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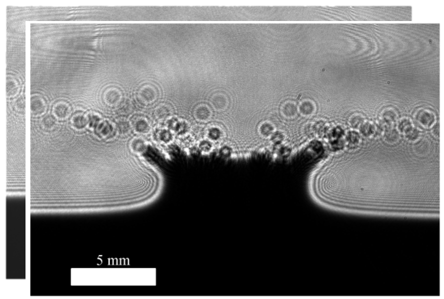

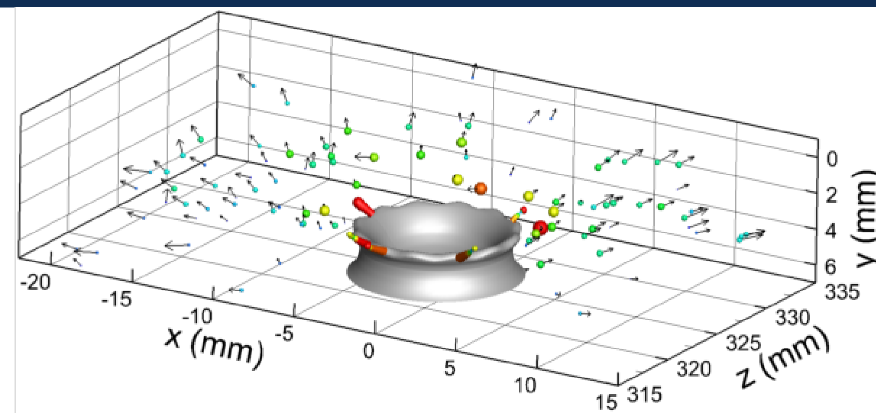

Experimental methods to quantify particle positional and displacement uncertainty along the depth direction in digital in-line holography

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U.S. DEPARTMENT OF ENERGY

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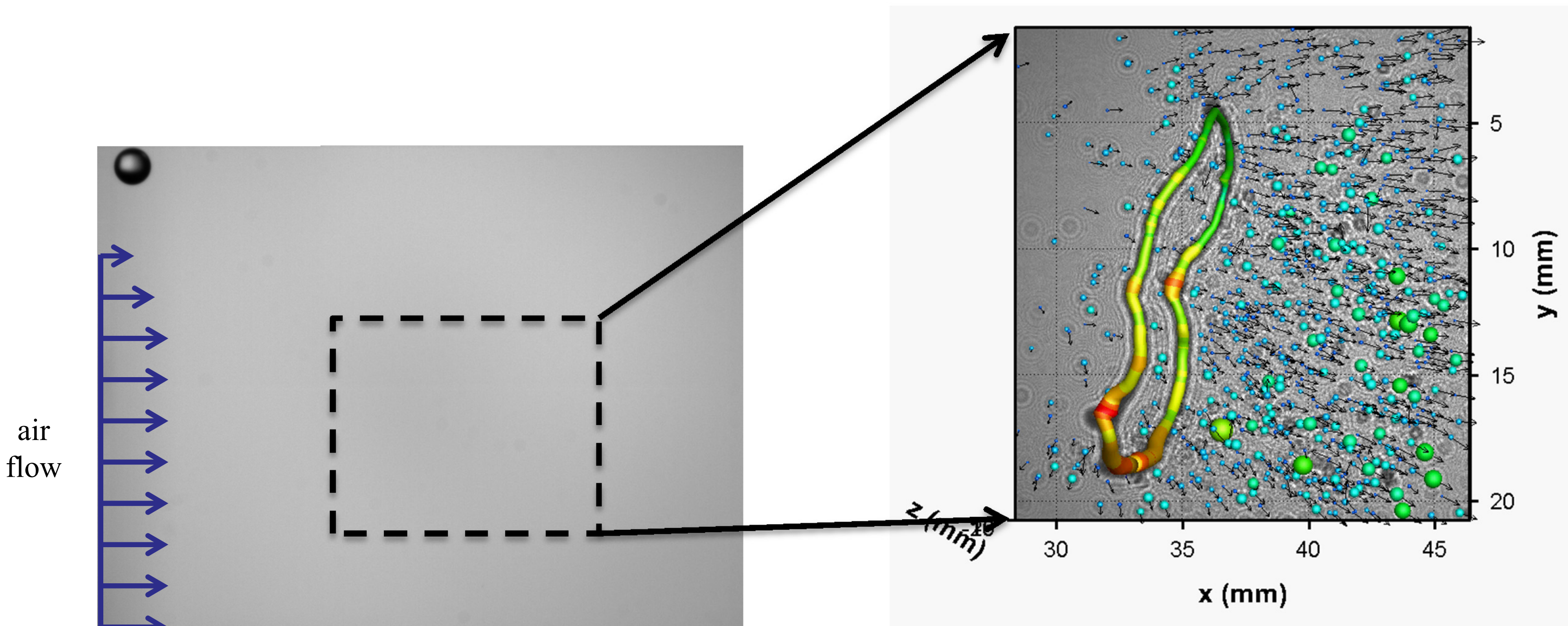
Motivation: 3D imaging for a 3D world

Challenge: 2D imaging or point-wise measurements cannot resolve 3D flow phenomena

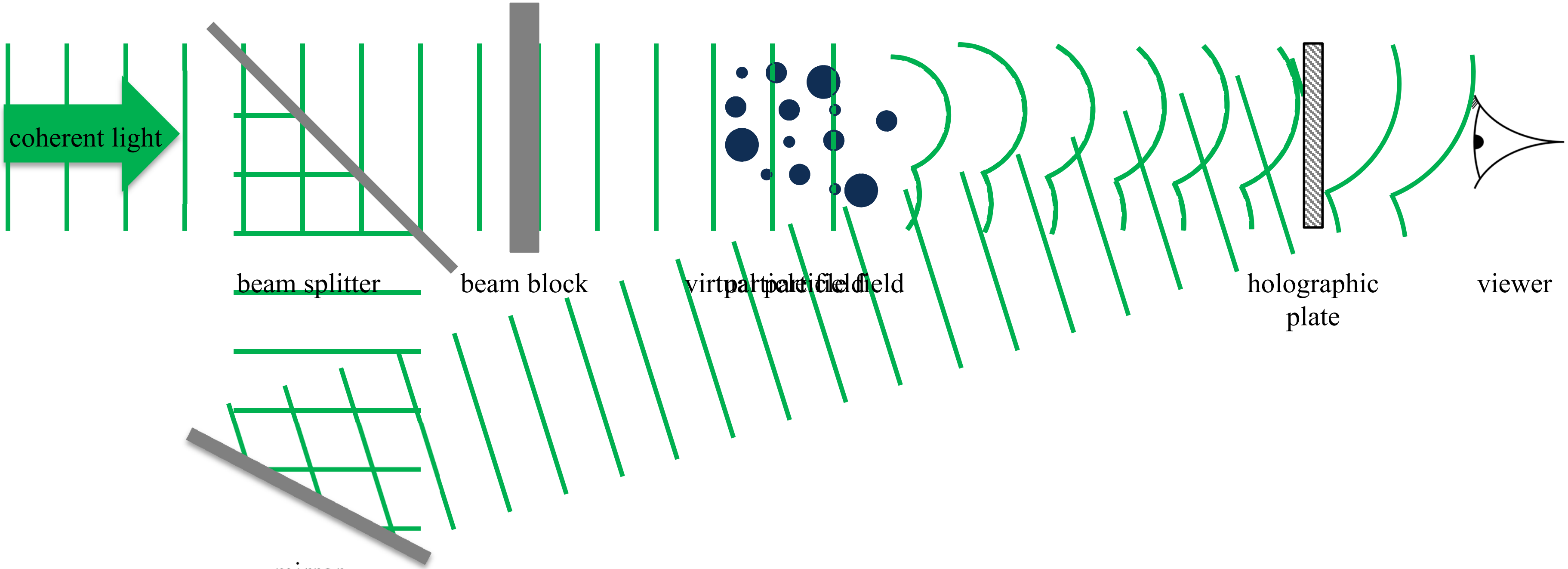
- Experimental repetition needed to capture spatial statistics



high-speed video of a ethanol drop
in an air-stream

digital holographic measurement
(Gao, Guildenbecher et al, 2013, *Opt. Lett.*)

What is holography?

