Demonstration of repeatability in a high-energy-density planar shear mixing layer experiment

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On laser-driven platforms the assumption of experiment repeatability is particularly important due to a typically low data acquisition rate that doesn't often allow for data redundancy. If the platform is repeatable, then measurements of the repeatable dynamics from multiple experiments can be treated as measurements of the same system. In high-energy-density hydrodynamic instability experiments the interface growth is assumed to be one of the repeatable aspects of the system. In this paper we demonstrate the repeatability of the instability growth in the counter-propagating shear experiment at the OMEGA laser facility, where the instability growth is characterized by the tracer layer thickness or mix-width evolution. In our previous experiment campaigns we have assumed the instability growth was repeatable enough to identify trends, but in this work we explicitly show that the mix-width measurements for nominally identical experiments are repeatable within the measurement error bars.

I. INTRODUCTION

A key underlying assumption to all laser-driven high-energy-density (HED) experiments is that the important dynamics of the system are repeatable over the course of multiple experiments as long as the defining metrics of the platform remain constant.[1–4] Experiment repeatability allows one to map the entire evolution of a system, even when diagnostics are only capable of capturing portions of a single experiment due to limitations like small-temporal or spatial windows compared to the experiment scales. If the platform is repeatable, then measurements of the repeatable dynamics from multiple experiments can be treated as measurements of the same system. While this basic technique is true in many types of experiments in many fields, on laser-driven platforms it is particularly important due to a typically low data acquisition rate that doesn't often allow for data redundancy.

In HED hydrodynamic instability and turbulence experiments interface growth is assumed to be one of the repeatable aspects of the system, so this class of experiments is often diagnosed with some form of imaging of the instability interface which effectively makes a movie of the system using frames from several different experiments.[5–9] The LANL counter-propagating (CP) shear experiments are part of this class of HED instability experiments.[10, 11] These experiments examine Kelvin-Helmholtz (KH) shear instability growth as seeded by variety of different boundary initial conditions.[12, 13] In general we define the experiment 'platform' as the overarching experiment setup, including laser drive and target geometry. Since the purpose of these experiments is to study the instability under a variety of initial conditions, and the instability growth has been shown to vary significantly between different initial conditions, it is useful

to define the set of experiments for each individual set of initial conditions as a single 'campaign'. Every individual experiment, or 'shot', in a campaign corresponds to a single physical target which is destroyed in the process of the experiment. With our current data acquisition rate for experiments at the OMEGA laser-facility, and even with the increased data acquisition rate for the associated NIF experiments, we require multiple shots per campaign to measure the instability evolution. So the underlying assumption for our platform is that the instability growth is repeatable within a campaign and we should be able to treat the images of our time sequence obtained by separate shots as realizations of the same underlying target with minimal considerations of shot-to-shot variation. In this manuscript we demonstrate repeatability at the shot-level within a campaign by repeating image timings, where we define repeatability as measurement agreement within the diagnostic and data analysis error of the platform.

II. EXPERIMENT PLATFORM

In this manuscript we will focus on results from the OMEGA counter-propagating shear platform. This platform uses a physics package located inside of a ~ 1.5 mm long, 0.5 mm inner diameter Be cylindrical shock tube.[14] The physics package (Fig. 1a) consists of two hemi-cylindrical low-density (60 mg/cm^3) CH foams around a thin solid metal plate which serves as a tracer layer. At opposite ends of the foams are two solid-gold 0.2 mm thick hemi-cylindrical plugs. At both ends of the Be tube are 0.075 mm Rexolite (polystyrene) ablator caps. Lasers directly irradiate the ablators to launch $110 \text{ } \mu\text{m/ns}$ shocks into the physics package, which are partially blocked by the gold plugs and collimated by the metal plate. This geometry results in two nominally identical counter-propagating shocks above and below the metal plate. When the shocks cross in the center of the system it creates a region of pressure-balanced

