Undergraduate Studies of Supersonic Flow from a Converging-Diverging Nozzle

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Bethel nozzle flow video library

At Bethel University, fluid mechanics is integrated into the physics and engineering programs through an introductory course in fluid mechanics that incorporates laboratory and computational components. In recent years, student projects have been carried out to study a number of applications involving compressible flows and shock waves [1, 2]. Here, undergraduate studies are carried out to examine the supersonic flow from an axisymmetric converging-diverging nozzle. Flow is initiated by the rupture of a diaphragm and exits from a small nozzle (with a 3/8" exit diameter) into standard atmospheric conditions from a one gallon tank. COMSOL simulations are carried out for the nozzle and comparisons are made to experiments based on high-speed video shadowgraph imaging and dual-beam interferometry measurements of fluid density.

COMSOL Simulation:

Simulations are carried out for unsteady, axisymmetric flow with the High Mach Number interface of the CFD module. Adaptive meshing is utilized to capture the structure of the flow, including the initial shock wave and the Mach diamonds that are present after flow from the nozzle has been fully established. The flow is driven by an initial pressure condition that is representative of the experimental condition upon rupture of the diaphragm. No-slip, thermally insulated boundary conditions are prescribed at all boundaries, except for the symmetry axis.

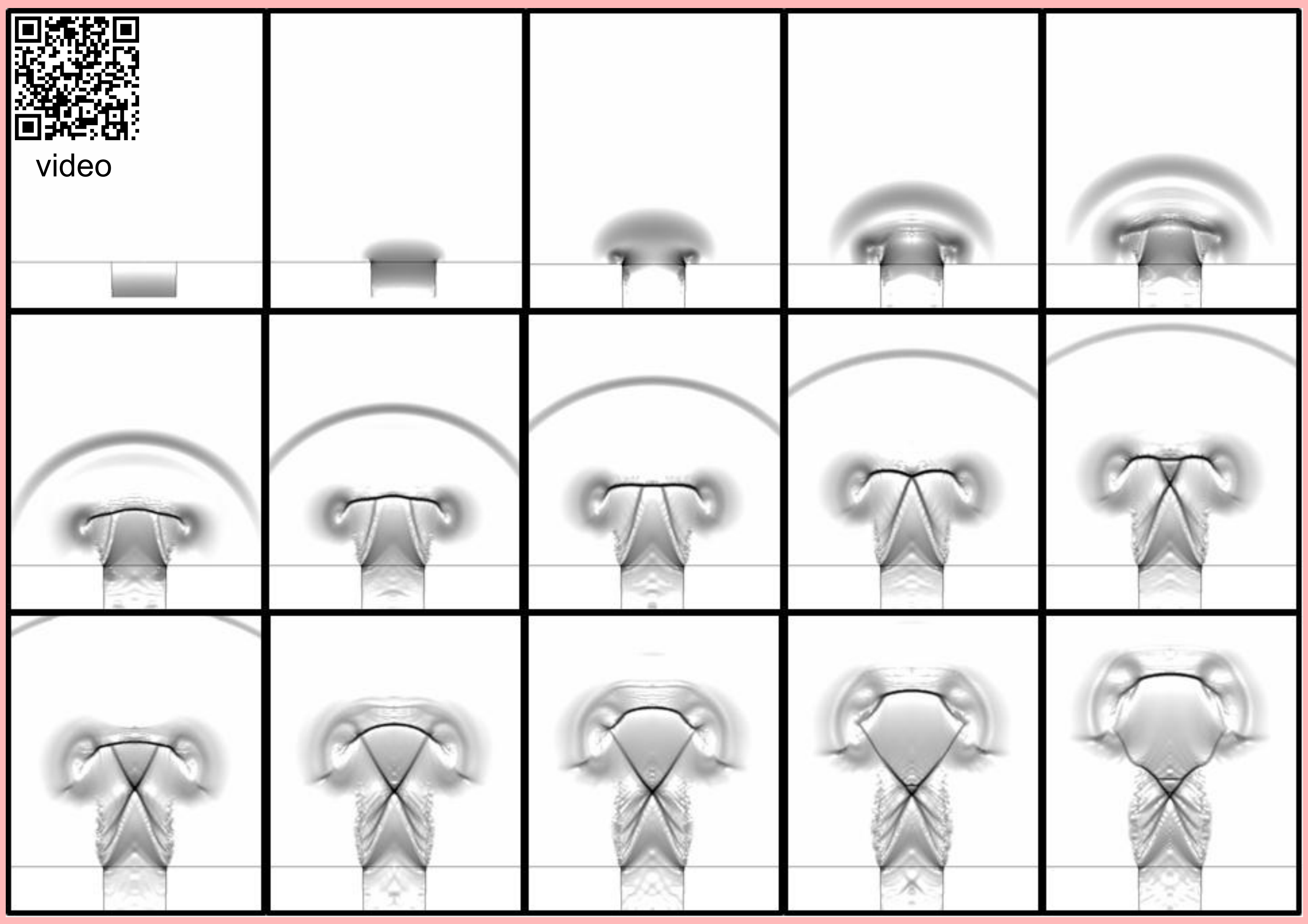


Figure 1. Sequence of images from the COMSOL simulation corresponding to the shadowgraph sequence shown in Figure 43. The images display the density gradient at 10 μs steps, with dark regions corresponding to maximum density gradient. The images are mirrored about the symmetry axis for clarity.

