Understanding particle–bubble attachment:
Experiments to improve flotation modelling

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Background and Motivations

- Flotation is an important industrial separation process
  - Minerals industry (froth flotation) — since *circa* 1885 * / 1902 **
  - Water treatment
  - Wastewater treatment
  - Food & drink
    - wine, juice, syrup, ...

- Minerals industry is 'more discriminating'
  - Needs to distinguish between particles
  - Mechanism:
    - Different affinities for air (or water)
      - May be *natural* or *induced* by additives
    - Called "hydrophobicity" (or "hydrophilicity")
      - Commonly attributed to contact angle
      - 'Interparticle forces' also play a role — electrostatics, van der Waals, ...

* Hoover; *Concentrating Ores by Flotation*; 1912. See also Taggart; *Handbook of Mineral Dressing*; 1945.

** Clark, Brake, Huls, Smith & Yu; *Minerals Engineering*; 2006; **19**(6–8): 758–765.

Recent research at CSIRO

- CFD models of flotation *
  - developed over > 10 years by “Minerals” CFD team
    - Peter Koh, Phil Schwarz, and colleagues
  - employs exact Navier–Stokes equations in a multi-fluid model
  - keeps track of particle number density
  - utilises induction time model
- Induction time model
  - predicts particle attachment
  - uses simple correlation*: $t_{ind} = 75\ d_p^{0.6} / \theta$ — could be improved
- Experimental input
  - longstanding work on hydrodynamics and efficiency
    - William Yang; and Leanne Smith, Warren Bruckard and several others
  - more recent interest in fundamentals of attachment
    - Fuping Hao, Tammy Chau and several others
    - varied particle size, roughness (~glass “ballotini”)
    - developed measurement of particle contact angle
    - established surface methylation procedure

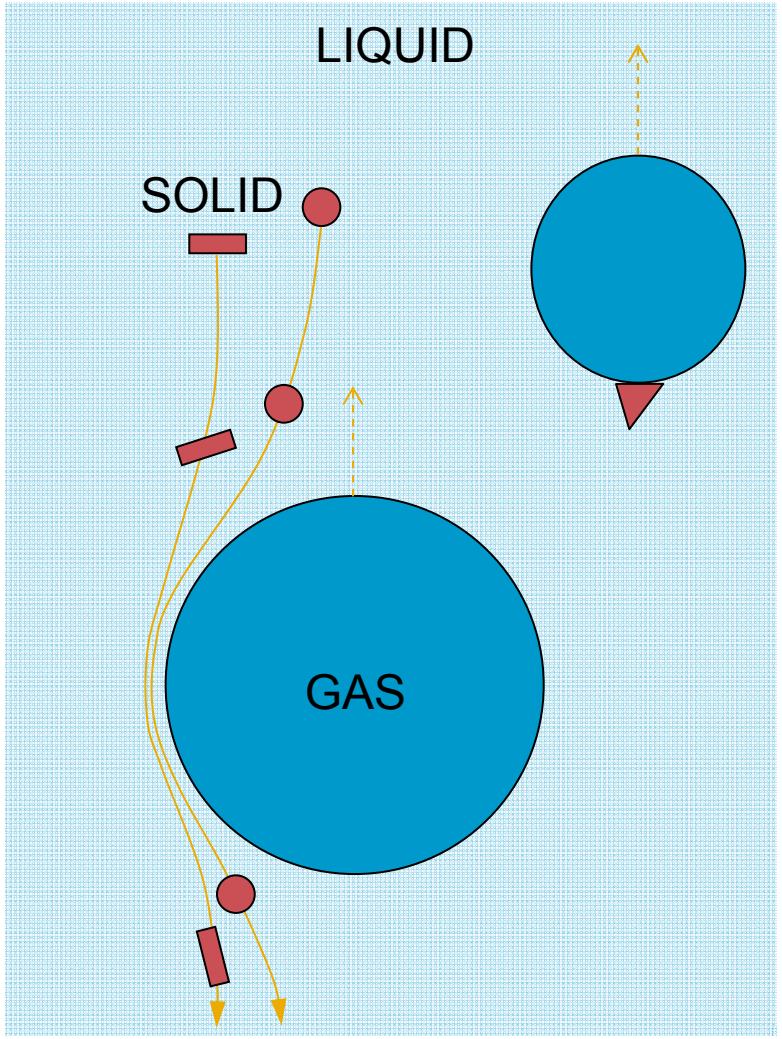
  …now moving into induction time measurement

* Koh & Schwarz; *Minerals Engineering*; 2006; **19**(6–8): 619–626.

Induction time concept

- Particles ~follow ‘streamlines’ around bubble
  - approach
  - slide
  - attach/withdraw
- Induction time is a ‘critical’ value (threshold)
- Attachment assured/favoured when
  sliding duration > induction time

- Sliding time depends on:
  - sizes, velocities, ...
- Induction time depends on:
  - surface properties
  - other factors?

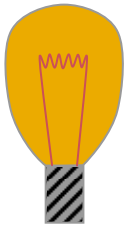


Experimental options

- Real system — ~10 m cell
  - too complicated to attribute individual effects
- Simple pilot-scale system / 'water model' — ~1 m cell
  - able to measure spatial properties
  - good for 'real' hydrodynamics
    - *e.g.* PIV work by William Yang & co.
- Simple 'benchtop' float cell — ~0.1 m cell
  - fair representation of hydrodynamics
  - measure *e.g.* % recovery from a mixture
    - *e.g.* Bruckard, Smith, Davey, Heyes, & co. at CSIRO; JKMRC; ....
- Single-object systems
  - atomic force microscope — captive particle & bubble ► force
  - 'pickup' — captive bubble picking up particles ► time
  - Hallimond tube ... — rising bubble in dilute suspension ► efficiency
  - 'dropping' — particle(s) dropped onto stationary bubble ► time, energy, ...

Experimental set-up

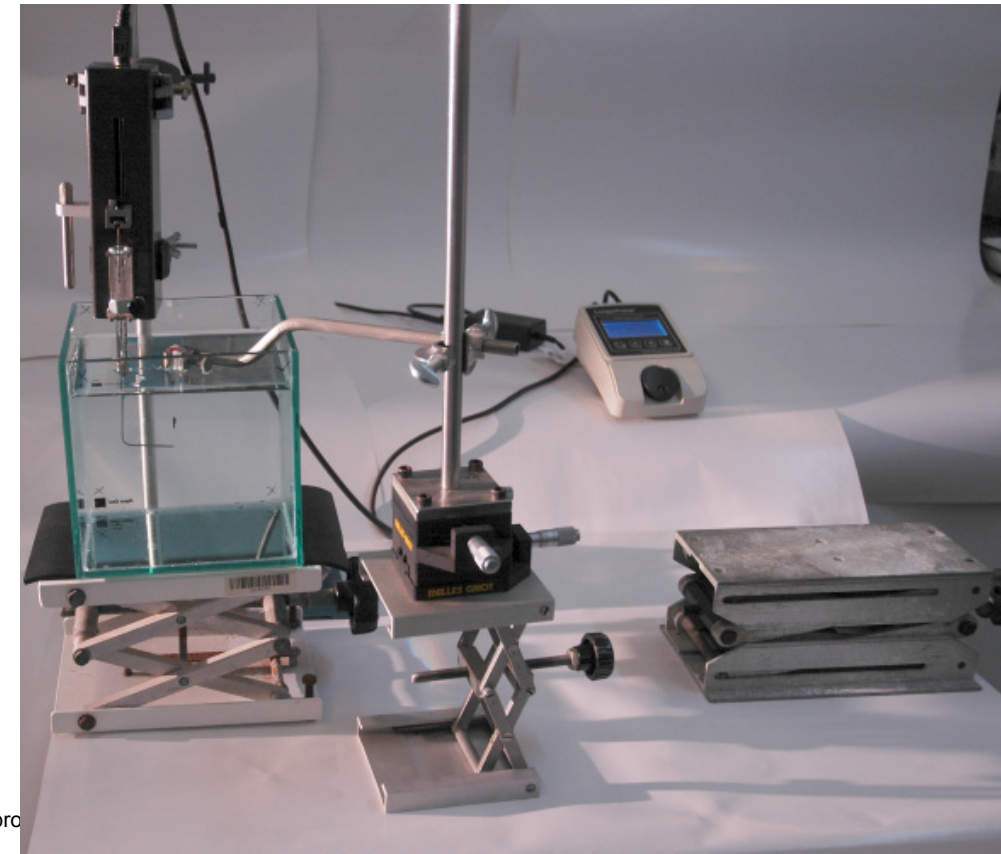
- Fine capillary blows air bubble
  - 0.5 mm OD, 0.3 mm ID
  - 1.5 mm OD, 1.1 mm ID
- Narrow dropper drops particles through water onto bubble
  - 1.0 mm OD, 0.5 mm ID
- High-speed camera with zoom lens
  - 0.18 mm depth of field
- Intense light



