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Magnetically-Driven Convergent Instability Growth platform on Z

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Abstract

Hydrodynamic instability growth is a fundamentally limiting process in many applications. In High Energy Density Physics (HEDP) systems such as inertial confinement fusion implosions and stellar explosions, hydro instabilities can dominate the evolution of the object and largely determine the final state achievable. Of particular interest is the process by which instabilities cause perturbations at a density or material interface to grow nonlinearly, introducing vorticity and eventually causing the two species to mix across the interface.

Although quantifying instabilities has been the subject of many investigations in planar geometry, few have been done in converging geometry. During FY17, the team executed six convergent geometry instability experiments. Based on earlier results, the platform was redesigned and improved with respect to load centering at installation making the installation reproducible and development of a new 7.2 keV, Co He-a backlighter system to better penetrate the liner. Together, the improvements yielded significantly improved experimental results.

The results in FY17 demonstrate the viability of using experiments on Z to quantify instability growth in cylindrically convergent geometry. Going forward, we will continue the partnership with staff and management at LANL to analyze the past experiments, compare to hydrodynamics growth models, and design future experiments.

ACKNOWLEDGMENTS

We thank the optical diagnostics team on Z for developing and fielding the PDV and VISAR diagnostics, the General Atomics target fabrication team for targets and probe-assemblies, and finally the entire Z operations team. We also thank Rob Gore and Leslie Welser-Sherrill at Los Alamos National Laboratory for meetings, important discussions, and sharing key insights in the early stages of the project.

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TABLE OF CONTENTS

FIGURES

EXECUTIVE SUMMARY

Hydrodynamic instability growth is a fundamentally limiting process in many applications and of particular interest is the process by which instabilities cause perturbations at a density or material interface to grow nonlinearly, introducing vorticity and eventually causing the two species to mix across the interface. Considerable research has been done in planar geometry to study interface growth, but few have been done in converging geometry. During FY17, the team executed six experiments on Z co-designed with LANL in two series: the first in November 2016 (Z3023 and Z3031) and the second in June 2017 (Z3108, Z3109, Z3110, and Z3111).

The instability platform was during the year redesigned and improved with respect load centering at installation making the installation reproducible and a new 7.2 keV, Co He-α backlighter system was developed to better penetrate the liner. Together, the improvements yielded significantly improved experimental results.

The platform consists of a beryllium liner, filled with liquid deuterium, and having an on-axis beryllium rod, shown in Figure 1. The on-axis rod has a pre-machined perturbation which, with the liquid deuterium, forms the unstable interface of interest. As the Z drive current rises, the liner begins to implode, which drives a converging shock in the liquid deuterium. As the shock converges, it strengthens and increases in velocity reaching ~30 km/s peak velocity. When the shock strikes the rod, the rod begins to compress and the interface perturbation will grow due to a combination of the Richtmeyer-Meshkov (RM) and Rayleigh-Taylor (RT) instabilities. In FY17, the team decided to continue to explore the instability growth resulting from this first shock phase for an interface perturbed with a single wavelength mode and expand the investigation with two experiments using a multi-mode perturbation. Planned future work include investigating the effect on instability growth of a second reflected shock.

Finally, two experiments yielding very exciting results were performed using a multimode perturbation on the target rod. The perturbation was created using a superposition of 10 wavelengths randomly chosen from a uniform distribution between 50 and 300 μm and phases between 0 and 2π. Each mode amplitude was drawn from a normal distribution with mean 0.033*λ. This scheme insures that each mode will be diagnosable at t=0 and no mode will start in the nonlinear regime. *The multi-mode results are more complex: despite starting in the linear growth regime, the radiographs show non-linear growth developing into mushroom shapes.*

The significant improvements in platform reproducibility and diagnostics capabilities made in FY17 demonstrated that it is a viable platform for studying instability growth in convergent geometry.

The project has been granted four Z experiments in CY18. With these experiments, we plan to obtain additional radiographs to complete the single mode, and possibly multimode, datasets, allowing us to complete and publish this study. We will continue the partnership with staff and management at LANL to further analyze the past experiments, compare to hydrodynamics growth models, and design the remaining experiments. We will target the highest priority physics goals and modify the liner, current pulse, and on-axis rod to best suit programmatic needs while incorporating existing diagnostic constraints.

