RAYLEIGH-TAYLOR INSTABILITY GROWTH ENIGMA: LINER STUDIES ON PEGASUS

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Abstract

The goal of the RTMIX series on Pegasus is to study Rayleigh-Taylor instability growth and mixing in a convergent geometry, at a metal-foam interface, as a function of material strength and initial perturbation amplitude. Results of three experiments will be presented. The first experiment, reported in the previous Pulsed Power Conference, involved a solid Z-pinch liner driven by a Pegasus current of $\sim$5.5 MA onto a high-density foam target. The inside diameter of the liner was smooth for the first experiment. No instability growth or mixing was observed at the resolution limit of the diagnostics, as expected. In the second experiment, azimuthally symmetric sine-wave perturbations were machined onto the inner diameter with a wavelength of 1.0 mm and amplitudes of 12.5 μm and 50 μm. Growth of the large amplitude perturbations was predicted, but growth of the small amplitude perturbations was expected to be inhibited by the material strength of the Cu. Neither amplitude perturbation grew. The third experiment was a repeat of the second with a low-strength Sn/In alloy (in place of the Cu) that should have melted early in the implosion. The Sn/In layer was mass-matched to the Cu layer that it replaced. Since the Sn/In layer was expected to be liquid during the unstable deceleration phase, no material strength stabilization should have occurred, and both amplitude perturbations should have shown dramatic growth. Preliminary inspection of radiographs from this experiment indicates no Rayleigh-Taylor instability growth!

I. Introduction

Acceleration-driven hydrodynamic instabilities can cause material mixing across an interface characterized by a density gradient. Linear Rayleigh-Taylor (RT) theory predicts the exponential growth of a sinusoidal surface perturbation.[1,2] Modifications to the growth rate for the effects of material strength, viscosity, and surface tension have been proposed and tested in multiple investigations.[3]

II. Experiments and Observations

In this paper we report the results from a series of three pulsed power experiments conducted on the Pegasus facility. The basic setup and preliminary results from the first experiment were reported at the last IEEE Pulsed Power Conference.[4] The experiments use a 5.5 MA current pulse to implode a solid z-pinch liner onto a high-density polystyrene foam core that has a 1.6-cm diameter and fits snuggly against the inside diameter of the liner.

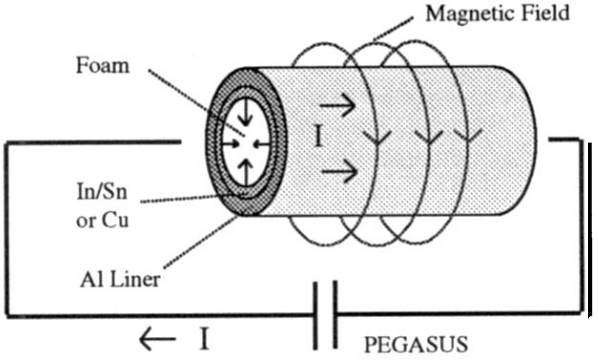

Figure 1. Schematic of RTMIX experimental setup shows Pegasus circuit, composite liner and foam core.

The liner for the first experiment had a 0.1-cm thick wall made of two layers, 0.08-cm of 1100-series aluminum on the outside and 0.02-cm of OFHC copper on the inside against the foam. The ends of the 2.0-cm-high load cylinder were tamped with massive tungsten glide planes to contain the foam core and support the decelerating pressure that drives the copper/foam interface RT unstable. Fig. 1 shows a schematic drawing of the experimental setup. The copper/foam interface in the first experiment was manufactured without intentional perturbations. Both predicted and observed instability growth during the first experiment was inhibited by the expected/assumed material strength of the copper layer during the unstable portion of the dynamic implosion. A 1D magnetohydrodynamic (MHD) simulation of the experiment is shown in Fig. 2. The 1D simulation predicts only the gross liner dynamics and obviously not 2D instability growth effects. Actually, Fig. 2 is a postshot simulation of the second experiment, but since the current, the liner outer diameter, and the average areal liner mass were essentially identical in all three experiments, Fig. 2 is applicable to all three experiments. Material strength of the inner layer has little effect on gross liner dynamics.

In the second experiment, azimuthally symmetric sinusoidal perturbations of 0.1-cm wavelength with two different amplitudes were machined onto the inner diameter of the copper. The smaller 12.5-μm-amplitude

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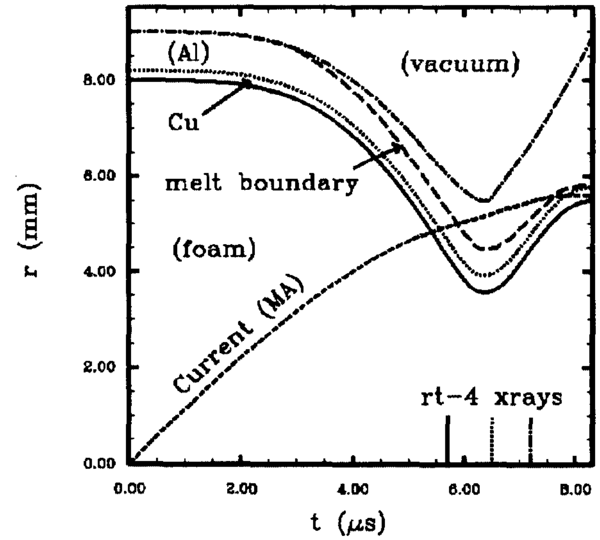

