Temperature (eV) | 2.2       | 2.4        |
| Electron Density ($\times 10^{14}$ cm$^{-3}$) | 5         | 21         |
| He Temperature (eV)     | 2.2       | 4.6        |
| Ar Temperature (eV)     | 2.2       | 5.5        |
| He Average Ionization $\bar{Z}$ | 0.73     | 0.89       |
| Ar Average Ionization $\bar{Z}$ | 1.15     | 1.47       |
| He Atomic Concentration $c_{a1}$ | 97%      | 95.8%      |
| Ar Atomic Concentration $c_{a2}$ | 3%       | 4.2%       |
| He Mass Concentration $c_{m1}$ | 76.4%    | 69.6%      |
| Ar Mass Concentration $c_{m2}$ | 23.6%    | 30.4%      |

FIG. 3. To establish a baseline, time-gated images (10-ns exposure) of single-ion-species plasma jet merging using narrow bandpass filters are shown. The 100%-Ar (left column) and 100%-He (right column) plasma shocks are much more prominently observed using the Ar-II and He-I filters, respectively. Red dashed arrows show the direction of individual plasma jet propagation toward the chamber center. Jet merging and shock generation occur near the centers of the images. In the bottom left image, dots correspond to the intersection locations of the jet collision plane with the spectroscopy (purple) and interferometry (green) lines of sight. The listed counts are over the whole image, for which 4096 counts is fully saturated.

Due to diagnostic limitations, the time sequence is composed of images from different experimental shots, rather than images from multiple times during a single experimental shot. The jets originate from the top left and bottom left in the images, and they merge near the image center. The 0 $\mu$s time is defined as the time when we observe the jets first starting to merge and form a shock structure. As the time sequence progresses, the individual jets continue to propagate at 11 km/s inward (toward image horizontal center) and $\sim$54 km/s parallel to the shock front (toward the image right). The plasma emission intensity is a function of electron temperature $T_e$ and ion density $n_i$, with larger temperatures and larger densities leading to higher ionization states and correspondingly more emission. Qualitatively, we see the jets merging to form two intensity peaks originating a finite distance away from the image center. This double-peaked shock profile has been observed in prior work studying single-ion-species plasma jet collisions with a similar plasma gun setup.\[35,36\]

The bottom row in Fig. 4 displays the spatial profile of the shock structure produced by merging multi-ion-species plasma jets, which are directly imaged using the narrow band-
FIG. 4. (Top 4 rows) Multi-ion-species plasma jet merging time evolution images of plasma self-emission using the Ar-II and He-I filters. Times defined such that $t = 0$ is the time at which the jets are first starting to merge. (Bottom row) Lineouts from the 2 $\mu$s images (in top rows) for the Ar-II (blue line) and He-I (red line) filtered images; peak Ar-II intensity is at intensity of 1, and peak He-II intensity is at intensity of 0. Horizontal bars show the shock widths: the distances between the 50%–90% intensity values. Shaded regions show the standard deviation of distance between peak ion intensities and the zero position.

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pass filters for Ar-II and He-I line emission. Normal to the shock front, we take lineouts with widths of 20 pixels (~1 cm). In the laboratory frame, the shock fronts are moving away from the zero position. Across the emission spatial profile, the lineout intensities are scaled between 0 (lowest emission) and 1 (peak emission). For the Ar-II filtered lineout, 0 corresponds to background (lowest emission of singly ionized Ar), and 1 corresponds to the peak singly ionized Ar emission. For the He-I filtered lineout, 1 corresponds to background (peak emission of neutral He), and 0 corresponds to peak singly ionized He emission (lowest emission of neutral He). Using these lineouts, we infer the shock-front separation between the peak intensities of Ar and He ions, showing that the He has moved farther ahead of
the shock (closer to the pre-shock region) than the Ar. Additionally, we observe the shock width (horizontal bars in the bottom row of Fig. 4 near the −2 cm position), which we approximate by the transition distance between the middle and peak intensity, here taken as 50%–90% of the peak value. The 50% and 90% values are chosen to reduce the influence of varying background levels and spurious pixel intensities on the measurements. These experimental results are obtained using the shock profile at 2 µs after the beginning of the plasma jet merging. This time is chosen by analyzing an image time sequence and correlating the density increase over time between the experimental time-resolved interferometry and the simulation results; see the bottom row of Fig. 2.

