Impact of ablator thickness and laser drive duration on a platform for supersonic, shockwave-driven hydrodynamic instability experiments

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We discuss changes to a target design that improved the quality and consistency of data obtained through a novel experimental platform that enables the study of hydrodynamic instabilities in a compressible regime. The experiment uses a laser to drive steady, supersonic shockwave over well-characterized initial perturbations. Early experiments were adversely affected by inadequate experimental timescales and, potentially, an unintended secondary shockwave. These issues were addressed by extending the 4×10^{13} W/cm² laser pulse from 19 ns to 28 ns, and increasing the ablator thickness from 185 μm to 500 μm . We present data demonstrating the performance of the platform.

INTRODUCTION

Hydrodynamic instabilities play a dominant role in the transport of mass, momentum, and energy in nearly all plasma environments, including the corona of the sun [1], magnetospheric boundaries [2], and astrophysical jets [3, 4]. In past decades, the contribution of these processes to the intermixing of fluids was underestimated in high-energy-density systems such as core-collapse supernovae [5, 6] and fusion experiments [7, 8]. Since then, significant improvements have been made to experimental techniques, diagnostics, and simulation codes. Here, we discuss an experimental platform that can sustain a steady, supersonic flow over a precision-machined, well-characterized material interface for unprecedented durations.

This platform combines the strengths of two major techniques currently used to study hydrodynamic instabilities. Shock tube experiments can sustain steady, supersonic flows for long durations, but rely on statistical assumptions about the initial conditions at the material interface [9–11]. Laser-driven experiments can seed tightly-controlled perturbations into the material interface and obtain astrophysically relevant temperatures and pressures, but are limited by small data sets and, previously, have relied upon blast waves to drive the growth

of the hydrodynamic instabilities [12, 13]. This laser-driven platform creates a shockwave instead of a blast wave using an 19 to 28 ns laser pulse, driving the evolution of the instabilities with a different mechanism and resulting in a nominally time-invariant velocity that remains supersonic long enough for effects of compressibility to measurably impact the evolution of the instability [14].

This platform has been used to study the Richtmyer-Meshkov instability [15], the Kelvin-Helmholtz instability [14, 16], and their mutual interaction. For the purpose of this discussion, we will focus on early experiments investigating the Kelvin-Helmholtz instability. The Kelvin-Helmholtz instability is a process can produce vortical structures and turbulence in a system of fluids with strong velocity shear [17, 18]. In a supersonic flow, the instability growth is inhibited and the resulting structure is altered [14, 19]. This inhibition of the Kelvin-Helmholtz vortex growth rate, along with the two-vortex merger rate, are the core components needed to develop a comprehensive model for the evolution of the Kelvin-Helmholtz instability in a compressible flow, such as one would find in many astrophysical and engineering systems [1–8]. Both aspects are still poorly understood, and hold the motivation for the current work. The experimental platform discussed here provides, for

the first time, the capabilities to diagnose the effects of compressibility on the evolution of hydrodynamic instabilities from well-controlled seed perturbations.

This platform produced the first experimental observations of a well-characterized interface evolving under the effects of the Kelvin-Helmholtz instability in a steady, supersonic flow [16]. Obtaining these data required adjustments to optimize the original target design.

TARGET DESIGN AND METHODOLOGY

This experimental platform utilized the OMEGA-EP facility to produce a steady, supersonic flow across a well-controlled and well-characterized seed perturbation. The OMEGA-EP facility is unique in the world for having four independently operated, highly energetic lasers [20]. For the purpose of these experiments, the target is irradiated with two to three lasers at a wavelength of 351 nm. Each of these beams contained 4 kJ of energy in a 10 ns square pulse, except for a 1 ns transitioning ramp as one laser pulse ends and another, overlapping pulse begins. This 1 ns transition period mitigates any potential problems from laser timing errors, and results in a nominally 19-28 ns square pulse, over a 1.1 mm diameter spot size, with an average intensity $\sim 4 \times 10^{13}$ W/cm². Currently, OMEGA-EP is the only facility capable of producing this combination of high-energies and long pulse durations. The extended laser pulse maintains pressure on the drive surface in order to sustain a strong, steady shock through the system at maximum compression. This results in a system that can seed instability growth with tightly controlled initial perturbations in a nominally time-invariant supersonic flow.