Comparison video

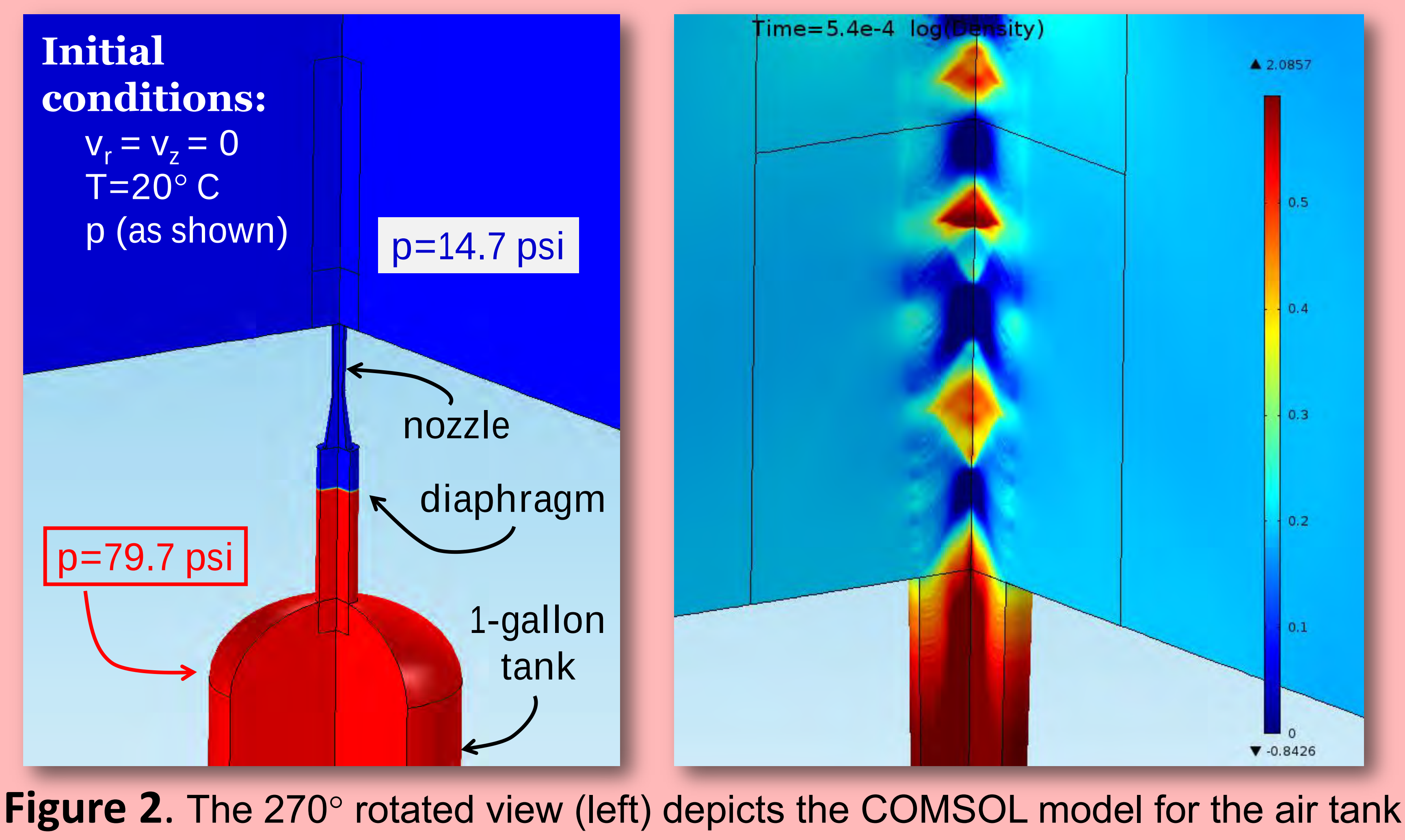


Figure 2. The 270° rotated view (left) depicts the COMSOL model for the air tank, nozzle, and exit flow region. The initial pressure condition transitions from high to low pressure at the diaphragm position. Density variations 540μs after the flow is initiated depict the formation of Mach diamonds at the nozzle exit (right).

References:

1. G. Olson, R. Peterson, B. Pulford, M. Seaberg, K. Stein, C. Stelter, and R. Weber, "The role of shock waves in expansion tube accelerators," *American Journal of Physics*, **74** (2006) 1071-1076.
2. K. Stein, "Fluid Mechanics and Computational Physics in the Advanced Undergraduate Laboratory," *Proceedings of the AAPT Topical Conference on Advanced Laboratories*, Ann Arbor, Michigan (2009).
3. K. Stein, R. Peterson, J. Houlton, J. Knapp, B. Peplinski, C. Scheevel, and D. Swenson, "Resonating with Students in the Undergraduate Physics Laboratory: Comprehending Acoustic Vibrations," *COMSOL Conference*, Boston, Massachusetts (2008).

High-Speed Video Shadowgraph Imaging:

High-speed video shadowgraph imaging is conducted at 100,000 frames per second to compare the initial flow from the nozzle with the COMSOL simulation. Features in the shadowgraph images result from changes in the index of refraction due to density gradients in the flow. As in the simulation, dark features correspond to the areas with large density gradient. Comparison between the shadowgraph and the simulation shows a strong spatial and temporal correlation in the initial shock structure and flow from the nozzle.