Using the shock profile lineouts and plasma parameters, we compare the length scales of our collisional plasma shocks. Taking statistics from 34 experimental shock-front profiles at the 2 µs time, we find a separation between the shock-front intensity peaks to be 0.68 ± 0.17 cm, a He shock width of 0.36 ± 0.09 cm (37 ± 9 post-shock He ion–ion mean free paths), and an Ar shock width of 0.52 ± 0.11 cm (57 ± 12 post-shock Ar ion–ion mean free paths). Additionally, we find the distance between the peak He ion intensity and the zero position to be 2.01 ± 0.33 cm, and the distance between the peak Ar ion intensity and the zero position to be 1.33 ± 0.17 cm; these distances are shown as the shaded regions in the bottom row of Fig. 4. Lastly, we find the ratio of the Ar shock width to He shock width to be 1.52 ± 0.34. These experimental uncertainty values are the shot-to-shot standard deviations. The experimental shock widths are in reasonable agreement to the theoretical prediction of >20 post-shock ion–ion mean free paths (for M < 2, 20) Furthermore, similar observations to our measurements of the ratios of shock widths for different species have been reported for neutral gas shocks [1].

V. COMPARISON OF SHOCK LENGTH SCALES TO MEAN FREE PATH AND INTERPENDENTRATION

Here, we compare the quantitative distances measured in the experiments to relevant length scales for the process of shock formation. This comparison allows us to better understand the physical picture.

Table I compares the characteristic length scale results for the multi-ion-species plasma jet merging. Post-shock length scales are calculated based on the following plasma conditions obtained from simulations (Sec. VI) and listed in Table I: peak electron number density \( n_e = 2.1 \times 10^{15} \text{ cm}^{-3} \), peak \( T_e = 2.4 \text{ eV} \), peak \( T_{i,\text{He}} = 4.6 \text{ eV} \), peak \( T_{i,\text{Ar}} = 5.5 \text{ eV} \), and average ionization states \( Z \) of 0.89 for He and 1.47 for Ar. The post-shock mean free path for an ion (unprimed) colliding with multiple ion species (primed) [37,15]

\[
L_{mf,p,i} = \sum_i \left( \frac{n_i}{n_{\text{tot},i}} \right) \nu_{e,i}' \tag{4}
\]

with thermal velocity \( v_{th,i} \) and energy loss collision rate \( \nu_{e,i}' \). Since we are not in the fast or slow limit, we use the exact collision-rate formula [37]. In this formula, because we add contributions from individual ion species with discrete ionization states, \( Z \), rather than using an average \( Z \), the collision rate is weighted by the individual species number density fraction \( n_i/n_{\text{tot},i} \). We compare the experimentally inferred shock width (as defined above in Sec. IV) to the ion–ion mean free path rather than to the electron–ion mean free path because the density jump and ion temperature jump within a shock front is predicted to occur over a distance of a few ion–ion mean free paths, while the electron temperature jump is predicted to occur over a (longer) distance of a few electron–ion mean free paths [37]. Furthermore, we calculate that the ion collision rates are dominant compared with the neutral collision rates \( \nu_n \approx n_n \pi d_n^2 v_{th,n} \), where \( d_n \) is the approximate Van der Waals atomic diameter, and also with the neutral charge exchange collision rates \( \nu_{CE} \approx n_n \sigma_{CE} v_{th,n} \), where \( \sigma_{CE} \approx 3 \times 10^{-15} \text{ cm}^2 \) is the charge exchange cross section [39,100].

The ion–ion interpenetration length is the pre-shock slowing distance over which ions from an individual jet (test particle, unprimed) will stream through the other jet (field
TABLE II. Plasma-jet-merging length scales.

| Length scale (cm) | He | Ar |
|-------------------|----|----|
| He-Ar shock-front separation (exp.) | 0.68 | |
| He-Ar shock-front separation (sim.) | 0.50 | |
| Shock width (exp.) | 0.36 | 0.52 |
| Shock width (sim.) | 0.44 | 0.57 |
| Post-shock mean free path (Eq. 4) | 0.0097 | 0.0092 |
| Jet characteristic size | 10 | 10 |
| Pre-shock interpenetration (Eq. 5) | 0.058 | 0.740 |

particles, primed) before becoming collisional.\cite{36,37,39,40,47,48,51}

\[ L_{s,i} = \frac{v_{rel}}{4 \sum_{i'} \left( \frac{n_{i}}{n_{\text{tot},i}} \right) \nu^{i,i'}_{s}} \]

with relative velocity \( v_{rel} \) and slowing-down collision rate \( \nu^{i,i'}_{s} \). Again, we use the entire collision-rate formula.\cite{47} In our parameter space, the ion–ion slowing dominates over ion–electron slowing, and thus the latter is ignored. Because our jet size is much larger than the interpenetration distance, the merging of the two supersonic plasma jets produces a shock.

