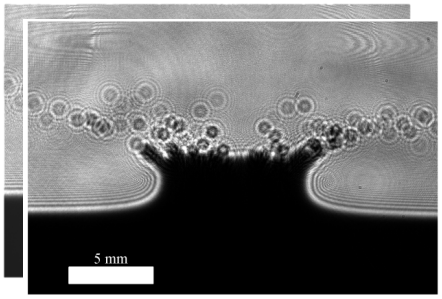
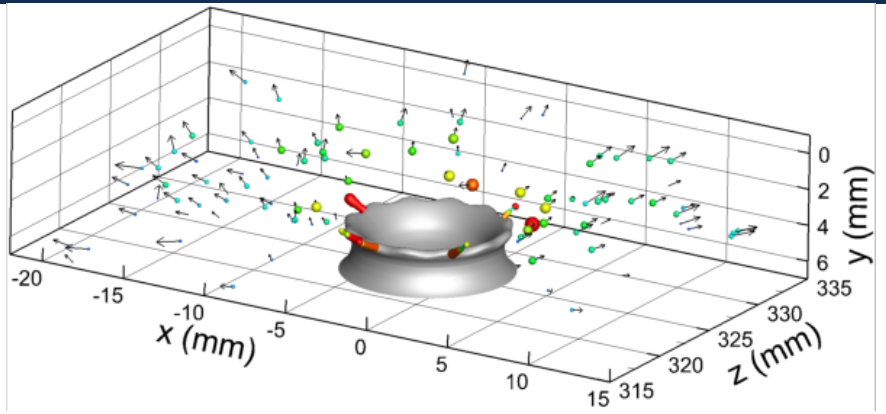
SAND2016-6834C

Exceptional service in the national interest

Sandia National Laboratories





High-Speed (20 kHz) Digital In-line Holography (DIH) to Quantify the Impact of a Viscous Drop on a Thin Film

Daniel R. Guildenbecher and Paul E. Sojka

July 28, 2016

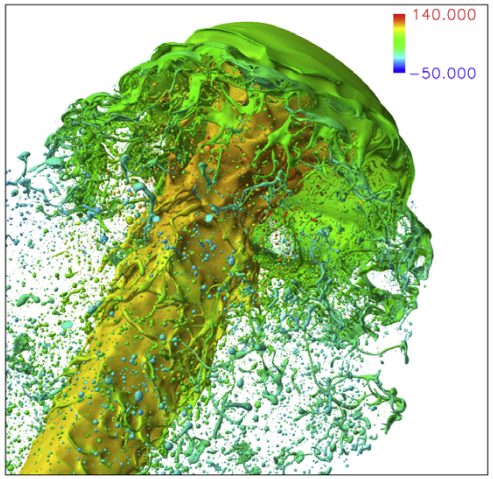
U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

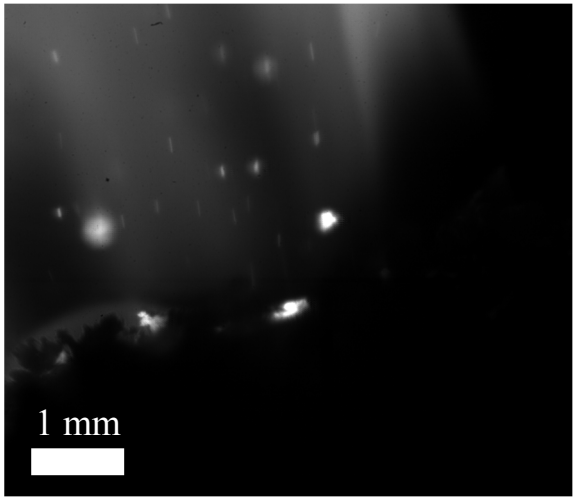
Motivation: Single-shot particle statistics

Sandia National Laboratories

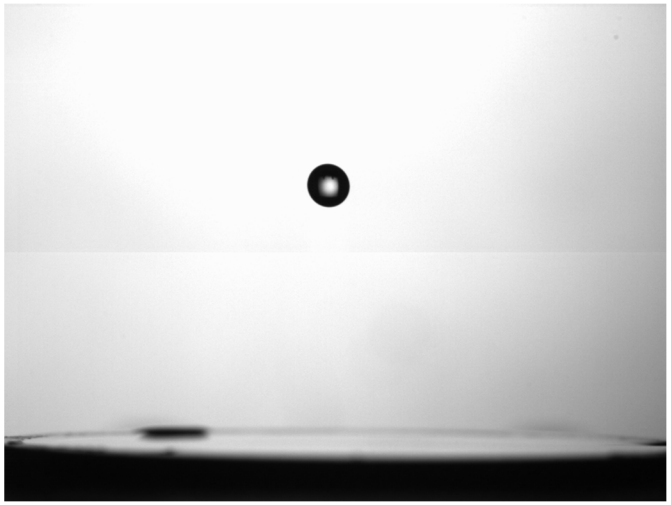
Multi-phase particle flows are often transient and highly 3D



Shinjo and Umemura, 2010,
Int. J. Multiphase Flow

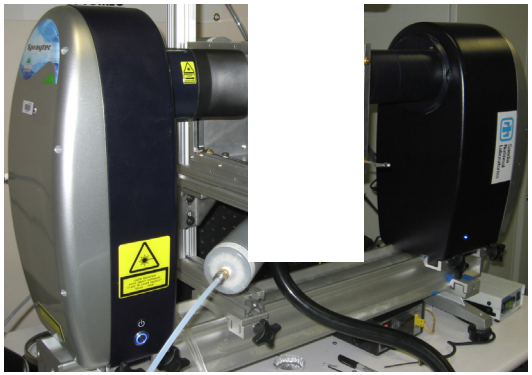


high-speed video of a burning propellant

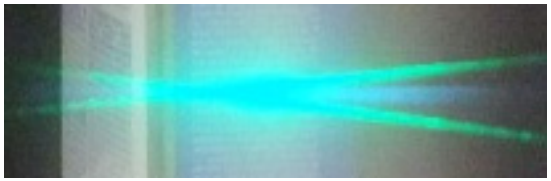


impact of a water drop on a thin-film.
Guildenbecher et al, 2013, *Exp. Fluids*.

