Experimental Characterization of the Stagnation Layer between Two Obliquely Merging Supersonic Plasma Jets

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We present spatially resolved measurements characterizing the stagnation layer between two obliquely merging supersonic plasma jets. Intra-jet collisionality is very high (λii ≪ 1 mm), but the inter-jet ion–ion mean free paths are on the same order as the stagnation layer thickness (a few cm). Fast-framing camera images show a double-peaked emission profile transverse to the stagnation layer, with the central emission dip consistent with a density dip observed in the interferometer data. We demonstrate that our observations are consistent with collisional oblique shocks.

Colliding plasmas have been studied in a variety of contexts, e.g., counterstreaming laser-produced plasmas supporting hohlraum design for indirect-drive inertial confinement fusion [1–3], forming and studying astrophysically relevant shocks [4–8], and for applications such as pulsed laser deposition [9] and laser-induced breakdown spectroscopy [10]. Physics issues arising in these studies include plasma interpenetration [11–16], shock formation [17–19], and the formation and dynamics of a stagnation layer [14, 20]. In this work, we present experimental results on two obliquely merging supersonic plasma jets, which are in a different and more collisional parameter regime than many of the colliding plasma examples mentioned above. Ours and other recent jet-merging experiments [21–23] were conducted to explore the feasibility of forming imploding spherical plasma liners via an array of merging plasma jets [24–26], which could have applications in forming cm-, μs-, and Mbar-scale plasmas for fundamental high-energy-density-physics studies [27] and as a standoff driver for magnetoinertial fusion [28–30]. Prior experiments studying the stagnation layer between colliding laser-produced or wire-array z-pinch [31] plasmas were on smaller spatial scales (mm or smaller) that could not be fully resolved by measurements. New results in the present work are the experimental identification and characterization of a few-cm thick stagnation layer between colliding plasmas, and the demonstration that our observations are consistent with hydrodynamic oblique shock theory [32].

Experiments reported here are conducted on the Plasma Liner Experiment (PLX) [33], in which two supersonic argon plasma jets are formed and launched by plasma railguns [34]. Plasma jet parameters at the exit of the railgun nozzle (peak n_e ≈ 2 × 10^16 cm^-3, peak T_e ≈ 1.4 eV, V_{jet} ≈ 30 km/s, Mach number M ≈ V_{jet}/C_{s,jet} ≈ 14, diameter = 5 cm, and length ≈ 20 cm) and their evolution during subsequent jet propagation have been characterized in detail [34]. The jet magnetic field inside the railgun is B ≈ 3 T, but the classical magnetic diffusion time is a few μs [35], and thus we ignore the effects of a magnetic field by the time of jet merging (> 20 μs). Experimental data are from an eight-chord laser (561 nm) interferometer [36–38], a visible-to-near-infrared 0.275 m survey spectrometer (600 lines/mm grating and 0.45 μs gating on the 1024-pixel MCP array detector), and an intensified charge-coupled device (CCD) visible-imaging camera (DiCam Pro, 1280 × 1024 pixels, 12-bit dynamic range). The interferometer and spectrometer chords intersect the merging jets at Z ≈ 84 cm (Fig. 1). Interferometer probe beams (diameter ≈ 3 mm) are each separated by 1.5 cm transverse to the merge plane. The spectrometer has an ≈ 7 cm diameter field-of-view in the vicinity of the merge plane. More details about the experimental setup are given elsewhere [35].

Figure 2 shows the time evolution of oblique jet merging. Formation of a stagnation layer between the two jets and its double-peaked emission profile in the transverse (R) direction are clearly visible. We made interferometer and spectrometer measurements of the stagnation layer at Z ≈ 84 cm (Fig. 3a) for the cases of top-only, bottom-only, and both jets firing. Figure 3b
shows the interferometer phase shift $\Delta \phi$ versus time at the $R = 2.25$ cm chord position for each case. Merged-jet measurements show that, at $R = 2.25$ cm, $\Delta \phi_{\text{merge}} > \Delta \phi_{\text{top}} + \Delta \phi_{\text{bottom}}$ (Fig. 3b), implying that simple jet interpenetration cannot account for the observed $\Delta \phi$ of the merged-jet stagnation layer (more quantitative analysis given later). However, at large $R$ (e.g., 6.75 cm), $\Delta \phi_{\text{interpenetration}} \approx \Delta \phi_{\text{top}} + \Delta \phi_{\text{bottom}}$ (not shown), consistent with jet interpenetration. Figure 3: shows $\Delta \phi$ vs. $R$ at four times for a merged jet. The $\Delta \phi$ dip at $R = 0.75$ cm and peak at $R = 2.25$–4 cm are well-aligned with the emission dip and peak (Fig. 3b), respectively.

