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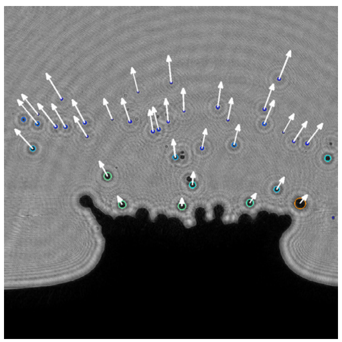

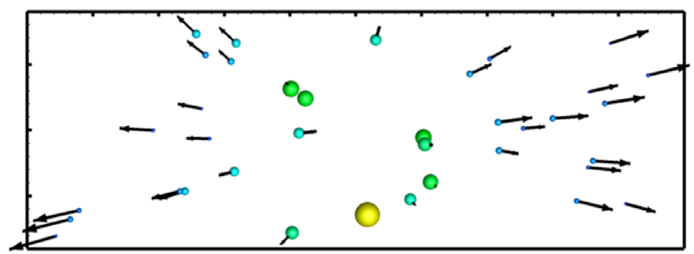

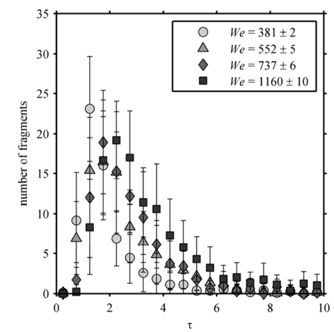

Demonstration of High Speed (20 kHz) Digital Inline Holographic (DIH) Imaging of a Multiphase Event: Drop Impact on a Thin Liquid Film