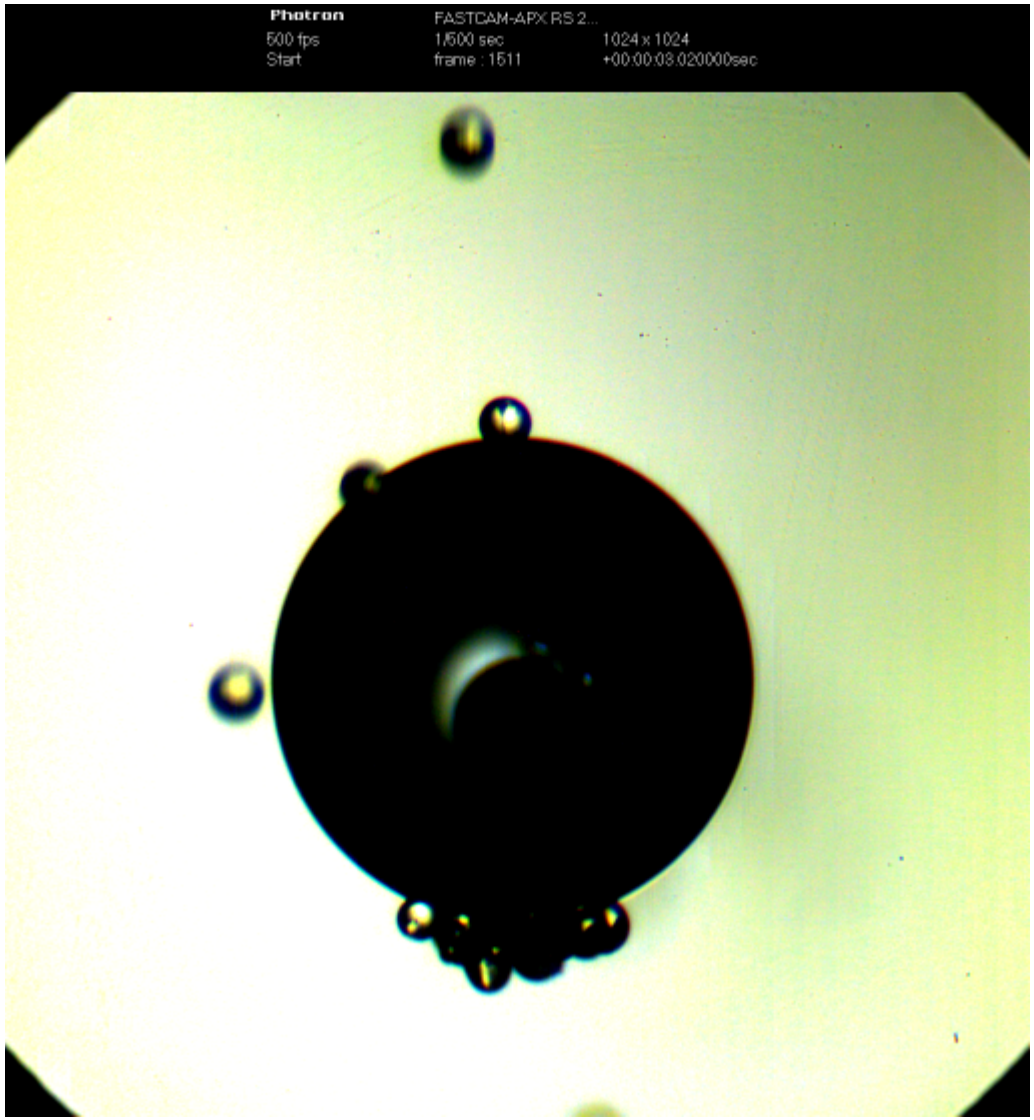
Results presented for “fully methylated” ballotini *

- θ ~ 90° by Washburn technique

* Koh, Hao, Smith, Chau & Bruckard; *International Journal of Mineral Processing*, 2009. **93**(2): 128–134.



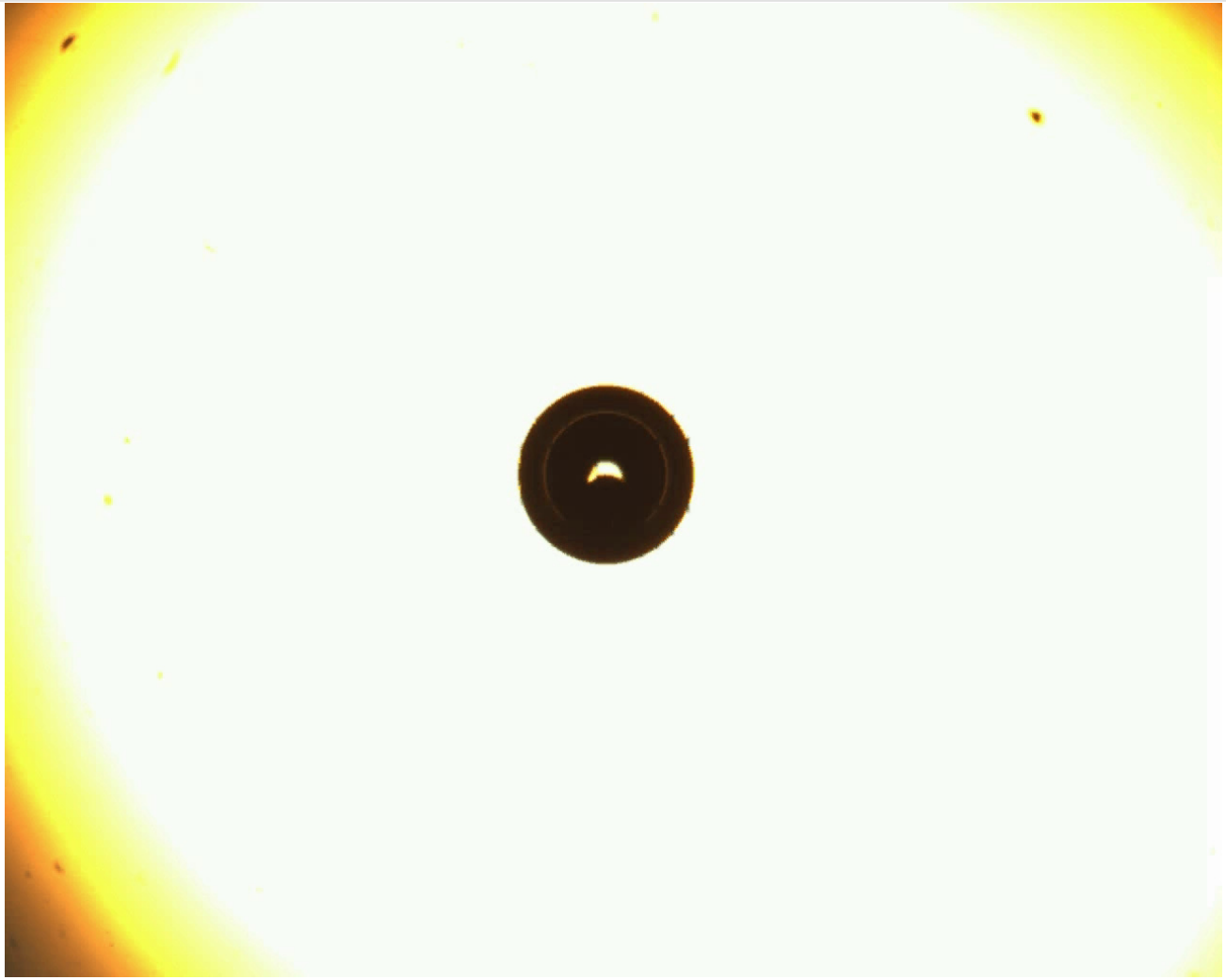
Typical image



0 0.25 0.5mm

Recorded at **500 fps**.

Particle dropping in ‘real time’



~140 µm glass spheres dropping onto **~1.3 mm air** bubble in deionised **water**.
Recorded at **500 fps**. Played back at actual speed.

