Dynamic MRI – Imaging Transport and Structure in Transient Systems

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Turing Gateway to Mathematics

The current team

Sponsors

EPSRC
Pioneering research and skills

Microsoft Research

Johnson Matthey, ExxonMobil, Shell, BP, Schlumberger, AstraZeneca, GlaxoSmithKline, Merck Sharp & Dohme, NPL

Overview

- **Introduction to MRI (and Chemical Engineering)**
- **Fast velocity imaging of fluids – dynamic flows**
  - **turbulent liquid flows**
  - **two phase flows**
    - chemical shift separation with compressed sensing
  - **do we need an image?**
    - Bayesian analysis of acquired data
- **Conclusions**

What is Chemical Engineering? – and why use MR?

The application of physical and life sciences to understand and develop processes and products

oil industry

chemical process technology

pharmaceutical industry

many different chemical species
chemical reaction
fluid flows
porous media
optically opaque

How to get a 2-D image with MRI: k-space

$$\omega(\mathbf{r}) = \gamma \mathbf{G} \cdot \mathbf{r}$$

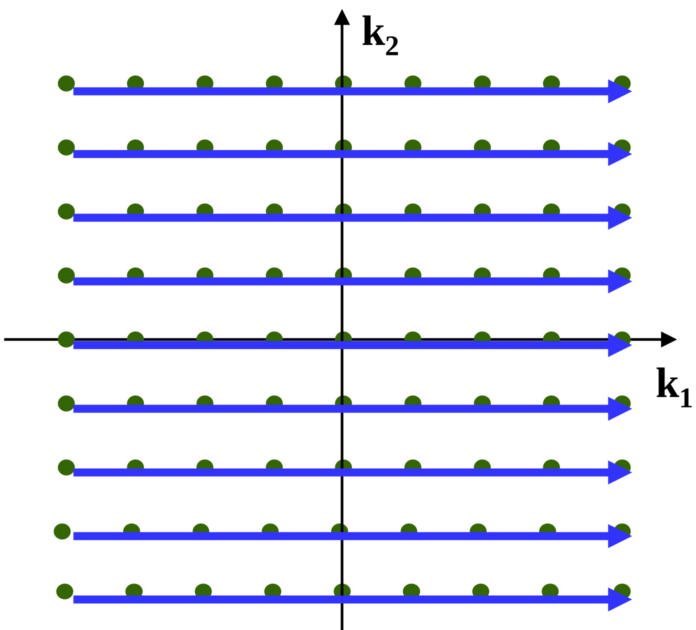
$$\mathbf{k} = \frac{\gamma \mathbf{G} t}{2\pi}$$

$$S(\mathbf{k}) = \iiint \rho(\mathbf{r}) \exp[\mathrm{i}2\pi\, \mathbf{k} \cdot \mathbf{r}]\, d\mathbf{r}$$

FT

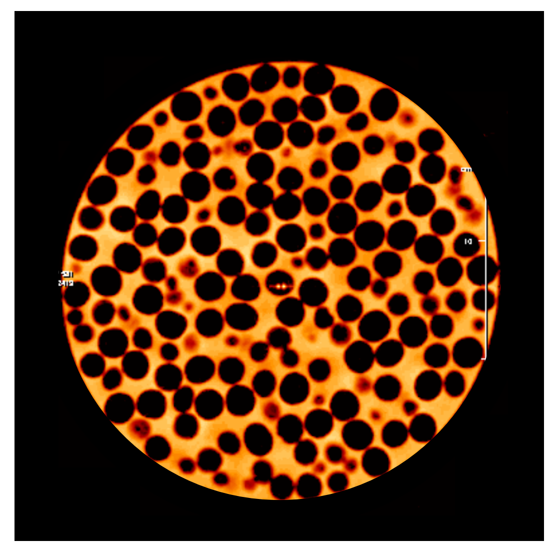
$$\rho(\mathbf{r}) = \iiint S(\mathbf{k}) \exp[-\mathrm{i}2\pi\, \mathbf{k} \cdot \mathbf{r}]\, d\mathbf{k}$$