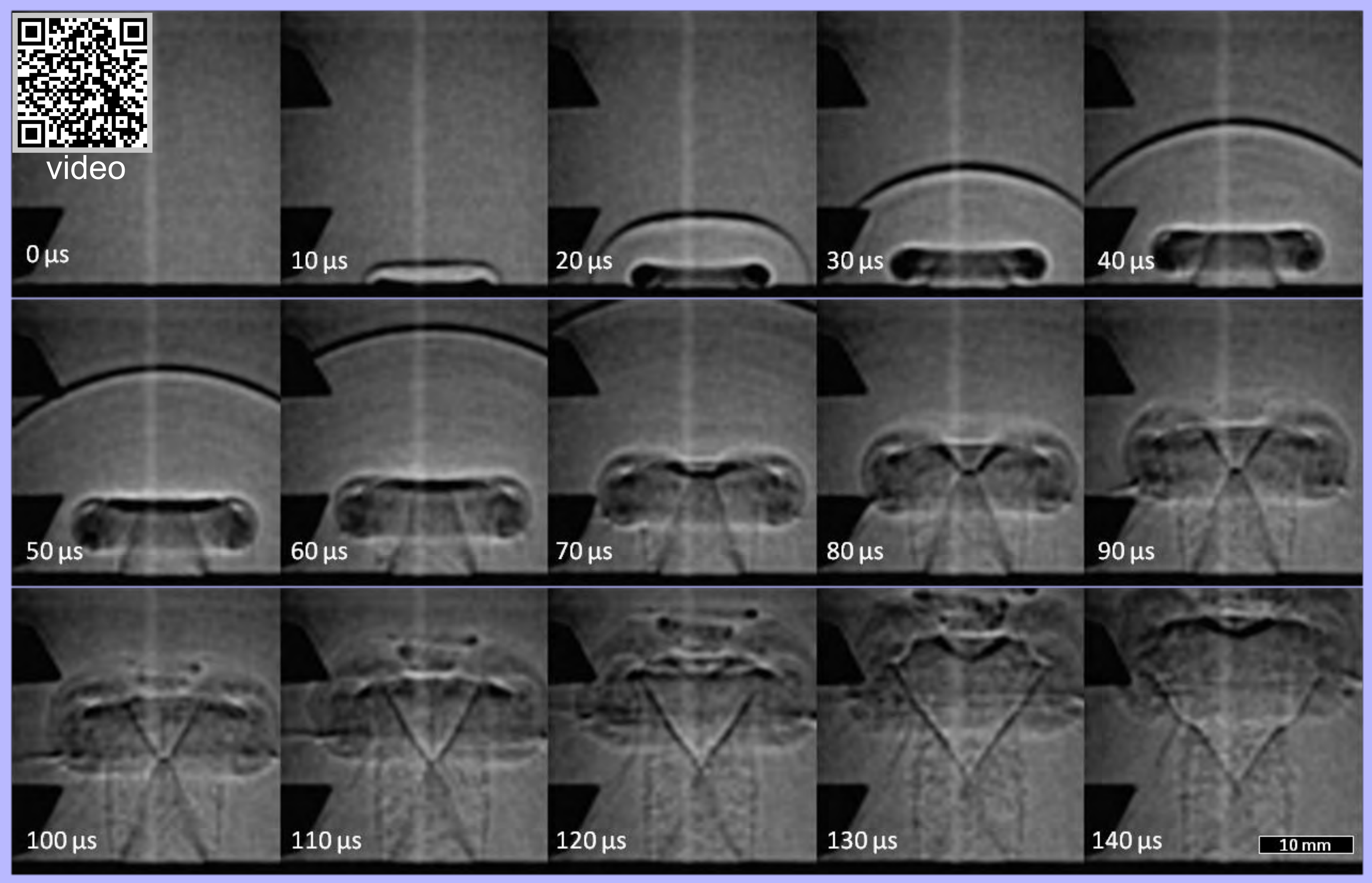


Figure 3. High-speed video shadowgraph image sequence depicting the initial shock wave and the formation of the Mach diamonds at the exit of the nozzle.

Dual-Beam Heterodyne Interferometry:

Dual-beam heterodyne interferometer measurements detect changes in air density due to shock features through resultant change in refractive index. An acousto-optic modulator frequency-shifts the stabilized He-Ne laser light used in the interferometer arms. When the frequency shifted light is recombined with original incident laser light, the phase change data from shocks is encoded on 80MHz beats on twin photodetectors. An RF mixer and LABVIEW VI decode and extract total phase shifts as a function of time from the interferometer output. COMSOL simulations integrated over a 1-D path can be compared to interferometer measurements at varying distances from the nozzle exit.