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

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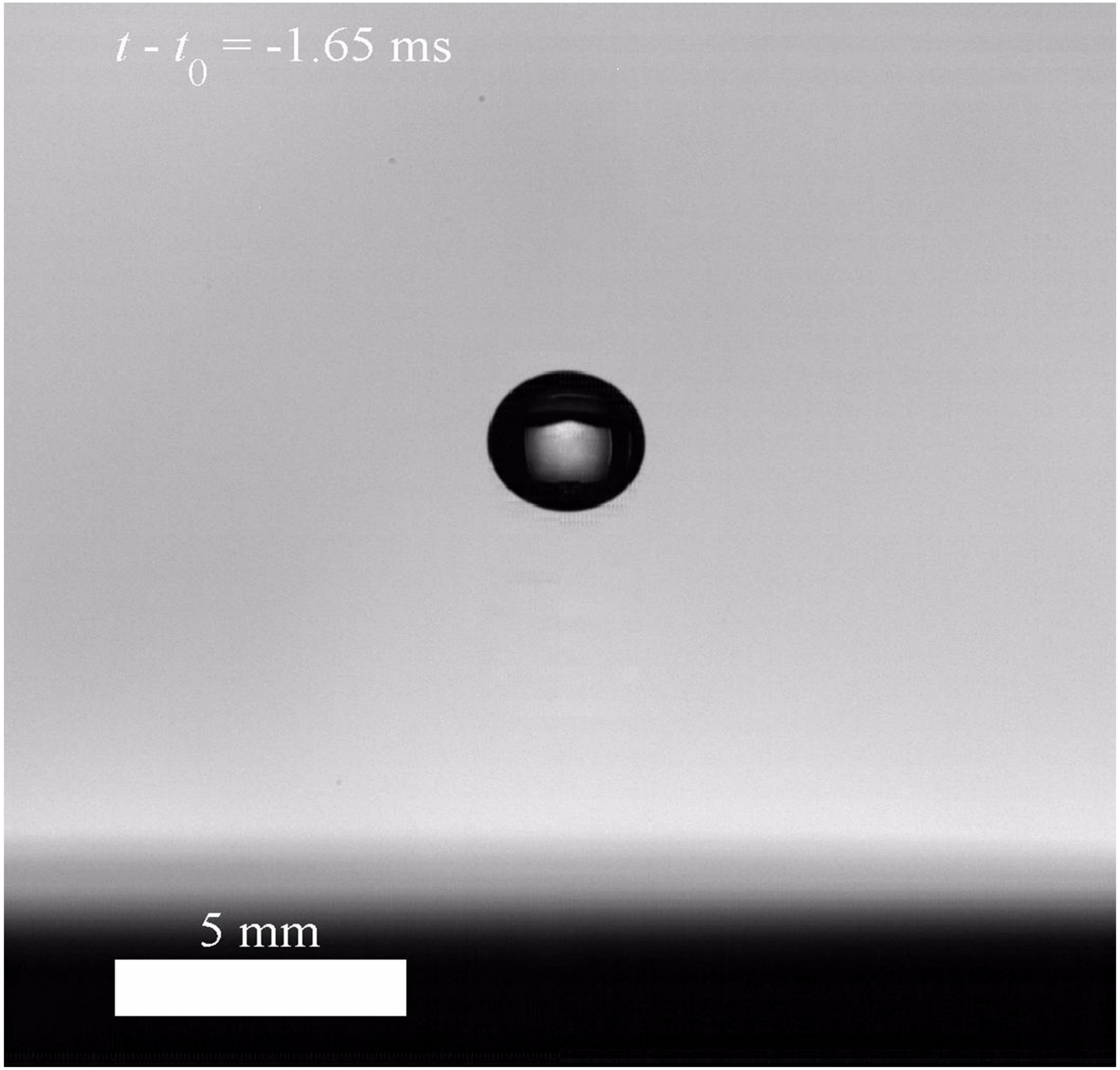
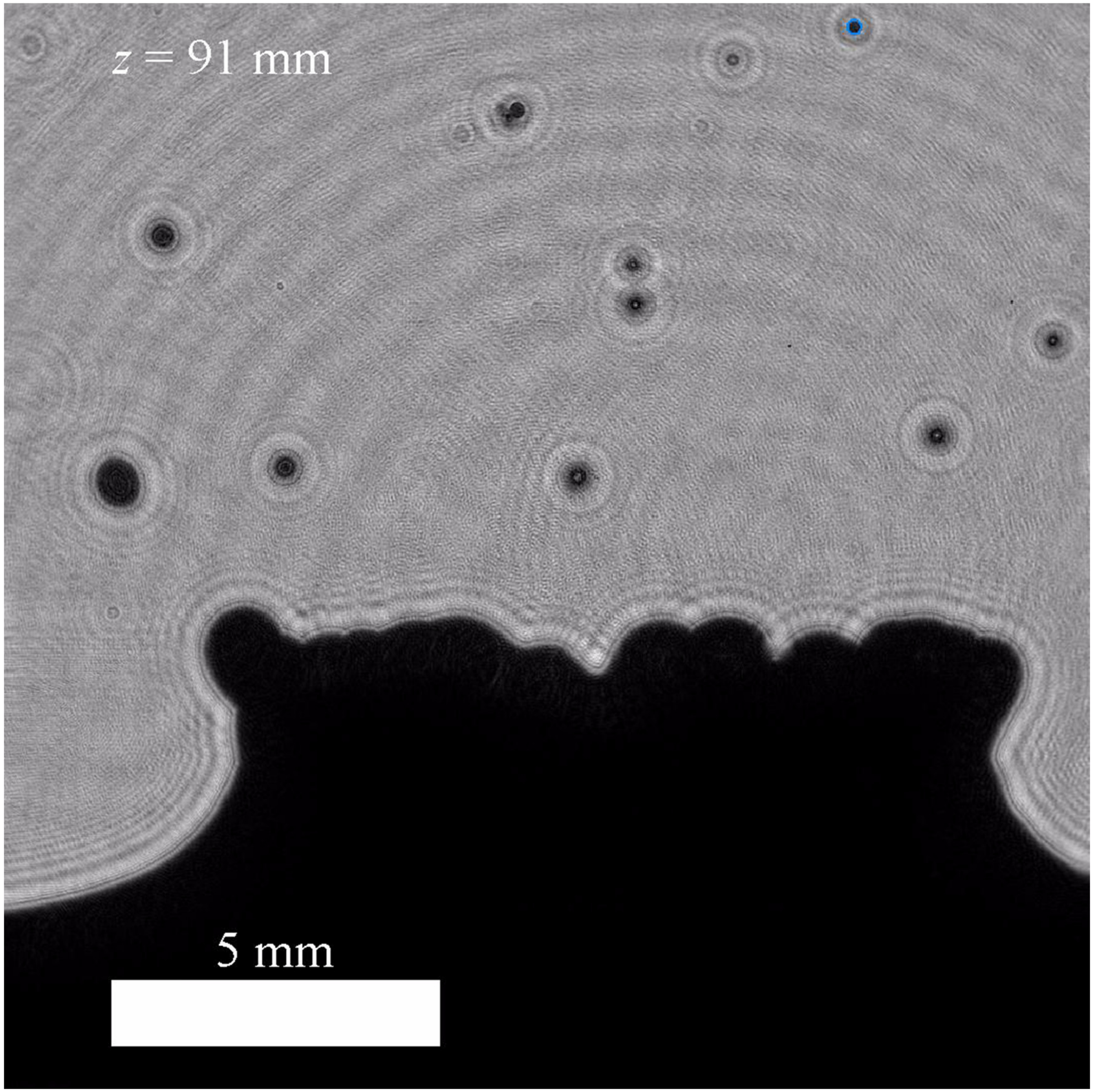
Conventional back lit imaging



<u>Demonstrated disadvantages:</u>

- individual particles cannot be located in 3D space and their 3C velocities cannot be computed
- particle size and shape cannot be measured at their in-focus location

Current status of DIH in spray research



Reported measurements:

- liquid drops (Gire *et al*., 2008; Lee *et al*., 2009; Lu *et al*., 2009; Gopalan and Katz, 2010; Yang and Kang, 2011; Yang *et al*., 2012; Buchmann *et al*., 2013)
- Solid particulates (Fugal *et al*., 2009; Jacob *et al*., 2009; Khanam *et al*., 2011; Spuler and Fugal, 2011; Wu *et al*. 2011)

What next?