- **Sample all of k and after FT we have a fully resolved image**

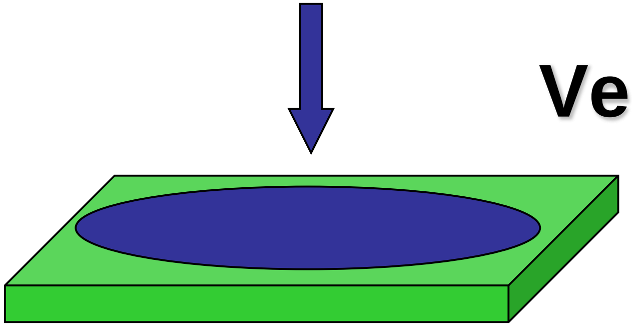


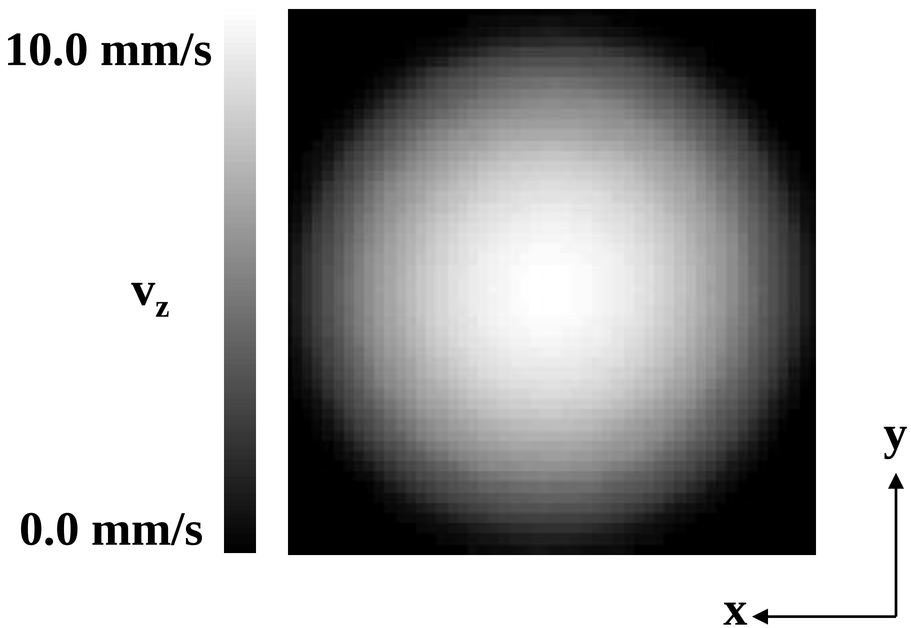
k-space raster

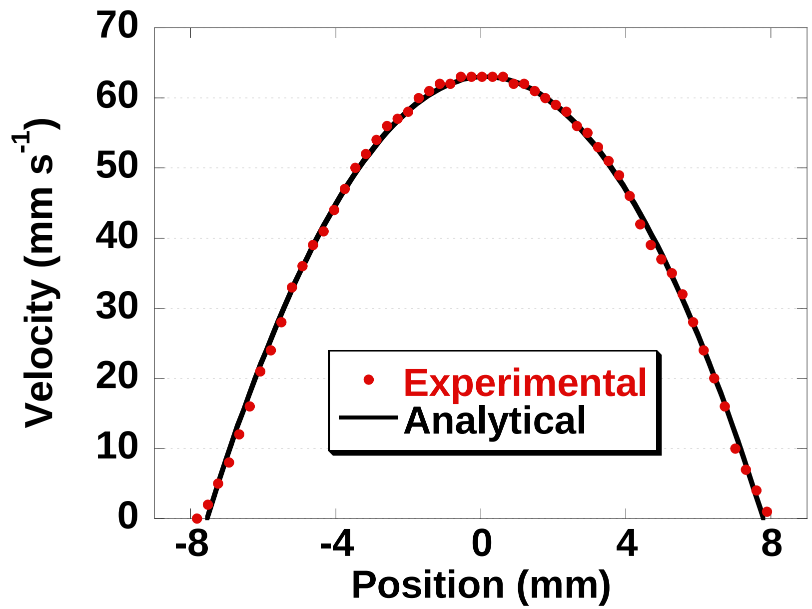
FT



Velocity imaging of flow in a pipe







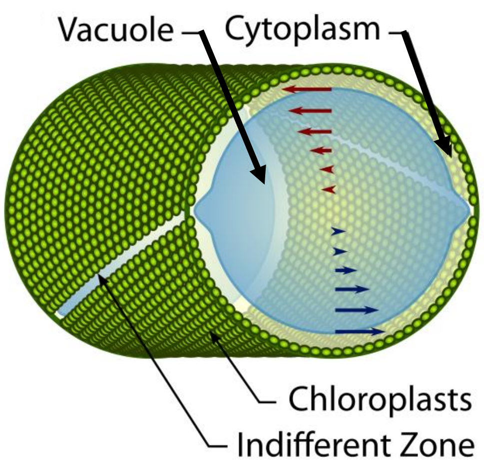
- Steady flow up to Re ~ 2200
  - laminar Newtonian flow, parabolic velocity profile
- Onset of turbulence at higher Re
  - time varying flow