VI. SIMULATION SHOCK PROFILE RESULTS

We now compare the shock profile and lengths obtained in the experiment to simulation results. The simulations reasonably agree with the experimental observations, although there is some disagreement in the post-shock region.

We have successfully employed multi-fluid simulations, using the CHICAGO code\cite{31,33} in which each plasma jet is modeled as a separate ion fluid that can contain different species, to model the plasma collision\cite{35,39,40}, including the interpenetration effects described in Sec. V. CHICAGO is a hybrid particle-in-cell code with the capability to model both ions and electrons as fluid species.\cite{31} The code may also be run in a magnetohydrodynamic (MHD) mode in which electron inertia is neglected. In the present research, the multi-ion MHD approach was found to generate identical results as those of lengthier simulations with electron inertia retained. For the 1D simulation presented in this work, the two jets are given an initial density profile, temperature, and velocity based on input from experimental measurements. The simulation grid cell length is 0.06 cm, and the shock profile results are similar to results from a simulation with a 0.015 cm grid cell length. PROPACEOS non-LTE data are used for the ion equations of state and opacities.\cite{43} Collisionality between ions and electrons is determined by a Spitzer model. At initial temperatures below 2 eV, there was no discernible interaction between the colliding jets.

The CHICAGO 1D multi-fluid simulations agree with the experimental results, showing: shock-front separation, He diffusing farther ahead of the shock (closer to the pre-shock region) than Ar, and different shock widths for different ions. Figure 5 displays the simulated densities and temperatures, respectively, for He and Ar in the individual plasma jets coming from the left and right (dashed and solid lines) at 2 \( \mu \)s after the jets start to merge. We use these individual jet shock profiles to obtain the following quantities. Simulations indicate a separation between the shock-front density peaks to be 0.50 ± 0.12 cm, a He shock width of 0.44 ± 0.12 cm (45 ± 12 post-shock He ion-ion mean free paths), and an Ar shock width of 0.57 ± 0.12 cm (62 ± 13 post-shock Ar ion-ion mean free paths). Additionally, we find the distance between the peak He ion intensity and the zero position to be 1.51 ± 0.06 cm, and the distance between the peak Ar ion intensity and the zero position to be 1.01 ± 0.06 cm. We also find the ratio of the Ar shock width to He shock width to be 1.29 ± 0.45. The simulation uncertainty values are based upon the 0.06 cm simulation resolution. Except for the distances between the peak intensities and the zero position, these simulation quantities agree with the experimental data.
While the experiments and simulations quantitatively agree within uncertainty bars regarding the magnitude of the shock-front separation and the He and Ar shock widths, the simulations predict a single-peaked shock structure near the collision center rather than the double-peaked and wider post-shock region observed in the experiments; see the dotted lines in the top row of Fig. 5 compared to the bottom row of Fig. 4. This difference correlates with the smaller distance between the center zero position and the ion density peaks found in the simulation compared to the experiments. As shown in the top row of Fig. 6, we use SPECT3D software to obtain synthetic intensity lineouts of the CHICAGO simulation density and temperature parameters. This synthetic intensity lineout does not reproduce the experimentally observed double-peaked shock profile or the decreases in relative intensity near the zero position for either Ar-II or He-I filter. Still, as shown in the bottom row of Fig. 6, the average ionization values for both species are increasing in the post-shock region near the center position of the plasma jet merging, as is expected. These differences in the post-shock region between experiments and simulation will be further assessed in future work. Possible sources of this discrepancy include the models of collisionality and thermal conduction in the post-shock region used in the simulations. Additionally, the simulation does not capture time-dependent effects of ionization and/or recombination during the transient process of shock formation, as is present in the experiments.
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FIG. 6. (Top) Synthetic intensity lineouts of plasma self-emission using the Ar-II (500 ± 25 nm) and He-I (589 ± 5 nm) filters with spect3D\textsuperscript{43}. Inputs for these intensities are the simulation total densities and temperatures shown in Fig. 5. Comparing with Fig. 4, the synthetic lineouts do not depict the experimentally observed double-peaked intensity feature. (Bottom) The ionization fractions of neutral He (He I), singly ionized He (He II), singly ionized Ar (Ar II), and doubly ionized Ar (Ar III) corresponding to the above synthetic intensity lineouts. The average ionization values for both He and Ar increase near the center post-shock region, despite the He-I filter intensity remaining large.