0 1 2mm

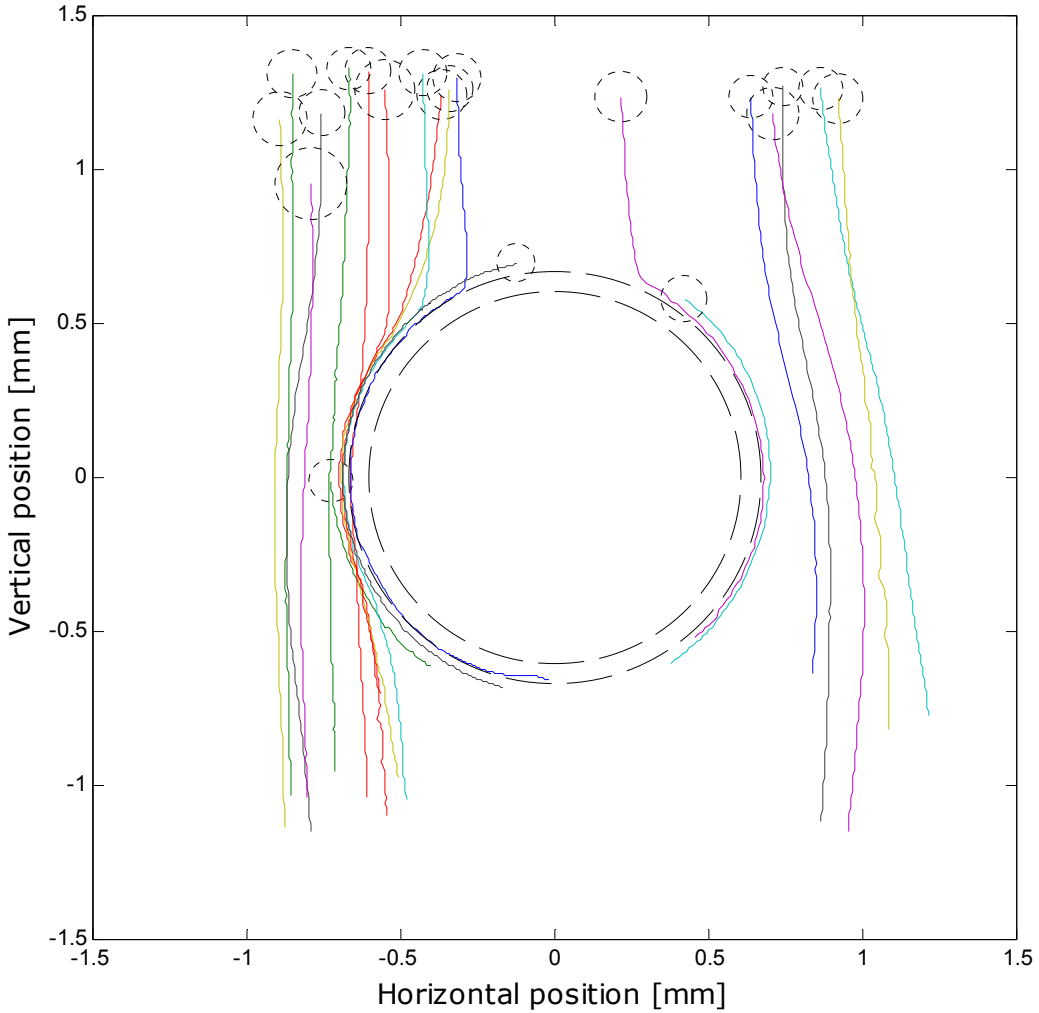
Particle dropping in ‘slow motion’, with attachment

~140 µm glass sphere dropping onto **~1.3 mm air** bubble in deionised **water**.

Recorded at **500 fps**. Played back at 1/50th speed.

0 1 2mm

Particle trajectories (path lines)

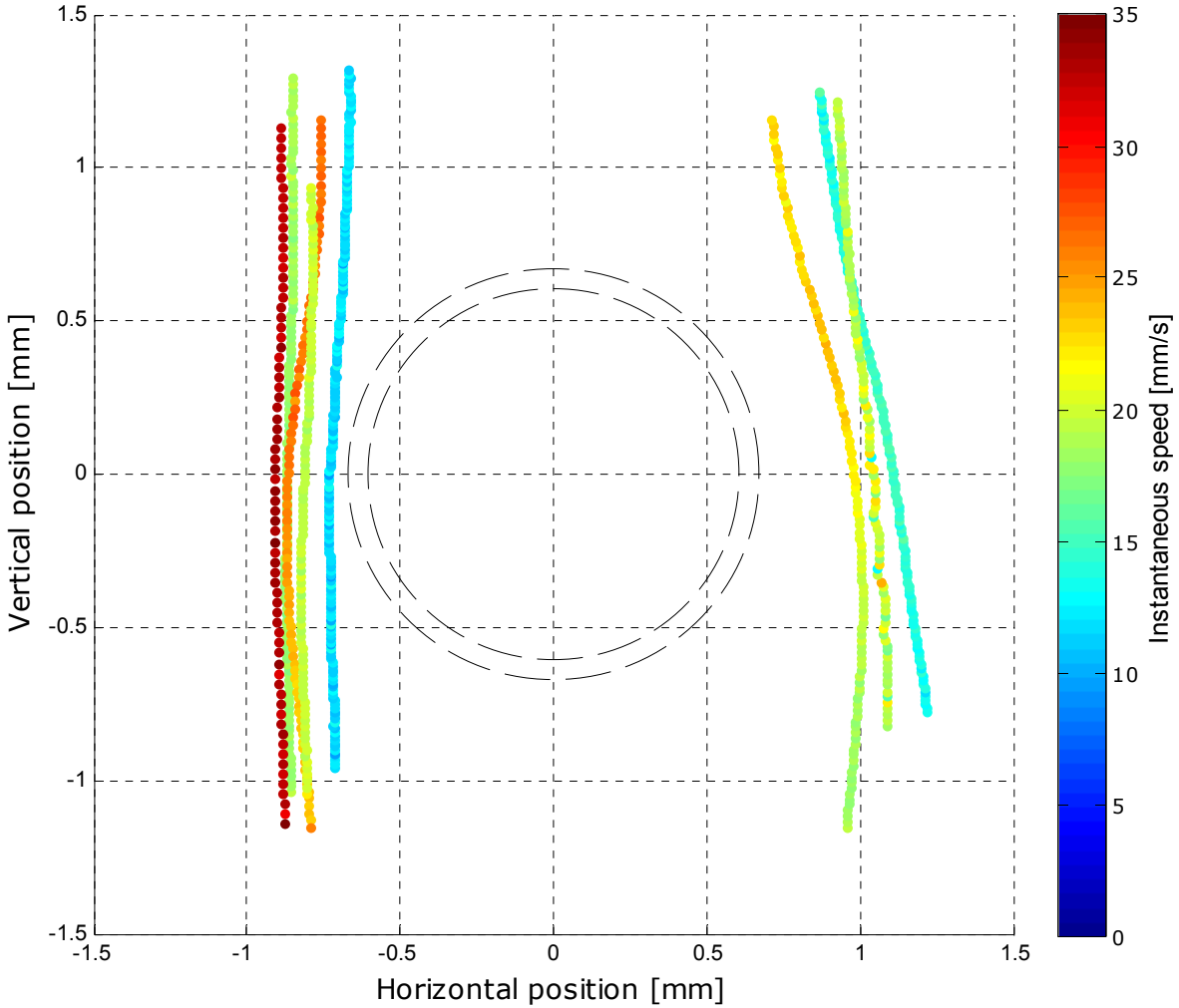


~125 to 150 µm glass spheres dropping onto **~1.3 mm air** bubbles in deionised **water**.

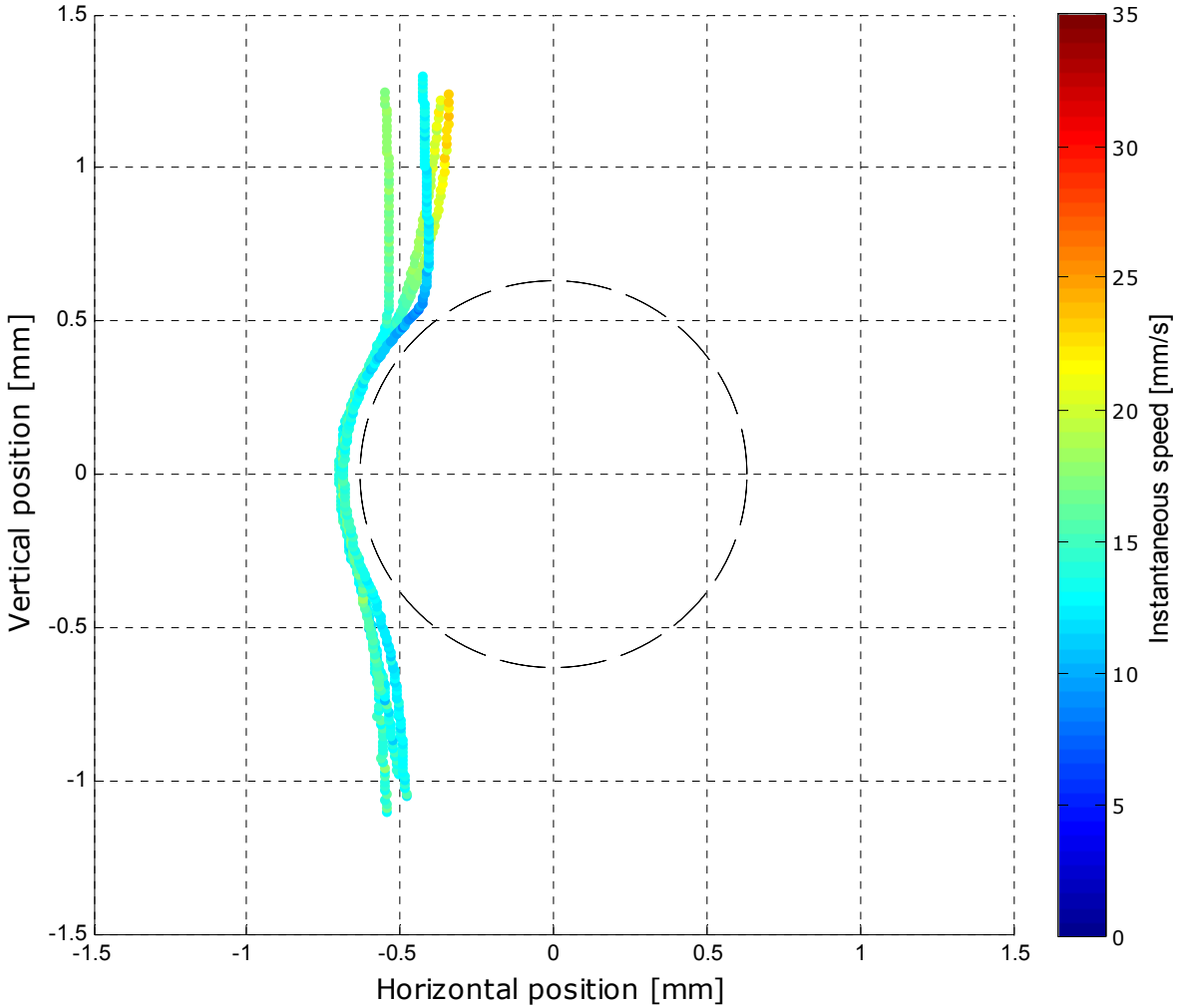
Recorded at **1000 fps**. Optical magnification of **~6.75×**, corresponding to **~2.5 µm/pixel**.