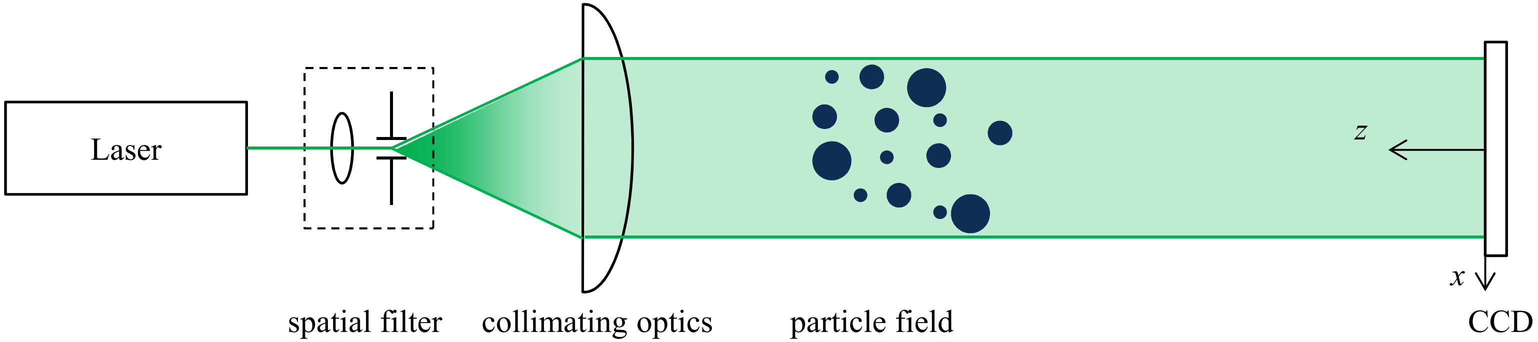


Optical method first proposed by Gabor in 1948

1. Coherent light scattered by particle field forms the object wave, E_o
2. Interference with a reference wave, E_r, forms the hologram: $h = |E_o+E_r|^2$
3. Reconstruction with E_r forms virtual images at original particle locations

$$h \cdot E_r = \underbrace{(|E_o|^2 + |E_r|^2)E_r}_{\text{DC term}} + \underbrace{|E_r|^2 E_o}_{\text{virtual image}} + \underbrace{E_r^2 E_o^*}_{\text{real image}}$$

Digital in-line holography (DIH)



Holographic plate and cumbersome wet-chemical processing replaced with digital sensor (CCD or CMOS)

- Resolution of digital sensors (order 100 line pairs/mm) is much less than resolution of photographic emulsions (order 5,000 line pairs/mm)
  - For suitable off axis angles, θ, the fringe frequency, f, is typically too large to resolve with digital sensors ($f = 2\sin(\theta/2)/\lambda$)
- Rather, the in-line configuration ($\theta = 0$) is typically utilized
  - Reference wave is that portion of the beam which passes through the particle field undisturbed
  - Consequently, the real image overlaps with an out-of-focus virtual image and DC term

Digital in-line holography (DIH)

- In the computer, we multiply the digitally recorded hologram h by an estimate of the complex conjugate of the reference wave $E_r{}^*$

$$h \cdot E_r^* = \underbrace{(|E_o|^2 + |E_r|^2)E_r^*}_{\text{DC term}} + \underbrace{E_r^{*2}E_o}_{\text{virtual image}} + \underbrace{|E_r|^2 E_o^*}_{\text{real image}}$$

- This complex amplitude can be numerically propagated to any distance along the optical axis, z, using the diffraction equations

$$E(x,y,z) = h(x,y) \cdot E_r^*(x,y) \otimes g(x,y,z)$$

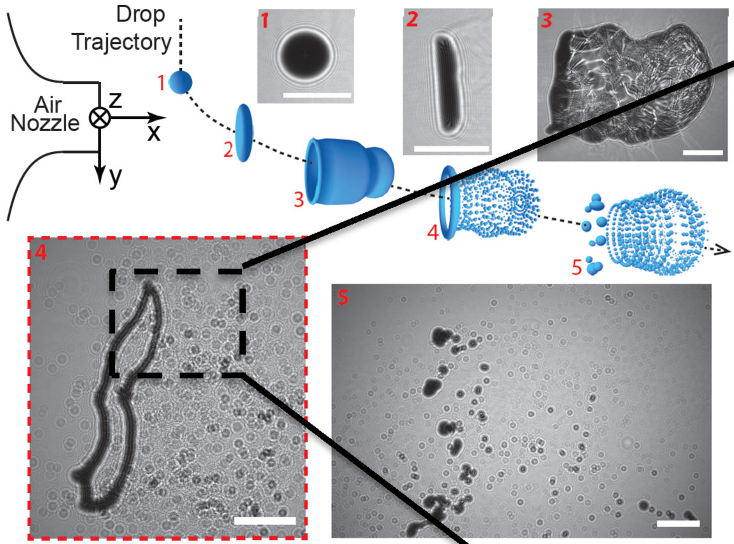
  - Rayleigh-Sommerfeld: $g\left(x,y,z\right) = e^{jk\sqrt{x^2+y^2+z^2}} \Big/ j\lambda\sqrt{x^2+y^2+z^2}$
  - Fresnel-Kirchhoff: $g\left(x,y,z\right) = \dfrac{e^{jkz}}{j\lambda z} e^{jk\left(x^2+y^2\right)/2z}$

- Numerically, the convolution is computed using the fast Fourier transform (FFT)

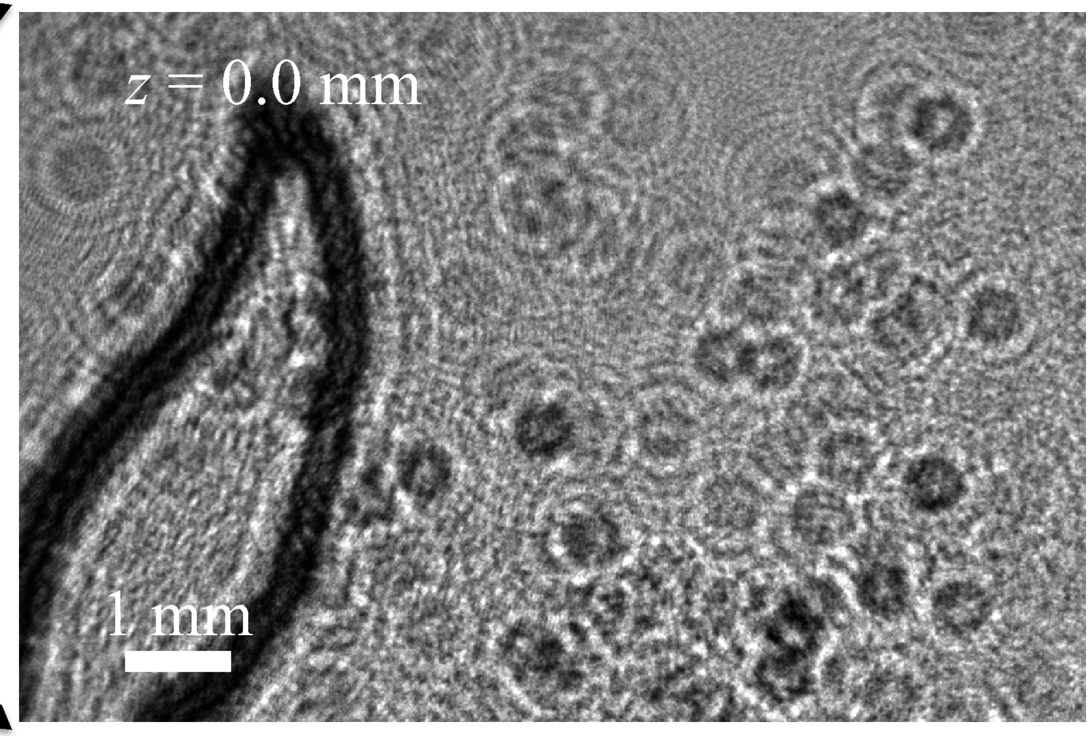
$$E(x,y,z) = FFT^{-1}\left\{FFT\left\{I_0(x,y)E_r^*(x,y)\right\}FFT\left\{g(x,y,z)\right\}\right\}$$