VII. DOMINANCE OF BARODIFFUSION IN THE PRESENT WORK

The shock-front separation results are consistent among the experiments, simulations, and theoretical predictions of ion species diffusion. In this section, we quantitatively estimate the expected species concentration change within the shock and calculate the relative contributions of the different diffusion mechanisms, showing that barodiffusion dominates in the present research.

As stated earlier in Sec. II: within a shock front, theory predicts that the lighter ion diffusion velocity (in the center of mass frame) points toward the pre-shock region, and the heavier ion diffusion velocity points in the opposite direction. This prediction is qualitatively consistent with our experimental and simulation results for the He/Ar mixture. The interspecies ion diffusion should change the relative species concentration. Experimentally, we did not directly measure the species concentration along the shock profile, but the simulations show interspecies ion diffusion. Compared to the initial condition of 97% He and 3% Ar atomic concentrations [76.4% He and 23.6% Ar mass concentrations], in the top row in Fig. 5 we find a minimum He atomic concentration in the post-shock region (corresponding to the zero position) of 95.8% [69.6% He mass concentration], and we find a maximum He atomic concentration at the shock front closer to the pre-shock region (corresponding to the ± 2.5 cm position) of 97.7% [80.7% He mass concentration].

We now quantitatively explore the effects of different diffusion flux terms on the species concentration. The diffusion terms depend upon the species concentration, masses, num-
ber densities, ionization states, and temperatures. The pre-shock and post-shock plasma parameters are listed in Table I. The goal of the following calculations are to serve as order-of-magnitude estimates to show consistency between the theory, experiments, and simulations. First, assuming no initial concentration separation for simplicity, we take \( \nabla c_{m1} = 0 \) in Eq. 2 and Eq. 3. We also approximate \( \partial t = 2 \mu s \). Taking a characteristic length scale as the shock width \( L_{SW} \approx 0.4 \text{ cm} \), we estimate \( \nabla = 1/L_{SW} \). Therefore, for a quantity \( Q \) in Eq. 3 we have \( (\nabla Q)/Q \approx (1/L_{SW})(Q_{post-shock} - Q_{pre-shock})/Q_{pre-shock} \). For our He/Ar mixture, we then calculate the diffusion coefficients to be \( D = 600 \text{ cm}^2/\mu s \), \( \kappa_p = 1.3 \), \( \kappa_i = 0.5 \), \( \kappa_T \approx -1 \), and \( \kappa_e = 1.3 \).\(^{24,28,52,53}\) See Appendix A for expressions for the diffusion coefficients. We also estimate the ambipolar electric field \( \nabla \phi \approx \nabla T_e/e \).\(^{54,55}\) Therefore, the relative contributions for each diffusion mechanism (the quantities in parentheses in Eq. 3) are 25.2 cm\(^{-1}\) for barodiffusion, 1.1 cm\(^{-1}\) for thermodiffusion (1.4 cm\(^{-1}\) for ion thermodiffusion and -0.2 cm\(^{-1}\) for electron thermodiffusion), and 1.7 cm\(^{-1}\) for electrodifferentiation. Starting with a He concentration \( c_{m1} = \rho_1/\rho = 76.4\% \), in Eq. 1 we obtain a He diffusion speed \( v_{D1} = 2.2 \times 10^{-2} \text{ cm/\mu s} \), corresponding in Eq. 2 to a change in concentration of \( \partial c_{m1} = 8.4\% \). This estimated calculation result is in reasonable agreement with the simulation concentration change from the above paragraph. Furthermore, these estimates show that barodiffusion is the dominant diffusion mechanism in the present research that causes the shock-front separation. This result contrasts with prior ICF experiments, for which the ion thermodiffusion mechanism dominated.\(^{19,20}\) Additional experimental testing and validation of the theory can be achieved by changing the species concentrations, which influence the contributions of the various diffusion mechanisms.