Particle velocities

Passing



Particle velocities

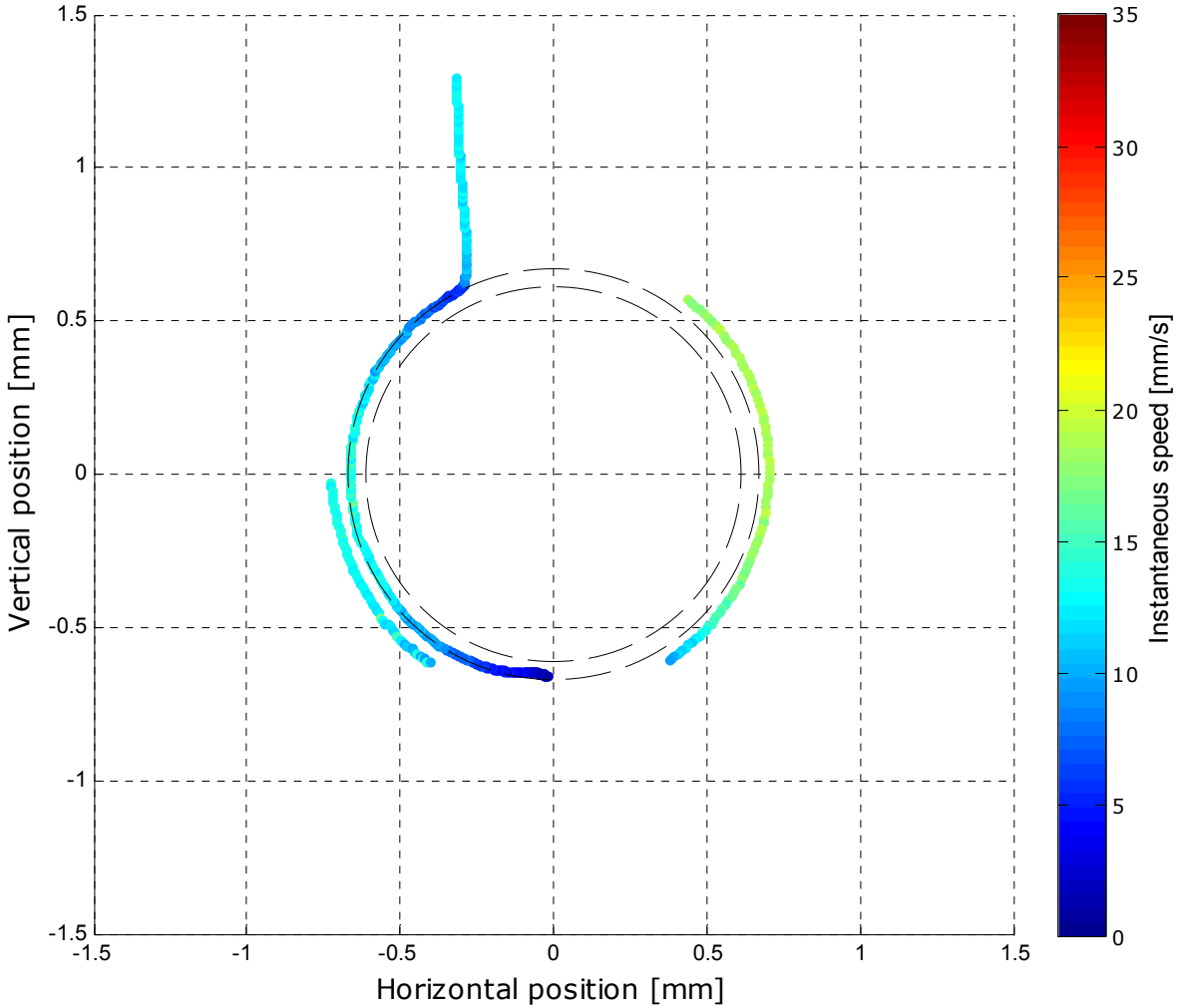


Sliding,

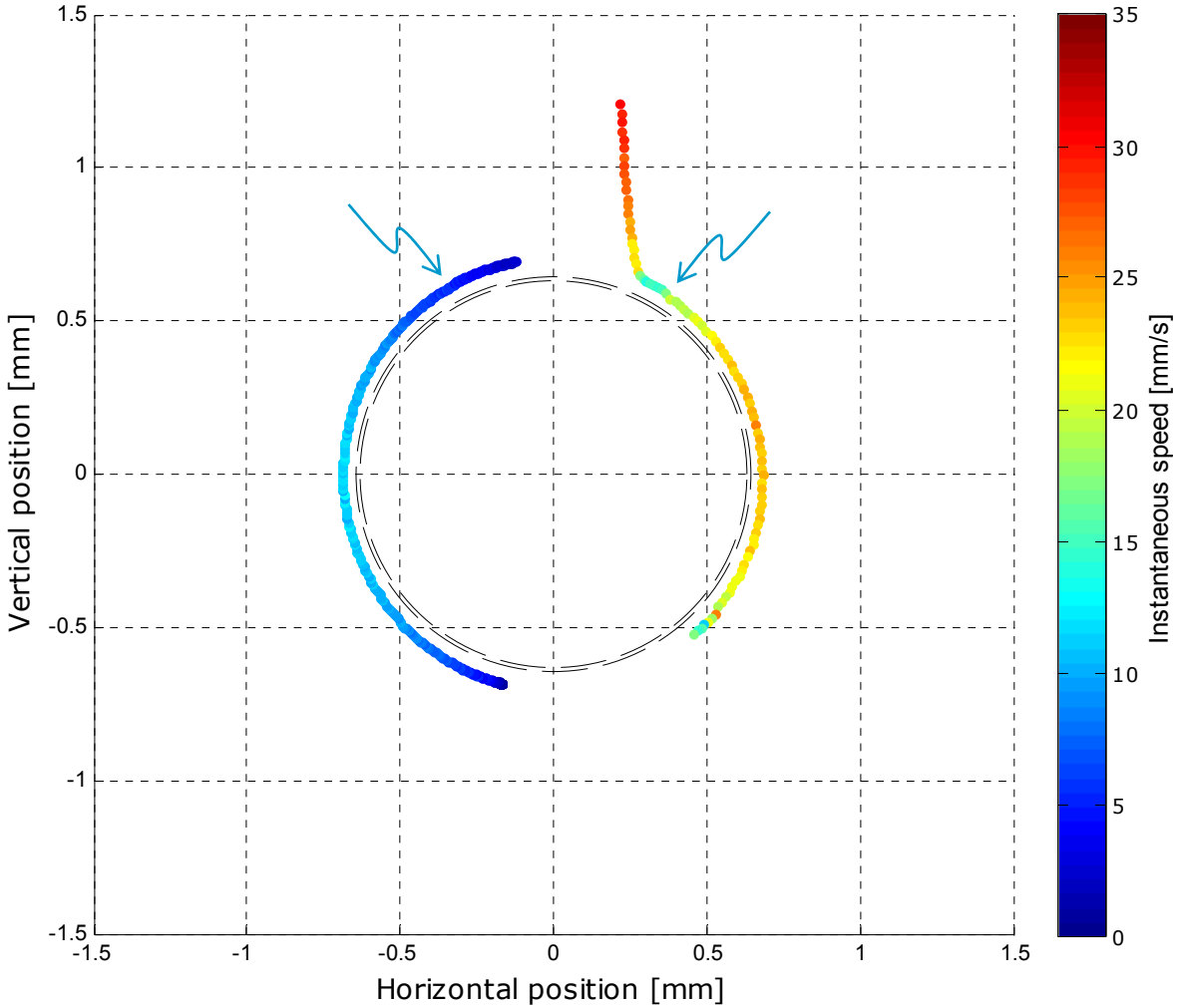
without attachment

Particle velocities

Attaching

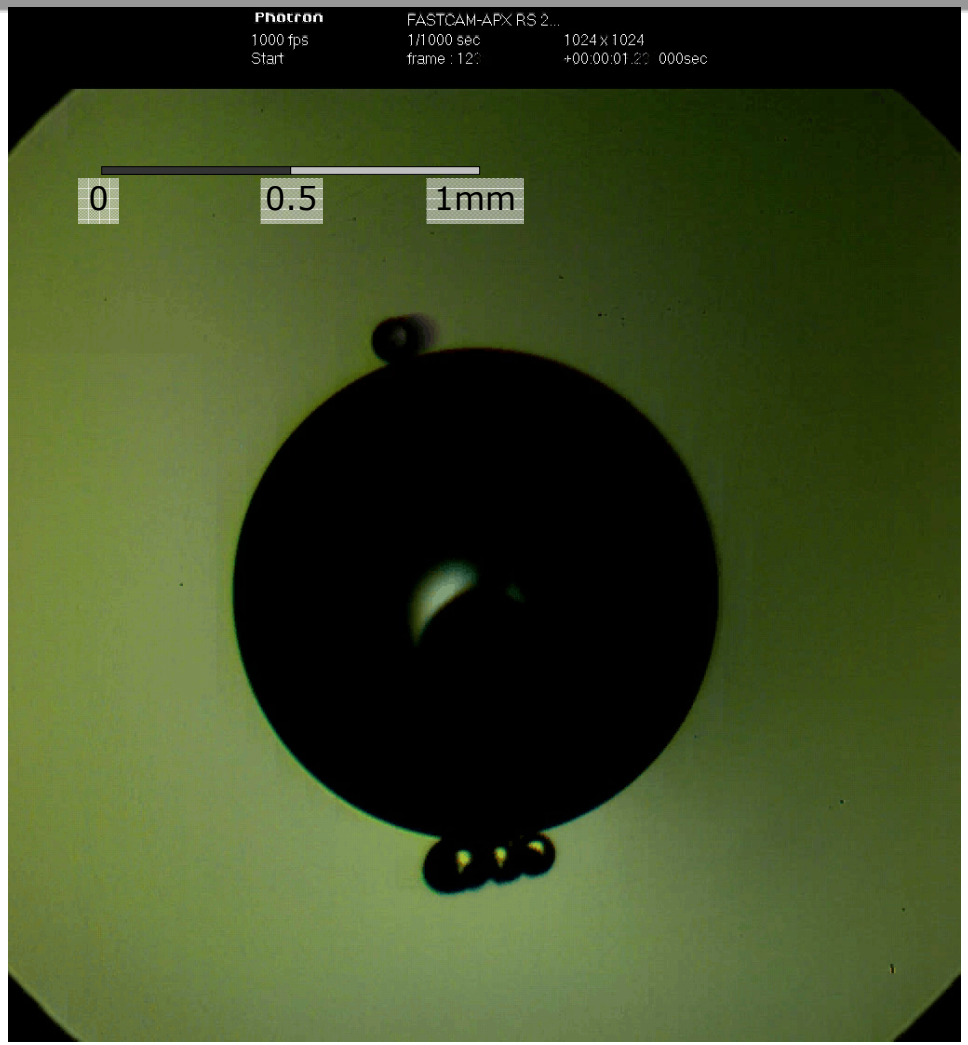


Particle velocities