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FIG. 1. (a) Pre-shot radiograph of a representative smooth/flat foil target with labeled components. The target consists of a cylindrical Be tube around two hemi-cylindrical foams separated by a metal $20\ \mu\text{m}$ thick Al tracer layer. The radiograph shows the ablator cap on the right side, which is directly irradiated to launch shocks into the system. Gold plugs at the ends of the tube block the shocks on that side of the tracer foil to create the counter-propagating shock geometry. (b) Pre-shot radiograph of a representative sinusoidal foil target with a $20\ \mu\text{m}$ thick Al foil with $\lambda = 100\ \mu\text{m}$.

shear flow. RAGE simulations estimate post-shock flow speeds of $70\ \mu\text{m/ns}$, $\sim 2\ \text{Mbar}$ pressures and $\approx 40\ \text{eV}$ temperatures in the foams. The Reynolds number of the system has previously been estimated to be $\text{Re} \sim 10^6 - 10^7$. [12] We only change the tracer layer characteristics to vary the initial conditions that seed the KH evolution. Each different set of tracer layer characteristics, such as tracer layer material [12, 13] or surface profile [15, 16], is considered its own campaign.

In this paper we demonstrate the repeatability of the instability growth, as represented by the tracer layer thickness or mix-width evolution, for several different initial condition campaigns. We show shot-to-shot mix-width repeatability within measurement error at one shot time from our sinusoidal foil campaign with a $20\ \mu\text{m}$ thick Al tracer and an initial sinusoidal perturbation (Fig. 1b) of wavelength $\lambda = 100\ \mu\text{m}$ (width of a single-peak, not the full 2π wavelength) coined into the foil. [14] We also show mix-width agreement within error bars for a larger experiment time window by comparing results from our campaign with smooth $20\ \mu\text{m}$ thick Al foils (Fig. 1a) with results from a campaign with $\lambda = 200\ \mu\text{m}$ foils.

The smooth Al foil results have previously been presented in [11] and [12]. The results from the smooth and $\lambda = 200\ \mu\text{m}$ campaigns are considered to be equivalent enough here to make assumptions about repeatability because variation in the instability growth, as represented by the mix-width, due to the difference in initial conditions is below the diagnostic and analysis resolution of the experiments.

III. EXPERIMENT RESULTS

The most direct way to demonstrate repeatability within a campaign is to compare results from multiple identical shots. In the current CP shear platform the only deliberate variation between campaigns is the design of the tracer foil and the diagnostic setup. Thus two shots using the same tracer foil, camera and detector, and x-ray backlighter (BL) material can be considered identical. Previous experiments [12] already demonstrated that otherwise identical shots do not yield repeatable instability mix-widths with the current data analysis techniques for significant variation in the detector sensitivity.

To compare the instability growth across shots we focus on the experiment time window of $10\ \text{ns} \leq t \leq 14\ \text{ns}$, after the passage of transients behind the shock front and after the experiment has entered the linear KH phase. Figure 2a,b shows the radiographs from a set of nominally identical shots for the campaign using $\lambda = 100\ \mu\text{m}$ sinusoidal foils and measured at $10\ \text{ns}$ after the initial drive using scandium BLs onto an x-ray framing camera with a CCD detector. These two shots were taken on two different shot days, where shot 77604 was from Shear 15B in June 2015 and shot 80966 was from Shear 16B in April 2016. The drive for these two shots was the same to within $< 1\%$ for both the total energy and energy balance between the two sets of drive beams. Shot 77604 had a total drive energy of 7714 J, where the two sets of drive beams had energies of 3850 J and 3863 J. Shot 80966 had a total drive energy of 7646 J, the sets of drive beams had energies of 3813 J and 3834 J. The sinusoidal foil profiles for the two shots had the same wavelength and similar surface roughness, but a significant difference in the sine wave amplitudes due to batch-to-batch variation in the repeatability of the coining method used to imprint the waves on the foils. The foil used in shot 80966 had an rms surface roughness of $0.52\ \mu\text{m}$ and an amplitude of $1.67 - 1.91\ \mu\text{m}$, as determined using a sinusoidal fit to surface scans of both sides of the foil. A representative foil from the target batch containing the target for shot 77604 showed only a slightly larger rms surface roughness, $0.72\ \mu\text{m}$, but a greater than factor of two larger amplitude of $4.01 - 4.21\ \mu\text{m}$.