Figure 1 shows a pre-experimental x-ray radiograph of a sample target. Starting from the left, we have a polycarbonate (PC) ($C_{16}H_{14}O_3$, $\rho = 1.1$ g/cm³) ablator. The lasers are incident upon this layer, and generate the initial shockwave. In the original experiment, the ablator was 185 μ m thick and irradiated with a 19 ns laser drive. In the subsequent experiment [16], the ablator was increased to 500 μ m and irradiated with a 28 ns drive. The PC ablator is followed by a 100 μ m thick layer of brominated plastic thermal insulator (CHBr) ($C_{50}H_{48}Br_2$, $\rho =$

1.2 g/cm³), which acts as a heat shield to prevent pre-heating of the materials that follow. The remainder of the target can be described as the “physics package,” and can be divided into a top half and a bottom half.

The top layer of the physics package is carbonized-resorcinol-formaldehyde foam (CRF) ($C_{1000}O_{48}H_{65}$, $\rho = 0.10$ g/cm³), which acts as our low-density fluid. Beneath it is an iodinated polystyrene tracer strip (CHI) ($C_{50}H_{47}I_3$, $\rho = 1.4$ g/cm³) embedded into a density-matched polyamide-imide block (PAI) ($C_{22}H_{14}O_4N_2$, $\rho = 1.4$ g/cm³), which together act as our high-density fluid. The iodinated plastic provides a narrow image plane that absorbs the majority of the Cu x-rays, while the surrounding polyamide-imide is highly transmissive to the Cu x-rays; this mitigates potential smearing of small-scale structure due to misalignment or edge effects. A 100 μ m wavelength, 5 μ m amplitude single-mode sinusoidal perturbation is machined into the surface of this plastic. Finally, a gold block rests between the thermal insulator and the heavier fluid, which slows down the lower half of the incoming shockwave such that it does not reach the plastic behind it on experimental timescales. This shock blocker maximizes our relative velocity and provides a clean start to the experiment, when the supersonic shear flow is first introduced over the machined perturbation.

FIG. 1: Radiograph by J. Cowan (LANL) showing the transmission of Cu x-rays through the different layers of the revised target. The thickness of the PC ablator has been increased from 185 μ m to 500 μ m.

The system reaches an Atwood number of ~ 0.8 and a convective Mach number of ~ 0.85 [14]. The convective Mach number, M_c , is defined as $\Delta u / (c_1 + c_2)$, where Δu is the relative velocity, and c is the speed of sound. From this definition, in the frame of reference of either fluid, the flow is said to be supersonic at $M_c \gtrsim 0.5$. The pressure of the shocked foam was experimentally inferred to be 0.63 ± 0.08 Mbar [16].

FIG. 2: 2D DAFNA simulation showing a density map of the experimental system at $t = 40$ ns. A 20 ns laser pulse is incident on a $200 \mu\text{m}$ thick PC ablator and $100 \mu\text{m}$ thick CHBr thermal insulator. A shockwave is driven through the foam, producing a strong, supersonic shear over a sinusoidal foam-plastic interface.

Figure 2 is a 2D design simulation of the anticipated system 40 ns after the laser drive begins [14]. This simulation was produced in DAFNA, a multi-material, HLLC-based Eulerian hydrodynamics code with interface tracking and adaptive mesh refinement capabilities. The simulation is initialized with a 1D Lagrangian radiation hydrodynamics code called HYADES [21]. The materials were treated as ideal gases with an adjustable adiabatic index; in this simulation, the adiabatic index was 1.67 for the CRF foam, and 2.1 for the PC ablator, CHBr insulator, and PAI plastic.

In Fig. 2, the shock is moving from the left to the right. As the shock propagates through the foam, a transmitted shock deflects the foam-plastic interface downwards. Along this deflected interface, the modulations begin evolving after the initial shock passes, and the steady, supersonic conditions cease once the thermal insulator that is entrained in the flow disturbs them. As such, the Kelvin-Helmholtz relevant region is said to be

what is downstream of the shockwave, yet upstream of the entrained material from the insulator and ablator. Modulations that are immediately behind the shock are in the early stages of evolution, whereas those at the downstream edge have been evolving for several times the characteristic evolutionary timescale of the instability [14, 22].