Figure 2. 1D MHD simulation of the second RTMIX experiment showing x-radiographic times for the third experiment and the dynamic position of melt boundary in the Al.

perturbation was predicted to be stabilized by the material strength of the copper, while the larger 50-μm amplitude should have experienced Rayleigh-Taylor growth. These predictions were partially based on analytic linear theory, backed up with 1D MHD simulations to determine interface accelerations and Atwood numbers.[4] The 1D simulations agreed well with the gross liner dynamics measured in all experiments. 2D Eulerian MHD simulations using a standard Steinberg-Guinan strength model[5] for the copper and aluminum also supported the analytic/1D predictions. The simulations predicted that the small-amplitude perturbations should be stable and the large-amplitude perturbations would grow well into the non-linear regime. Surprisingly, both perturbations were stable in the experiment

For the third experiment, we attempted to eliminate strength effects to test RT growth in a regime that was thought to be better understood. Hence, the perturbed layer of copper in the second experiment was replaced with a "strengthless copper" simulant. The material of choice was a soft, low-melting-point alloy made of an approximately 50/50 mixture of tin and indium. The reference density of Sn/In solder was 7.3 g/cm^3 as compared to the Cu density that was 8.9 g/cm^3. Therefore, a slightly thicker mass-matched layer of Sn/In was used in place of the Cu to preserve the acceleration history of the interface and to facilitate a good A/B comparison with the first two experiments. Theory and simulation suggested that both the large and small amplitudes would show unstable RT growth. Radiographic times for the third experiment are shown in Fig. 2. Note that the times are chosen to capture the beginning of the RT unstable phase, the minimum liner radius, and the end of the RT unstable phase. The eight panels of Fig. 3 show a comparison of 2D MHD simulations with the data The experimental radiographs are cropped to show the end of the liner that had the large amplitude perturbations. Neither the large nor the small amplitude perturbations showed any signs of instability growth in the experiment, in disagreement with predictions!

III. Possible (not necessarily probable) Sources of Anomalous Stability

Several explanations have been offered to account for the anomalous stability of the inside diameter of a convergent-geometry z-pinch liner decelerated by the compressed central foam. The following list of possible explanations, in order of most-to-least-likely (in the authors' judgement), is offered for contemplation.

- Poorly understood dynamic properties of the foam could be inadequately accounted for in the analytic theory and in the 1D and 2D simulations. In all cases, the foam is treated as a simple (compressible in the simulations) fluid. Some feature of the foam, like voids, cross-linking, anomalous heating or ramp-like behavior during void collapse, may contribute to the unexpected stability. An experimental approach to address this possibility would be to field a similar Sn/In experiment with a real fluid/gas substitute for the foam. Constraints on initial pressure and density, compressibility, convergence ratio, and compressed density at minimum volume limit the possible choices. Possible candidates are propane and butane.
- The dynamic acceleration history of the interface is such that there is a long period of RT stability during the first part of the implosion, followed by a very short unstable period as the liner is rapidly decelerated in the bounce off of the compressed foam core. If there is an important "history effect" on stability, or if the surface perturbations are significantly altered (made smaller) during the stable part of the implosion, the estimates of interface stability could be unreliable.
- The Sn/In solder might not really melt as expected, implying that material strength effects were still playing a role that is not understood. Since the Sn/In melts at 118°C and is soft enough to be dented with a fingernail at reference conditions, strength effects should have been swamped even if the layer did not melt.
- Shear at the metal/foam interface, which does have a stabilizing effect, could be drastically underestimated by the simulations.
- Convergent geometry effects are not taken into account in the analytic estimates of stability. Likewise, experience with 2D Eulerian MHD simulations indicates that the Eulerian algorithm frequently overestimates instability growth. These two effects, working in concert, could be responsible for our faulty prediction.