VIII. CONCLUSION

Within a collisional multi-ion-species plasma shock front containing 97% He and 3% Ar, we experimentally observe shock-front separation and species-dependent shock widths. Experiments, 1D multi-fluid plasma simulations, and theoretical predictions are all consistent in showing that the lighter He ions diffuse farther ahead within the overall shock front than the heavier Ar ions. The experimental shock profiles of different ion species were directly imaged using narrow bandpass visible wavelength filters. Multi-fluid plasma simulations allowed for reasonably accurate modeling of the plasma jet merging and multi-ion-species effects. The fundamental experimental data in the present work can be used to validate models and benchmark numerical simulations of multi-ion-species collisional plasma shocks of relevance to HED, MIF, and ICF experiments. Additional work can be performed to obtain species concentration measurements at multiple points across the shock profile during a single experimental shot. These measurements will likely require a more detailed spectroscopic study of the emission line ratios in comparison with the PRISMSPect atomic modeling calculations. More experiments can be conducted in order to acquire data for other times during the shock propagation, which can provide information about time-dependent effects during the process of shock formation including ionization, recombination, and kinetic (non-Maxwellian) effects.

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Appendix A: Diffusion Coefficient Calculations

For reference, we list the equations to determine the diffusion coefficients, where subscript “1” refers to the lighter ion species with mass $m_1$, and subscript “2” refers to the heavier ion species with mass $m_2$. The classical diffusion coefficient, $D$, is

$$D = \frac{\rho T_i}{A_{12}\mu_{12}\nu_{12}} \times \frac{c_{m1}(1 - c_{m1})}{c_{m1}m_2 + (1 - c_{m1})m_1} \tag{A1}$$

where the new variables are the transport coefficient $A_{12}$ ($\sim 1$, here) and reduced mass $\mu_{12} = m_1m_2/(m_1 + m_2)$. The collision frequency $\nu_{12}$ is the energy loss collision rate. Next, the barodiffusion ratio, $\kappa_p$, is

$$\kappa_p = c_{m1}(1 - c_{m1})(m_2 - m_1)(\frac{c_{m1}}{m_1} + \frac{1 - c_{m1}}{m_2}) \tag{A2}$$

The electrodiffusion ratio, $\kappa_e$, is

$$\kappa_e = m_1m_2c_{m1}(1 - c_{m1})\left(\frac{c_{m1}}{m_1} + \frac{1 - c_{m1}}{m_2}\right)\left(\frac{Z_1}{m_1} - \frac{Z_2}{m_2}\right) \tag{A3}$$

The ion thermodiffusion ratio, $\kappa_{Ti}$, is

$$\kappa_{Ti} = m_1m_2\left(\frac{c_{m1}}{m_1} + \frac{1 - c_{m1}}{m_2}\right)\left(c_{m1}B_{11} + \frac{(1 - c_{m1})B_{12}}{m_1}\right) \tag{A4}$$

and the electron thermodiffusion ratio, $\kappa_{Te}$, is

$$\kappa_{Te} = m_1m_2\left(\frac{c_{m1}}{m_1} + \frac{1 - c_{m1}}{m_2}\right)\left(c_{m1}Z_1 + \frac{(1 - c_{m1})Z_2}{m_2}\right)$$

$$\times \left[\frac{(1 - c_{m1})B_{1e} - c_{m1}B_{2e}}{T_i} \frac{T_e}{T_i}\right] \tag{A5}$$

where $B_{11}, B_{12}, B_{1e},$ and $B_{2e}$ are transport coefficients that can be evaluated numerically. The electron thermodiffusion ratio, $\kappa_{Te}$, can also be written as

$$\kappa_{Te} = -Z^2_{eff}c_{m1}(1 - c_{m1})(c_{m1} + (1 - c_{m1})\frac{m_1}{m_2})$$

$$\times \left(\frac{m_2}{m_1}\frac{Z_2^2}{Z_1^2}\frac{T_e}{T_i}\frac{\beta_0}{Z_{eff}}\right) \tag{A6}$$

where the coefficient $\beta_0$ is

$$\beta_0 = \frac{30Z_{eff}(11Z_{eff} + 15\sqrt{2})}{217Z_{eff}^2 + 604\sqrt{2}Z_{eff} + 288} \tag{A7}$$

where $Z_{eff}$ is

$$Z_{eff} = \frac{n_1Z_1^2 + n_2Z_2^2}{n_1Z_1 + n_2Z_2} \tag{A8}$$

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