Observations of vortex merger and growth reduction in a dual-mode, supersonic Kelvin-Helmholtz instability experiment

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Introduction

The Kelvin-Helmholtz instability is a fundamental hydrodynamic process that generates vortical structures and turbulence at an interface with shear flow.

In a supersonic flow, the growth rate of the Kelvin-Helmholtz instability (KHI) is inhibited.

We share the results of laser-driven experiments designed to produce the first observations of the KHI evolving from well-characterized, single-mode and dual-mode initial conditions in a supersonic flow.

Figure 1: We design scaled experiments to study the the behavior of fluids under extreme temperatures and pressures, such as those found in fusion experiments and astrophysical systems.

Photocredit: NASA, Voyager I (1979)

Objectives

1. Design and develop the experimental platform
2. Produce the first data of the KHI evolving from single-mode and dual-mode initial conditions in a supersonic flow
3. Validate or refine simulation codes based on the results

$$\gamma = \frac{k(\Delta u)}{2}\sqrt{1-A^2}\left(\frac{\sqrt{-1-M^2+\sqrt{1+4M^2}}}{M}\right)$$

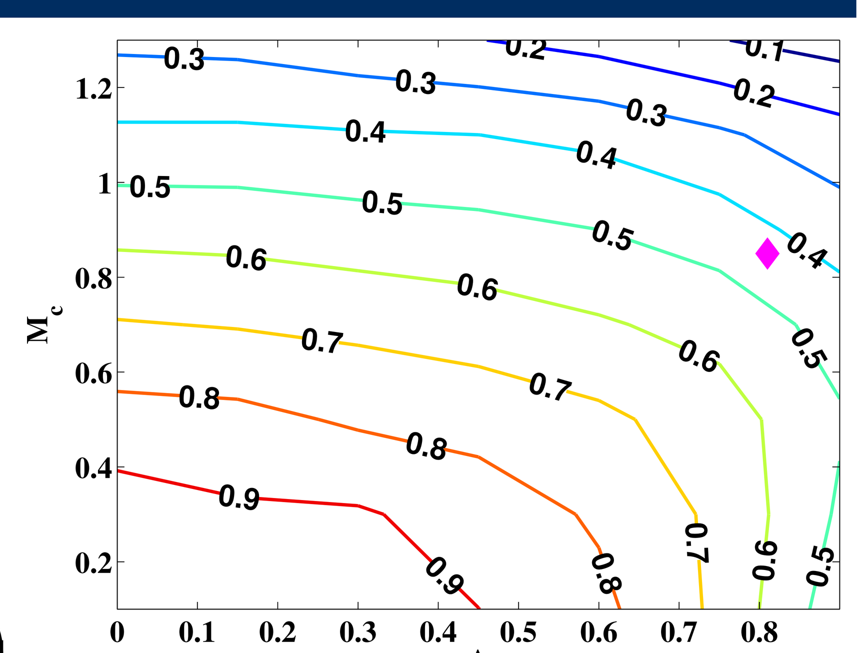

Figure 2: The ratio of the compressible to incompressible growth rate coefficients is reduced by about half for this experiment

Materials and Methods

We developed a novel experimental platform, firing three 10-ns laser pulses in sequence to sustain a shockwave in carbon foam for roughly 70-ns.