The interferometer $\Delta \phi$ measurements are used to estimate the ion plus neutral density $n_{\text{tot}}$. Our interferometer is sensitive to bound and free electrons in the plasma \cite{38}, so $\Delta \phi$ contributions from all species and ionization states must be considered. The $\Delta \phi$ satisfies $\int n_{\text{tot}} \, dl = \frac{\lambda^2}{4 \pi} \frac{\Delta \phi}{\operatorname{Err}}$, where the integral is over the chord length, $C_e = \lambda^2/4 \pi e m_e c^2$ is the phase sensitivity to electrons, $Z_{\text{eff}} = n_e/n_{\text{tot}}$ is the mean charge, $\operatorname{Err} = \sum_{j,k} (2 \pi/\lambda C_e n_{\text{tot}}) K_{j,k} m_k n_{j,k}$ is the error in the phase shift due to all ionization states $j$ of all ion species $k$, $m_k$ is the atomic mass of ion species $k$, and $K_{j,k}$ is the specific refraction. Uncertainty in plasma jet composition (due to impurities) can be accounted for by bounding $n_{\text{tot}}$ at the extremes $\operatorname{Err} = 0$ and $\operatorname{Err} = \operatorname{Err}_{\text{max}} = (2 \pi m_e/\lambda C_e) K_{\text{max}}$, where $K_{\text{max}}$ is the largest specific refraction of all the species present. Since we do not know precisely the impurity fraction or mixture ratios of impurities, we perform our data analysis by considering the two extreme cases of (i) 100% argon and (ii) 30% argon with 70% impurities. The latter is chosen based on the difference in measured chamber pressure rise for gas-injection-only versus full plasma discharges. Identification of bright Al and O spectral lines in our data suggest that impurities are from the alumina-based railgun insulators. Thus, for case (ii), we approximate the plasma jet to be 43% O and 24% Al and assume that $\operatorname{Err}_{\text{max}} = \operatorname{Err}_{\text{Al}}$. Top-jet-only experiments provide single-jet $\Delta \phi$ vs. time at $R = 84$ cm and $R = 2.25$ cm (Fig. 3b). The average single-jet peak phase shift is $\Delta \phi = 4.3 \pm 0.3$° for the data considered (shots 1265–1267). All chord positions $R = 0.75$–11.25 cm (Fig. 3a) have similar $\Delta \phi \approx 4$°. Using $\Delta \phi = 4$°, $Z_{\text{eff}} = 0.94$ (inferred from spectroscopy analysis \cite{39} assuming 100% argon), $\operatorname{Err}_{\text{max}} = 0.082$, and a jet diameter of 22 cm (from CCD images \cite{39}), gives a single-jet density range of $n_{\text{tot}} = n_{\text{single}} = 2.1$–$2.3 \times 10^{14}$ cm$^{-3}$. The latter result changes by only a few percent for the 30%/70% mixture, which changes the inferred $Z_{\text{eff}}$ to 0.92.

By using the interferometry estimates for merged-jet density (shown later) and comparing our spectroscopy data with non-LTE spectral calculations using PrismSPECT \cite{39}, we infer $Z_{\text{eff}}$ and $T_e$ of the stagnation layer at $Z \approx 84$ cm. PrismSPECT results for $Z_{\text{eff}}$ and $T_e$ are sensitive to the specific plasma mixture used. Based on the presence of certain Ar $\Pi$ lines in the data and by comparing to PrismSPECT results, we bound estimates of $Z_{\text{eff}}$ and $T_e$ using the 100% argon and 30%/70% mixture cases. For the former (Fig. 3a), we infer that peak $T_e \geq 1.4$ eV and $Z_{\text{eff}} = 0.94$. For the latter (Fig. 3b), we
infer that $2.2 \text{ eV} \leq \text{peak } T_e < 2.3 \text{ eV}$ and $Z_{\text{eff}} = 1.3–1.4$, with the upper bounds determined by the absence of an Al III line in the data. For the mixture, $M \approx 9$ compared to $M \approx 14$ for pure argon.