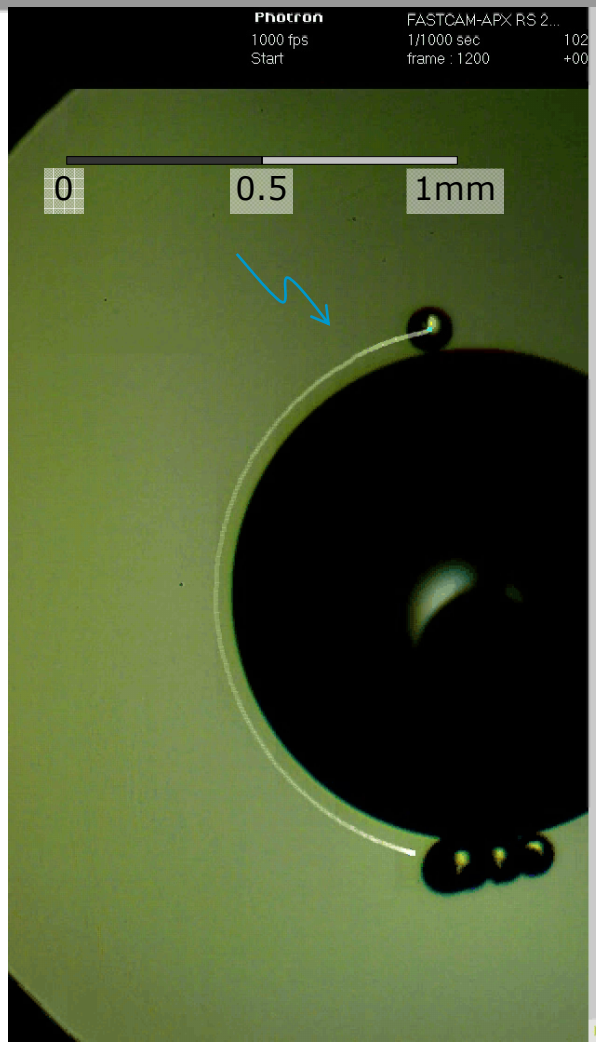
Attaching with 'jump in'

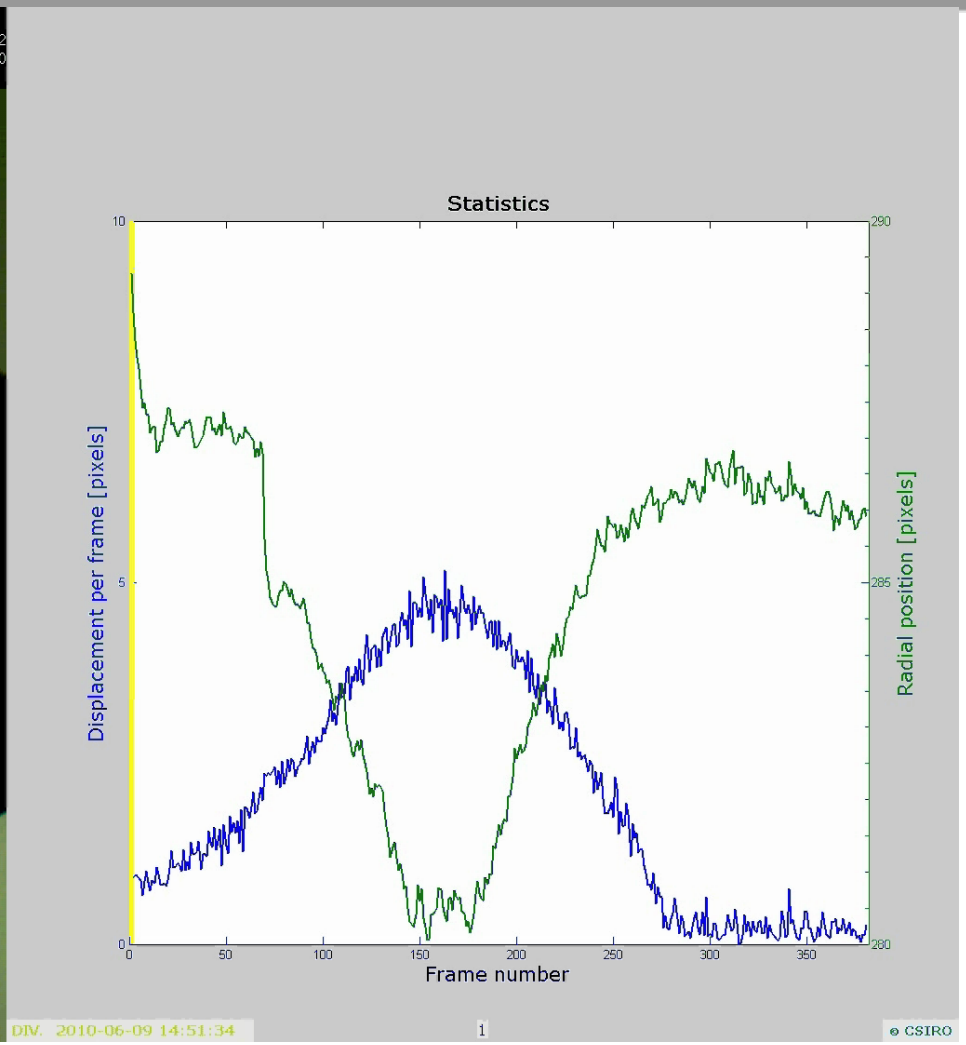
Attachment event



~125 µm glass sphere dropping onto **1.3 mm air** bubble in deionised **water**.
Recorded at **1000 fps**. Played back at actual speed.