Achievements:

- Developed, tested, and verified accuracy of hybrid method to reduce transverse direction position and velocity uncertainty (Guildenbecher *et al*., 2013a; Gao *et al*., 2013a; Gao *et al*. 2013b)
- Developed, tested and verified sequential image correlation technique to improve position and velocity accuracy and reduced false positives and particle overlap effects (Guildenbecher *et al*., 2013b; Gao *et al*., 2014)

Current issues:

- Need better time resolution without losing spatial accuracy
- Need systems simple enough so that hardware cost is competitive with other multi-phase flow diagnostic techniques

Preferred DIH system design

Optimum sensor has maximum imaging elements (4872 x 3248 pixels), minimum pixel pitch (6.5 x 6.5 μm), largest gain (16 bit), greatest framing rate (20 kHz)

- Scientific CCD camera allows better image size (15x CMOS) and smaller pixel pitch (1/3x CMOS), but run at ~10 Hz
- CMOS allows much greater framing rate (x2000)

Can increased framing rate be used to compensate (in part) for reduction in number of imaging elements?

DIH experimental apparatus

Configuration:

- Drop falling onto thin liquid film
- Images captured using Photron SAZ (20 kHz framing rate) camera with Infinity K2/Distamax long distance microscope with CF1 objective lens

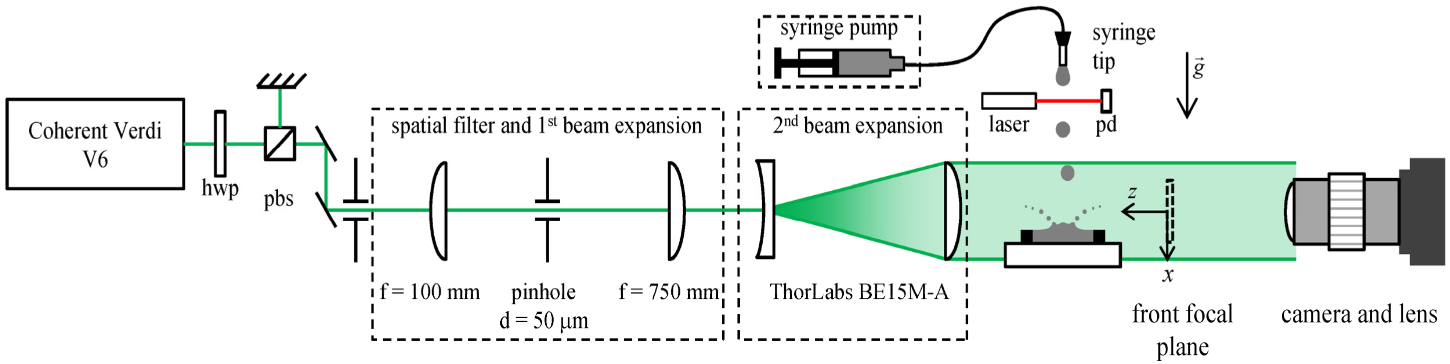


Figure 2. Experimental configuration for kHz DIH of drop impact on a thin film. *hwp*: half wave plant, *pbs*: polarizing beam splitter, *pd*: photodiode.

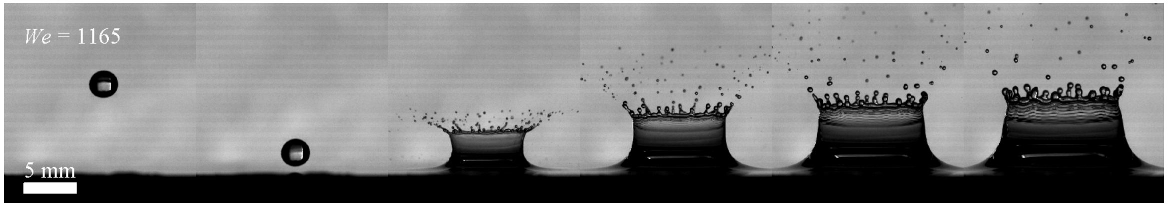


Figure 1. Select results from high-speed backlit imaging.