- Visualized via the reconstructed amplitude, $A = |E|$, or intensity, $I = |E|^2$

Digital in-line holography (DIH)



digital holograms of the breakup of an ethanol drop in an air-stream (Gao, Guildenbecher et al 2013, *Opt. Lett.*)



Reconstructed amplitude throughout depth, *z*

- In-focus structures are clearly observed at different depths, *z*
- "Rings" around the in-focus structures are the out-of-focus virtual images

The depth-of-focus problem

The spatial extent of the diffraction pattern limits the angular aperture, Ω, from which a particle is effectively reconstructed (Meng et al, 2004, *Meas. Sci. Technol.*):

- From the central diffraction lobe → $\Omega \approx 2\lambda/d$
- Using the traditional definition of depth-of-focus, δ, based on change of intensity within the particle center → $\delta \approx 4\lambda/\Omega^2$
- Therefore: for in-line holography, $\delta \approx d^2/\lambda$
    - Example: d = 465 μm, λ = 532 nm → $\delta \approx$ 400 mm!

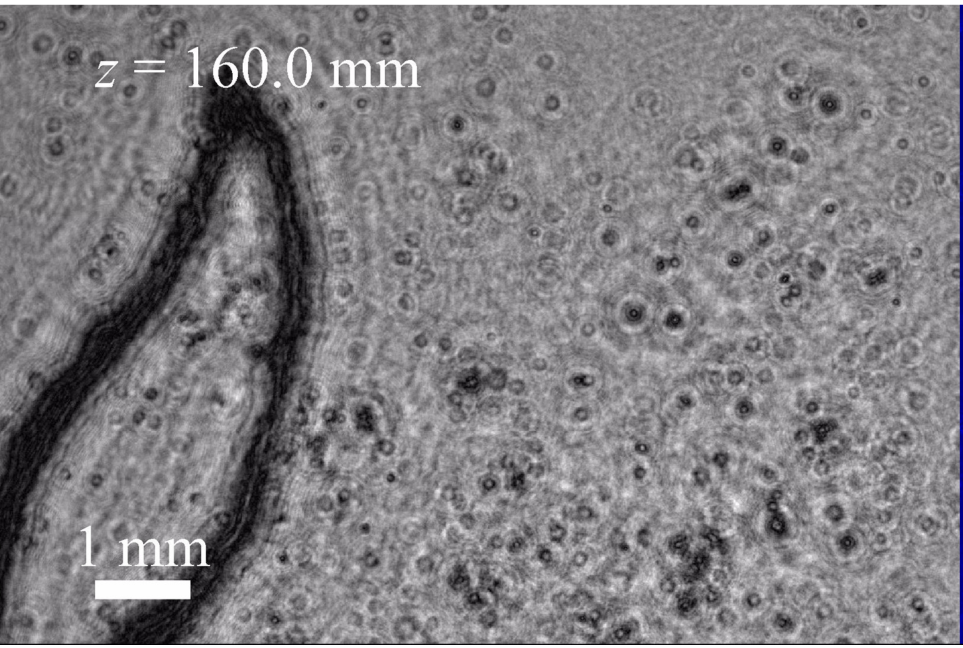
Literature contains two basic methods to find the focal plane with improved accuracy:

1. Fit a model to the observed diffraction patterns (inverse method)
    - Generally accurate with small depth uncertainty
    - Limited to objects with known diffraction patterns (spheres)
2. Reconstruct the amplitude (or intensity) throughout depth and apply a focus metric to find "in-focus" objects
    - No *a-priori* knowledge of particle shape required
    - Accuracy is a strong function of the chosen focus metric

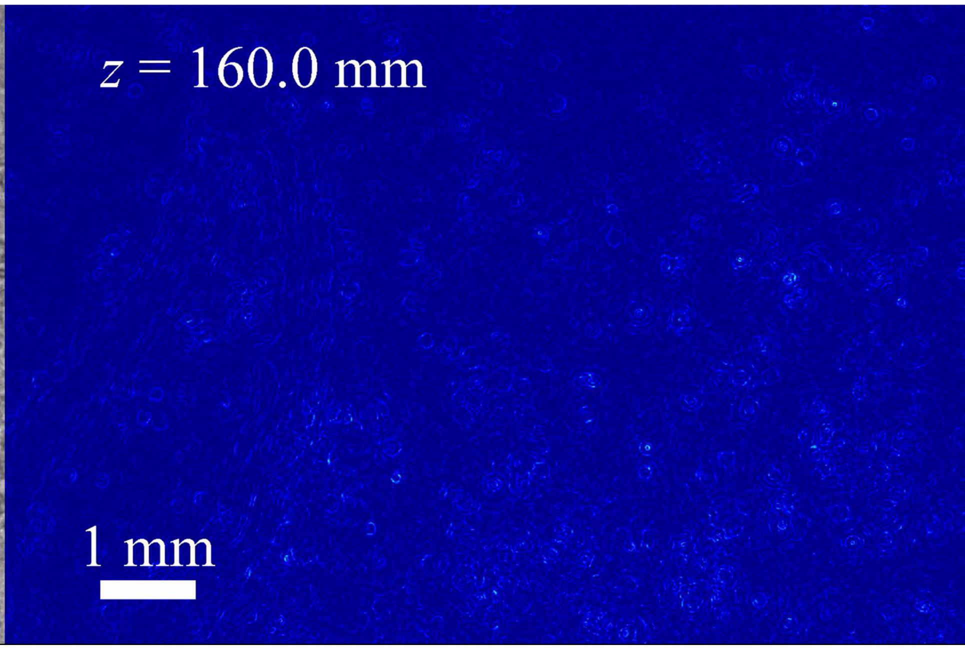
Hybrid particle extraction method

Basic idea: In-focus regions display a minimum amplitude within the particle interior and a maximum sharpness at the particle edges