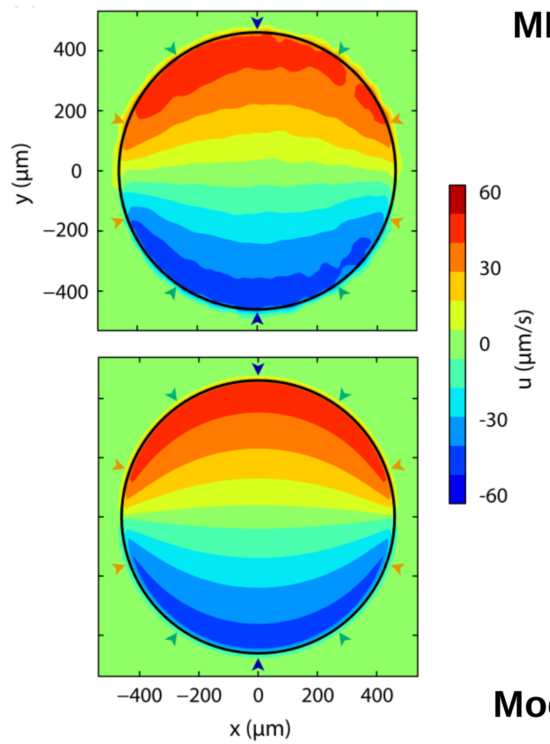
$$Re = \frac{\rho v d}{\mu}$$

Range of applicability

- **Quantitative relationship between phase and displacement**
  - **measurement over wide range of velocities 10^{-6}-10^{2} m s^{-1}**
  - **'velocity' over different timescales 10^{-3}-10^{1} s**

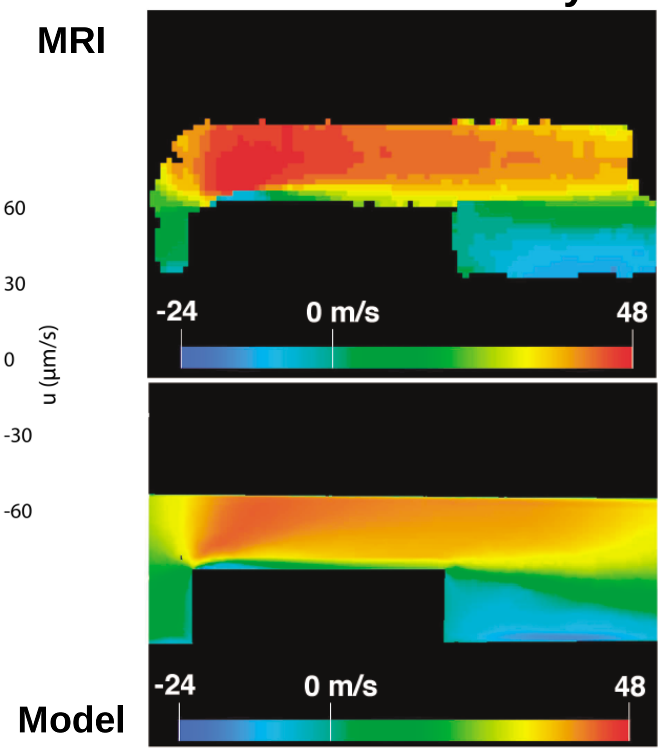
Flow through single cell





van de Meent AJS, LFG et al., *J. Fluid Mech*, 642, 5 (2010)

Flow over bluff body

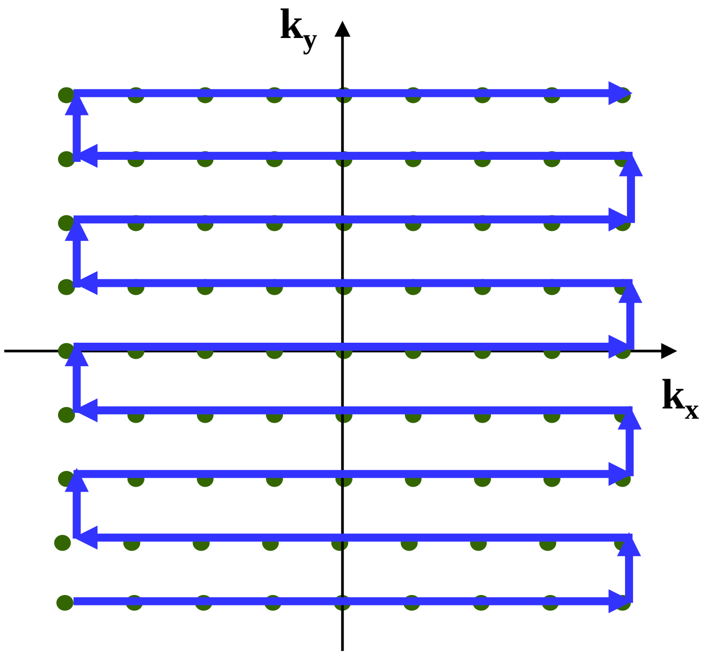


Newling et al., *Phys. Rev. Lett.*, 93(15), 154503 (2004)