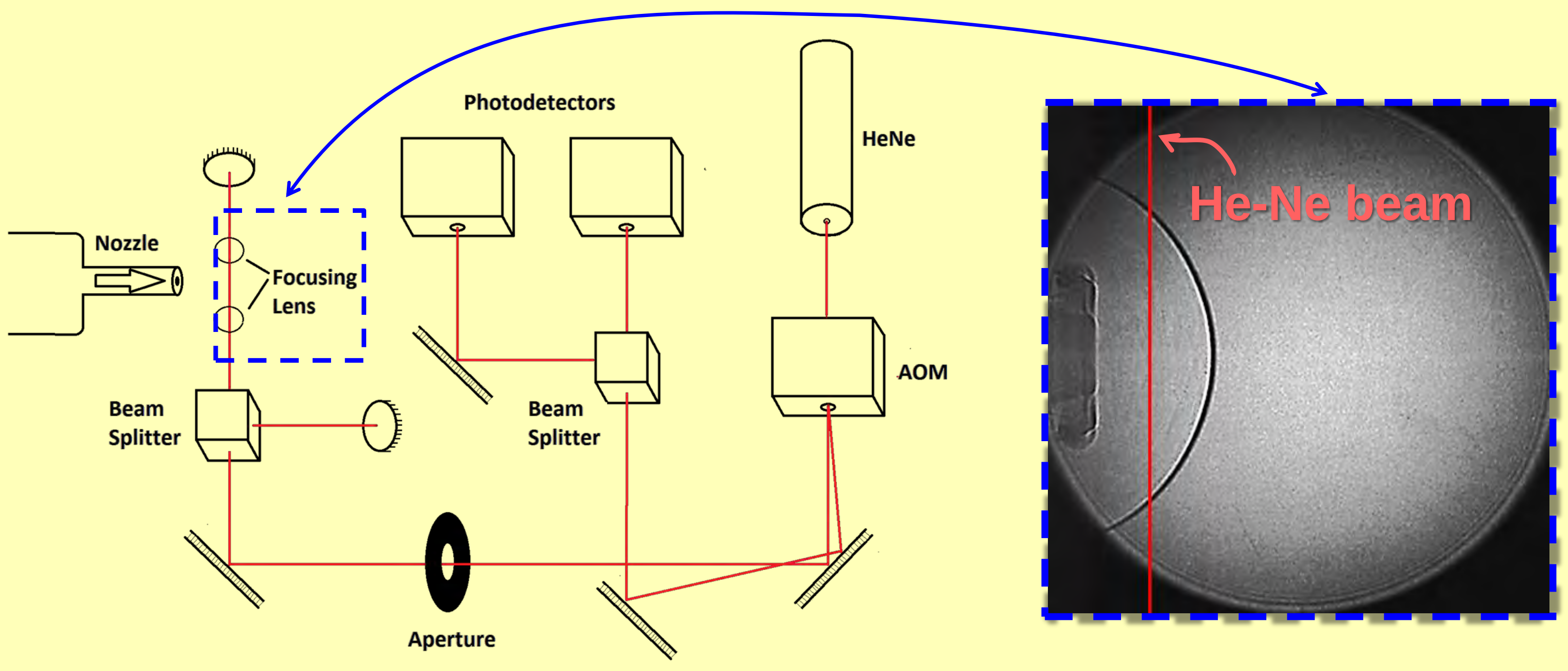
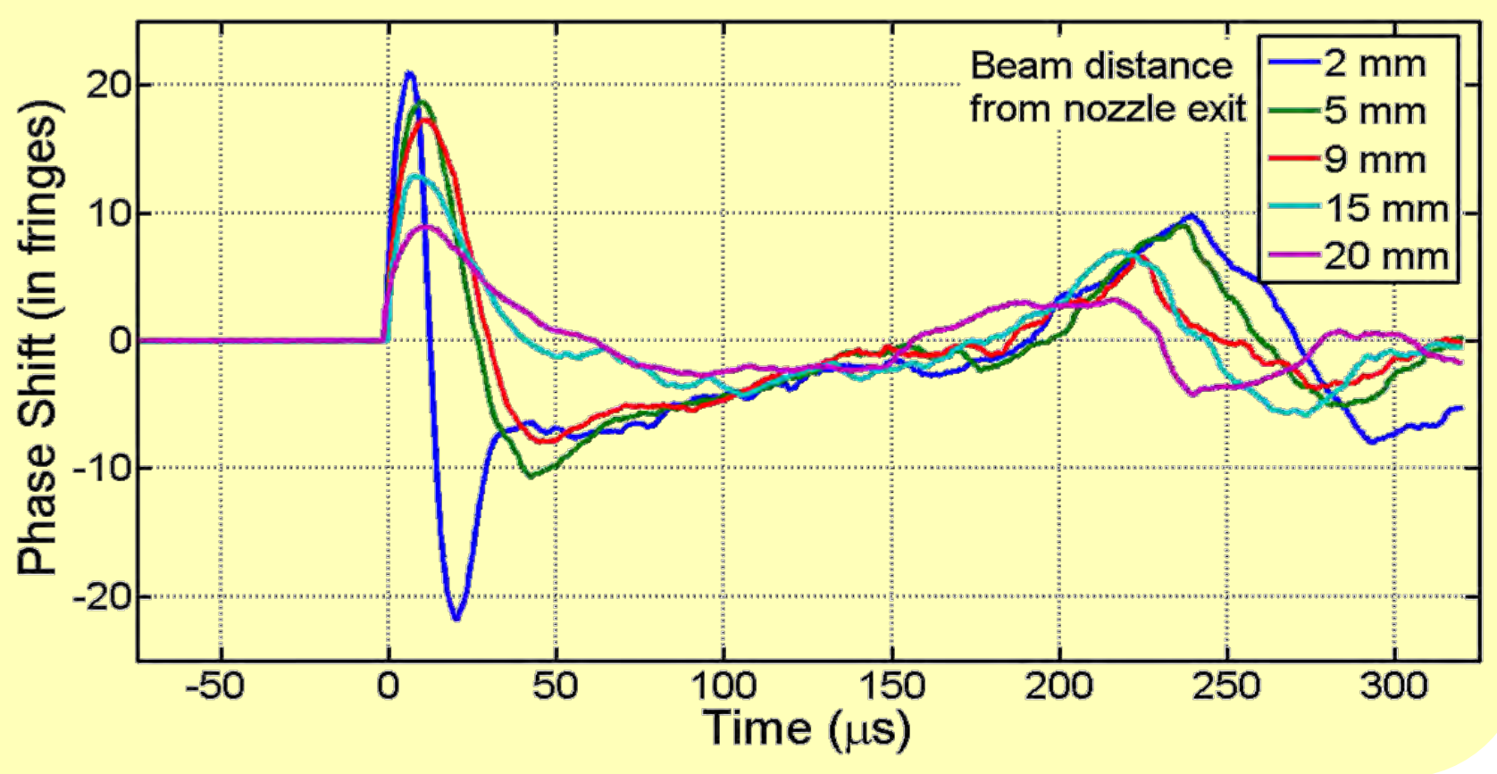


Figure 4. Experimental setup for the dual-beam heterodyne interferometer (left), with one arm of the interferometry passing through the nozzle flow field (right). An expanded view is shown at the nozzle exit, depicting the He-Ne laser pass

Figure 5. Interferometer measurements of total phase shift detected at various distances from the nozzle exit. The first peak on the graph corresponds to the initial shock wave, and it is followed by a decrease in phase, signifying the low pressure region following the shock.



Acknowledgment: Portions of this work were supported by the NASA-MN Space Grant Consortium.