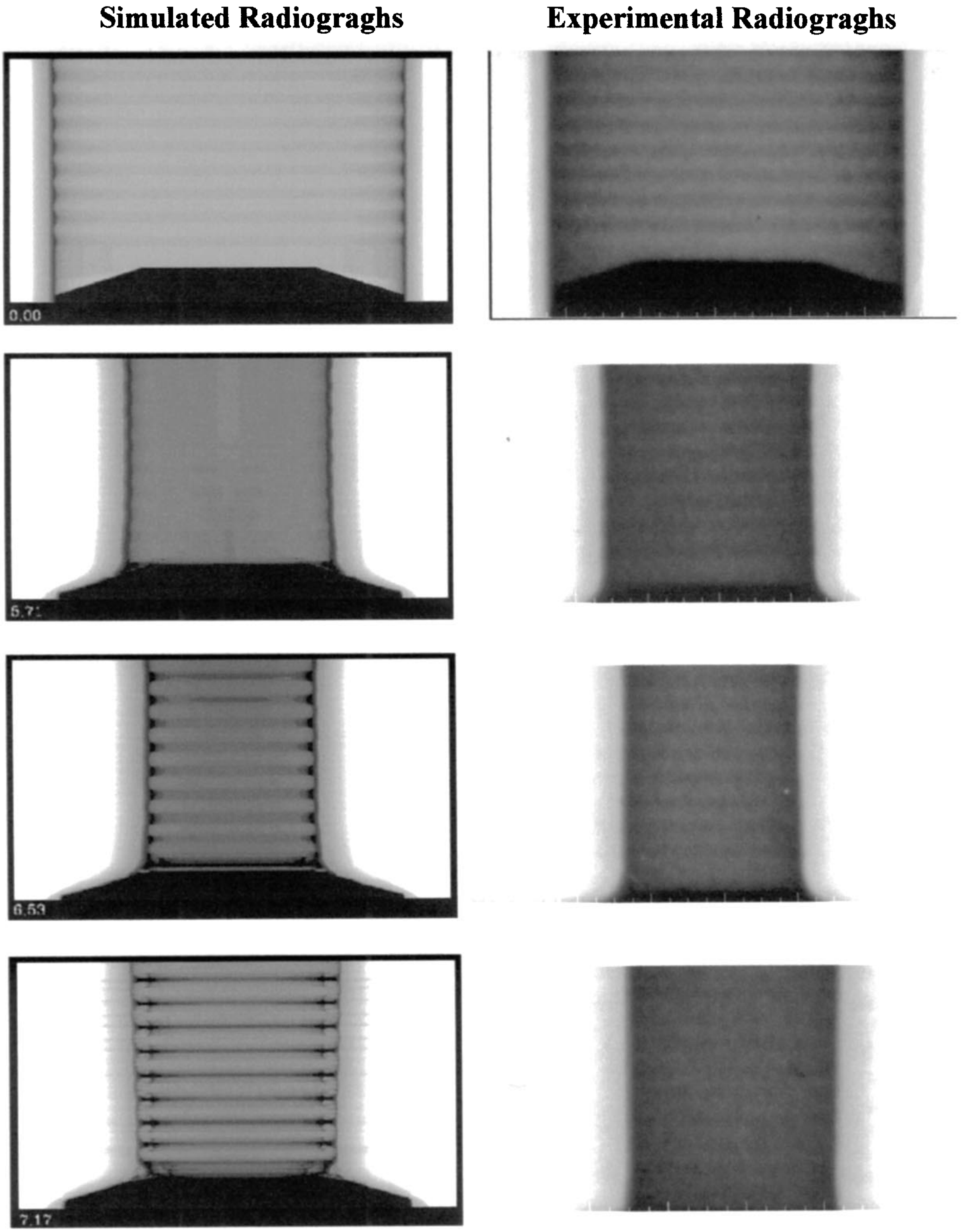

Figure 3. Comparison of 2D MHD simulations (left) with cropped x-radiographs from the third experiment (right). The dynamic evolution of the large-amplitude perturbations at the interface between the Sn/In and the foam is shown at 0., 5.7, 6.5, and 7.2 μs with time increasing from top to bottom. Note that the simulations predict significant instability growth that is not seen in the data.

- During the process of compressing the foam, shocks and reflected shocks are launched in the foam. These shocks drive Richmeyer-Meshkov (RM) processes at the metal/foam interface. Maybe in some strange and wonderful way in this geometry, RM and RT mechanisms interact to cancel each other. "Two wrongs make a right?"
- Magnetic field diffusion into the liner could be contributing to the anomalous stability of the interface. This is thought to be the least likely culprit since the experiment was specifically designed to minimize magnetic field effects; and, to first order, the azimuthal field would be expected to enhance instability growth rather than inhibit it.

IV. Future Investigations

The plan for understanding the anomalous stability observed in these experiments involves several lines of investigation listed below, none of which are yet complete.

- characterization and improved modeling of the foam
- comparison with 2D Lagrangian simulations
- experiment(s) with a liquid in place of the foam
- characterization and improved modeling of the Sn/In solder (both equation of state and constitutive models)

Obviously this paper reports a work in progress. Results of further experiments and analysis are planned for the next IEEE Pulsed Power Conference.

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[1] Lord Rayleigh, *Scientific Papers* (Dover, NY, 1964),Vol II, pg. 200.

[2] G. I. Taylor, Proc. R. Soc. London Ser. **A** 201,192 (1950).

[3] D. H. Sharp, Physica **12D**, 3, 1984 and references therein.

[4] M. G. Sheppard *et. al.*, in 11th IEEE International Pulsed Power Conference, Vol. II, pg. 1399, ed. G. Cooperstein and I. Vitkovitsky, 1997.

[5] D. Steinberg, "Equation of State and Strength Properties of Selected Materials," UCRL-MA-106436, Feb. 13, 1996, Lawrence Livermore National Laboratory.