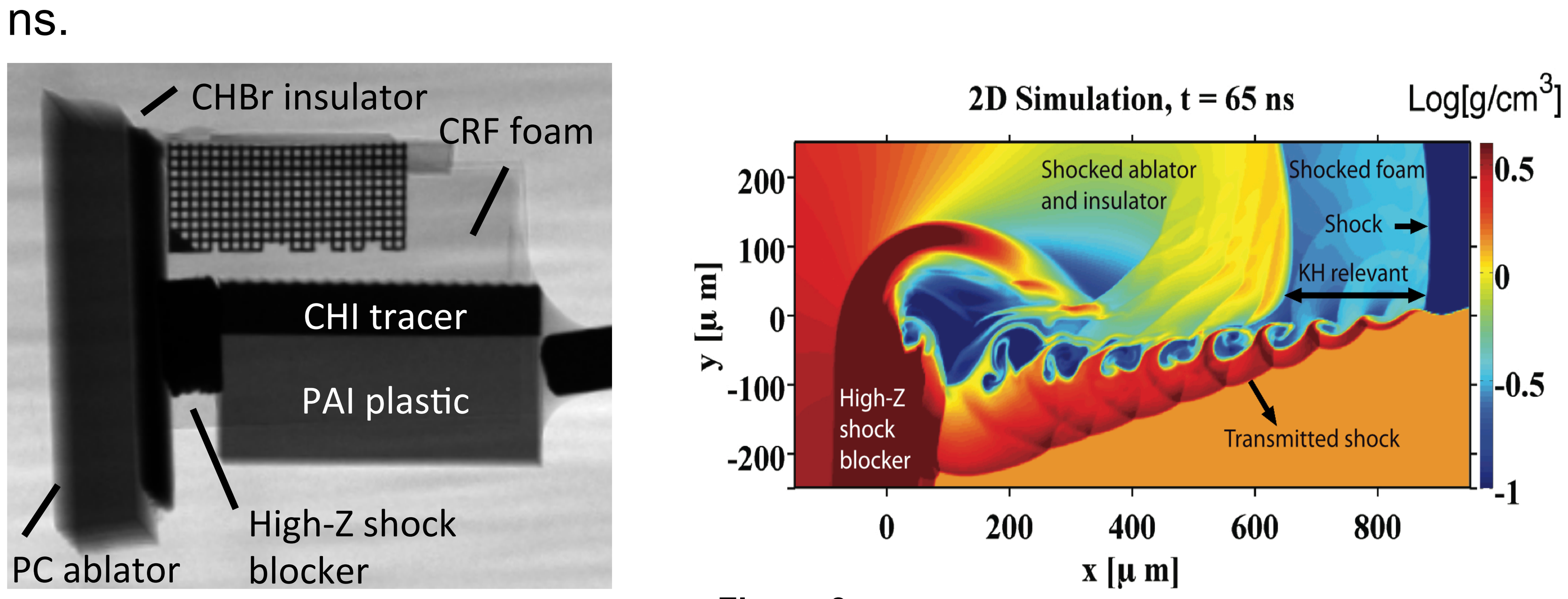

Figure 3:
Left: Our primary diagnostic is Cu K_α x ray radiography. An unshocked target is shown
Right: 2D simulations are used for both design work and data analysis

Results and Discussion

The data supports the predicted reduction in the KHI growth rate.

The red line denotes the predicted amplitude vs. time of the seed perturbations evolving under experimental conditions.

The black line is from a simulation with an increased pressure and, hence, sound speed, minimizing the effect of compressibility.

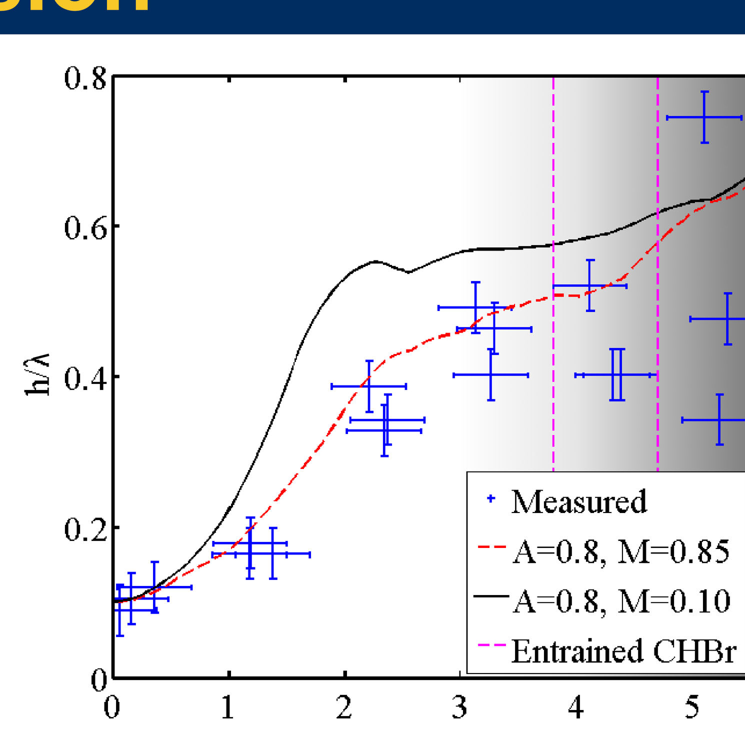

Figure 4: The data supports predictions of growth inhibition, until disturbed by the thermal insulator