Yet our diagnostics are mostly limited to 1D or 2D



laser diffraction



phase Doppler

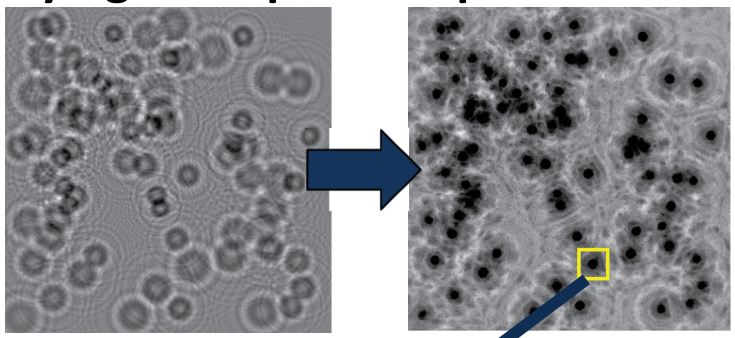
Digital Holography is one potential solution

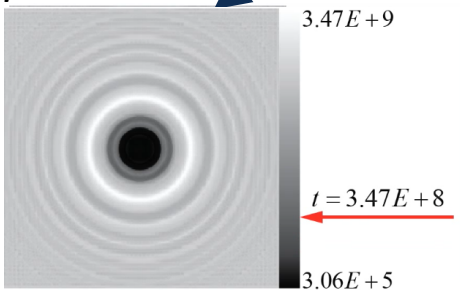
- Large 3D measurement volumes → 1000s of particles from single-shot experiments
- High-speed recording for transient dynamics
- Direct imaging of non-spherical particles

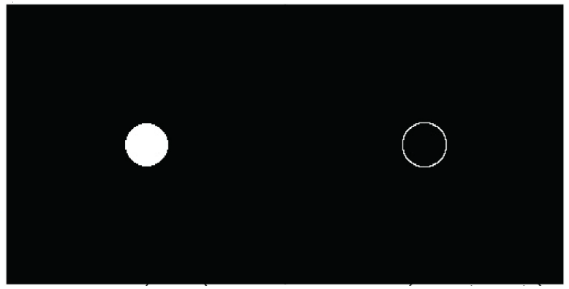
Hybrid method for particle measurement

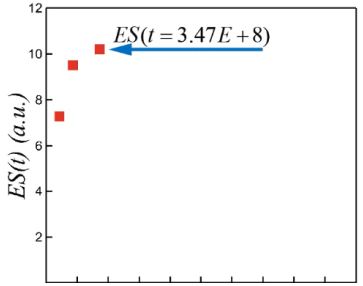
We are most interested in quantifying non-spherical particles

- No *a-priori* shape information → inverse methods are challenging
- Instead, we reconstruct the amplitude (or intensity) throughout depth and apply a focus metric
  - *Hybrid method* detailed in Guildenbecher et al 2013, *Appl. Opt.;* Gao et al 2013, *Opt. Express;* Gao et al 2014, *Appl. Opt*.