DIH experimental apparatus

Analysis Hardware:

Processing holograms can be time consuming

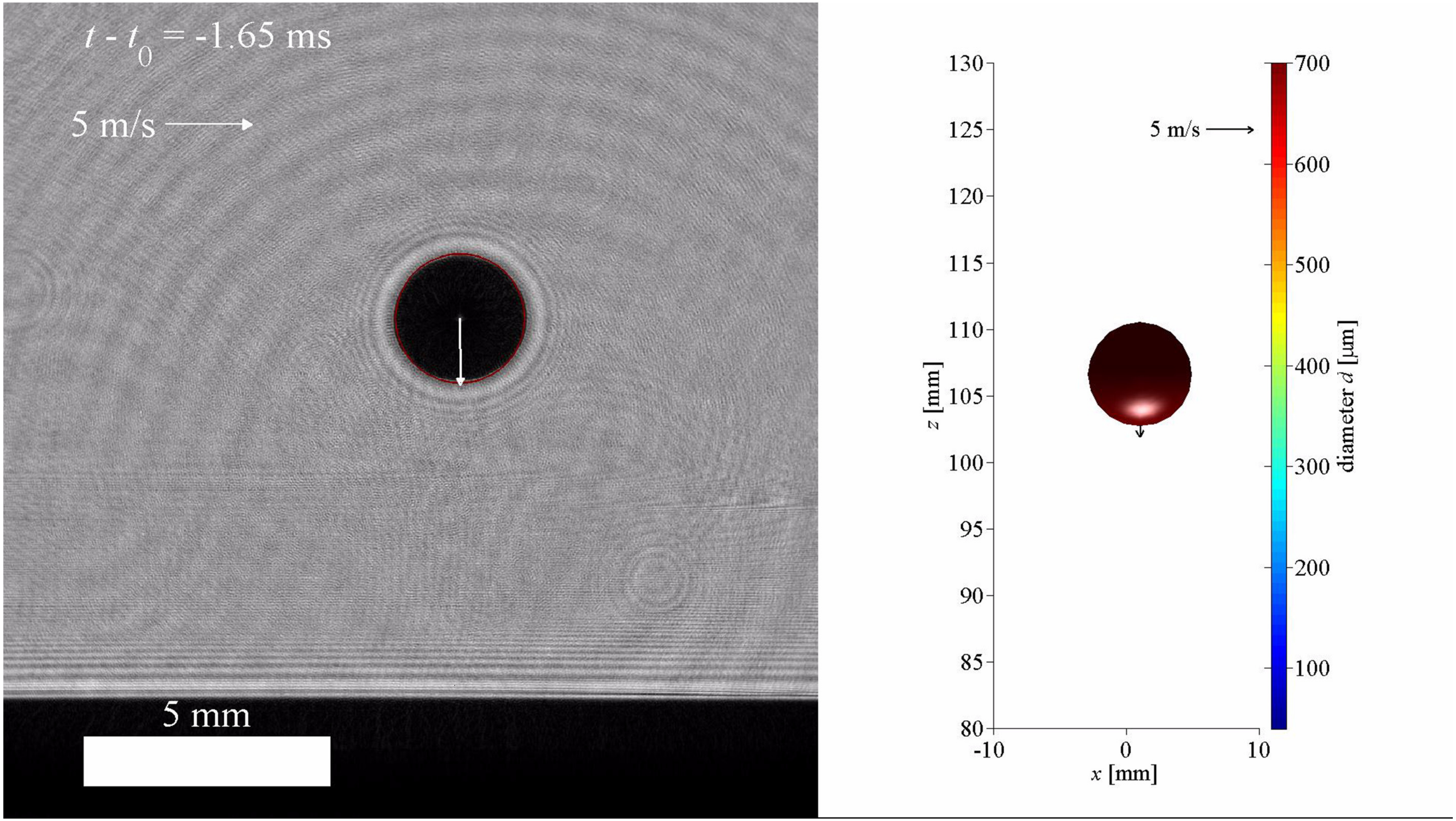
- Typical rates can be 30 minutes per frame for a 4872 x 3248 array

We reduced the per pixel processing time by an order of magnitude when using the following approach

- Dual Xeon E5-2665 cores operating at 2.4 GHz w/128 Gb of RAM
- NVIDIA K40 GPU
- MATLAB v2014a with the parallel computing toolbox running 16 frames at a time
  - Data from approximately 12000 frames is processed within a 24 hour period
  - Typical run is approximately 600 frames