We focus our analysis near the center of the shock tube (as shown by the delineated areas in Fig. 2a,b), where the experiment is shear flow dominated since the shear instability growth is only measurable we assume to be repeatable. Near the ends of the shock tube where the

FIG. 2. Radiographs of the tracer layer evolution for the $\lambda = 100 \mu\text{m}$ sinusoidal foil at 12 ns from (a) shot 77604 and (b) shot 80966 on two different experiment days. Individual shot numbers and areas included in mix-width analysis are located on each radiograph. (c-d) Line-outs (blue) and Gaussian fit sections (red) for each sub-window used to determine mix-width. (e-f) Histograms showing the distribution of the mixing half-widths for each sub-window in the corresponding radiograph.

platform is more dominated by transient shock interactions, for example with the end of the foil and corner of the gold plug which cause the large s-shaped wisp structures, there is always structure shot-to-shot variation. This variation is expected since the transients are not assumed to be repeatable. These radiographs do show variation in the experiment center as well between the shots, where periodic structure is more evident on shot 77604. The difference in structure present is most likely due to variation in on-shot BL intensity since shot 77604 has a BL signal 2–3 times higher, ~ 2000 – 3000 counts, than shot 80966, ~ 1000 counts, in the region of interest.

Mixing half-widths and error bars for the $\lambda = 100 \mu\text{m}$ foils were determined using the fitting metrics in [12], but were additionally averaged over an $\approx 100 \mu\text{m}$ window about the center of the tube (Fig. 2a,b)). Specifically, the values are averaged over the results of $\lambda/(w/2) \approx 20$ overlapping sub-windows of the image where the window width is $w = 10 \mu\text{m}$. Each sub window is the same sub-window used in previous work to determine a single averaged line-out. The individual line-outs for each sub-window are shown in Fig. 2c,d, as well as their corresponding regions of Gaussian fit shown out to the $\sigma = 2.5$ limit used to calculate the mixing half-width.

The difference in signal intensity between the two radiographs, due to the shot-to-shot BL variation, is apparent here with the lower signal line-outs showing a

lower count level and a relatively flatter peak shape. The lower initial BL signal on shot 80966 results in less light ultimately reaching the detector after being attenuated by the target, specifically near the center of the tracer foil. For shot 80966 the flat peak is due to the transmitted signal being so low that it is effectively a region of zero transmission where the normally Gaussian-like transmission profile has been cut-off. Similar distortion of the line-out profile has been observed in previous experiments with higher-Z, Ti tracer layers [12] where the transmission through the center of the tracer layer was zero even with high initial BL signal. In order to reduce the error introduced by shot-to-shot BL variation and distortion of the line-out peaks due to low transmission, the fitting routine we used excludes values in the line-out of greater than 80% of the maximum value, as shown by the truncation of the Gaussian fits near the line-out peaks.

Figure 2e,f shows the distribution of sub-window mix-widths for both radiographs. Both shots have similar distribution windows of $\sim 20 \mu\text{m}$ width. However shot 80966 has a centrally-peaked shape as might be expected for a probability distribution function, but shot 77604 has a more bi-modal distribution. The mix-width distribution for shot 77604 is most likely due to asymmetric feature on the right-side of some of the line-outs, which is due to the presence of the transient s-shaped wisp in

FIG. 3. Mixing half-width vs. time for two $\lambda = 100 \mu\text{m}$ sinusoidal foil data sets (diamond and circle), one $\lambda = 200 \mu\text{m}$ sinusoidal foil data set (square), and a smooth foil data set (triangle). The shot number for each data point is included in the plot.

the region of interest. The mix-width distributions may be of further interest in future analysis of the entire set of sinusoidal foil campaigns.