- Validity of this assumption has been verified through simulation



Reconstructed amplitude throughout depth, *z*



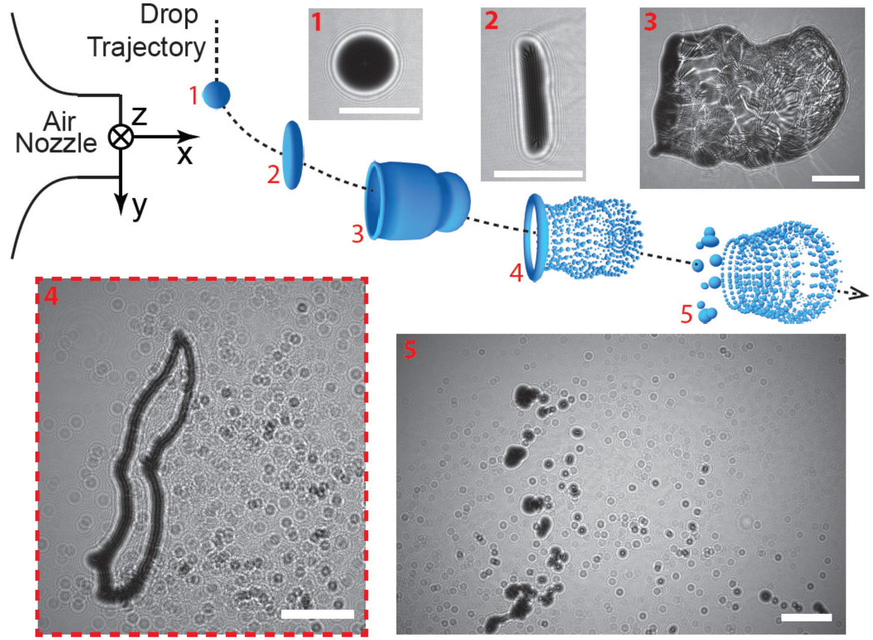
Reconstructed edge sharpness throughout depth, *z*

- Optimum threshold for particle extraction is automatically extracted from the threshold of the amplitude which displays maximum edge sharpness
  - Further details in Guildenbecher et al, 2013, *Appl. Opt.* and Gao, Guildenbecher, et al, 2013, *Opt. Express.*

Aerodynamic drop fragmentation

<u>Motivation:</u> fundamental spray process and an important canonical problem for multiphase simulations

- No viable methods to measure secondary drop size/velocity statistics or the 3D morphology of the ring shaped ligament



digital holograms of the breakup of an ethanol drop in an air-stream (Gao, Guildenbecher et al 2013, *Opt. Lett.*)

<u>Experimental configuration:</u> Double-pulsed laser and imaging hardware as typically used in PIV

- λ = 532 nm, 5 ns pulsewidth
- Interline transfer CCD (4008 $\times$ 2672, 9 μm pixel pitch)
- Temporal separation, Δt = 62 μs, determined by laser timing
    - Note: experiments in Guildenbecher et al, 2013, *Proceedings of Digital Holography and 3-D Imaging* confirm no loss of accuracy due to the reduced coherence length of these lasers

Aerodynamic drop fragmentation

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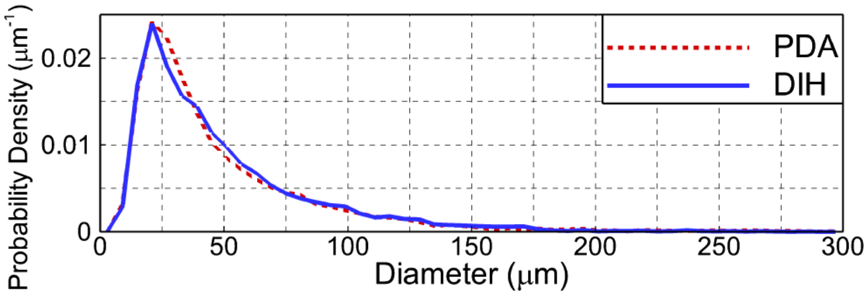
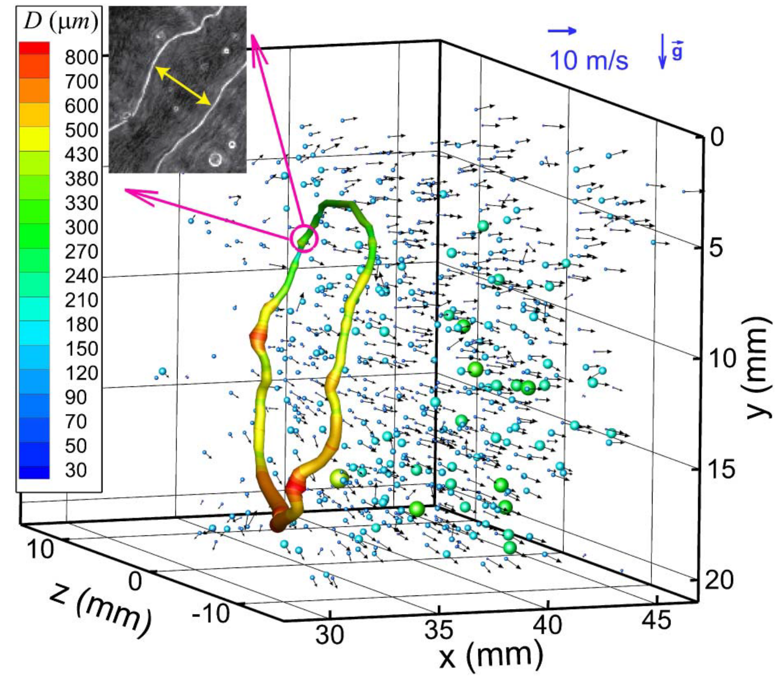
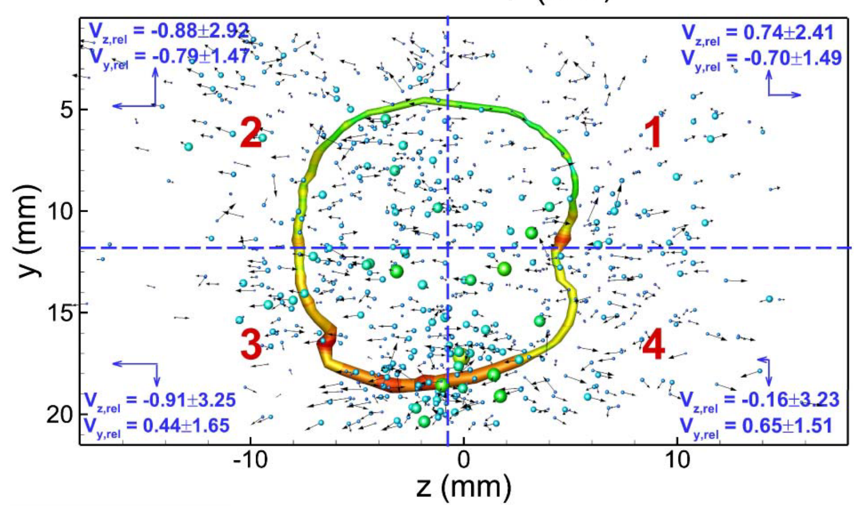
- Secondary drop sizes/positions extracted by the hybrid method
  - Comparison with phase Doppler anemometer (PDA) data confirms accuracy of measured sizes





- Ring measured from *z*-location of maximum edge sharpness
  - Total volume of ring + secondary drops is within 2.2% of the initial volume
- 3C velocity measured by particle matching between successive frames
  - Expected symmetry observed with higher uncertainty in *z*-direction



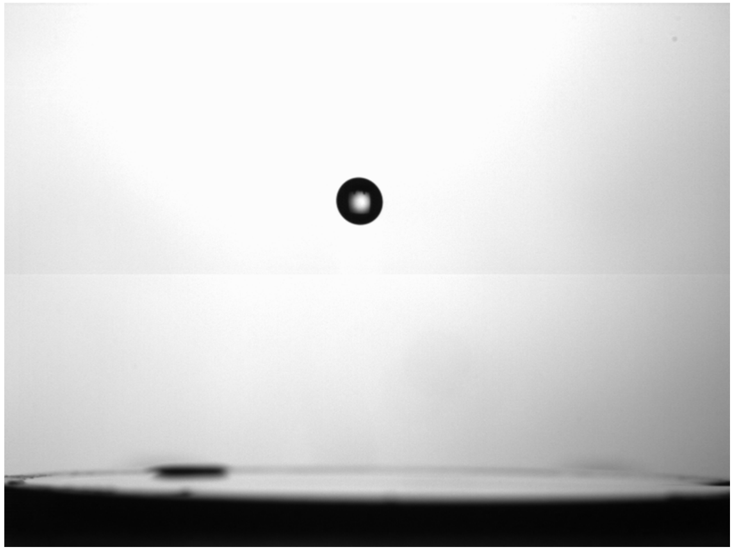
Drop impact on a thin film

Motivation: measurement of secondary droplet by other methods requires significant experimental repetition