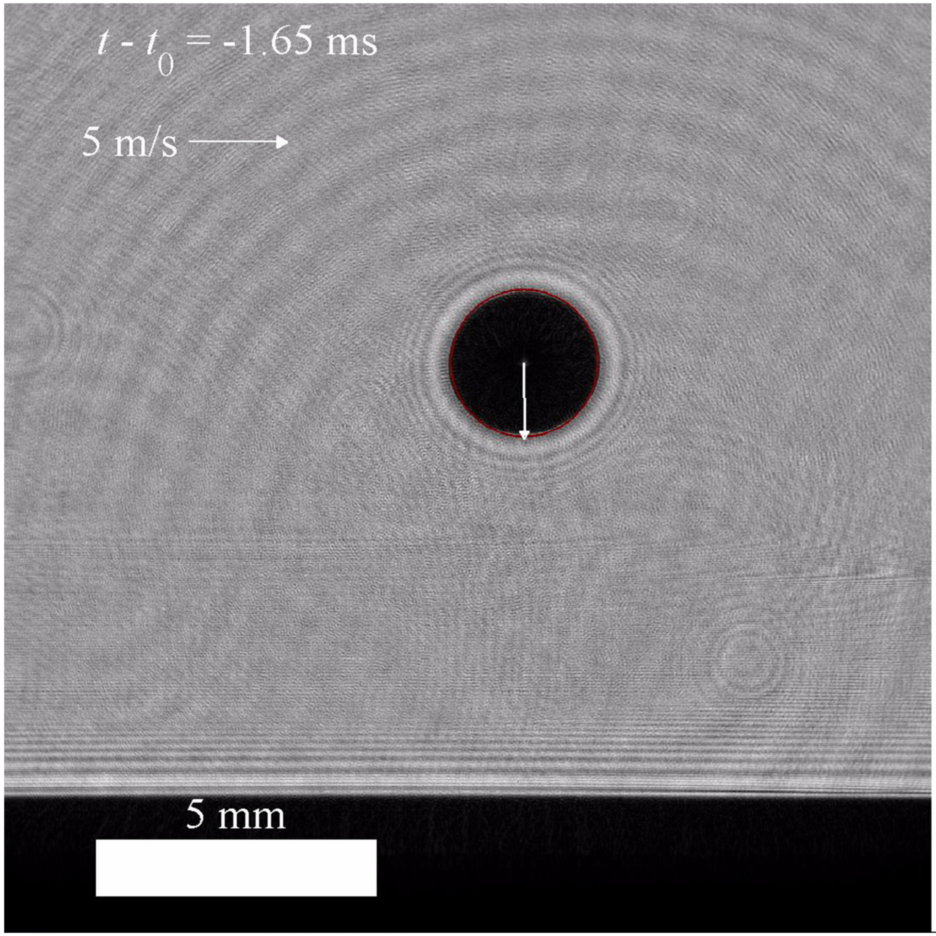
This allows us to process all the high framing rate CMOS pixels in less time than for the low framing rate CCD case

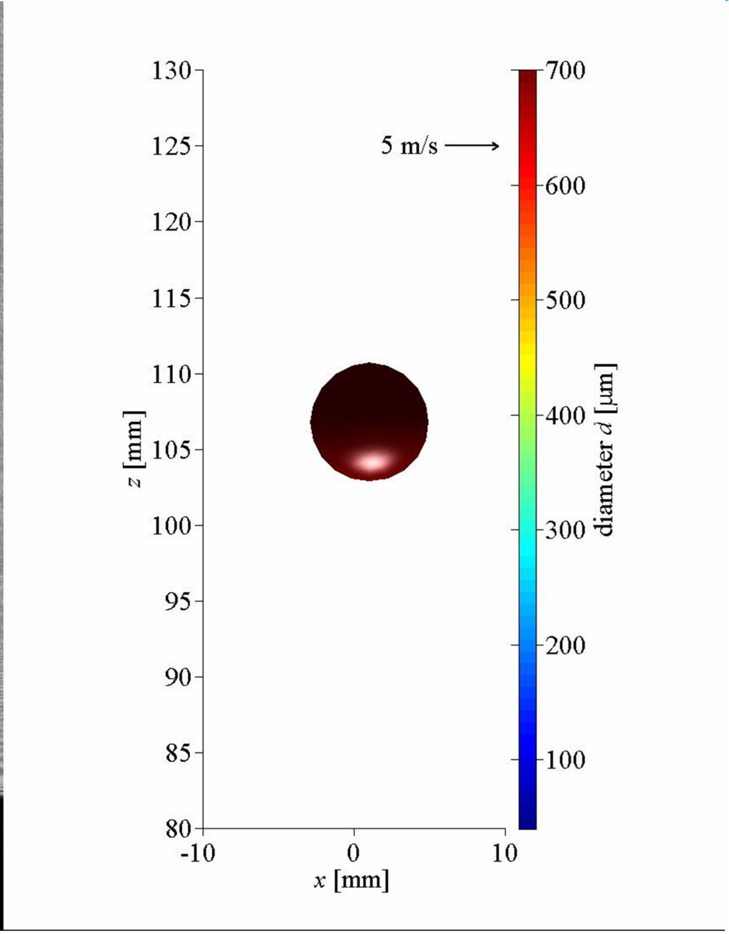
DIH results



t - t0 = -1.65 ms
5 m/s
5 mm
130
125
120
115
110
105
100
95
90
85
80
z [mm]
-10
0
10
x [mm]
5 m/s
700
600
500
400
300
200
100
diameter d [μm]