One final laser beam is used to irradiate a 1 mm diameter, $20 \mu\text{m}$ thick copper foil with 850 J of 1053 nm wavelength laser light, focused to a $200 \mu\text{m}$ diameter spot size in a 10 ps pulse, to generate x-rays for a spherical crystal imager diagnostic. The spherical crystal imager was used as an x-ray radiography diagnostic; x-rays propagate through the target to a bent crystal, designed to select out the transmission of Cu K_α radiation (8.0 keV) at a ~ 10 to $15 \mu\text{m}$ spatial resolution [23], and are then imaged onto a FujiTM MS image plate.

RESULTS AND DISCUSSION

The platform successfully produced the first data of hydrodynamic instability evolution in a steady, supersonic flow from well-characterized initial conditions [16]. However, changes needed to be made to the initial target design to improve the quality and consistency of this data. Figure 3 provides an example of data taken from two different Kelvin-Helmholtz instability campaigns. The first campaign, shown on the left, had a $185 \mu\text{m}$ thick PC ablator and 19 ns laser drive, compared to the $500 \mu\text{m}$ thick PC ablator and 28 ns drive in the revised experiment on the right. The images on top are raw radiographs, and the cutouts are samples of the data after they have been processed through a contrast-enhancing unsharp mask algorithm [14, 16, 24]. This algorithm creates a copy of the image, smeared at the diagnostic spatial resolution, and then subtracts this blurred image from the original to locate edges. This information is then combined with the original image to enhance the visibility of those edge features.

One can see from Fig. 3a that while the amplitude of the modulations does change in the original campaign, the modulations do not develop the small-scale rollup structures characteristic to the Kelvin-Helmholtz insta-

FIG. 3: **Left:** First experimental campaign with a $185\ \mu\text{m}$ thick ablator and $19\ \text{ns}$ drive. **Right:** Second experimental campaign with a $500\ \mu\text{m}$ thick ablator and $28\ \text{ns}$ drive. **Top:** Raw radiographic data. **Bottom:** Contrast-enhanced data.

bility, as seen in the simulation in Fig. 2 [14]. One contributing factor is that the Kelvin-Helmholtz relevant region was smaller than anticipated, resulting in modulations that were disturbed by the entrained insulator and ablator material before they had adequate time to fully develop. This could be due to the foam reaching a higher compression limit than anticipated; in the simulations, the adiabatic index is assumed to be 1.67 for the CRF, resulting in a maximum of a 4x compression. First-order estimates of the experimentally observed foam compression, taken by dividing the distance the shock has traveled through the foam by the length of the Kelvin-Helmholtz relevant zone, suggests that the foam reached a compression of $\sim 5x \pm 1.5$ [16].

The evolution may also have been disturbed by the presence of an unintended secondary shock, which we refer to as a reshock. When the shockwave passes from the thermal insulator into the lower density foam, a rarefac-

tion wave is launched back towards the direction of the drive surface. If this expansion wave reaches the critical surface before the laser drive shuts off, then the large pressure gradient is enough to launch a secondary shock-wave through the system that can overtake the initial shock and disturb the evolution of the modulations [25]. This reshock can be mitigated or prevented by thickening the ablator package, so as to delay the returning rarefaction wave until the drive pressure has released. Figure 4 demonstrates this with a pair of 1D radiation hydrodynamic simulations performed with the Hyades code. This code uses the same laser parameters as Fig. 2, but adjusts the initial thicknesses of the PC ablator. Additionally, the PC ablator and CHBr insulator now use polystyrene SESAME equation of state tables instead of an ideal gas model, and the foam uses a carbon foam equation of state table. Various other combinations of equation of state tables or ideal gas adiabatic indices,

FIG. 4: Density (a,c) and pressure (b,d) zone - time plots from 1D Hyades simulations. **Left:** 150 μm thick PC ablator. **Right:** 220 μm thick PC ablator.

ranging from 1.4 to 1.75, were also explored.