NOMENCLATURE

Abbreviation	Definition
1D	One-dimensional, often used in computational context of how many spatial dimensions that are included in the simulation.
ALEGRA	Arbitrary-Lagrangian-Eularian General Research Application, a large-deformation shock-physics code developed at Sandia National Laboratories.
HEDP	High Energy Density Physics
keV	kilo electron Volt, unit for energy of radiation.
LANL	Los Alamos National Laboratory
Mbar	Million bar, unit for pressure.
MHD	Magneto Hydro Dynamics
MRT	Magnetic Rayleigh-Taylor instability, instability due to differences in magnetic field pressure
NIF	National Ignition Facility
RM	Richtmeyer-Meshkov instability
RT	Rayleigh-Taylor instability
SNL	Sandia National Laboratories
Z	Sandia's Z-machine

1. INTRODUCTION

Hydrodynamic instability growth is a fundamentally limiting process in many applications. In High Energy Density Physics (HEDP) applications, such as inertial confinement fusion implosions and stellar explosions, hydro instabilities can dominate the evolution of the object and largely determine the final state achievable. For instance, in capsules imploded on the National Ignition Facility (NIF), the ablation front is unstable to the Rayleigh-Taylor (RT) instability during acceleration and the hotspot/dense fuel interface is unstable during deceleration. These instabilities lead to shape deformation, residual kinetic energy at stagnation, and mix, which all conspire to limit the burn duration and the terminal fuel pressure achieved. Of particular interest is the process by which instabilities cause perturbations at a density or material interface to grow nonlinearly, introducing vorticity and eventually causing the two species to mix across the interface.

Hydro instabilities have been studied for decades, but this is largely limited to planar geometry due to the ease of diagnosis and relative simplicity of interpretation of the results. Some examples exist in convergent geometry [1,2] but these platforms suffered from poor spatial resolution and were primarily focused on instability growth at the ablation front in radiation driven implosions. However, convergence effects are important to include in order to confidently assess an integrated model's ability to capture the essential features of a given experiment. This is necessary to test directly because in a converging (or diverging) geometry the drive conditions are never constant, density contrast at interfaces is not constant, gradients are fundamental to the system, and the critical spatial scales of interest are continuously changing. All of these features make abstracting the essential physics into simple scaling parameters and linear theory essentially impossible, requiring the use of integrated models.

In this report we present work done on the Z machine at Sandia National Laboratories in conjunction with Los Alamos National Laboratories (LANL) to develop a platform for studying convergent instability growth, with the aim of eventually studying the transition to interfacial mix. The Z machine is able to drive cylindrical liner implosions to high pressures (>> 10 Mbar) at large spatial scales (stagnation radius >> 100 μm). The large spatial scales are important because radiography is the primary tool used to study instability growth. Using a relatively large target allows instability wavelengths to be studied that are well-resolved by the diagnostic at all times.

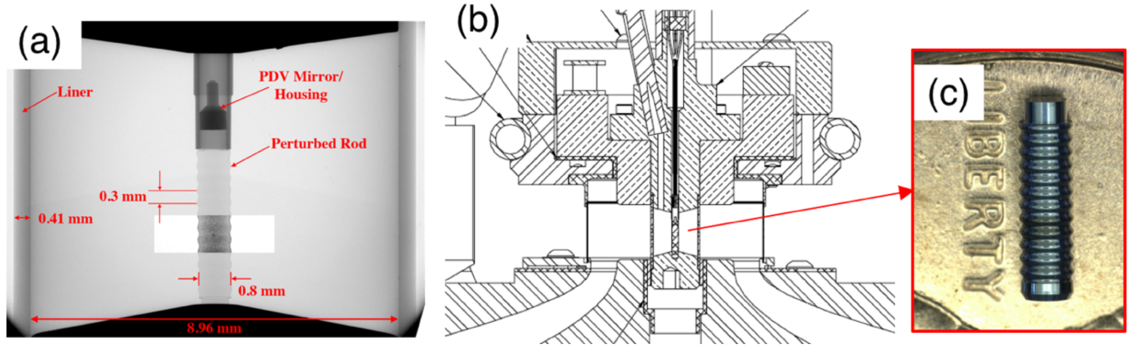

Figure 1 (a) Preshot radiograph of the assembled target. (b) Engineering drawing of the target, final power flow feed, and return current can. (c) Photograph of the perturbed beryllium rod.

Sandia and the team have extensive experience in fielding experiments in cylindrical convergence to study fundamental behavior of liner dynamics [3], implosion and stagnation physics [4] and of course applied integrated Inertial Confinement Fusion (ICF) platforms [5]. It was therefore natural to evolve a cylindrical platform to study instability growth.

The instability platform consists of a beryllium liner, filled with liquid deuterium, and having an on-axis beryllium rod, shown in Figure 1 (a) and (b). The on-axis rod has a pre-machined perturbation which, with the liquid deuterium, forms the unstable interface of interest. The on-axis rod is shown in Figure 1 (c).