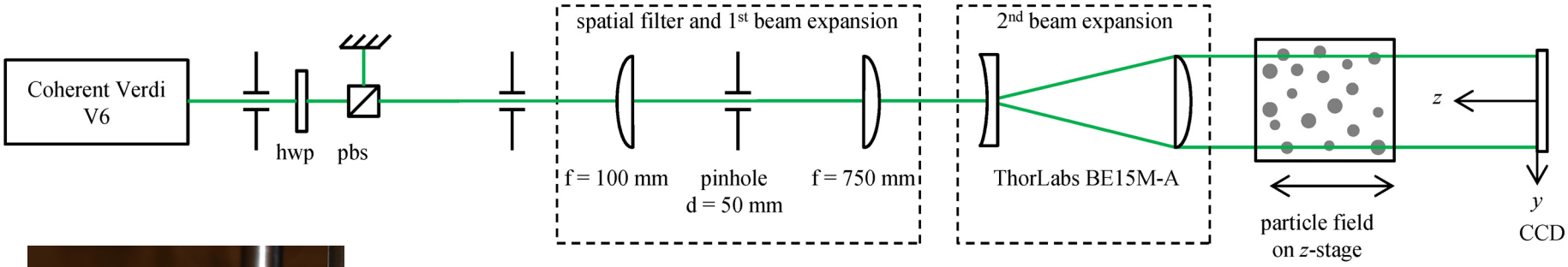


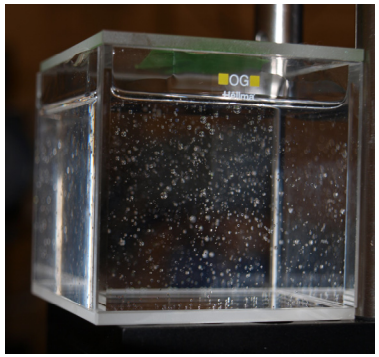






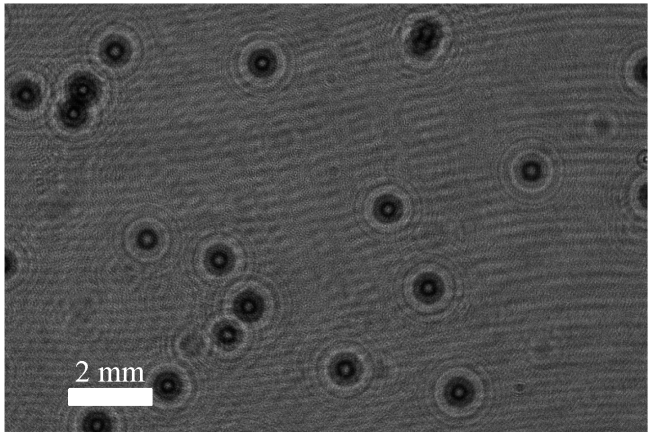
Experimental validation



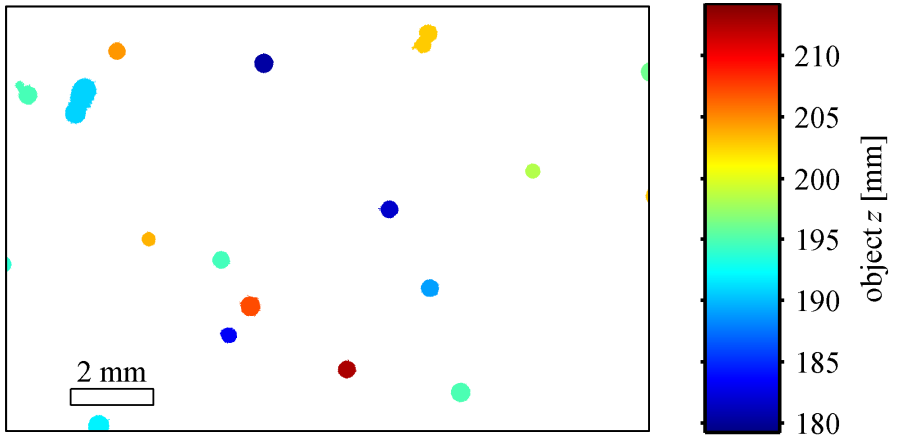


particle field

- Quasi-stationary particle field
  - Polystyrene beads ($\bar{d} \approx 465\,\mu m$) in 10,000 cSt silicone oil
  - Settling velocity ≈ 0.8 µm/s
- Multiple holograms recorded, displacing the particle field 2 mm in the *z*-direction between each acquisition

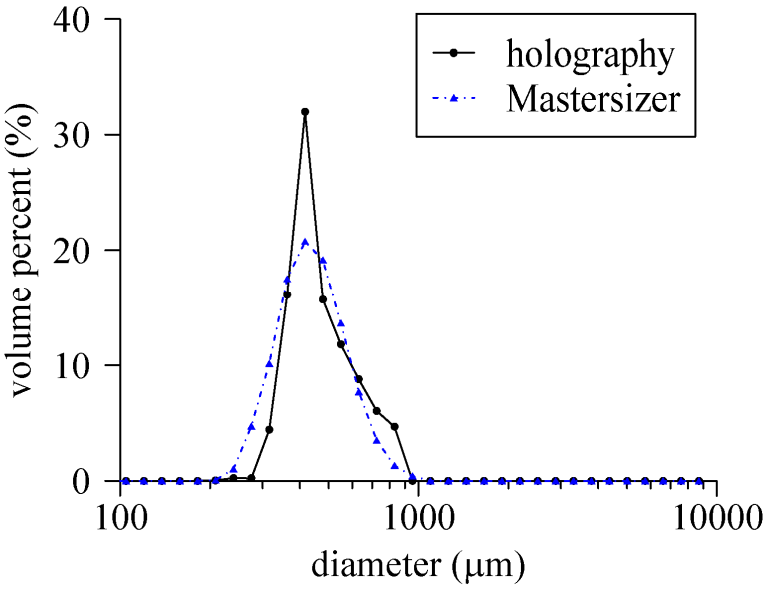


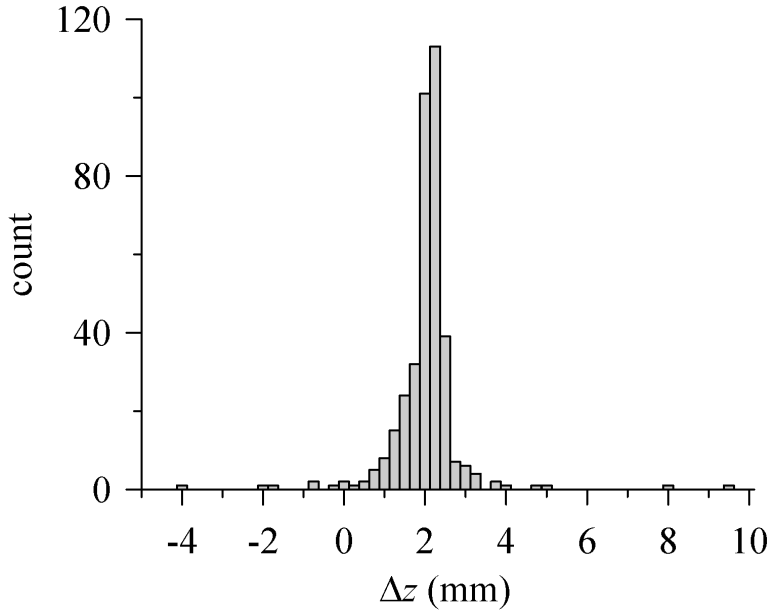
hologram



Detected objects colored by *z*-position

Experimental validation





Diameter measured from area of the detected 2D morphology

- Actual mass median diameter = 465 μm
- Measured mass median diameter = 474 μm
  - Error of 2.0% with respect to actual value