Dynamic processes

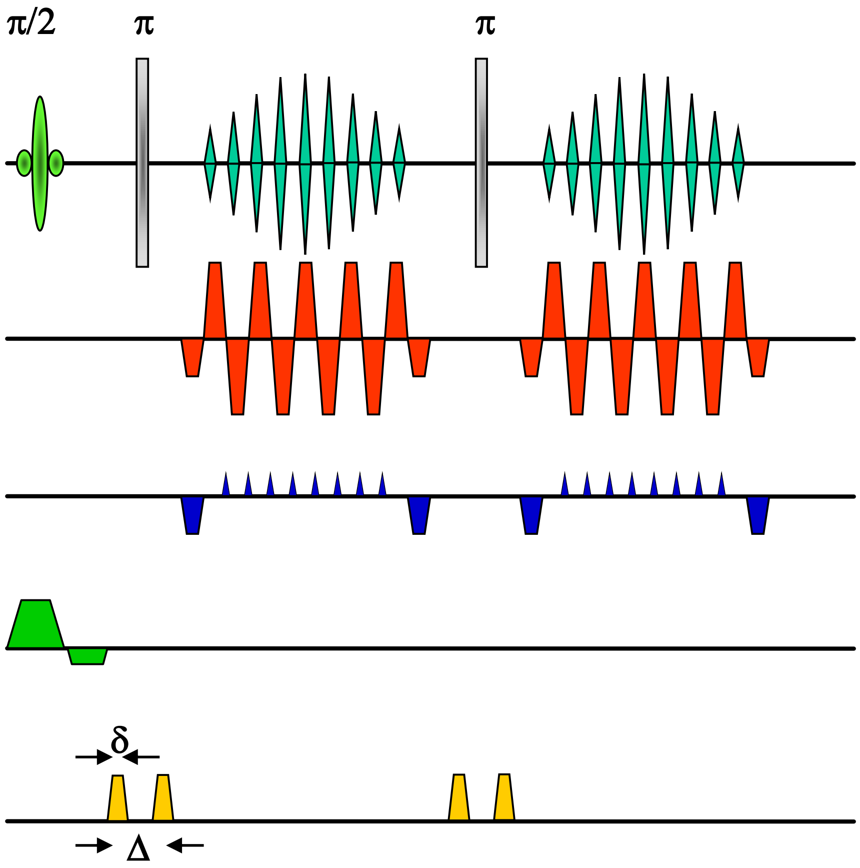
- **Many systems of practical interest demonstrate some change with time**
  - **changing velocity**
  - **changing structure**
- **Imaging approaches to dynamic processes**
  - **time averaged**
    - image over long times compared to fluctuations
  - **'snapshot' imaging**
    - speed up acquisitions
  - **periodic systems**
    - triggered acquisitions
- **How can MRI velocity imaging be used?**