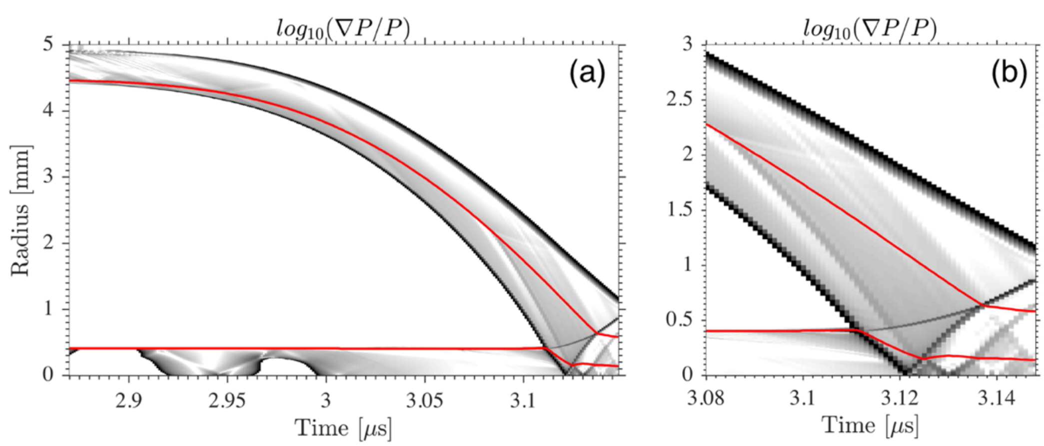

Figure 2. (a) RT plot showing the dynamics of the target. Grayscale is the gradient in pressure divided by the pressure. Red lines are the liner/deuterium interface and the deuterium/rod interface. (b) Same as (a) but zoomed in to see first shock and reverberation phases.

An R-T plot of grad(P)/P calculated using the ALEGRA-HEDP code, is shown in Figure 2 depicting the dynamics of the system. The red lines show the liner/deuterium interface and the deuterium/rod interface. In Figure 2 (a), as the Z drive current rises, the liner begins to implode, which drives a converging shock in the liquid deuterium. As the shock converges, it strengthens and increases in velocity reaching ~30 km/s peak velocity. *When the shock strikes the rod (close up shown in Figure 2 (b)) the rod begins to compress and the interface perturbation will grow due to a combination of the Richtmeyer-Meshkov (RM) and Rayleigh-Taylor instabilities*. This phase is heretofore referred to as the "first-shock" growth phase. Once the shock reflects off the axis of symmetry, it will strike the unstable interface again, sending a transmitted shock out towards the liner and a reflected shock back towards the axis. These shock will reverberate as the liner and rod decelerate. This phase is heretofore referred to as the "reverberation" growth phase and ends when the liner disassembles.

Figure 3 shows the radially resolved evolution of the density (left side) and pressure (right side) during the first shock phase of the experiment. When the shock first strikes the rod interface, the pressure is ~30 Mbar. The shock pressure grows continuously as it converges, reaching a pressure of ~200 Mbar when it re-shocks the rod. At this phase, the rod is 10's of g/cm3 and the deuterium is ~8 g/cm3. During the reverberation phase, the rod and fuel have flat pressure profiles, that gradually equilibrate.

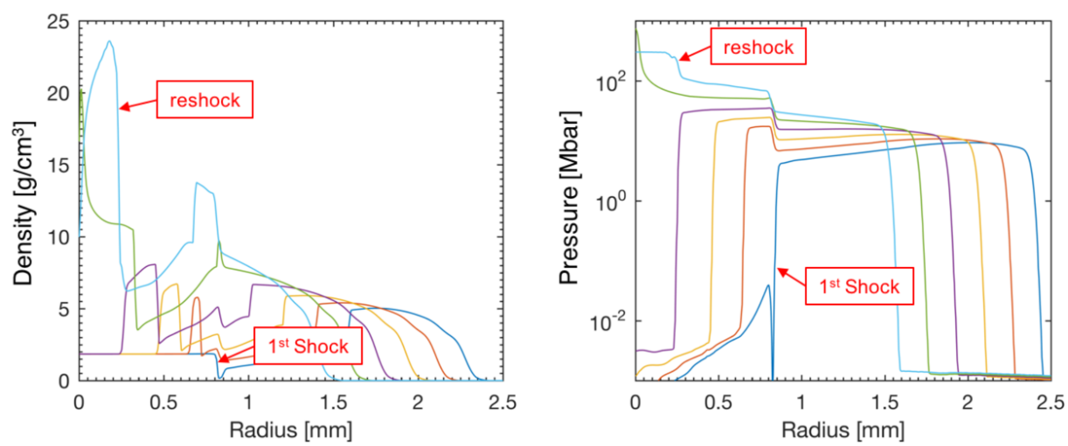

Figure 3. (left panel) 1D evolution of the density during first shock. (right panel) same for the pressure.