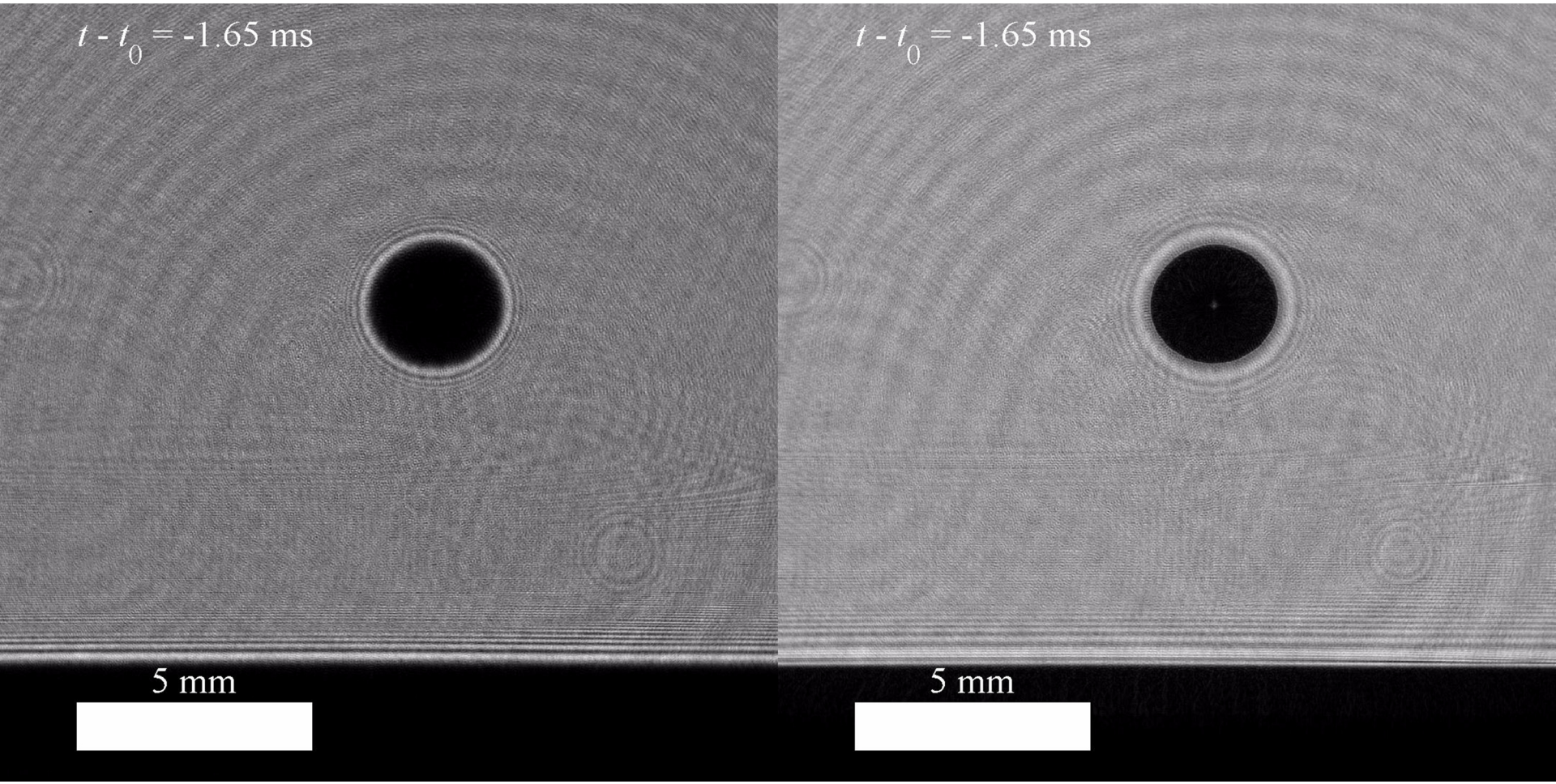
Displacement found by particle matching between successive holograms

- Actual displacement = 2.0 mm
- Mean detected displacement = 1.91 mm +/- 0.81 mm
  - Standard deviation of 1.74 times mean diameter

High-speed (kHz) DIH

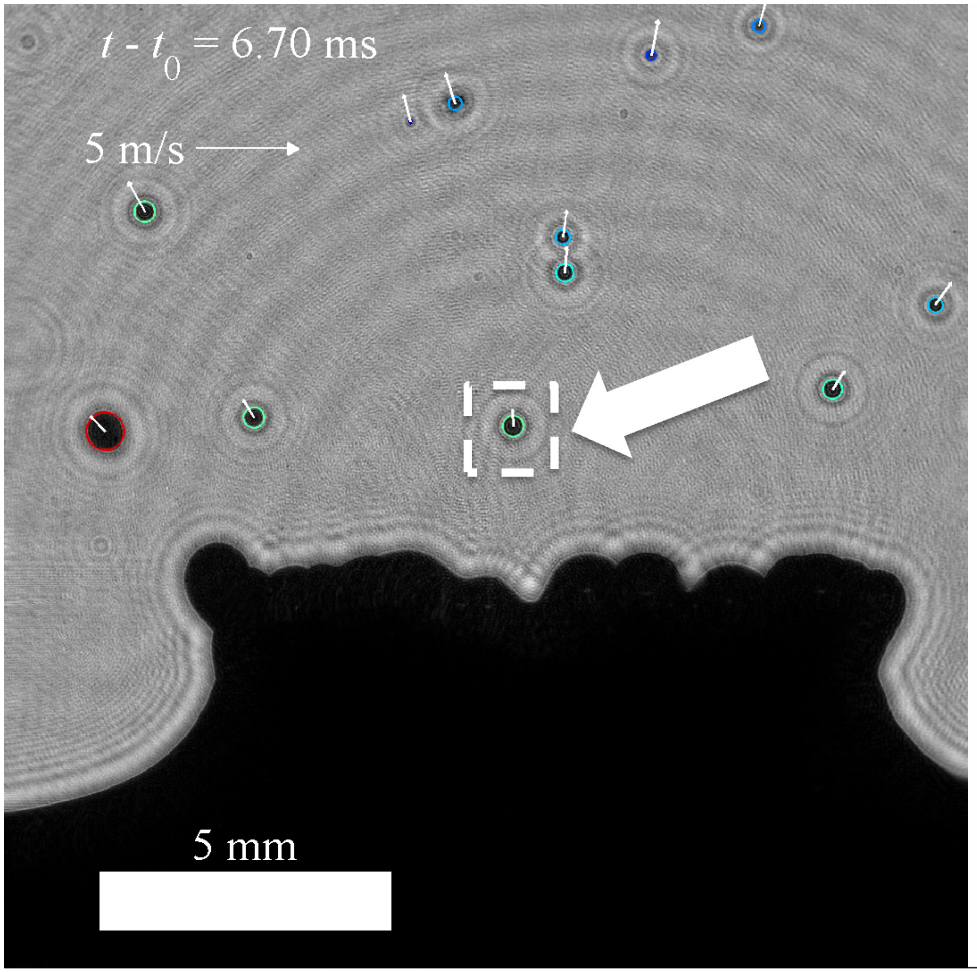
Sandia National Laboratories

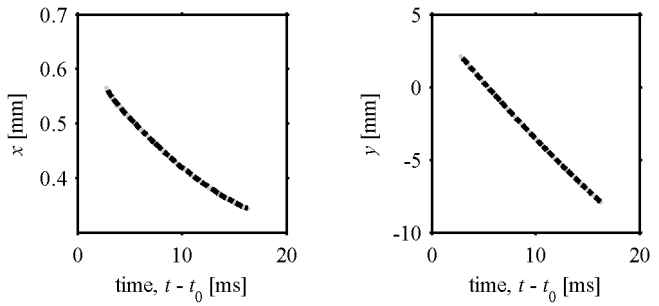
Increased temporal resolution is possible using high-speed (kHz rate) cameras