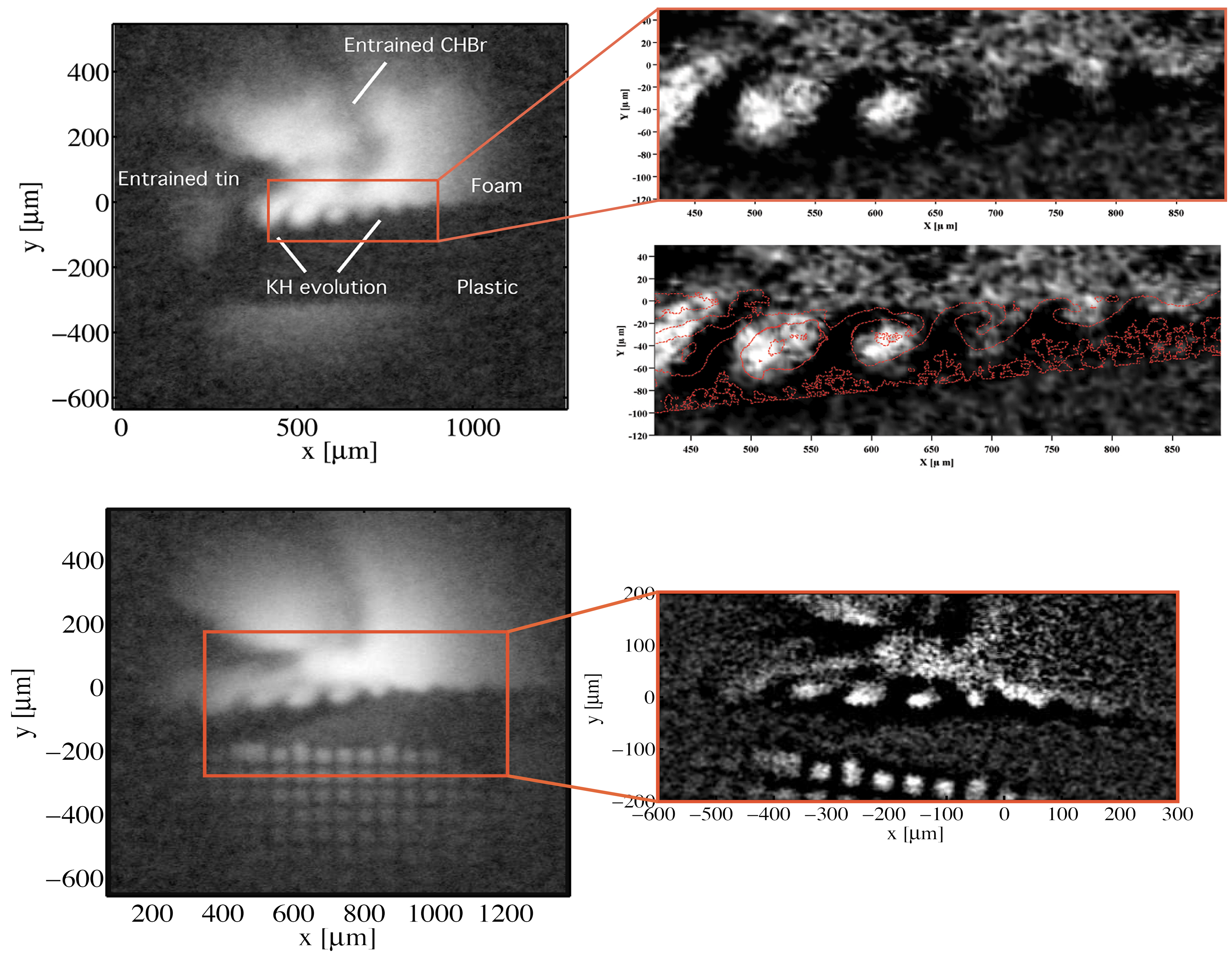

Figure 5:
Top: Single-mode data is in detailed agreement with simulations
Bottom: Preliminary analysis of the dual-mode data shows promising signs of vortex merger

Large scale behavior, such as modulation amplitude growth, has been well-reproduced with 2D simulations.

Fine-scale structures that exist on the edge of the diagnostic resolution limit (~10-15 μm), such as the curled tips of the modulations, also appear to be in reasonable agreement with simulations. It is difficult to determine whether the small discrepancies reflect a real difference, or simply experimental uncertainties. Additional data can provide insights as to whether simulation codes correctly handle the development of structures and turbulence at small scales.

Conclusions

1. We developed an experimental platform that can sustain a steady, supersonic flow for timescales that greatly exceed the characteristic timescale of common hydrodynamic instabilities. This platform can be given well-characterized seed perturbations as part of the tightly controlled initial conditions.
2. This platform was used to produce the first experimental observations of the Kelvin-Helmholtz instability evolving from well-defined, single-mode and dual-mode initial conditions in a supersonic flow. The data supports an inhibition in the growth rate of the KHI.
3. Additional analysis will also provide the first measurements of the vortex merger rate of well-characterized seed perturbations evolving under the Kelvin-Helmholtz instability.

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