2. INITIAL EXPLORATORY EXPERIMENTS

A single exploratory experiment was conducted in April 2015 to assess the viability of the platform. In this experiment a relatively high aspect ratio liner (AR=9.6) was compressed using a 300 ns, 15 MA peak current pulse from Z. 6.151 keV, monochromatic x-ray radiography was used as the primary diagnostic to measure the evolution of the perturbation [6]. Radial Photon Doppler Velocimetry (PDV) was used to measure the velocity of the imploding deuterium shock before it struck the rod [4,7]. The rod was 800 μm initial diameter and the perturbation had a wavelength of 300 μm and peak-to-peak amplitude of 30 μm. Shortly after the shock strikes the rod, the interface is accelerated to an approximately constant velocity. This suggests that the dominant instability at play would be the RM instability.

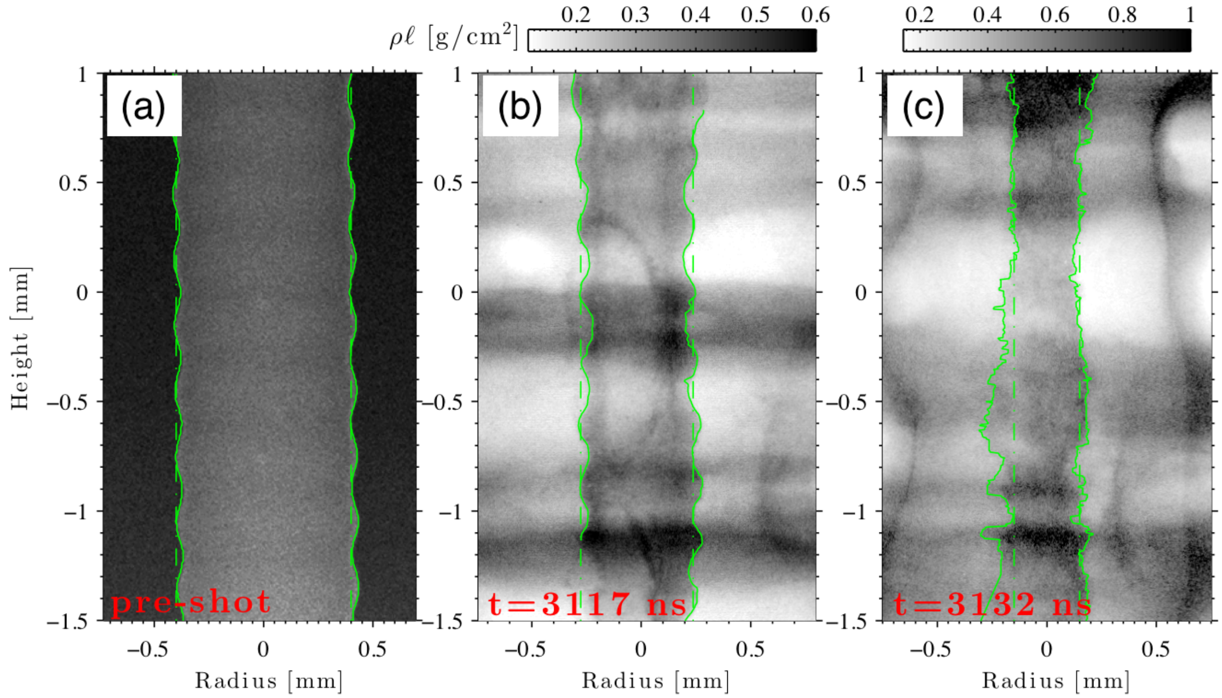

Figure 4. (a) Preshot radiograph showing the perturbed rod. Solid green lines are the rod interface and dashed green lines are the mean interface position. (b) Radiograph taken during the first shock phase. (c) Radiograph taken during the reverberation phase.

Two high quality radiographs were obtained, one during first shock and one during the reverberation phase. Figure 4 shows the evolution of the rod during this experiment. Figure 4 (a) is a pre-shot radiograph, (b) shows the growth during first shock and (c) shows the rod morphology during reverberation. The solid green lines highlight the interface determined using an edge detection algorithm and the dashed green lines indicate the mean interface position.