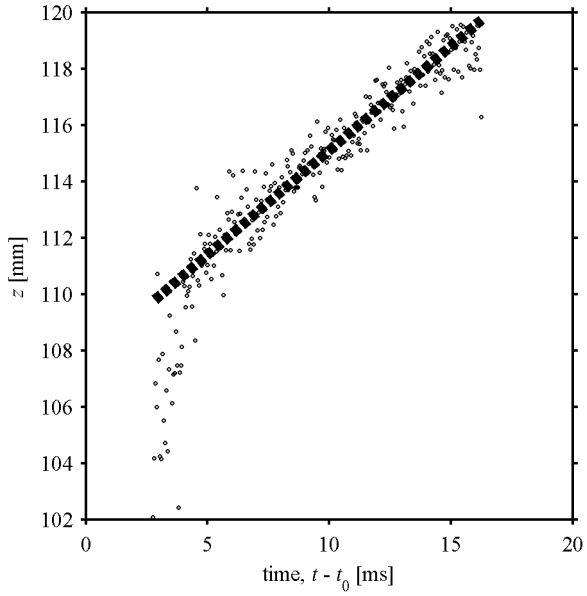


Challenges: (1) higher readout noise, fewer pixels, larger pixel pitches
(2) very large data sets (10s of Gb)

High-speed (kHz) DIH

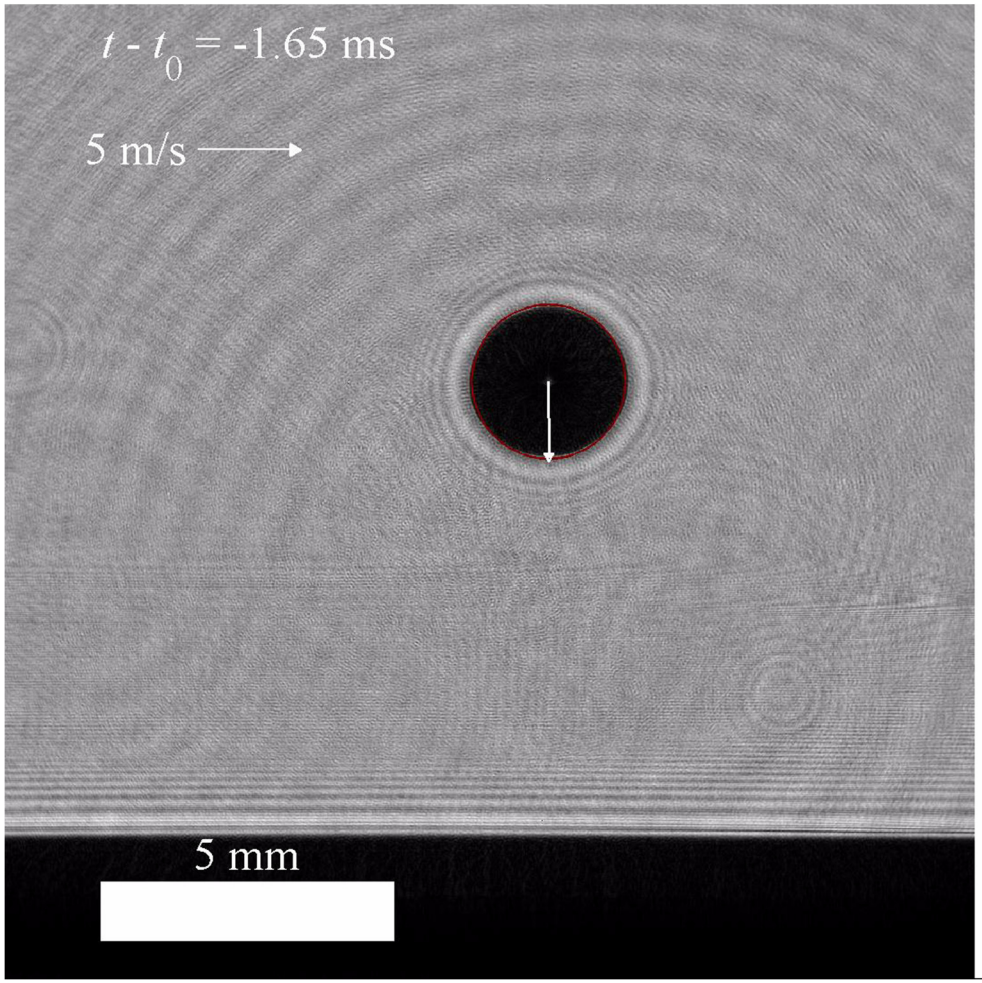


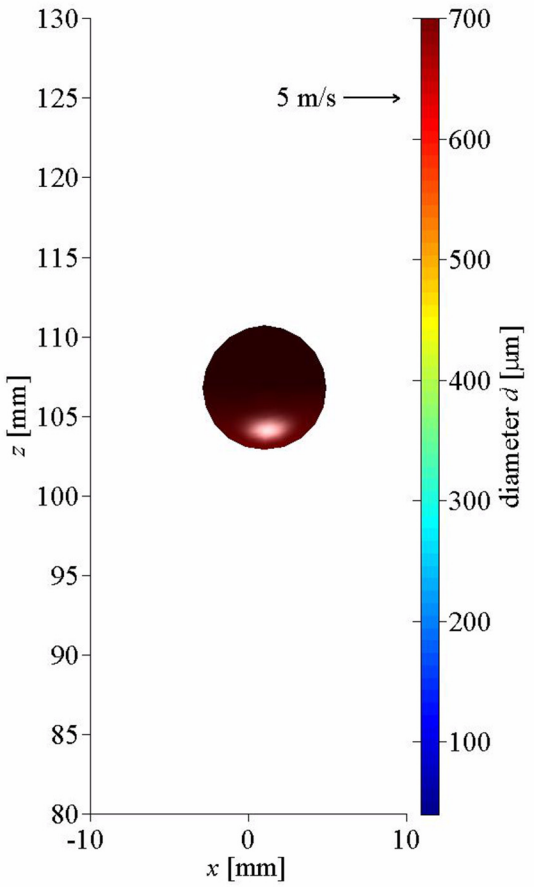




- Frame-to-frame particle matching illustrates the depth-of-focus problem
- With sufficient temporal resolution, particles trajectories can be fit to temporal models