Turbulent velocity imaging



k-space raster

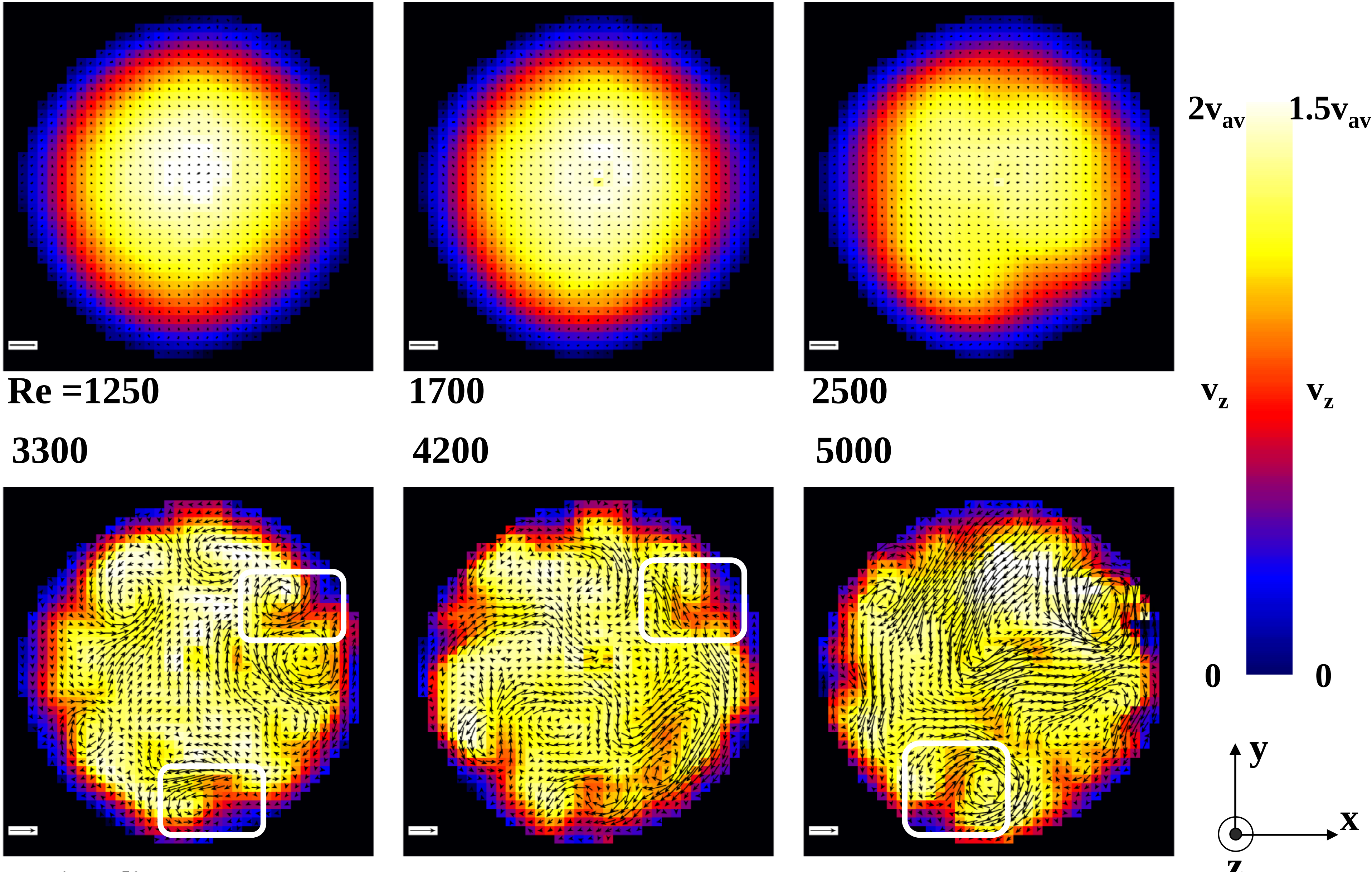
ultra-fast velocity imaging sequence: GERVAIS



2D image time:
1 velocity component in 20 ms
3 velocity components in 60 ms

GERVAIS *J Magn. Reson.* 166 (2004) 182
Gradient Echo Rapid Velocity and Acceleration Imaging Sequence

Turbulent velocity imaging



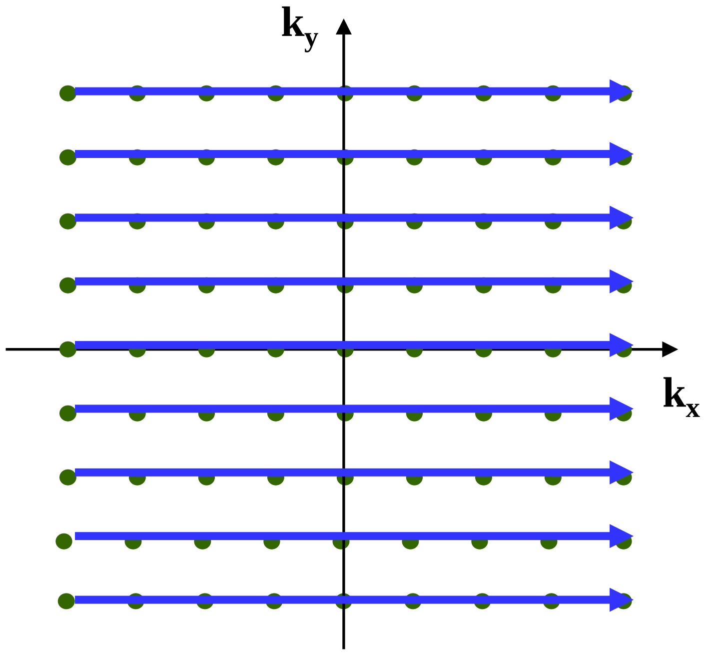
Pipe diameter: 29 mm, 1400 μm × 700 μm

Sederman et al., *JMR*, (2004)

Can we image even faster?