This experiment showed several notable features. On first shock, the perturbation amplitude has grown by approximately a factor of 3, and the rod has compressed by a factor of ~2. The compression appears fairly symmetric which is important for the application. Additionally, clear evidence is seen of the spontaneous growth of modes much shorter than the initial perturbation. In the second image, obtained during the reverberation phase, the initial perturbation appears to be gone. The structure at this stage is dominated by broadband structure, at higher mode number than the imposed perturbation. This behavior is curious, and hints at a potential transition from nonlinear instability growth to hydrodynamic mix. However, there are other explanations for this structure. The initial perturbation may undergo a phase inversion under re-shock, which we could have momentarily captured. Additionally, the liner is not as stable as we would like. This could introduce asymmetric flows which could exacerbate the amount of mix apparent in the radiographs.

Due to these encouraging initial results and the apparently high symmetry observed on first shock, we decided to pursue the platform further, focusing on improving liner stability and diagnosability.

3. RECENT EXPERIMENTS WITH IMPROVED SYMMETRY AND DIAGNOSTICS

In 2016 and 2017 we performed five experiments implementing several changes to improve the liner stability, shock uniformity and diagnosability. The liner aspect ratio was reduced to reduce Magnetic Rayleigh-Taylor (MRT) feedthrough and the glide plane angles were increased at the electrodes to reduce the prevalence of the wall instability. The reduced liner aspect ratio required an increase in the peak current to provide similar dynamics. Additionally, we required an increased photon energy backlighter to penetrate the liner. For this reason, we developed a 7.2 keV, Co He-a backlighter system [8]. Figure 4(a) shows a full radiograph from the one of these experiments. There is some axial nonuniformity in the rod compression, and a long wavelength perturbation can be seen on the liner. However, there is a large region in the center where the rod compression is uniform and cylindrical. Figure 4(b) shows a close up of the rod, demonstrating clear growth of the initial perturbation. Additionally, the shock front can be made out in the rod. The rod compression and shock front location provide valuable information constraining the simulations.

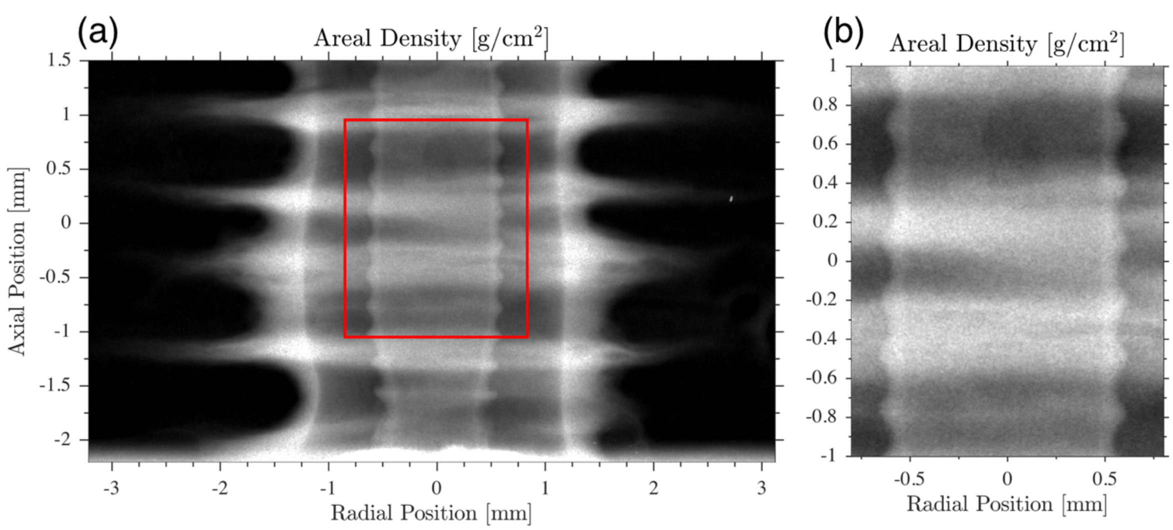

Figure 5. (a) Entire radiograph showing the liner and rod during the first shock phase. (b) Close up of the rod only.

Figure 5 shows a summary of all data taken on the single mode rod across three experiments. The first image is taken before the shock has reached the rod, given an effective initial condition and confirming no unforeseen preheating of the rod that could be cause by e.g. a fraction of the machine current being conducted in the rod.