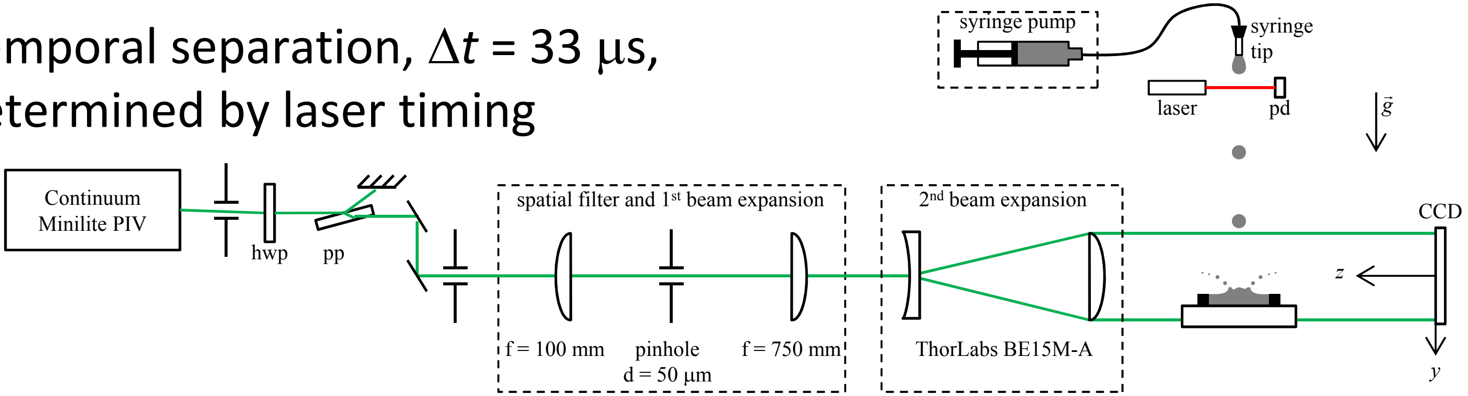
- Process symmetry provides opportunities to validate accuracy

Experimental configuration:

- Double pulsed laser (λ = 532 nm, 5 ns pulsewidth)
- Interline transfer CCD (4872 × 3248, 7.4 μm pixel pitch)
- Temporal separation, Δt = 33 μs, determined by laser timing



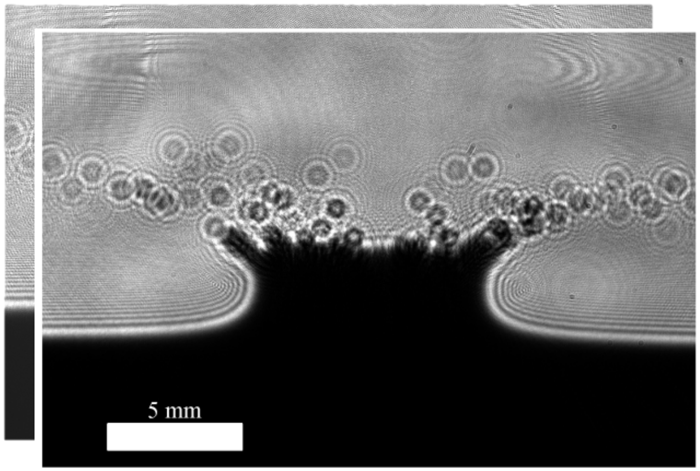
impact of a 3 mm water drop on a 2 mm water film (Guildenbecher et al, 2013, *Exp. Fluids*.)

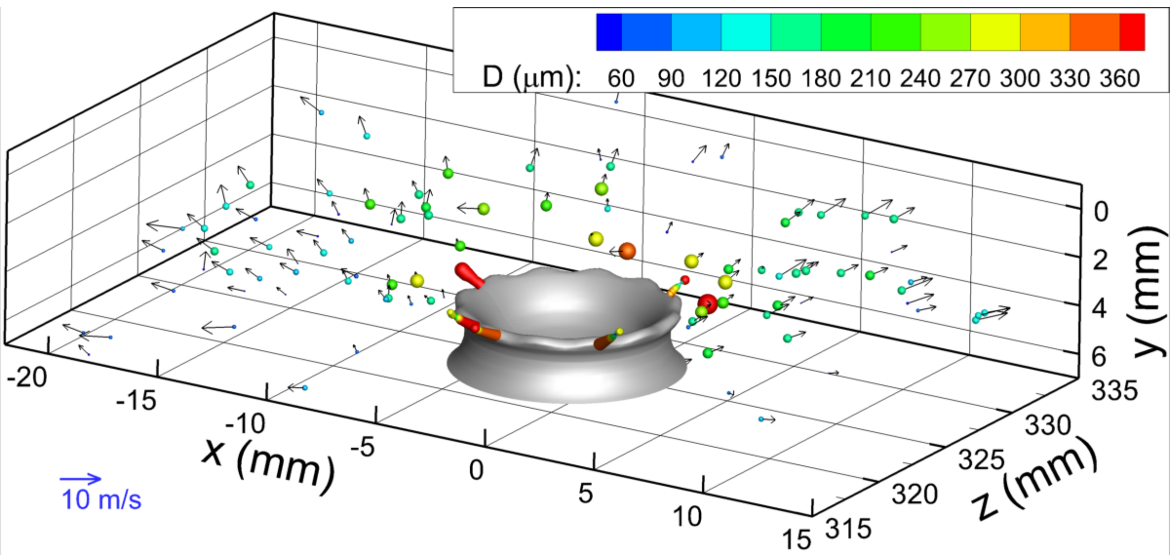


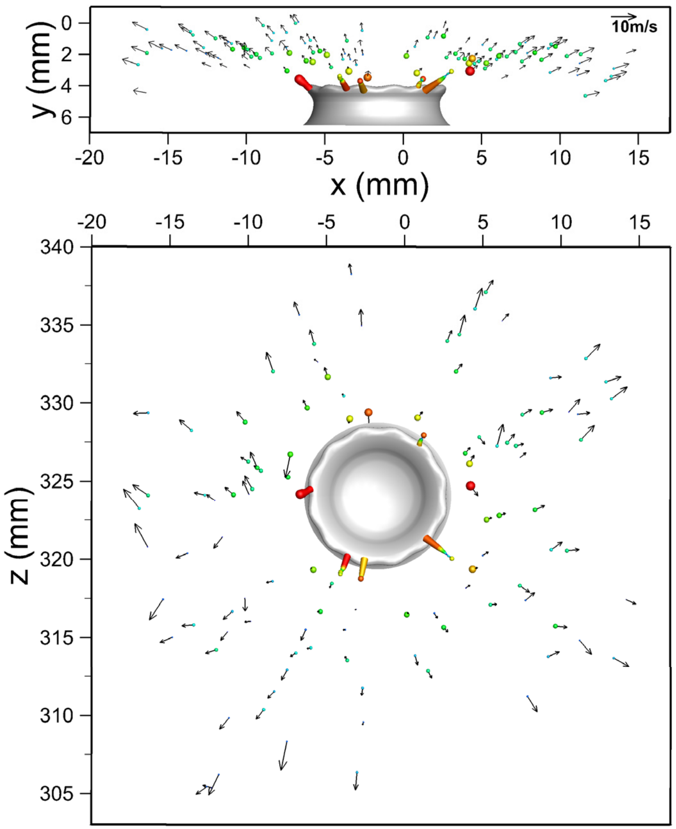
experimental configuration of holographic recording of drop impact on a thin film (Guildenbecher et al, 2013, *Exp. Fluids*.)