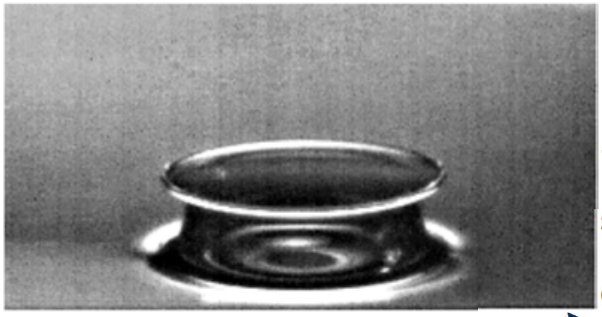
High-speed (kHz) DIH



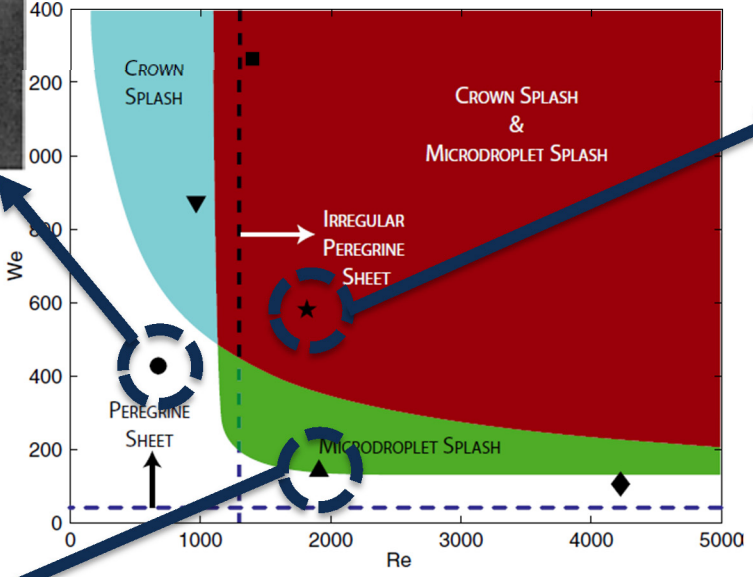


Regression based Multi-frame Tracking (RMT) allows for 3D-3C temporal measurements (Guildenbecher *et al.*, 2016, *Appl. Opt.*)

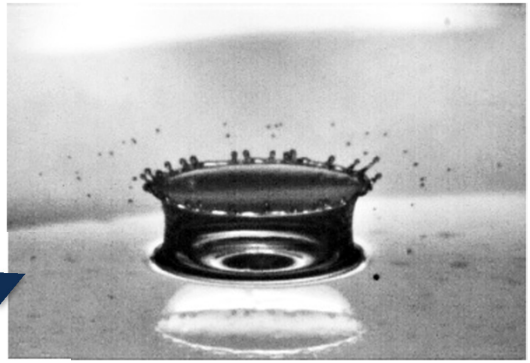
Viscosity has a significant effect



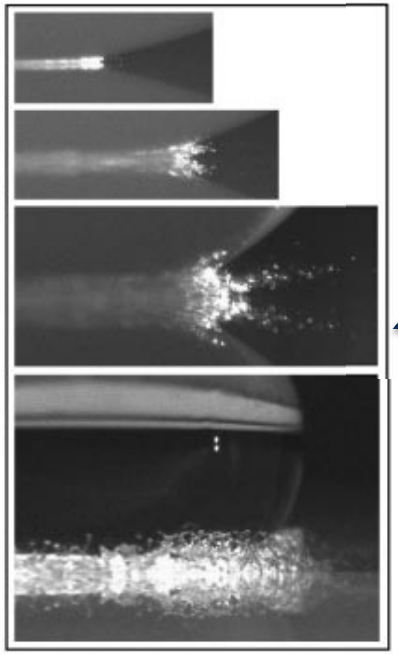
Deegan et al, 2008, *Nonlinearity*



Deegan et al, 2008, *Nonlinearity*



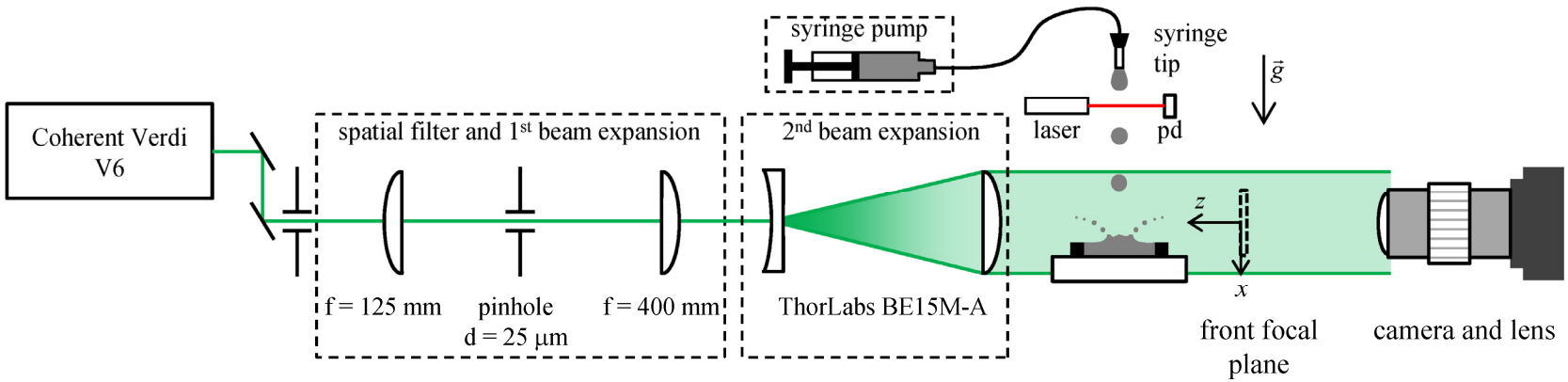
Deegan et al, 2008, *Nonlinearity*



Thoroddsen, 2002, *J. Fluid Mechanics*

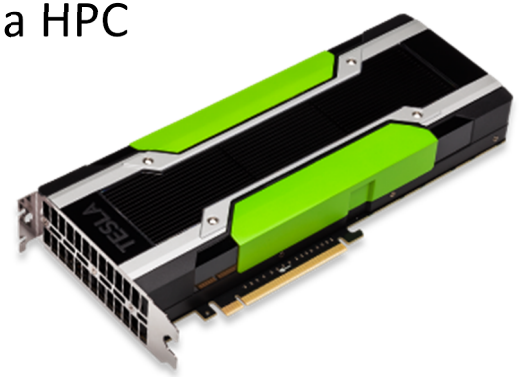
<u>Goal:</u> Quantify effects of viscosity on the properties of the secondary fragments