DIH results





Using the increased number of frames to smooth trajectories clearly leads to fewer unphysical results

It also reduces z-positional uncertainty by a factor of 36

DIH results

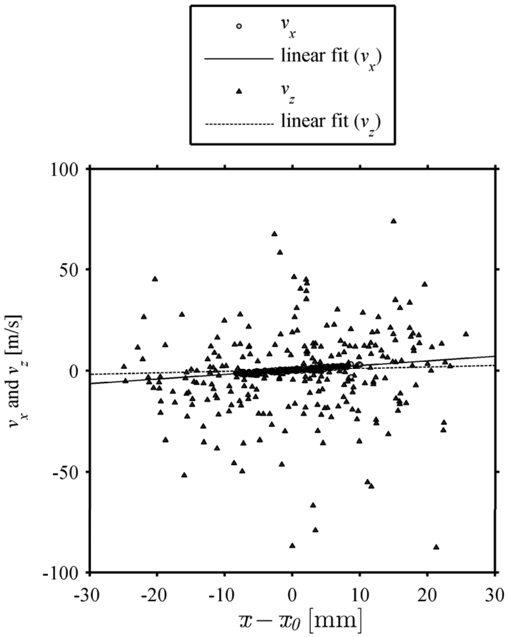


Figure 5. In-plane versus out-of-plane velocities measured by frame-to-frame particle matching.

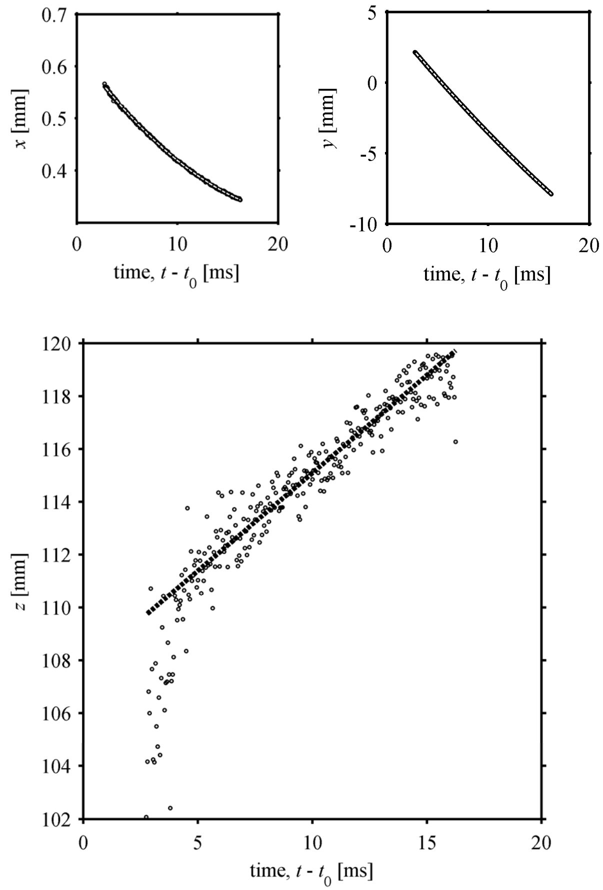


Figure 6. Measured *x* (top left), *y* (top right), and *z* (bottom) positions of a single fragment and the best-fit trajectories.

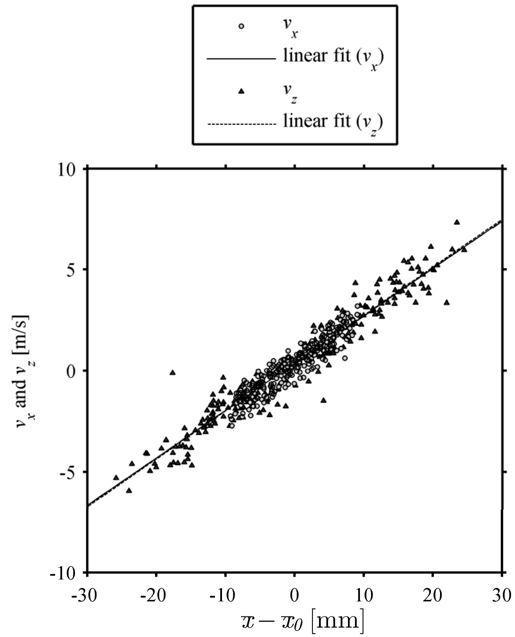


Figure 9. In-plane versus out-of-plane velocities after fitting fragment tracks to smooth trajectories.

Using additional frames to fit z-trajectory reduces V_z scatter

Influence of *We* on impact dynamics

Table 1. Initial conditions, given as the mean from all videos ± the standard deviation of the mean from each video.