However, even with the foil sinusoid amplitude variations and the observed difference in the radiographs the average mix-widths for these two shots agree within error bars, as shown in Fig. 3. In this case we choose our measurement to be the average of the fits to multiple line-outs from discrete sub-windows instead of fitting to an average line-out over the entire $\approx 100 \mu\text{m}$ window, because averaging over the entire window introduces additional measurement error due to the tilt of the tracer layer in the radiograph. This averaging technique removes any structure variation effects, which are assumed to be non-repeatable in absolute thickness and location, over one wavelength of the original perturbation. Thus we are only measuring the bulk interface growth which, as assumed, is repeatable within the measurement error for these experiments at this time.

To demonstrate instability repeatability over a larger instability growth time interval we compare shot results from two nominally equivalent campaigns, smooth Al foils and $\lambda = 200 \mu\text{m}$ foils. As stated previously, we consider the results of the two campaigns to be equivalent, or part of the same campaign, because the instability growth is observed to be the same, within the diagnostic and analysis error, between the two foil types. The similar instability growth between the two campaigns is theorized to occur because $\lambda = 200 \mu\text{m}$ is a long enough wavelength to display growth rates near the asymptotic limit of the system as $\lambda \rightarrow \infty$, which is the theoretical limit of the wavelength of a smooth foil. The exact na-

ture of the expected growth of the system for pre-seeded modes is still under investigation as part of the larger initial condition variation campaign. So while there might be variation in the instability growth between the smooth and $\lambda = 200 \mu\text{m}$ foil types, the variation is small enough to be below the experiment resolution of the platform.

The growth of the smooth and $\lambda = 200 \mu\text{m}$ foil types is observed to be qualitatively similar in the radiographs (Fig. 4) and quantitatively repeatable in the measurements of the layer width at the center of the shock tube (Fig. 3). The drive for these shots was the same to within $< 4\%$ for the total energy ($7846 \pm 103 \text{ J}$) and each individual shot had energy balance within $< 3\%$ between the two sets of drive beams ($3873 \pm 56 \text{ J}$, $3973 \pm 48 \text{ J}$). The radiographs show very similar layer evolutions, near the center of the shock tube, between the two shots at 10 ns and the two shots at 12 ns. At 14 ns the edge structure variation in between the shots is more pronounced, since the prominence of transient effects increases at late-times in the experiment.[11] The increase in the effects of transients in the system is reflected in the deviation of the average mix-width between the two shots at 14 ns. Mix-widths and error bars for the $\lambda = 200 \mu\text{m}$ foils were determined using the same fitting as discussed for the $\lambda = 100 \mu\text{m}$ foils. The measured mix-widths of both the smooth and $\lambda = 200 \mu\text{m}$ foils again agree within error bars for the entire $10 \text{ ns} \leq t \leq 12 \text{ ns}$ window, as seen in Fig. 3.

Thus we have demonstrated that the instability growth of the system is shot-to-shot repeatable within a campaign, both for a single experiment time ($\lambda = 100 \mu\text{m}$ campaign) and for multiple experiment times (smooth/ $\lambda = 200 \mu\text{m}$ campaign). In an analogous study of repeatability in OMEGA-laser-driven targets launching shocks into gas-filled tubes,[1] it was found that no single pair out of 8 shots could demonstrate repeatability of all relevant metrics. A detailed statistical analysis [3] found that the observables of the system were not robust against a number of individually minor uncertain details of the experiment, including variations in target fabrication, laser drive, and gas fill, causing the final main observable of shock location to have a distribution which could be understood as a sum of the effects of several uncertain parameters. The situation is better here, where as discussed the main observable of shear mixing width has been designed to be as insensitive as possible against drive transients and other varying components, and the checks performed here show no reason to doubt that this has been achieved for these parameters and times.