With estimates of the stagnation layer $Z_{\text{eff}}$ in hand, we estimate the stagnation layer density and compare it with the single-jet (un-shocked) density. At $R = 2.25 \text{ cm}$, the average peak $\Delta \phi = 14.3 \pm 2.4^\circ$ (Fig. 3c) (shots 1117–1196). Using $\Delta \phi = 14^\circ$, chord path length of 22 cm, and $Z_{\text{eff}} = 0.94$ (100% argon case), $n_t = n_{\text{merged}} = 7.5–8.2 \times 10^{14} \text{ cm}^{-3}$. In this case the density increase $n_{\text{merged}}/n_{\text{single}} = 3.2–3.8$. For $Z_{\text{eff}} = 1.4$ (30%/70% mixture case), the stagnation layer density is $n_t = n_{\text{merged}} = 5.0–5.3 \times 10^{14} \text{ cm}^{-3}$, and the density increase is $n_{\text{merged}}/n_{\text{single}} = 2.1–2.5$. Thus, the observed range of $n_{\text{merged}}/n_{\text{single}} = 2.1–3.8$, exceeding the factor of two expected for jet interpenetration.

We compare the experimentally inferred density jumps with oblique shock theory [34]. At $Z \approx 84 \text{ cm}$ and $M = 9–14$, the theory predicts a shock angle $\beta \approx 19^\circ–20^\circ$, as discussed later. For $\gamma = 1.4$, the predicted density jump across an oblique shock [28] is $n_{\text{shock}}/n_{\text{unshocked}} = (M \sin \beta)^2/(M \sin \beta)^2(\gamma - 1) - 2) \approx 4.0–4.9$. Difference between the measured and predicted density jumps could be due to 3D (e.g., pressure-relief in the out-of-page dimension) and/or equation-of-state (e.g., ionization [22]) effects not modeled by the theory.

The stagnation layer thicknesses as observed in the merged-jet emission (Fig. 5) and $\Delta \phi$ vs. $R$ profiles (Fig. 3) are similar in scale (few cm). In a collisional plasma, the layer thickness is expected [14] to be of order the counter-streaming ion–ion mean free path (mfp) $\lambda_{\text{ii}} \approx v_{\text{rel}}/\nu_{\text{ii}}$ [22], where $v_{\text{rel}}$ is the relative transverse velocity between obliquely merging jets and the slowing down rate in the fast approximation ($v_{\text{rel}} \gg v_{\text{ii}}$) is $v_{\text{ii}} \approx 9.0 \times 10^{-8}(1/\mu_i + 1/\mu_i)\mu_i^{1/2}/e^{3/2}/n_i(Z_{\text{eff}} Z'_{\text{eff}})^2$ [40]. Note that in our parameter regime, the inter-jet $\lambda_{\text{ii}} \gtrsim \lambda_{\text{ii}}$. We estimate $\lambda_{\text{ii}}$ by considering jets of 100% argon and the 30%/70% mixture previously discussed, in all cases using $v_{\text{rel}} = 20 \text{ km/s}$. For Ar–Ar stopping, $\lambda_{\text{ii}} = 3.47 \text{ cm}$ (for $n_i = 8 \times 10^{14} \text{ cm}^{-3}$, $T_e = 1.4 \text{ eV}$, $Z_{\text{eff}} = 0.94$). Pure Al–Al and O–O stopping yield $\lambda_{\text{ii}} = 0.16$ and 0.62 cm, respectively (for $n_i = 5 \times 10^{14} \text{ cm}^{-3}$, $T_e = 2.2 \text{ eV}$, $Z_{\text{eff, Al}} = 2.0$, $Z_{\text{eff, O}} = 1.0$). For inter-species collisions in a mixed-species jet, using the mixture given in Fig. 4, $\lambda_{\text{ii}} \approx 0.57–6.18 \text{ cm}$. We have also estimated the inter-jet mfp due to Ar$^+-$Ar charge-exchange and momentum transfer [41] to be $\approx 3 \text{ cm}$. These estimates imply that our inter-jet merging is collisional, which is consistent with a more detailed treatment of inter-jet ion–ion stopping including jet profile effects [22].