Drop impact on a thin film

Again processed with the hybrid method







holographic reconstruction of
drop impact on a thin film
(Guildenbecher et al, 2013, *Exp. Fluids*.)

Experimental validation

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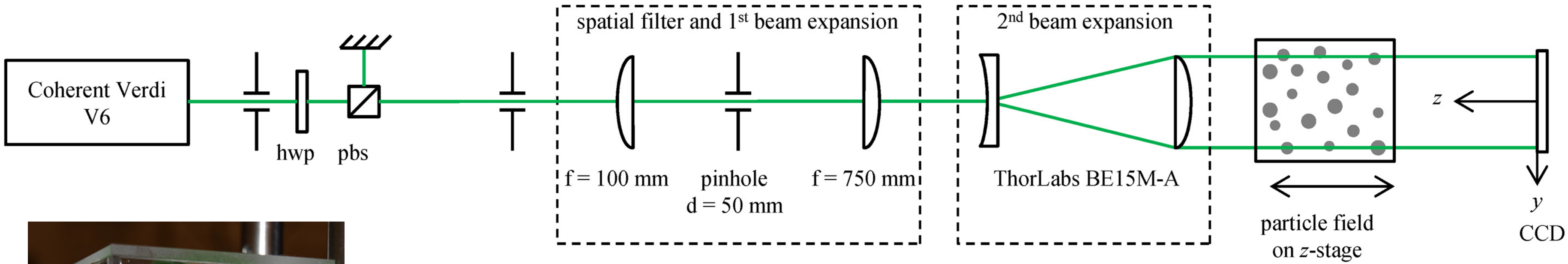
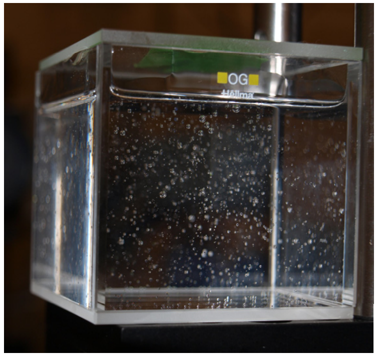
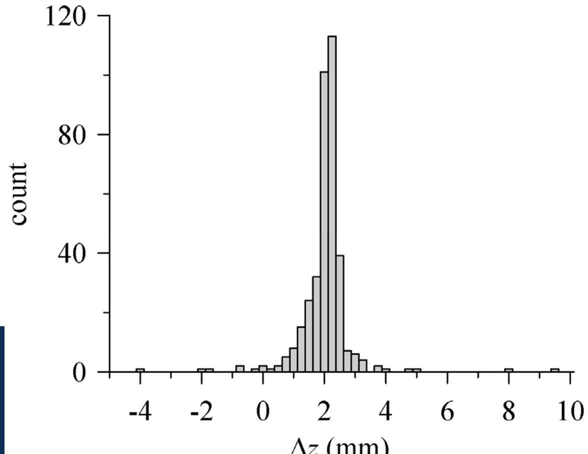




particle field

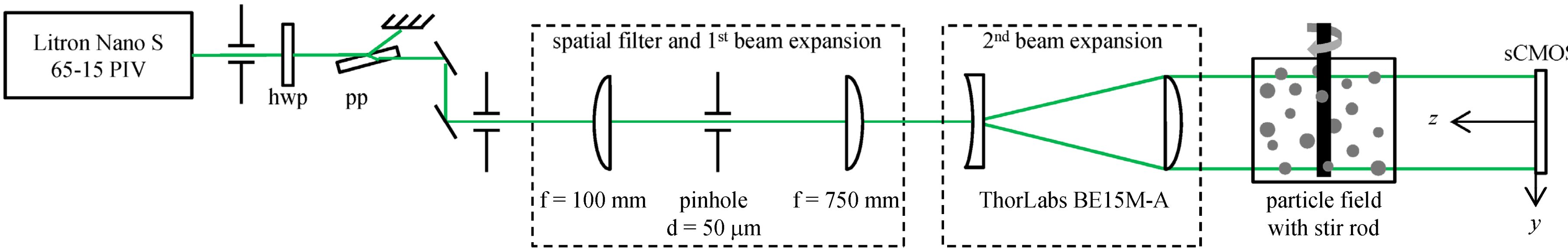
- Quasi-stationary particle field
  - Polystyrene beads ($\bar{d} \approx 465\,\mu\text{m}$) in 10,000 cSt silicone oil
  - Settling velocity ≈ 1 μm/s
- Multiple holograms recorded, displacing the particle field 2 mm in the z-direction between each acquisition
- Displacement found by particle matching between successive holograms
  - Actual displacement, Δz = 2.0 mm
  - Measured displacement, Δz = 1.91 mm ± 0.81 mm
    - Standard deviation of 1.74 times mean diameter

Issue: overall *z*-positions are not validated and effects due to particle motion are not considered

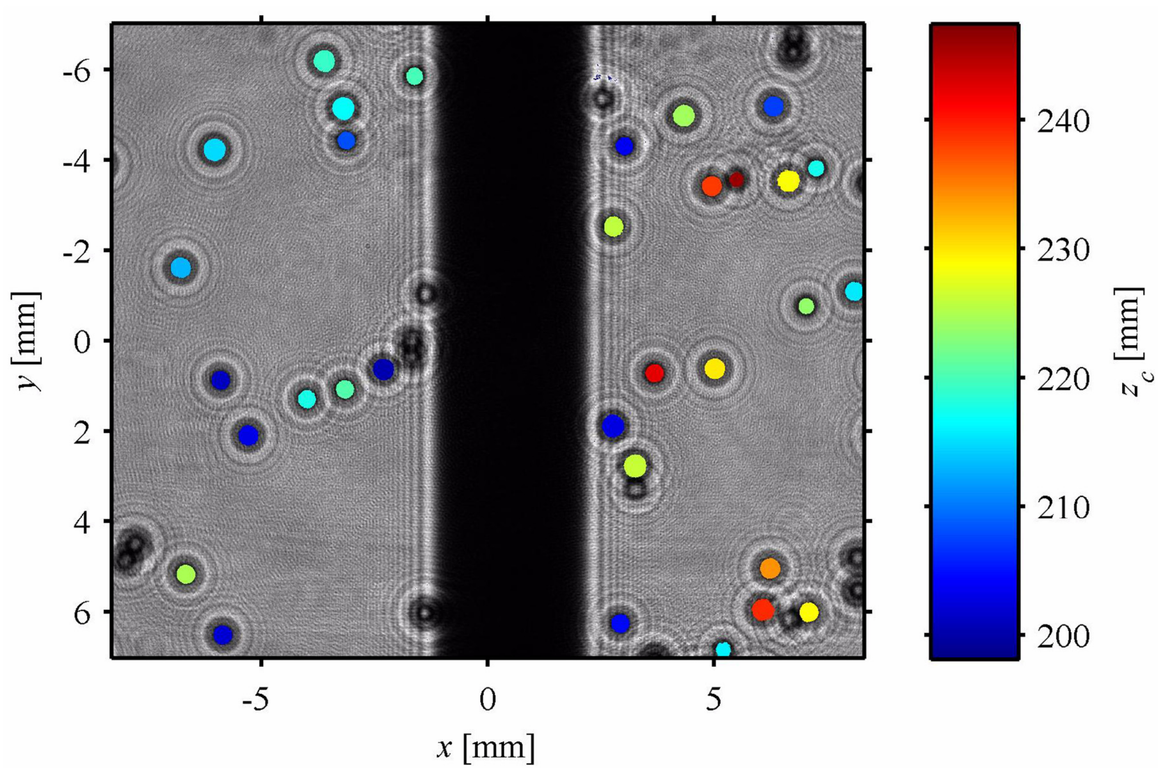


histogram of measured displacements

Experimental configuration for *z* validation



- Particles stirred by a rotating rod (r_0 = 1.58 mm, ω_0=100 rpm)
- Recorded at 15Hz with a LaVision sCMOS camera (2560 × 2160, 6.5 μm pixel pitch)