Approximate fall height, h (mm)	Number of videos analyzed	Initial diameter, d_0 (mm)	Impact velocity, V_0 (m/s)	Dimensionless film thickness, δ	Impact Weber number, We
600±10	22	2.639±0.007	3.22±0.01	1.124±0.002	381±2
900±10	26	2.619±0.011	3.89±0.01	1.115±0.003	552±5
1250±15	13	2.645±0.009	4.48±0.01	1.126±0.003	737±6
2250±20	20	2.648±0.006	5.62±0.02	1.127±0.002	1160±10

Influence of *We* on impact dynamics

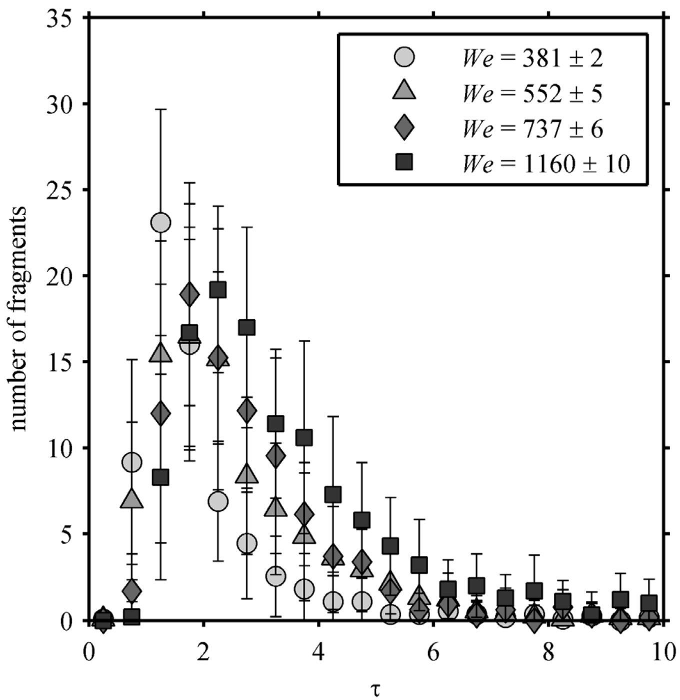


Figure 10. Mean number of fragments produced versus dimensionless time. Symbols are the means from all videos, uncertainty bars are the standard deviation of the mean from each video.

- Regardless of *We*, the number of fragments initially increases as the impacting drop forms a crown, then a rim with fingers, and then fragments which separate from the fingers
- The subsequent decrease is due to
  - the cessation of finger formation as the rim begins to retract into the crown and the crown falls toward the free surface
  - drops that were formed early are moving out of the field of view.
- An increase in *We* alters the mean number of fragments versus time:
  - additional fragments are found at times above about 2
  - the peak number of fragments is reduced
  - the time at which the peak number of fragments is produced increases

This is due to the longer amount of time it takes for the higher *We* case to form its crown, fingers and fragments, and to the longer duration for which the higher *We* case produces fragments (before the crown begins to retract)

Influence of *We* on impact dynamics

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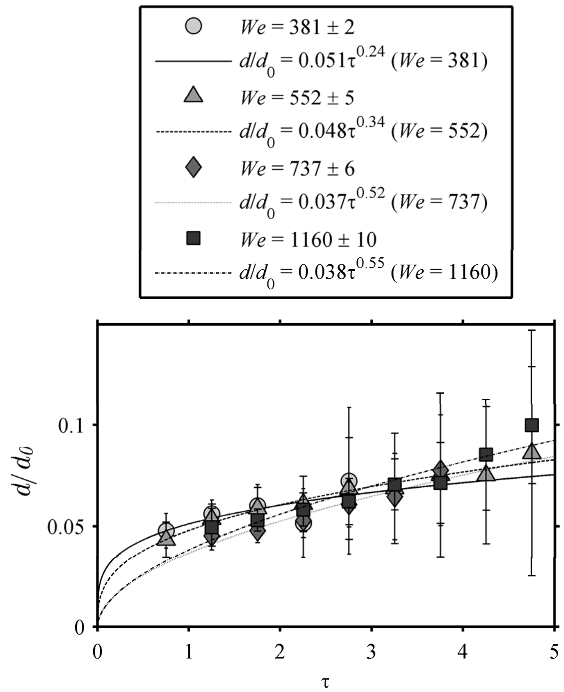

Figure 11. Dimensionless mean fragment size versus time. Symbols are the means from all videos, uncertainty bars are the standard deviations of the mean from each video.