The second image is the same as in Figure 4(b) and the third image is later during the first shock phase. In this image the perturbation has grown by a factor of 2.75. To right side of the dashed line are two images taken during the reverberation phase. These images show highly nonlinear structures with a fair degree of asymmetry. Additionally, portions of the liner are becoming opaque to the backlighter, making it difficult to track the perturbation evolution during this phase. This has led us to the conclusion that this platform is well suited to diagnosing the non-linear growth of the imposed perturbation during the first shock phase, but potentially not during the reverberation phase.

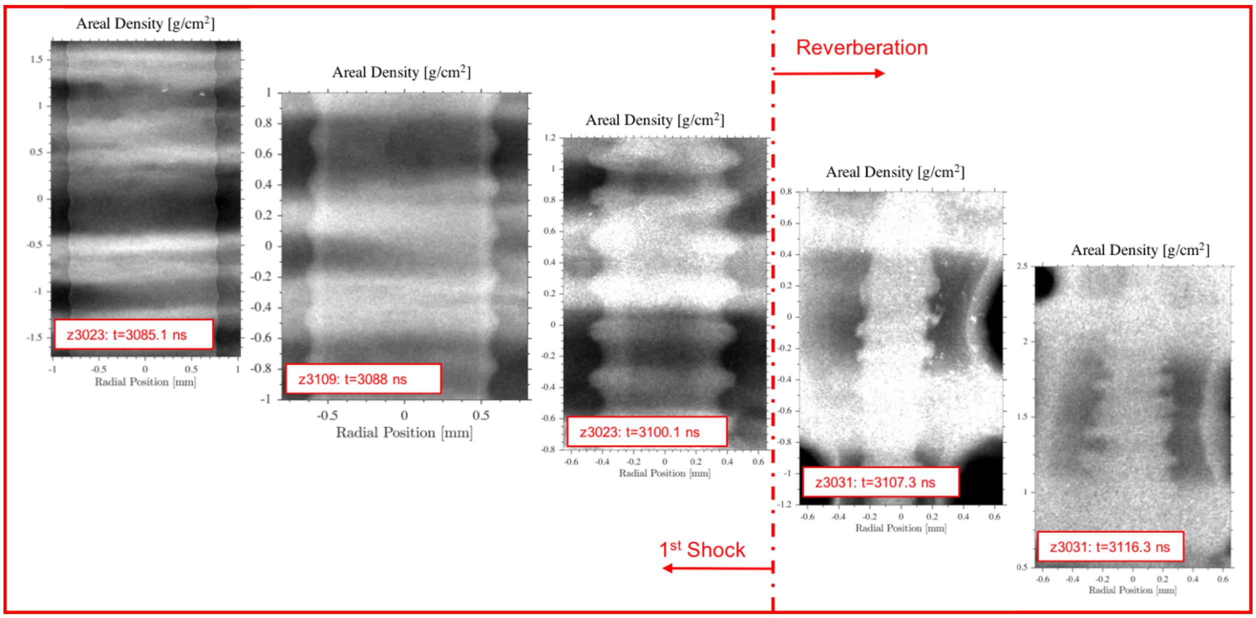

Figure 6. Summary of all data taken on the current single mode target during first shock and reverberation.

Finally, two experiments were performed using a multimode perturbation on the rod. The perturbation was created using a superposition of 10 wavelengths randomly chosen from a uniform distribution between 50 and 300 μm and phases between 0 and 2π. Each mode amplitude was drawn from a normal distribution with mean $0.033*\lambda$. This scheme insures that each mode will be diagnosable at t=0 and no mode will start in the nonlinear regime. The designed perturbation is shown below in Figure 7.