Viscous drop impact

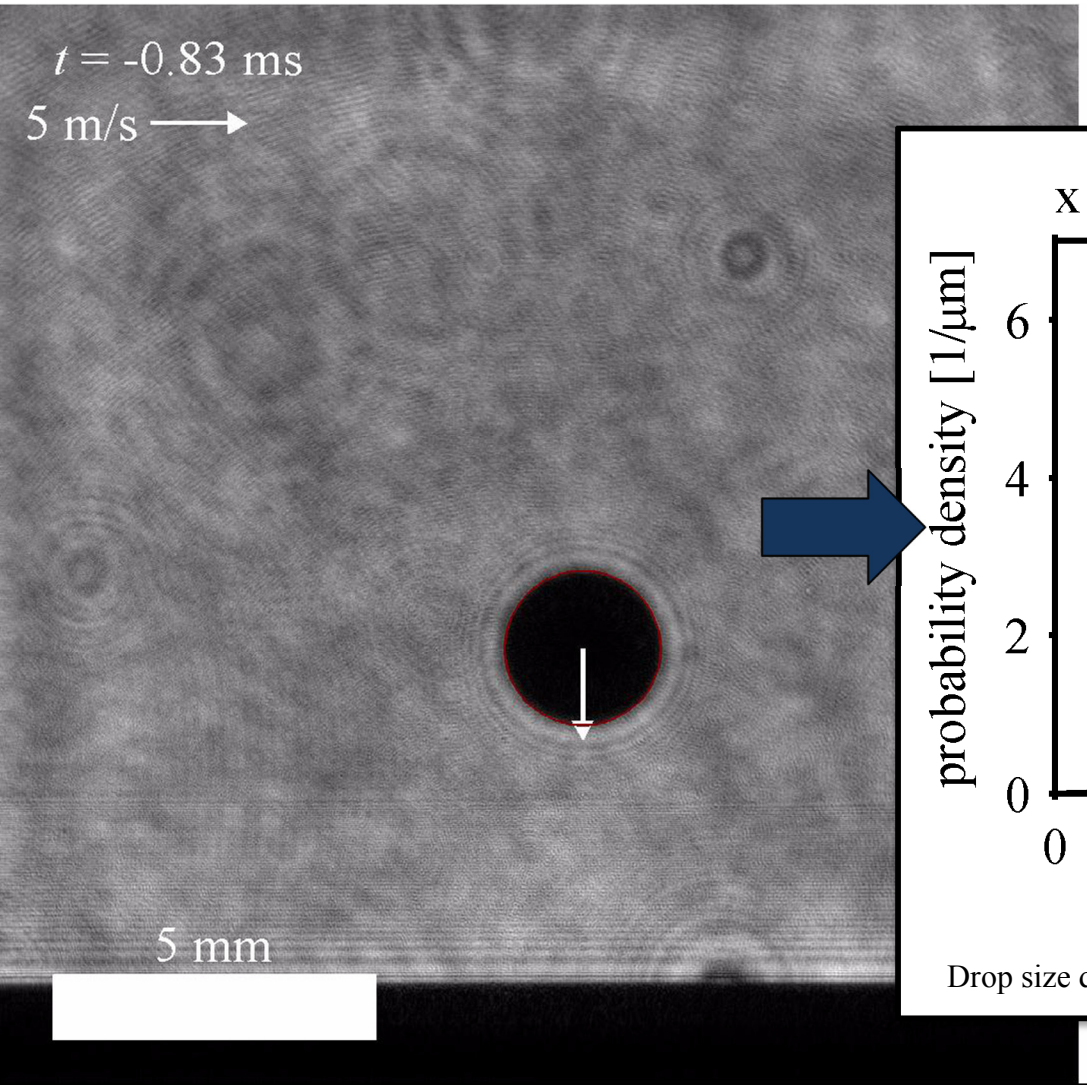


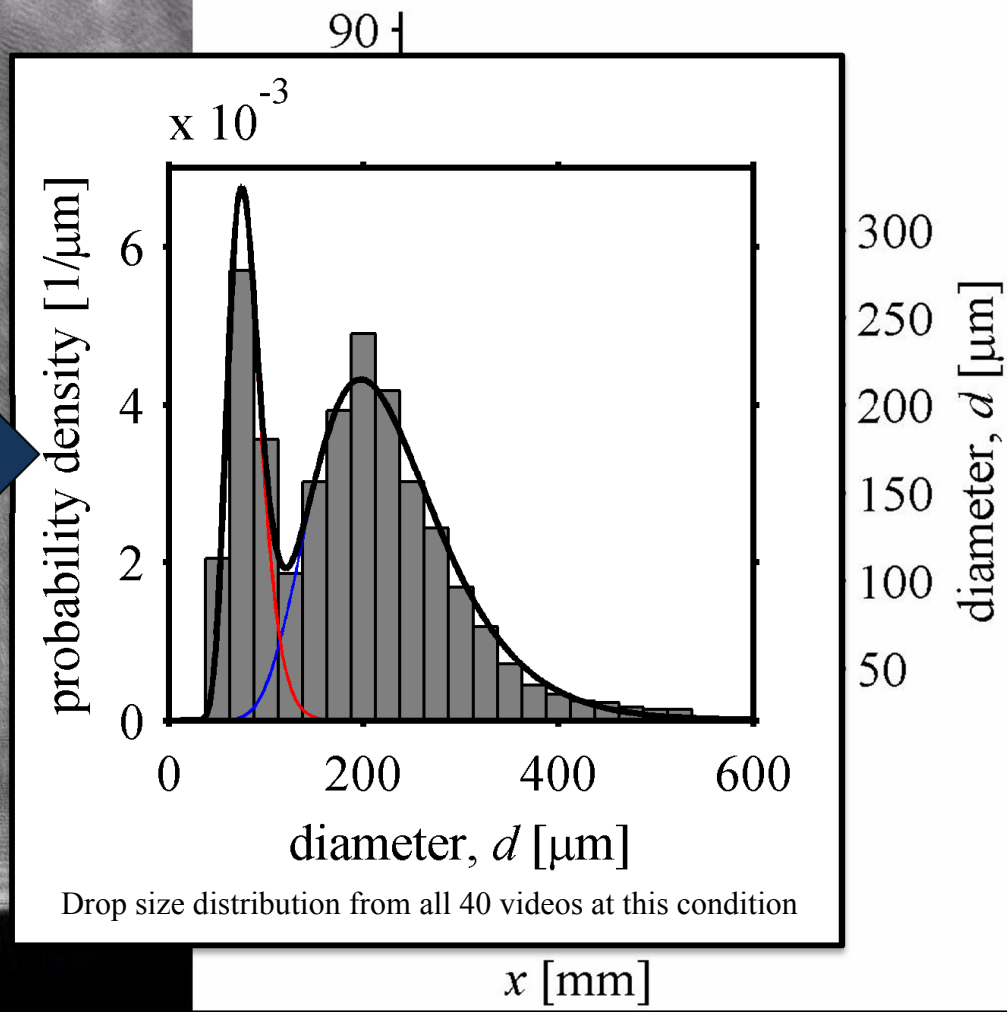
- Five different materials investigated (mixtures of water, methanol, and glycerin)
- Three different fall heights investigated for each material
- Forty impact events investigated at each condition
- Data processed using custom MATLAB® routines on a HPC cluster consisting of four NVIDIA K80® GPUs
  - Requiring approximately 19 days of wall-clock time