- The continual rise in dimensionless diameter is expected and due to deceleration of the crown and rim as the rim-to-film-surface distance increases
  - Deceleration leads to lower growth rates for finger formation and the size of any fragments shed from them
- Increasing *We* shifts mean fragment size to larger values at longer times
  - may be attributed to the longer amount of time it takes for the higher *We* case to form its crown, fingers and fragments, and to the longer duration for which the higher *We* case produces fragments

DIH

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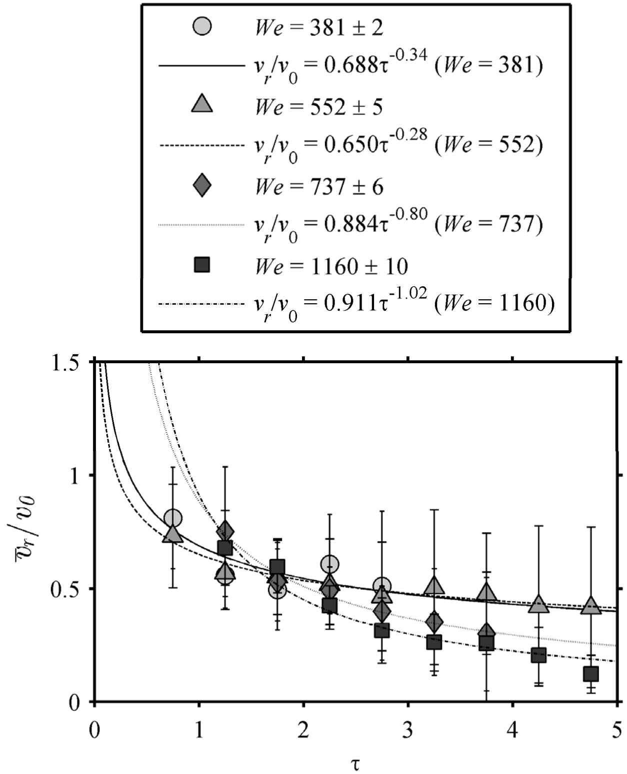

Figure 12. Dimensionless mean fragment radial velocity versus time. Symbols are the means from all videos, uncertainty bars are the standard deviations of the mean from each video.

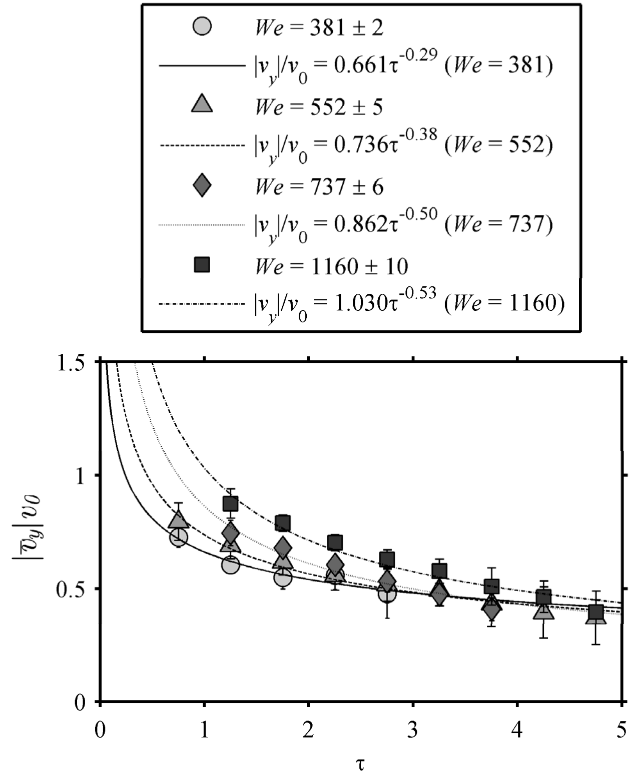

Figure 13. Dimensionless mean fragment *y*-velocity versus time. Symbols are the means from all videos, uncertainty bars are the standard deviations of the mean from each video.

Consistent with previous results where $V \propto t^{-0.5}$

Summary

- kHz digital in-line holography (DIH) has been demonstrated for 3D, temporal quantification of the fragments produced when a water drop impacts a thin film of water
  - High-speed CMOS sensors increase the depth uncertainty compared to low-speed scientific CCD sensors. Nevertheless, by resolving fragment positions over multiple frames and fitting the trajectories to smooth models, improved 3D (x36) positional accuracy is achieved
  - System hardware can be purchased for about $165,000
  - Processing times are such that 12000 frames can be analyzed overnight using a system costing below $19,000

Summary

- For *We* from 381 to 1160, the number of fragments first increases with dimensionless time and then falls off, regardless of *We*
- When *We* increases, additional fragments are found at times above about 2, the peak number of fragments is reduced, and the time at which the peak number of fragments is produced increases
- As expected, non-dimensional diameters increase as a function of time, while the non-dimensional velocities decrease with time
- Increasing We shifts non-dimensional diameters to larger values at longer dimensionless times
- Velocity scaling with τ is consistent with previous results

Conclusions

- **kHz sampling rate DIH measurements can be made while improving accuracy of computed fragment positions (x36) and velocities**
- **Hardware costs are comparable to those for point size and velocity measurement instruments**

Questions?