Attachment event

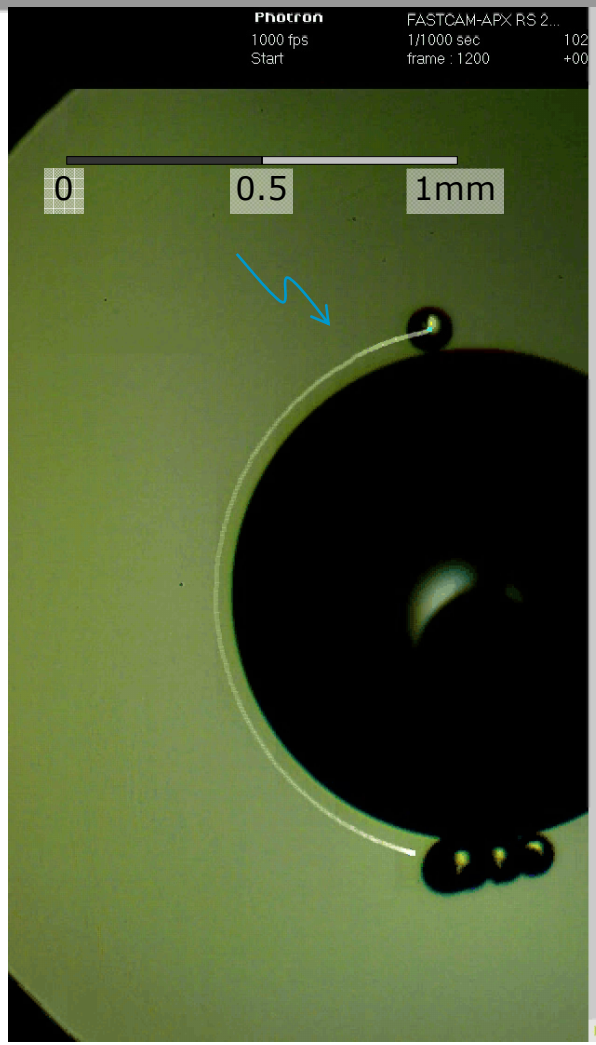


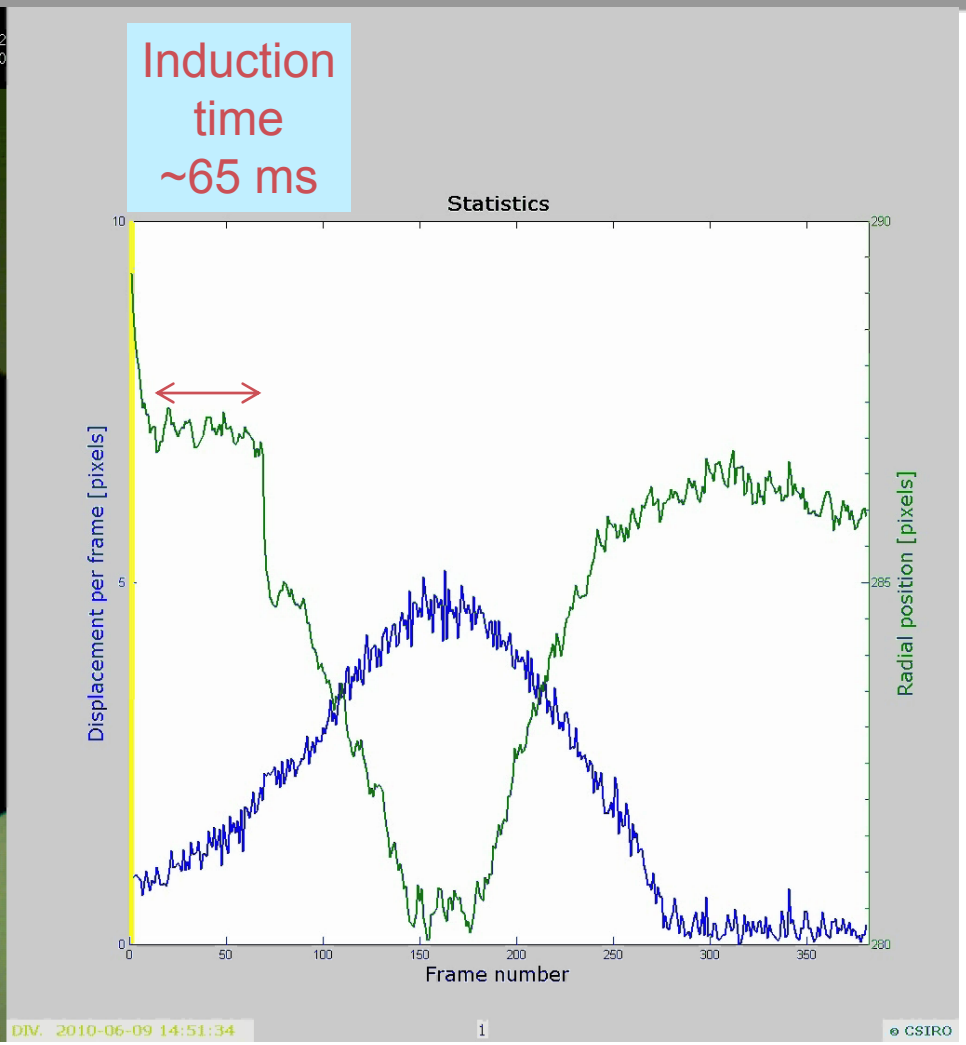


~120 µm glass sphere dropping onto **1.3 mm air** bubble in deionised **water**.

Recorded at **1000 fps**. Played back at 1/50th speed.

Attachment event

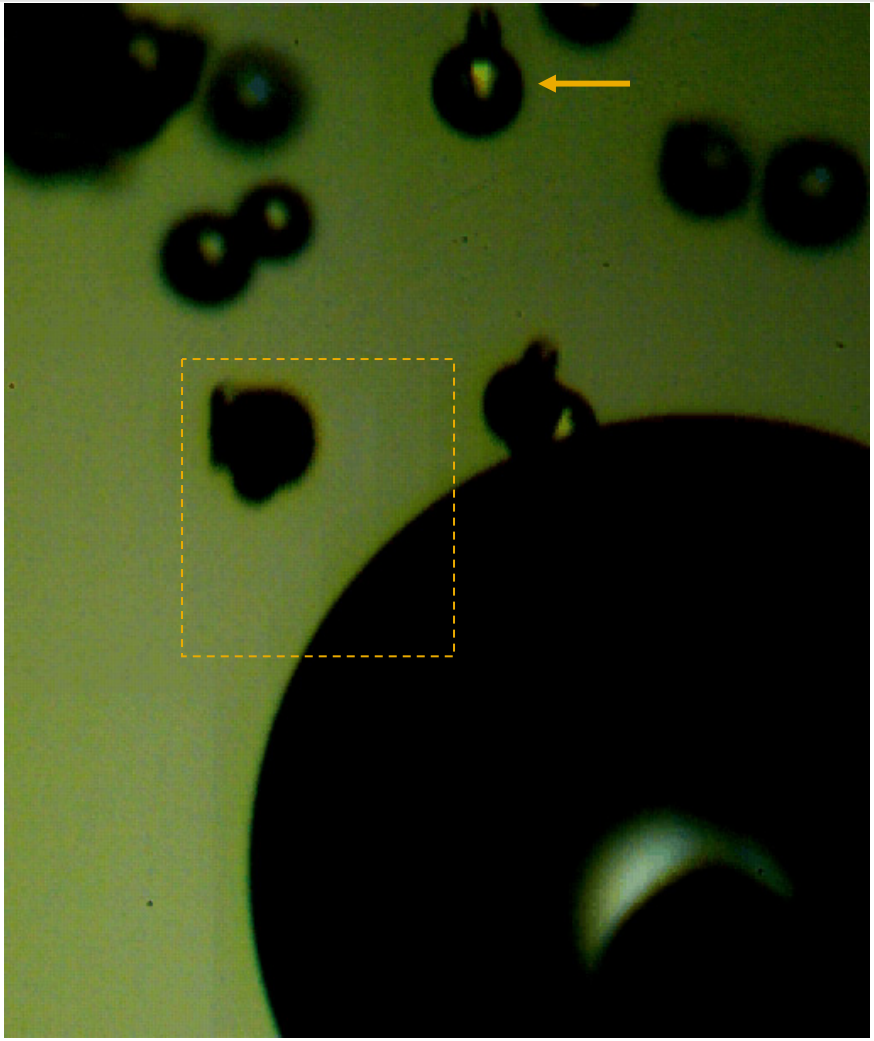




~120 µm glass sphere dropping onto **1.3 mm air** bubble in deionised **water**.

Recorded at **1000 fps**. Played back at 1/50th speed.

Jump-in, with particle rotation



0 0.25 0.5mm

~140 µm glass sphere with 'satellite' dropping onto **1.3 mm air** bubble in deionised **water**.
Recorded at **1000 fps**. Played back at 1/100th speed.

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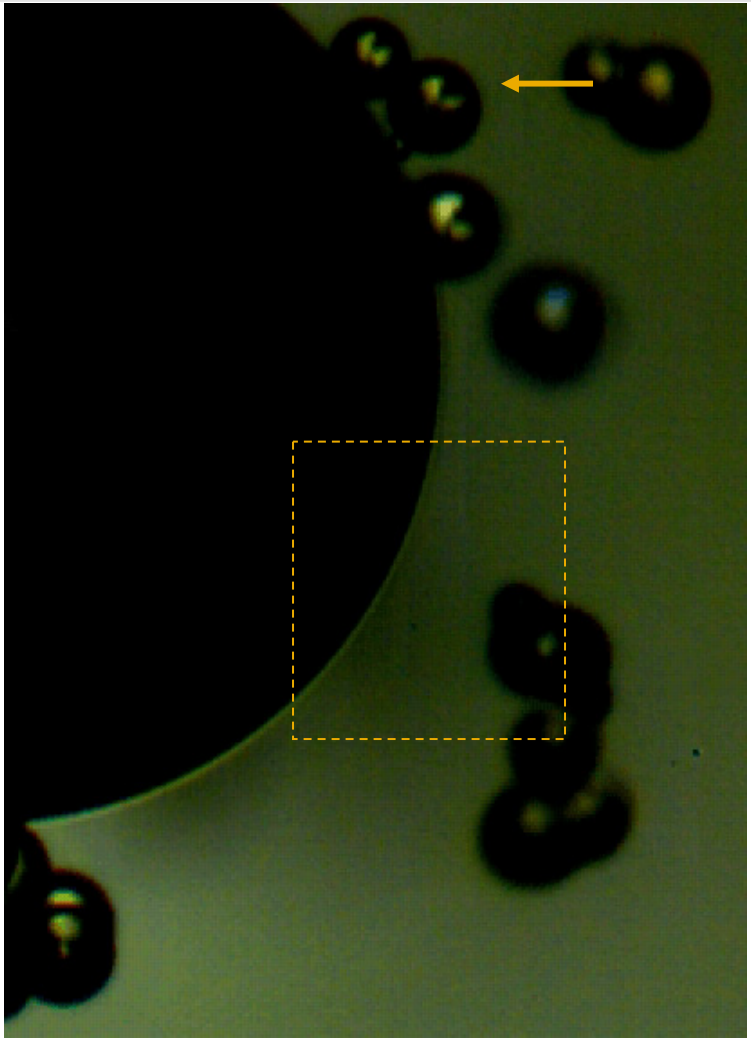
Jump-in, below equator of bubble



0 0.25 0.5mm

~110–140 µm glass doublet + ‘satellite’ dropping on **1.25 mm air** bubble in deionised **water**.
Recorded at **1000 fps**. Played back at 3/200th speed.