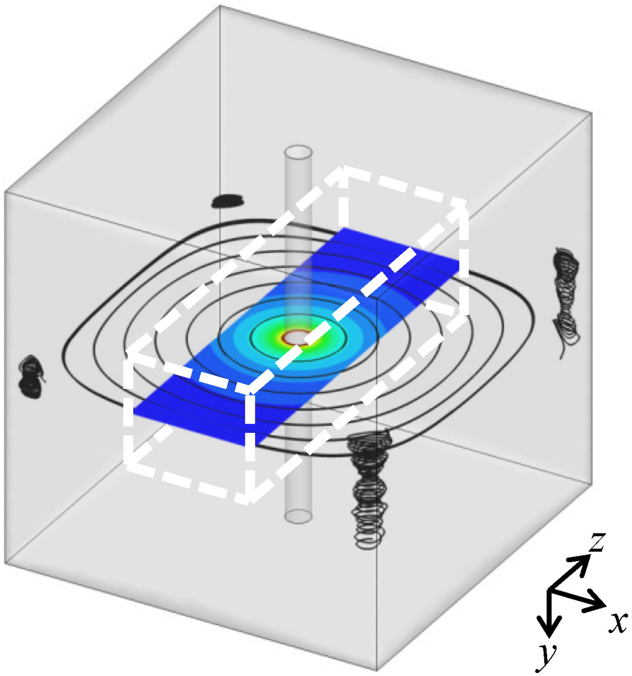
particles measured with the hybrid method, background shows the recorded holograms

Extraction of theoretical trajectory

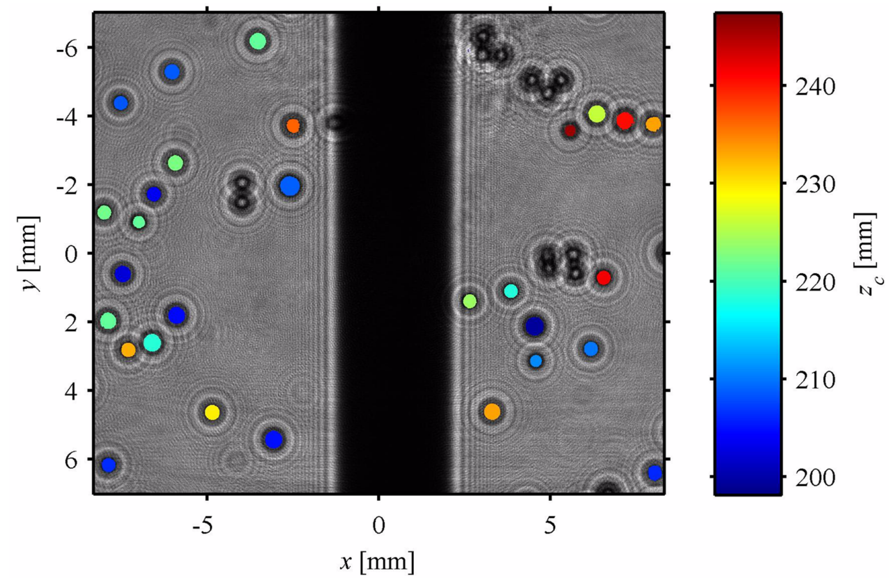
In the x-z plane, particles are expected to travel in near perfect circles

$$x(t) = r\cos(\omega t + \theta_0)$$

- Assuming measured x-positions have minimal error, curve fit → r, ω, θ_0



simulated flow field showing streamlines and total velocity contour within the center x-z plane of the field of view (dotted lines)