→ 600 videos, 1.3 TB of raw data!



Viscous drop impact

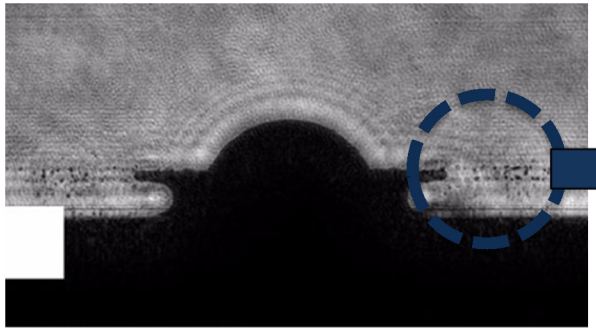




Multi-mode size distribution indicates multiple fragmentation mechanisms

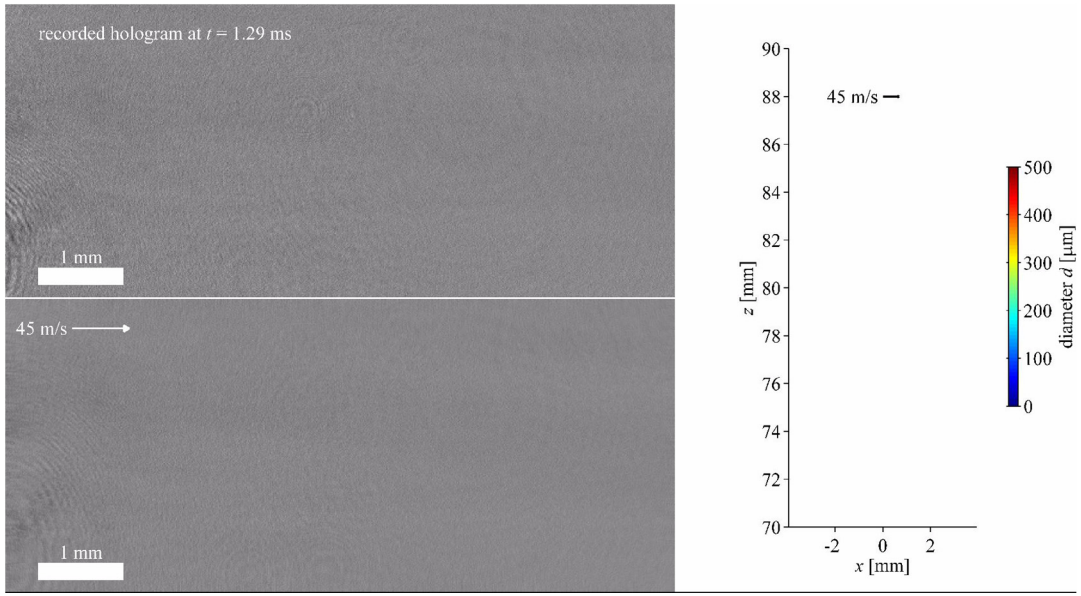
Current challenges in kHz DIH

1. We get good temporal resolution, but the limited number of pixels reduces the effective particle size dynamic range



Could we quantify these fragments, perhaps via intelligent super-sampling?

2. Data processing routines can be computationally intensive
   - The community might benefit from a comparison of published methods
3. For more complex, 3D flows the depth-of-focus problem remains an issue



breakup of a water jet in a cross flow, recorded at 100 kHz

Conclusions

Sandia National Laboratories

kHz DIH provides

- Measurement of dynamic events
- Particle size-velocity statistics
- Insight into drop fragmentation

… and opportunities for research:

- Improvement of dynamic range
- Increase processing accuracy/speed
- Address depth-of-focus problem

Acknowledgements:

This work was supported by the Laboratory Directed Research and Development and the Weapons Systems Engineering Assessment Technology program at Sandia National Laboratories (SNL)

Many thanks to all of my excellent collaborators: *Jian Gao* (Johns Hopkins University), *Phillip L. Reu* (SNL), *Jun Chen* (Purdue University), *Sean P. Kearney* (SNL), *Kathryn G. Hoffmeister* (SNL), *Thomas W. Grasser* (SNL), *H. Lee Stauffacher* (SNL), *Marcia A. Cooper* (SNL), *Luke Engvall* (University of Colorado), *Justin L. Wager* (SNL), *Thomas A. Reichardt* (SNL), *Paul A. Farias* (SNL), *Joseph D. Olles* (SNL), *Ellen Y. Chen* (SNL), and many others….

Questions