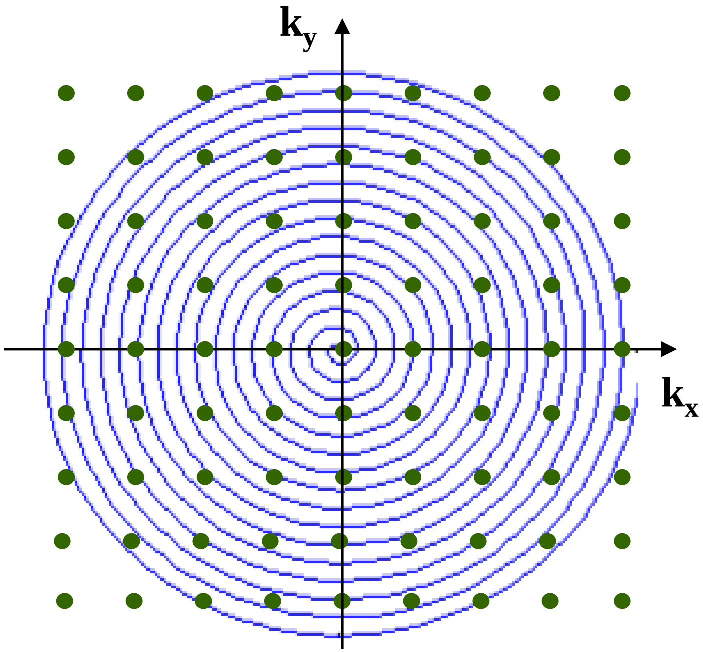
- **We want to reduce timescales further**
    - 60 ms is still long for many systems
- **Can we acquire all data points in a more efficient and robust way?**
    - **faster images**
    - **minimise errors for high velocity flows**
    - **fast continuous image acquisition**
- **Do we need to acquire all of our k-space data points?**
    - **under-sampling – ‘sparse’ acquisition**
    - **non-FT reconstruction**