Early findings

- Current set-up is advantageous
  - fair representation of real (hydro)dynamics
  - allows direct imaging of sliding
  - velocities, gaps & times can be estimated directly
- 'Jump-in' event interpreted as attachment
  - could also be TPCL expansion
- Behaviour varies
  - jump-in 'event' often not apparent — seen in 6 of 15 attachments
  - induction times in the range ~6 to 70 ms for the system presented — if defined as duration of sliding until jump-in event
- Observations challenge some common assumptions
  - no apparent change in velocity upon attachment
  - rotation of particle upon jump-in
  - 'jump in' below equator of bubble
- Scope to enhance complete flotation model

Acknowledgements

CSIRO

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and
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Thank you

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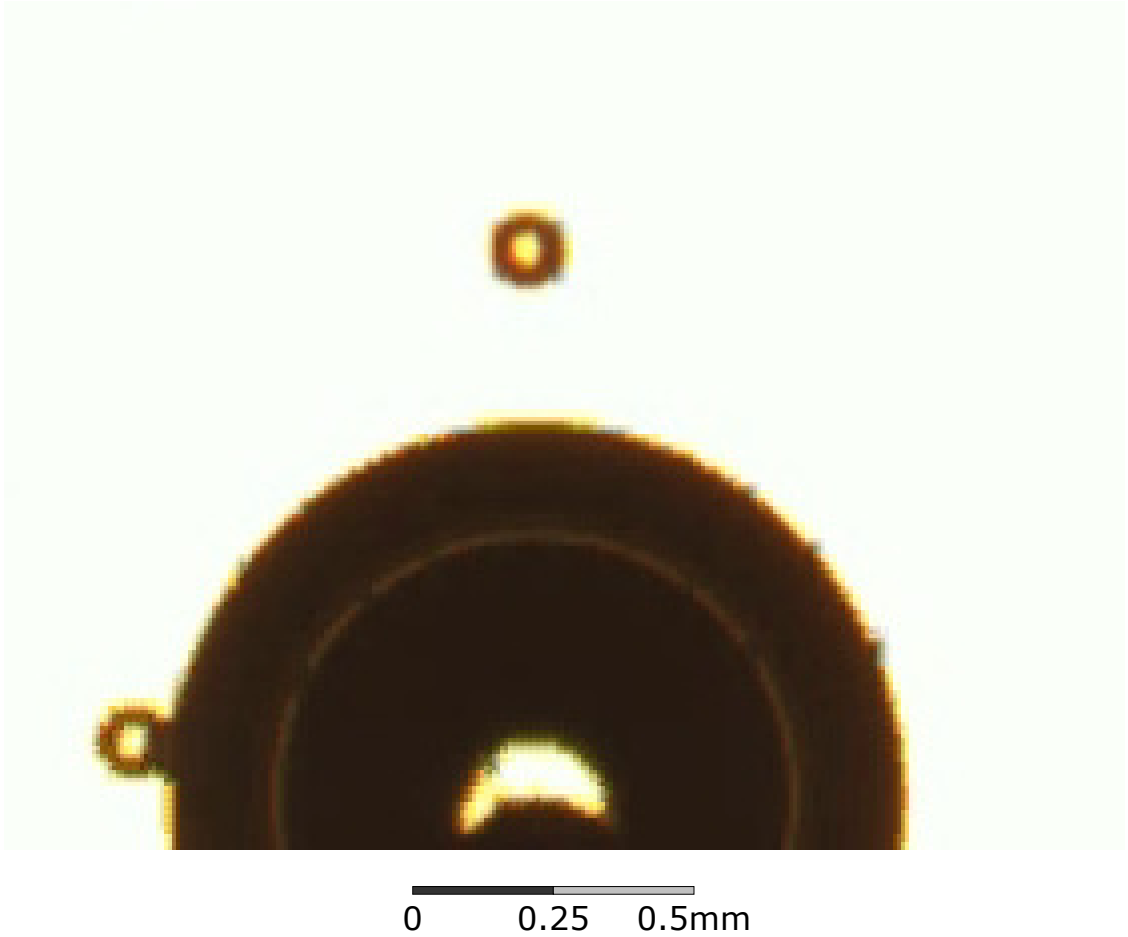
Scales of length and time

- Lengthscales
  - bubbles: <1000 to 3000 μm
  - particles: 50 to 150 μm — comparable to human hair diameter [1]
  - electrostatic forces: < 1 μm (except in very pure water) [2]
  - van der Waals / dispersion forces: < 1 μm [3]
  - 'hydrophobic forces': < 0.1 μm (?)
- Velocities ...*in a quiescent fluid away from any boundaries!*
  - bubbles: ~0.2 m/s [4]
  - particles: 0.002 to 0.02 m/s — comparable to snail's pace [5]
- Timescales
  - time for a 2 mm bubble to travel 2 mm: ~ 10 ms
  - time for a 100 μm particle to travel 2 mm: ~ 200 ms

    — comparable to blink of an eye [6]

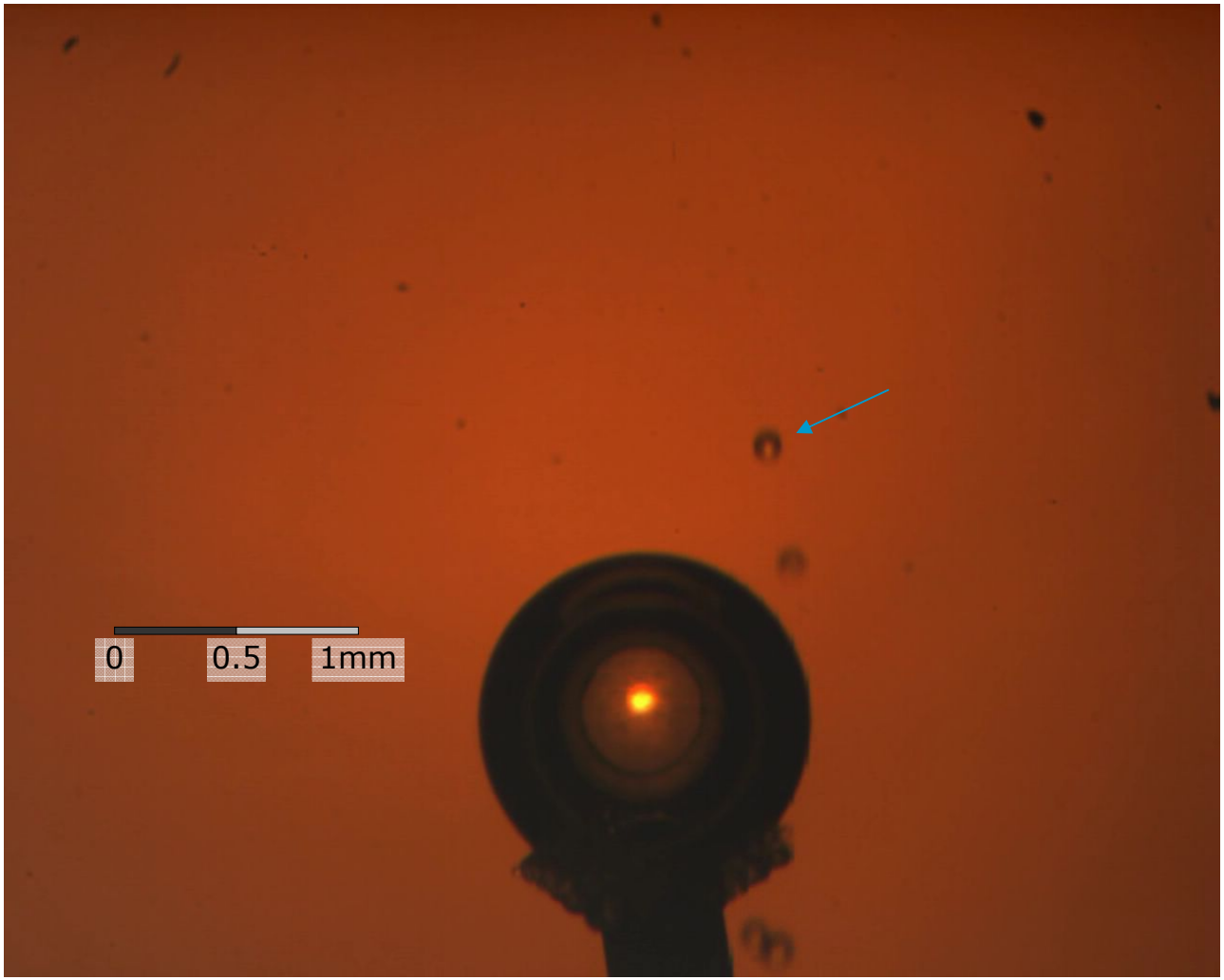
[1] Erik, Havitcioglu, Aktan & Karakus, 2008; *cf*. http://hypertextbook.com/facts/1999/BrianLey.shtml
[2] Hughes, 2000
[3] Görner & Pich, 1989
[4] Nguyen & Schulze, 2004
[5] http://hypertextbook.com/facts/AngieYee.shtml
[6] Lo Castro, 2008