Figure 4 shows density (Fig. 4a, 4c) and pressure (Fig. 4b, 4d) changing with time, with time along the abscissa and distance along the ordinate. In Fig. 4a and 4c, the initial thickness of the PC ablator is 150 μm (35 μm below the nominal experimental thickness), whereas in Fig. 4b and 4d, the initial thickness of the PC ablator is 220 μm (35 μm greater than the nominal experimental thickness). Both are followed by 100 μm of CHBr thermal insulator and 1500 μm of CRF foam, and have identical laser conditions. In Fig. 4a and 4c, we can observe the reshock overtaking the initial, driving shockwave, which has the potential to disturb the evolution and fine structure of the shear instability. In Fig. 4b and 4d, the ablator is thick enough to mitigate this secondary shockwave.

The $\pm 35 \mu\text{m}$ in Fig. 4 were chosen for two reasons. First and foremost, a reshock always occurred in these simulations when the ablator thickness was reduced to 35 μm below the nominal thickness for all tested combi-

nations of equation of state tables and adiabatic indices, while 35 μm above the nominal was always observed to be free of a reshock. As a secondary reason, the metrology station we used to perform our pre-experimental evaluation of our target had a $\sim 35 \mu\text{m}$ uncertainty.

Figure 5 presents an alternate view of the same data, with cell number instead of distance along the ordinate. Each cell represents an equivalent mass of the given material, and the transition between materials occurs at predefined cell numbers. Again, the reshock can be seen overtaking the original shockwave in Fig. 5a and 5c, but is not present in Fig. 5b and 5d.

Depending on which equation of state table or what value adiabatic index is chosen for the various materials, the thickness of the original ablator package may or may not have reached the threshold thickness required to prevent this reshock. When we further factor in the variability of individual targets, it is left ambiguous whether or not this reshock may have occurred within the original experiment, and if so, how much of an influence it would

FIG. 5: Density (a,c) and pressure (b,d) cell-number - time plots from 1D Hyades simulations. Each cell contains an equal mass of the specified material. **Left:** 150 μm thick PC ablator. **Right:** 220 μm thick PC ablator.

have had on the development of the instability.

Both concerns, the insufficient size of the Kelvin-Helmholtz relevant zone and the possibility of a reshock, were addressed in a subsequent campaign by thickening the ablator package and extending the drive duration from 19 ns to 28 ns. Extending the duration of the laser drive extends the maximum duration of the experiment by increasing the length of time over which the shock-wave is supported by ablation pressure. This, in turn, provides more time for the primary shockwave to outpace the material that has become entrained in the flow, increasing our instability-relevant region. The ablator thickness was increased to 500 μm to compensate for the longer drive duration; this was the thinnest piece that could be ordered from our supplier that still exceeded the threshold thickness needed to eliminate the reshock for all tested combinations of equation of state tables and adiabatic indices. After this change, data and simulation consistently achieved good agreement for large and medium-scale structures [16].

Due to limitations in time and experimental resources, we were unable to perform an experiment in which we changed only the ablator thickness or the laser drive duration exclusively. This remains a topic of interest that can be explored in future experiments. This experiment could also explore the extent to which different types of hydrodynamic instabilities are affected by the reshock (e.g. whether the Rayleigh-Taylor and Kelvin-Helmholtz instabilities are affected to the same degree by the presence of a reshock).

CONCLUSION

An experimental platform was developed for OMEGA-EP to study the evolution of hydrodynamic instabilities in a steady, supersonic flow. An extended laser pulse was used to drive a shockwave over a well-characterized material interface. After analyzing the data from an initial Kelvin-Helmholtz instability experiment, it was determined that we needed better image quality and a

larger Kelvin-Helmholtz relevant zone. We achieved this by increasing the duration of the laser drive and looking later in time. This change required a thicker ablator, which also addressed the possibility of a reshock that didn't come through in the design stage. Obtaining data later in time also lowered the impact of source effects on the background noise. After these changes, the quality and consistency of the experimental data was significantly improved, and the results were well-reproduced with 2D simulations [16]. These results demonstrate the experimental platform's ability to produce the first data on the effects of compressibility on the Kelvin-Helmholtz instability's growth rate from single-mode initial conditions. These data, in conjunction with future work, will contribute to the development of a comprehensive model for compressible Kelvin-Helmholtz instability behavior. Additional experiments will use this platform to explore multi-vortex Kelvin-Helmholtz behavior, and extend the platform to study additional hydrodynamic instability behavior.

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