Spiral imaging and compressed sensing

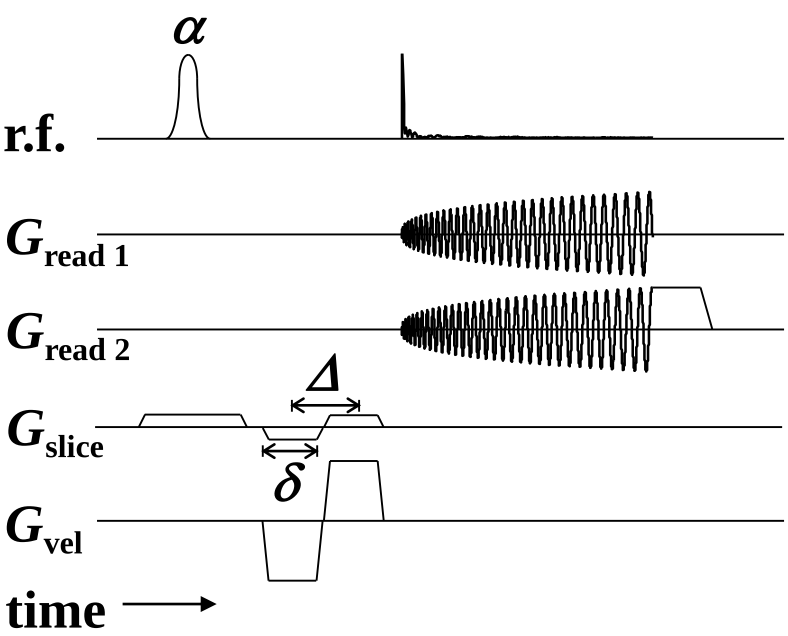


k-space raster

Spiral imaging and compressed sensing

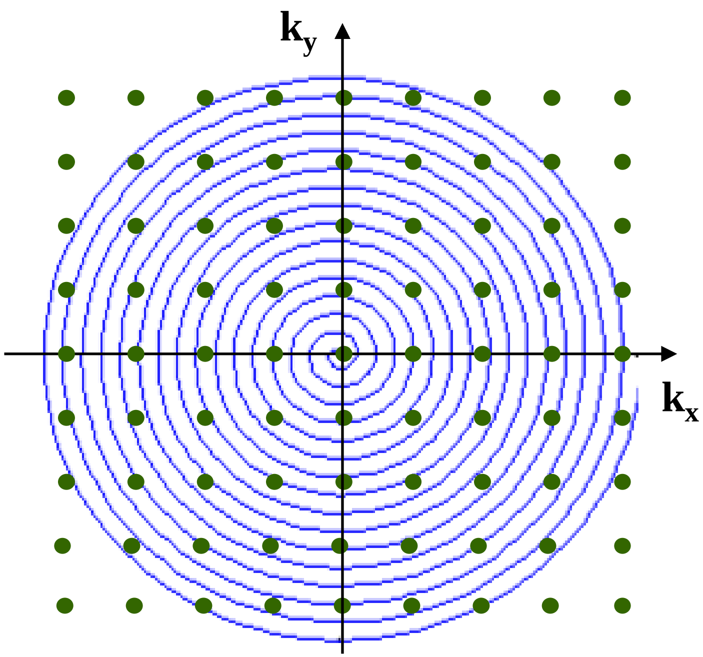


k-space raster

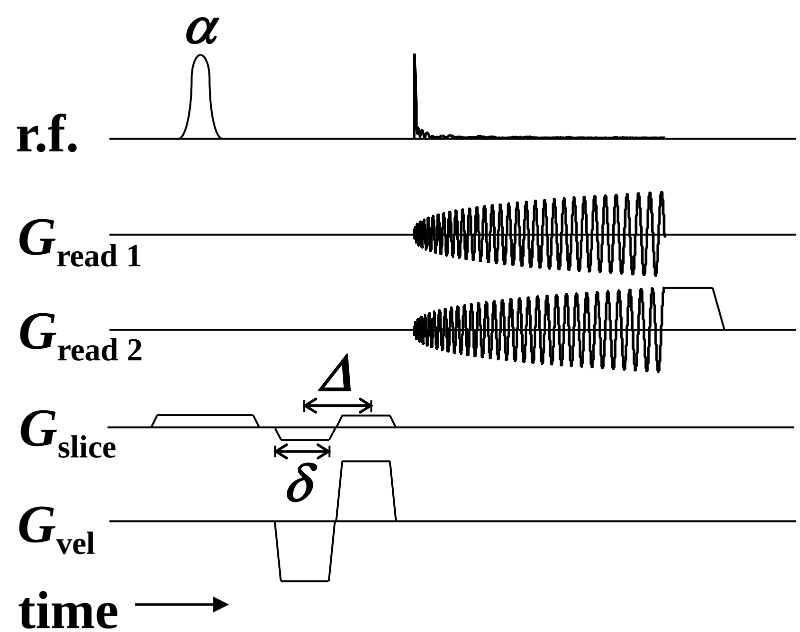


- **Benefits**
  - ‘simple’ MRI pulse sequence
  - faster coverage of k-space – for given hardware limitations
  - robustness to velocity effects
  - short recycle ➔ ‘movie’ acquisition

Spiral imaging and compressed sensing



k-space raster



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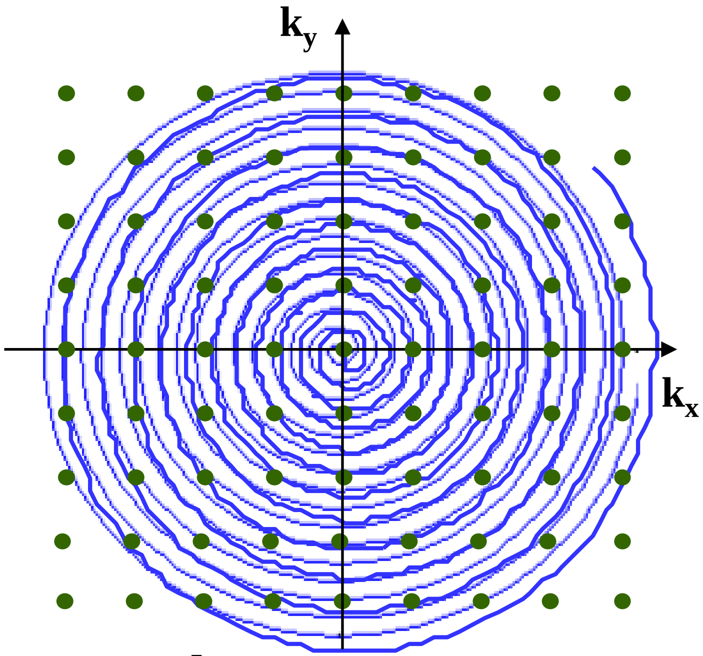
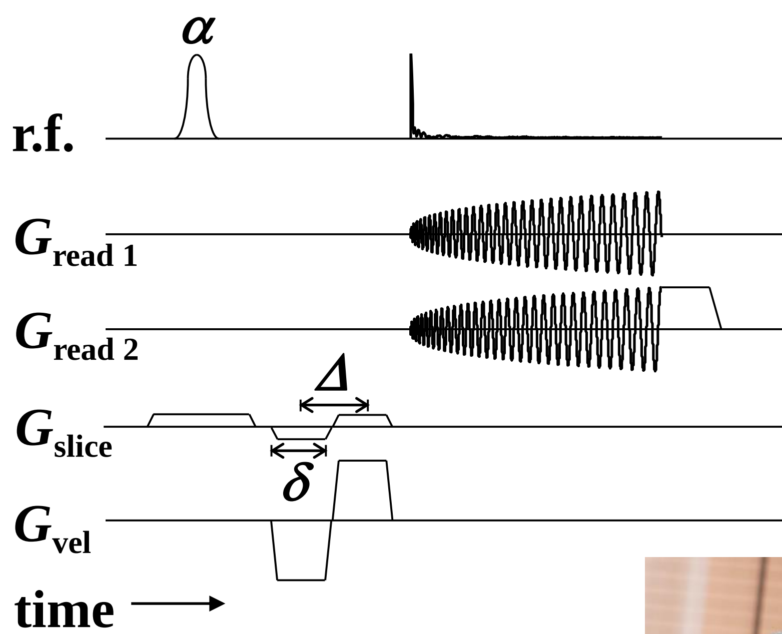
Spiral imaging and compressed sensing