Particle dropping in ‘slow motion’, with attachment

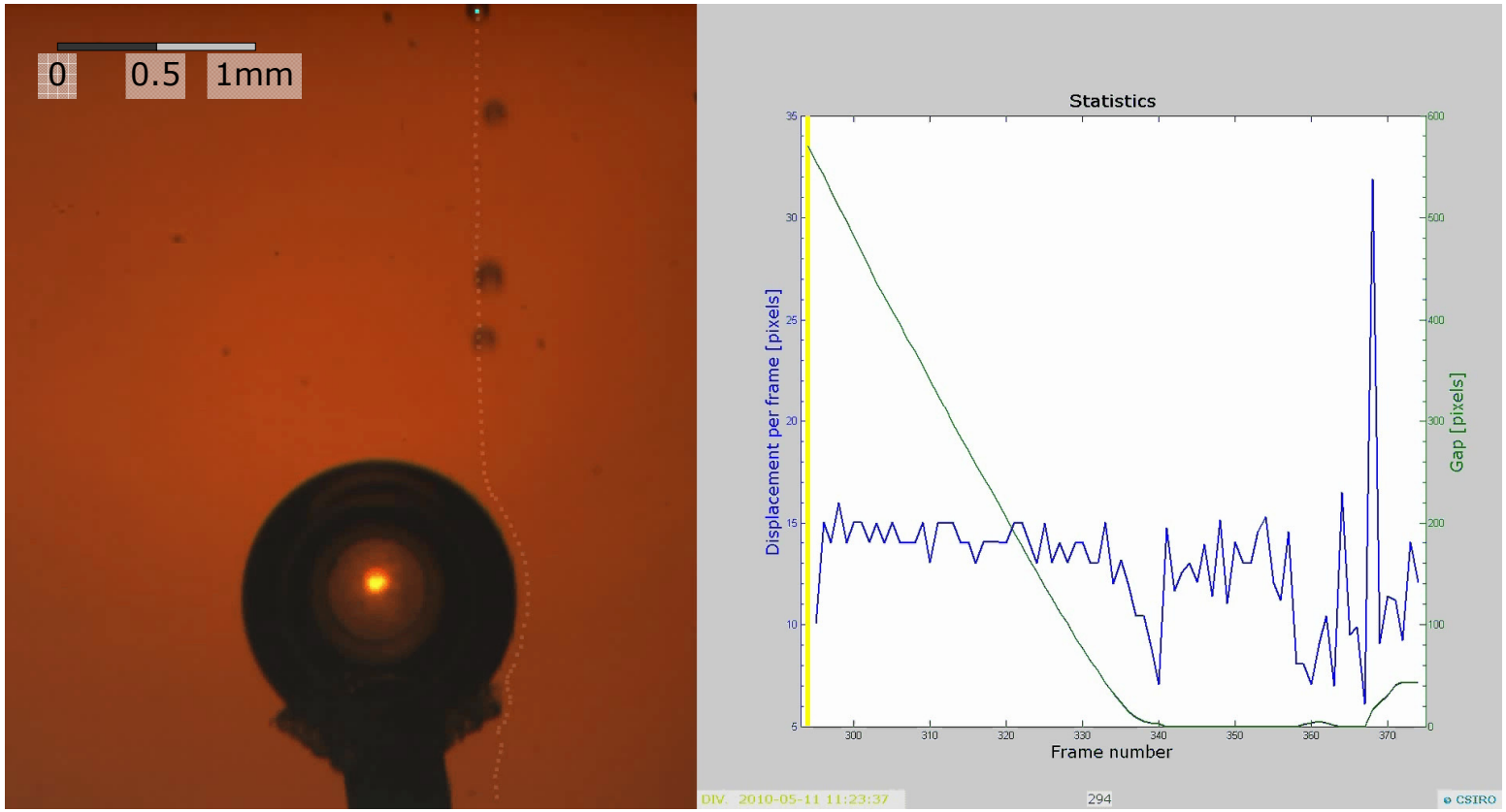


~140 µm glass sphere dropping onto **~1.3 mm air** bubble in deionised **water**.
Recorded at **500 fps**. Played back at 1/50th speed, with ***digital* zoom**.

Video processing, using *MATLAB*

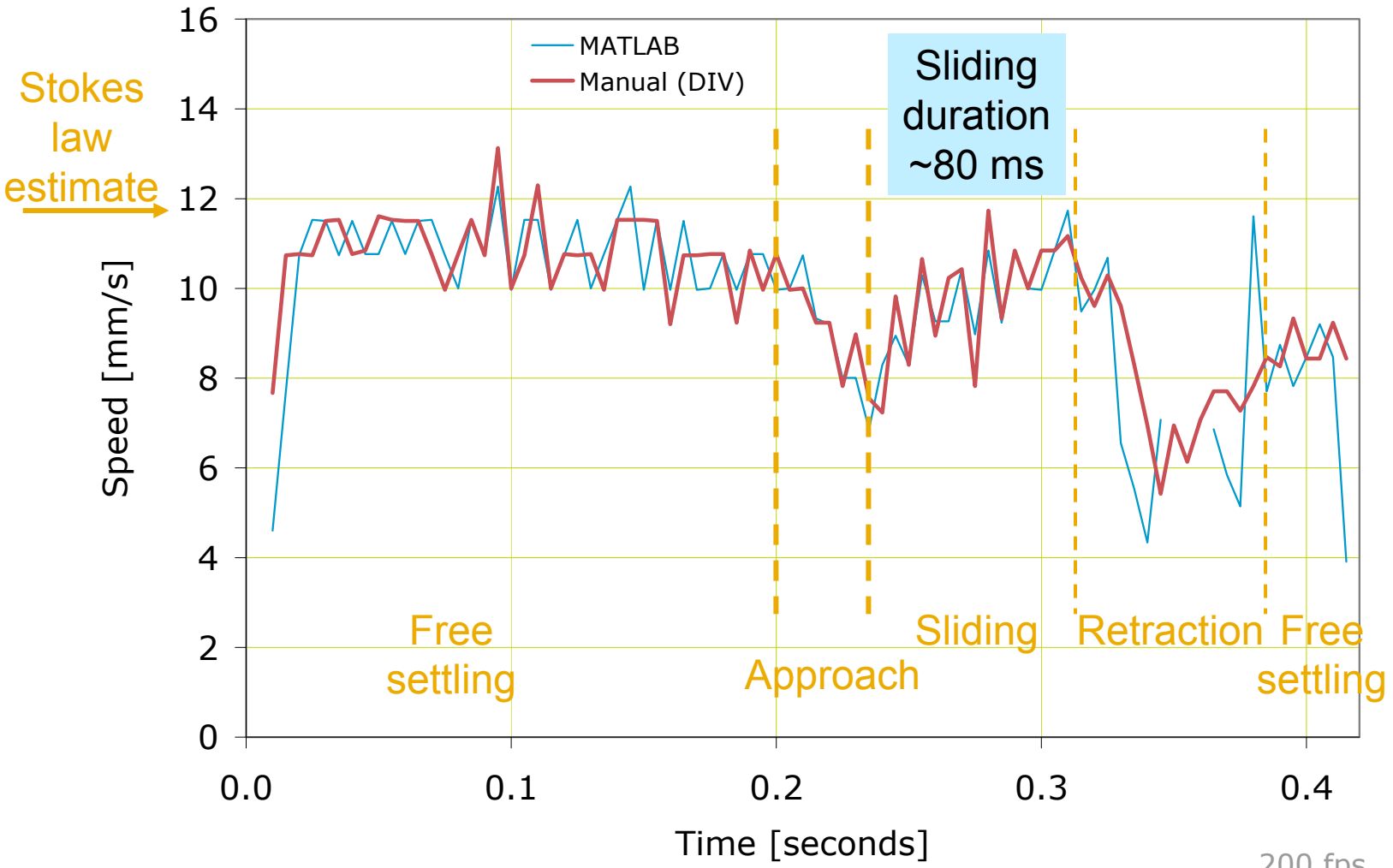


Preliminary results:
Sliding and withdrawal — video



Smooth **~130 µm glass** particle dropping onto **1.4 mm air** bubble in deionised **water**.
Recorded at **200 fps**. Played back at 1/50th speed.

Preliminary results: Particle velocity



200 fps