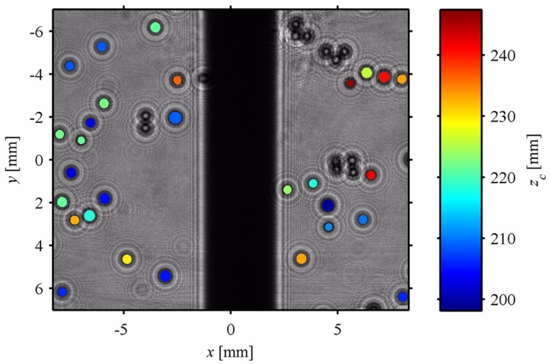


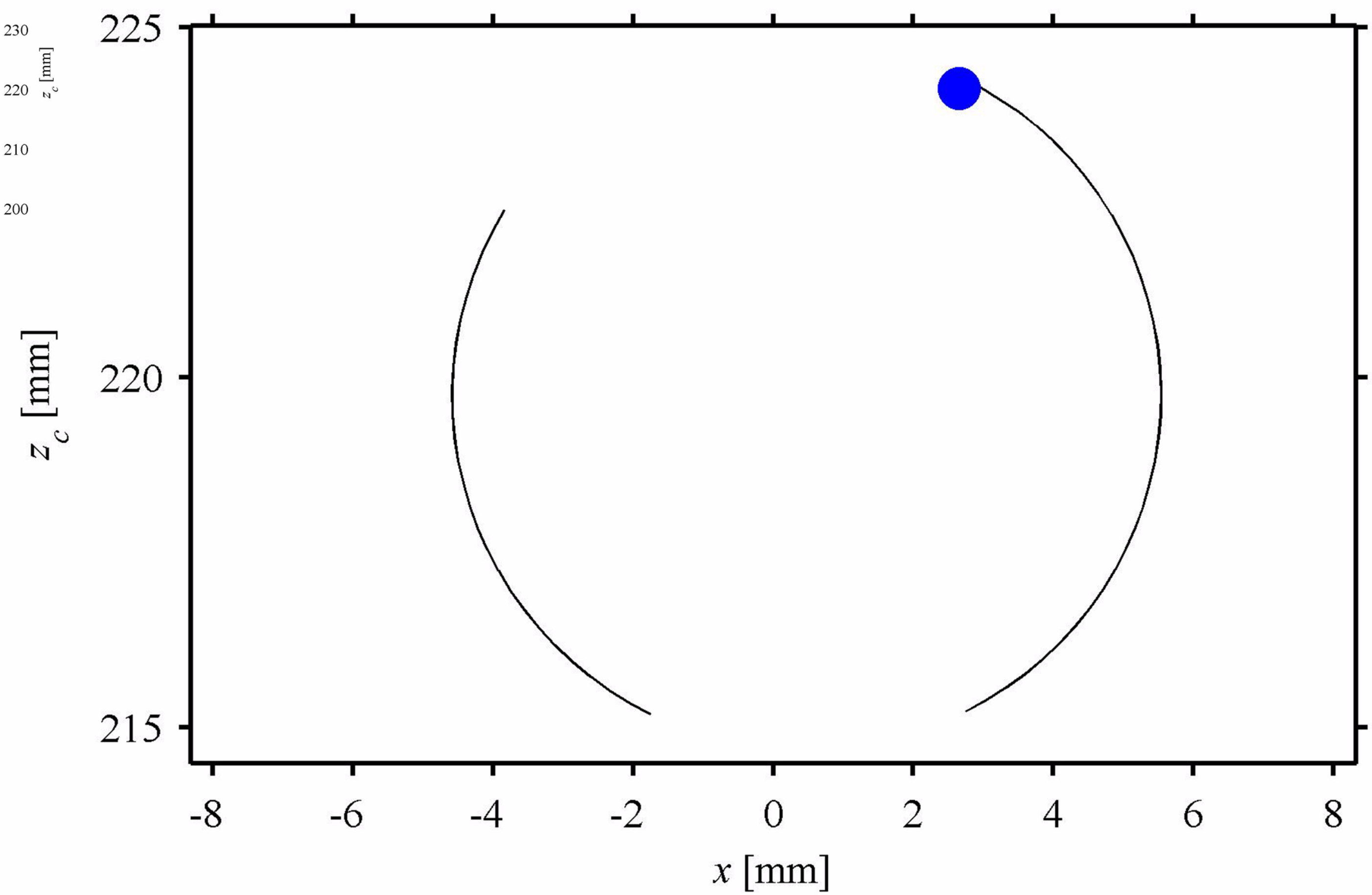
example in-plane trajectory

- Measured r = 5.04 mm, ω = 9.414 rpm
- At this r, simulation gives ω = 9.406 rpm

Comparison with measured results

Predicted z-trajectory: $z(t) = r\sin(\omega t + \theta_0)$ and $\Delta z(t) = r\omega\cos(\omega t + \theta_0)\cdot\Delta t$





measured x-z trajectory vs. predicted

Conclusions

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For all trajectories

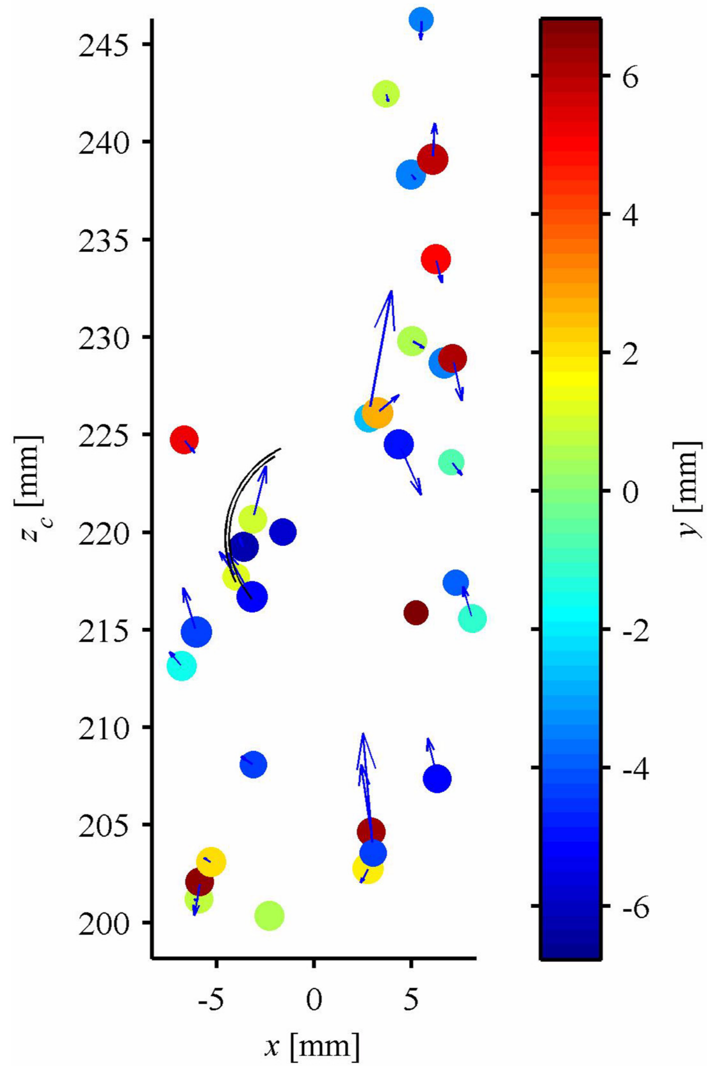
- Error in measured z = -0.04 ± 1.51 mm
- Error in measured Δz = -0.03 ± 1.05 mm
  - Standard deviation of $2.3 \cdot \bar{d}$

Experiments repeated with smaller particles ($\bar{d} = 118\,\mu m$, see paper for details)

- Error in measured z = -0.003 ± 0.379 mm
- Error in measured Δz = -0.001 ± 0.302 mm
  - Standard deviation of $2.6 \cdot \bar{d}$

Next steps:

- Compare results with alternative particle detection methods
- Use results to quantify effects of particle overlap and other experimental noise sources



all measured x-z trajectories vs. predicted

3D, 3C fluid velocity measurements?

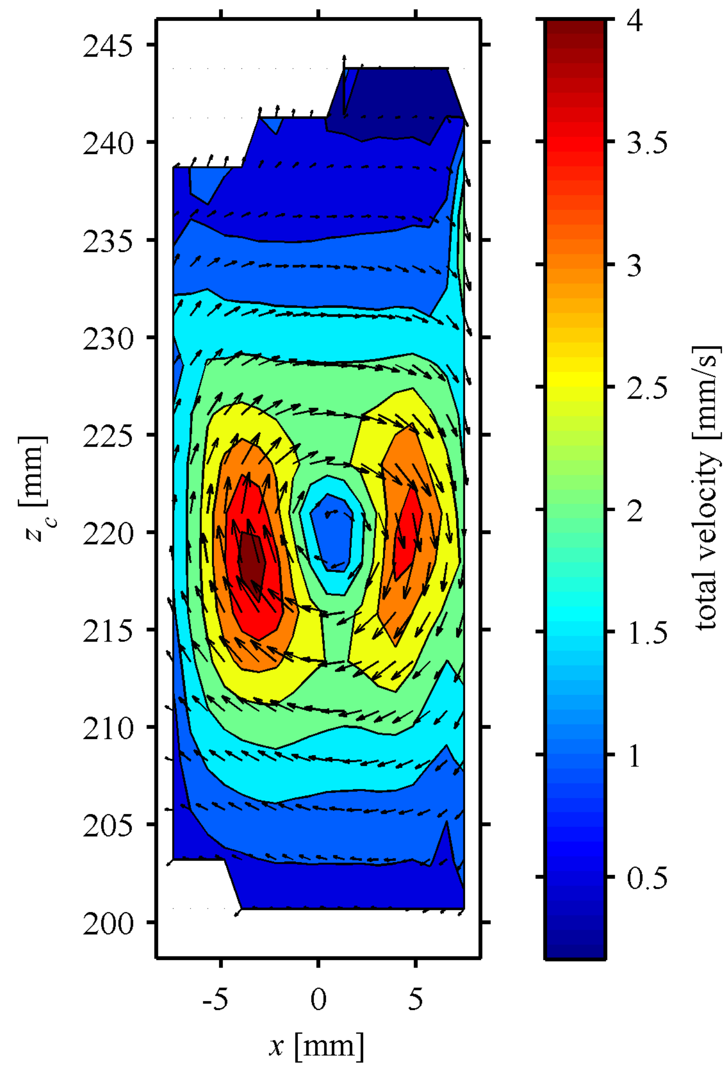
Advantages:

- Simple optical setup requiring only one line-of-sight view
- Large depth of field (hundreds of mm possible)
- Particle sizes can be measured (if desired)

Challenges:

- High uncertainty in the *z*-direction
- Particle field must be relatively spare providing only limited vectors
- Vectors at random positions
- Methods not as mature as PIV or even tomographic-PIV

Note: the literature contains many works on holographic-PIV. My own work has not been focused on these applications



mean measured *x*-*z* velocities

Questions?