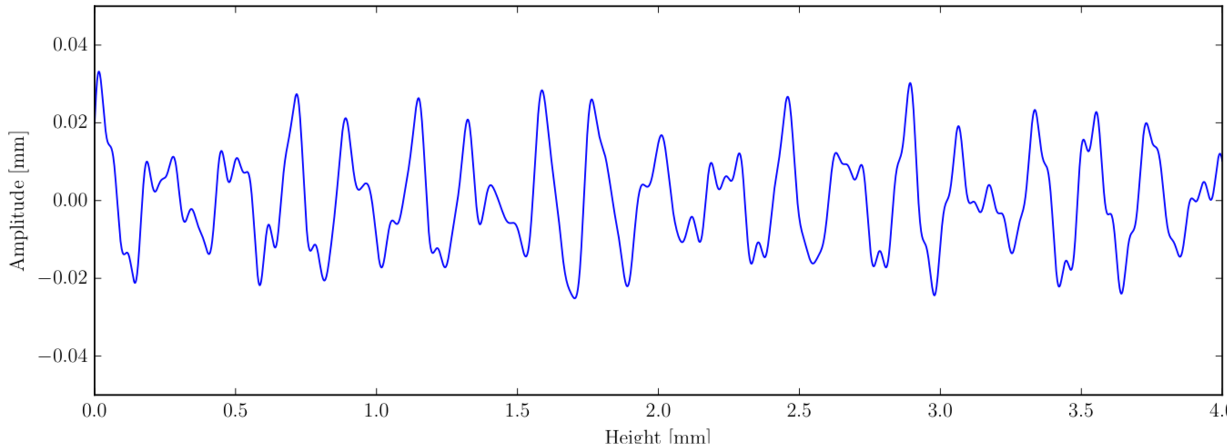

Figure 7. Machined multi-mode perturbation. Although the perturbation was chosen to begin evolution in the linear regime, the evolution rapidly turned non-linear and the typical mushroom-shaped evolution was captured on a radiograph.

The results of the two multimode experiments are shown in Figure 7. (a) shows a photograph of the multimode rod with the PDV housing partially assembled on top. Figure 7(b)-(d) show the evolution of the rod during first shock. The growth is seen to exhibit nonlinear behavior almost immediately, with clear mushrooms forming by the second image. In the third image the largest wavelengths dominate the observed structures. Additionally, the shock front can be seen, with a higher density inside the shock. This indicates that the shock has reflected off the axis of symmetry, but has not yet struck the interface, indicating the first shock phase is nearly over.

These images are incredibly exciting, but require significantly more analysis, which is ongoing and will continue in FY18.

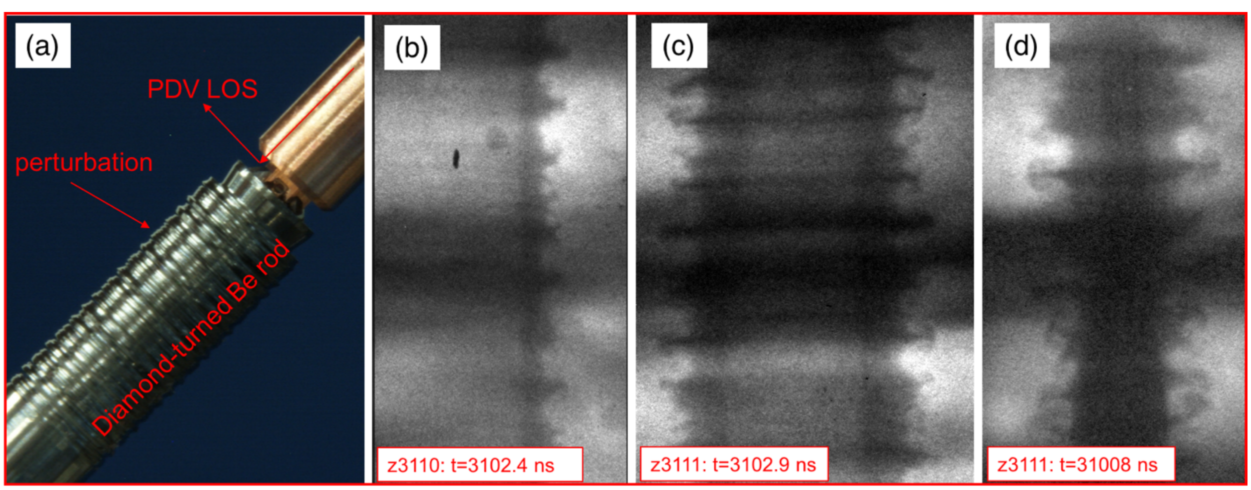

Figure 8. : (a) Photograph of the multimode rod, showing the perturbation as well as the PDV assembly. (b)-(d) Three radiograph of the multimode rod during first shock.

Importantly, a new PDV probe design was implemented in these experiments. This design returned the highest quality PDV signal we have seen to date from a liquid filled liner implosion, shown in Figure 9. In this image, we can clearly see the liner velocity trace, increasing in magnitude to an apparent velocity of 10 km/s, at which point it disappears. Additionally, we can see the shock velocity which reaches a peak measurable apparent velocity of 34 km/s. The apparent velocity is not quite accurate, due to various missing correction factors needed due to the geometry of the target, which give a true peak velocity is ~45 km/s. The shock velocity is lost at this point due to the bandwidth limits of the instrument, however it will strike the rod very shortly after this time.

With further analysis, these data will provide a strict constraint on the state of the shock just before it impacts the rod.