Assuming that the emission layers are post-shocked plasma, we postulate that their edges (at larger $|R|$) are the shock boundaries (Fig. 6). Qualitatively, the merging geometry for an individual jet resembles that of a supersonic flow past a wedge [34] and should result in the formation of a linear attached shock at an angle $\beta$ with respect to the original flow direction. The angle $\beta$ is a function of $M$ and the wedge angle $\delta$ between the jet flow and the midplane, and satisfies $\tan \delta = 2 \cot \beta \left[ \frac{M_t^2 \sin^2 \beta - 1}{M_t^2 (\gamma + \cos 2\delta) + 2} \right]$ [34]. In our case, $\tan \delta = (23 \text{ cm})/Z_i$, where $Z_i$ is the point at which jets first interact. We estimated $Z_i$ from CCD images as the minimum $Z$ for which merged-jet emission is observed, with $Z_i = 45 \text{ cm}$ at $t = 26 \mu s$ evolving to $Z_i \approx 25 \text{ cm}$ at $t = 46 \mu s$. For this range of $Z_i$, we predict shock angles (relative to the midplane) $\beta - \delta \approx 8^\circ–17^\circ (M = 9)$ and $7^\circ–15^\circ (M = 14)$. For shot 1089 with $Z_i \approx 30 \text{ cm}$, $\beta - \delta \approx 5^\circ$ (Fig. 6), which.
is within a factor of two of the predicted $\beta - \delta \approx 9^\circ - 10^\circ$. This is reasonable given that the prediction does not include 3D nor equation-of-state effects. Oblique shock theory also predicts the formation of a detached shock, which would have a curved shock boundary for $\delta > \delta_{\text{max}} \approx 45^\circ$ (for $M = 9 - 14$ and $Z_i \approx 25$ cm at late times). CCD images at $t \geq 42 \mu s$ (Fig. 2) show curvature of the emission layers away from the midplane, suggestive of detached shocks.

To further evaluate the consistency of the observed stagnation layer structure with hydrodynamic oblique shock theory and to help interpret the emission profile dips seen in Figs. 2 and 5, we model the transverse dynamics of the oblique merging using 1D multi-fluid collisional plasma simulations of merging jets. We treat the electrons as one fluid and the ions of each jet as a second and third fluid, respectively, thus allowing for interpenetration between the two jets. Simulations were performed using the USim code (formerly called Nautilus). Algorithms on which USim is based have been verified against shock-relevant problems. In the simulations, the jets are assumed to be 100% Ar II with initial $n_e = n_i = 10^{14}$ cm$^{-3}$, $T_e = T_i = 1.4$ eV, and velocities of $\pm 30$ km/s (i.e., transverse component of $V_{\text{jet}} \approx 30$ km/s). We used a density profile in the leading edge of the jet as shown in the upper-left panel of Fig. 7. The simulation used a cell size of $\sim 100 \mu m$. Details of the semi-implicit numerical algorithm are described in [47]. As shown in Fig. 7 at 1 $\mu s$ after merging begins, there is a small initial density buildup at the midplane; the electrons are very highly collisional and the incoming electron fluid of each jet must pile up at the midplane. At $5 \mu s$, outward-propagating, sharp density jumps have formed, and a density dip appears at the midplane. The density jumps are consistent with reflected shocks in that the density jump ($\sim 3 \times$) and its propagation speed ($\sim 2.4$ km/s), as observed in the simulation, agree very well (within 5%) with Rankine–Hugoniot jump condition predictions using the upstream and downstream densities and pressures. The midplane density dip (consistent with the emission profile dip) arises to maintain pressure balance in the presence of midplane shock heating. The relatively slow reflected shock speed is consistent with the experimental observation in that the emission peaks do not move very far over $10 \mu s$. Finally, interpenetration between the two jets reaches $\sim 1$ cm (lower-right panel of Fig. 7), consistent with earlier estimates of inter-jet–ion collisional mfp $\sim 1$ cm. These comparisons support the interpretation that our experimental observations are consistent with collisional oblique shocks.

In summary, we have experimentally characterized the stagnation layer between two obliquely merging supersonic plasma jets. The jets are individually very highly collisional, but the inter-jet–ion collisional mfp is of order the stagnation layer thickness of a few centimeters. CCD images show the formation of a stagnation layer with a double-peaked emission profile transverse to the layer, with the central emission dip consistent with a density dip observed in the interferometer data. The geometry of the observed stagnation layer structure is consistent with hydrodynamic oblique shock theory. Furthermore, collisional 1D multi-fluid plasma simulations that model the transverse dynamics of the oblique merging show the formation and evolution of reflected shocks with a central density dip consistent with the observed stagnation layer emission profile dip. Ongoing experiments are now employing lower jet density and higher jet velocity to study head-on jet merging with very low inter-jet–ion collisionality.

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FIG. 6. CCD image (shot 1089, $t = 30 \mu s$) with postulated shock boundaries (solid white lines) and observed shock angle $\beta - \delta \approx 5^\circ$ relative to the midplane.

FIG. 7. Density profiles from a 1D multi-fluid collisional plasma simulation that models the transverse ($R$) dynamics of our oblique jet-merging experiments.
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