It is worth noting that the campaign-to-campaign variation is a small perturbation of the overall platform in the work presented here, as well as in the other work using this platform. Our assumptions of repeatability for campaigns on this platform require that the instability growth dominates any transient/non-repeatable phenomenon in the measurement region. Should a perturbation to the platform violate this requirement, then our repeatability assumptions would not hold. So changes to

FIG. 4. Radiographs of the tracer layer evolution for both the smooth foil (top row) and $\lambda = 200 \mu\text{m}$ sinusoidal foil during the linear shear instability growth phase of the experiment, $9 \text{ ns} \lesssim t \lesssim 16 \text{ ns}$. Individual shot numbers are located on each radiograph. Radiographs of the smooth foil data were originally presented in [11].

the platform cannot be made arbitrarily with the expectation that the experiments will be comparable to previous campaigns. For example, in [12] when we decreased the thickness of the tracer layer we also had to increase the layer density proportionately (preserving areal density) by changing the tracer layer material. This change in the tracer material served to keep bulk hydrodynamic response of the layer similar, both to prevent shocks from breaking through the layer and preventing the desired shear flow (and instability) from forming, and so that we could consider the full dataset in a unified framework. However, even this small platform perturbation coupled in non-hydrodynamic effects, since changing the layer material and density changes the tracer layer expansion due to preheat and thus the experiment initial conditions. For those campaigns the preheat variation was small, but a tracer layer material change would be expected to violate campaign repeatability if, for example, the preheat absorbed by the tracer foil were scaled to either become significantly less than the melting temperature of the material ($\lesssim 0.1 \text{ eV}$) so the layer remained solid, or became comparable to the post-shock drive temperature ($\gtrsim 10 \text{ eV}$) and drove significant enough expansion of the layer to change the experiment flow properties.

Large perturbations to the platform of course are not expected to be comparable across campaign. For example, we made significant changes to the laser drive energy and duration, and the target size when adapting the platform from OMEGA to NIF.[17] The much longer ($\sim 10\times$) supported flow duration in the NIF experiments significantly changes the KH instability development, such that OMEGA and NIF data are not comparable at late-times

in the experiment. An example of the large perturbations to the platform degrading the shot-to-shot repeatability performance can be seen from the Sherrill/Fincke experiments,[18] which arguably uses the same platform drive, exterior geometry, and diagnostic setup. However, the either the change to the interior target geometry to a Richtmyer-Meshkov instability study configuration or the change to very thin tracer layers was sufficient to introduce large amounts of shot-to-shot stochasticity. It is currently theorized that larger stochasticity is due to the introduction of significant transient shocks by the geometry modification, which undermines the assumption that experiment is dominated by a repeatable phenomenon like the instability growth.

IV. CONCLUSIONS

An underlying assumption of the LANL counter-propagating shear platform is that the instability growth is repeatable within a campaign (set of initial conditions) and thus we should be able to treat the images of our time sequence obtained by separate shots as realizations of the same underlying target with minimal considerations of shot-to-shot variation. In the paper we demonstrated that the instability growth of the system is shot-to-shot repeatable, where we define repeatability as measurement agreement within the diagnostic and data analysis resolution of the platform. We showed shot-to-shot repeatability within a campaign, with examples from multiple campaigns, both for a single experiment time ($\lambda = 100 \mu\text{m}$ campaign) and for multiple

experiment times (smooth/ $\lambda = 200 \mu\text{m}$ campaign). For our previous experimental campaigns we have assumed the instability growth was repeatable enough to identify trends, but in this work we showed explicitly that the mix-width measurements for nominally identical shots are repeatable within the measurement error bars. We explicitly attempted to replicate shot timing and initial conditions (tracer foil profile), 12 ns and $\lambda = 100 \mu\text{m}$ respectively, on two different shot days for a single data point. Even with a notable profile amplitude variation for the tracer foil profile, for similar drive and interface wavelengths the mix-widths of these two experiments agree. Similarly, we have data over a wider time frame from two different, but equivalent for this study, initial condition campaigns (smooth and $\lambda = 200 \mu\text{m}$ foils), that display similar growth behavior and showed agreement of the measured instability growth within error. So we have demonstrated that our measurement technique cap-

tures the repeatable aspects of the interface growth, and strengthened our assertion that within a campaign on our platform the instability growth measured over multiple shots can be treated as measurements of the same system.

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