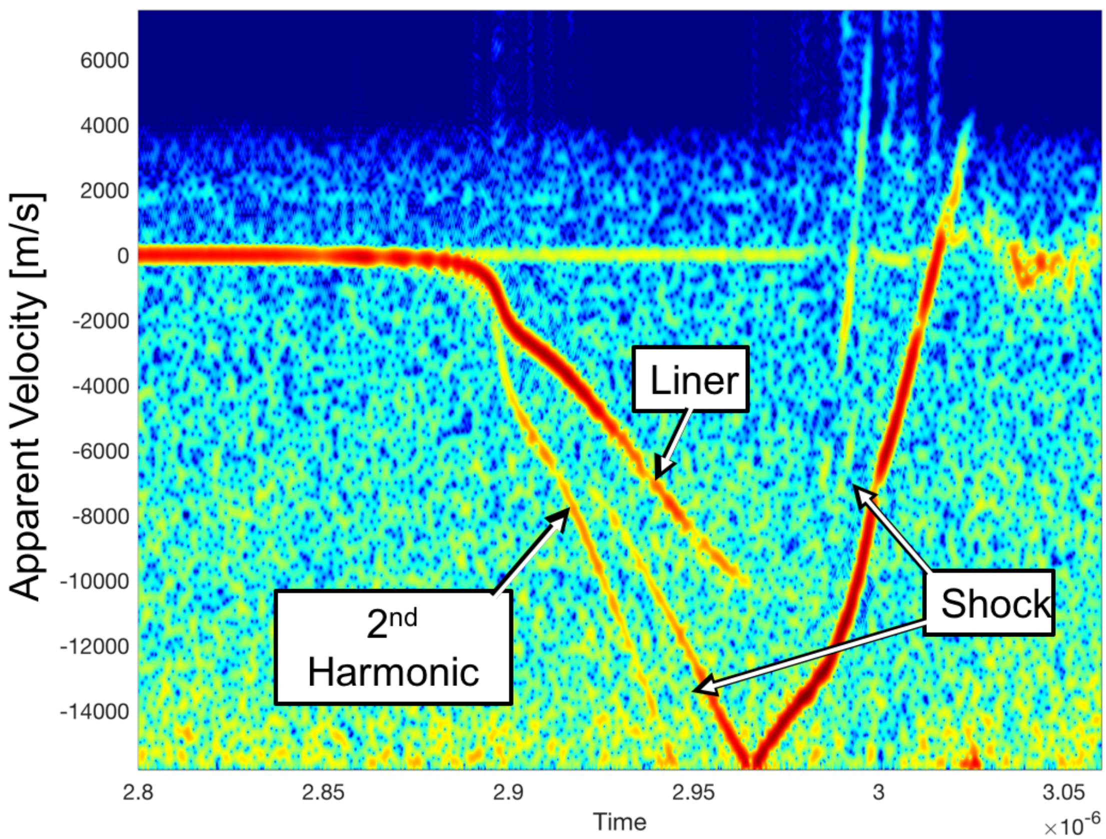

Figure 9. PDV Spectrogram obtained on shot Z3110. Velocity traces from the liner and shock are clearly visible.

4. CONCLUSIONS AND FUTURE PLANS

The immediate next steps involve detailed analysis of the existing images and completion of post-shot simulations using the measured machine current and as-built target specifications. The data analysis will include tracking of the interface and calculation of the growth factor in the single mode images. The multimode images will require more sophisticated analysis. We likely we need a spectral decomposition of the intensity image, rather than attempting to pull out an interface contour. This cannot be analyzed in the same way as the single mode interface contours due to the non-unique nature of the interface. The best way to process and analyze these images is an ongoing area of research.

We also plan to compare these data to synthetic radiographs created by post processing integrated simulations, which will require the aforementioned detailed post-shot simulations. *Importantly, we plan to compare with rad-hydro simulations that include mix models and other state of the art numerical techniques not included in the MHD models applied to design the experiments.*

Finally, it will be tremendously insightful to compare the single mode data to theoretical predictions. This is complicated by the convergent nature of the experiment which results in continuous variation of the parameters of interest. This can possibly be overcome by choosing an appropriate regularization scheme to simplify the analysis.

The team has been granted four Z experiments in CY18. With these experiments, we would like to get additional radiographs to complete the single mode, and possibly multimode, datasets, allowing us to complete and publish this study.

We will continue to partner with colleagues at LANL to analyze past experiments and design the remaining shot series. We will together with LANL target the highest priority physics under their guidance and modify the liner, current pulse, and on-axis rod to best suit programmatic needs while incorporating existing diagnostic constraints.

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