k-space raster

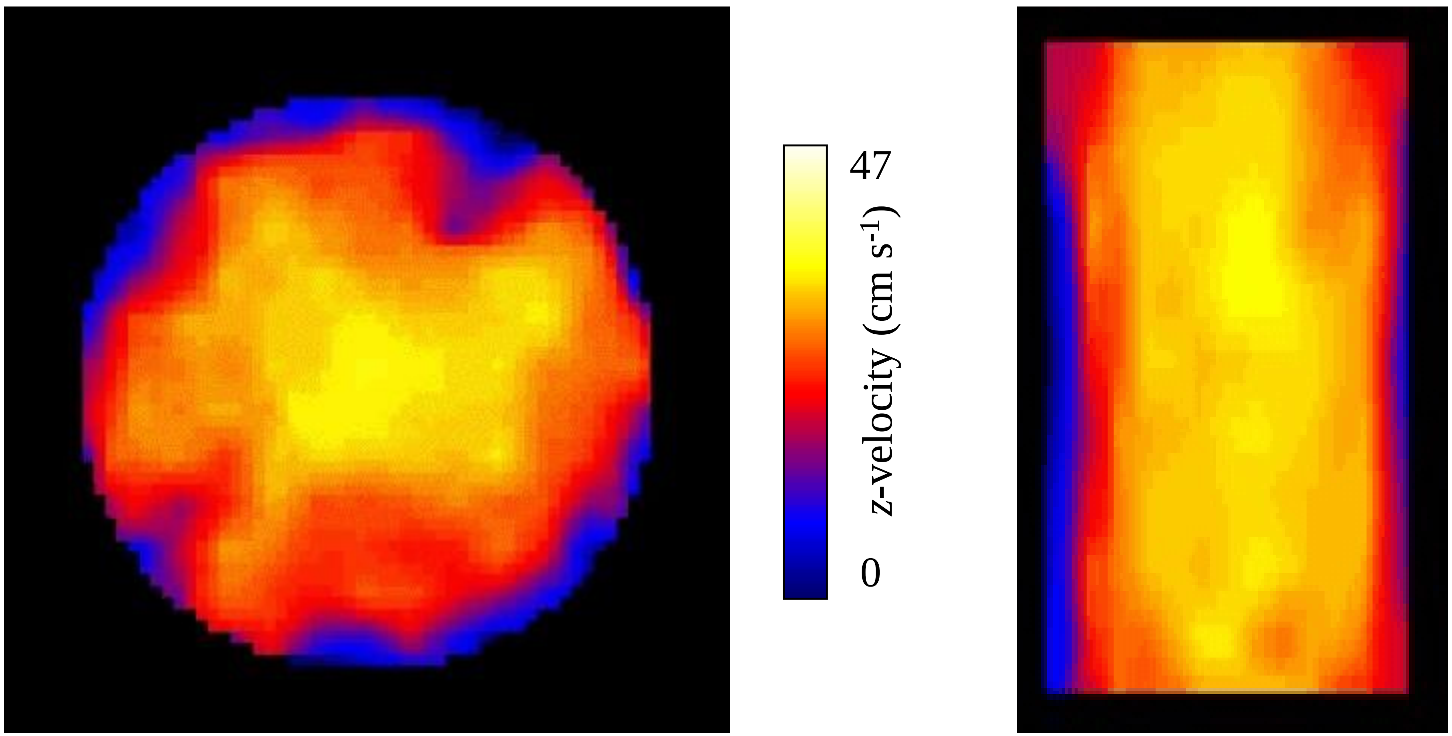


- **Compressed sensing**
  - **if an image can be represented in some transform domain by significantly fewer data points, it must be possible to acquire fewer data points in the first place**

Andrew Blake
Microsoft Research/Alan Turing Institute

Spiral and CS: results

- **High resolution pipe flow velocity images at Re = 5000**
  - **acquire 28% cf fully sampled image**
  - **64 × 64 pixels, resolution of 325 μm × 325 μm**
  - **repetition time of 5.3 ms, 188 fps**

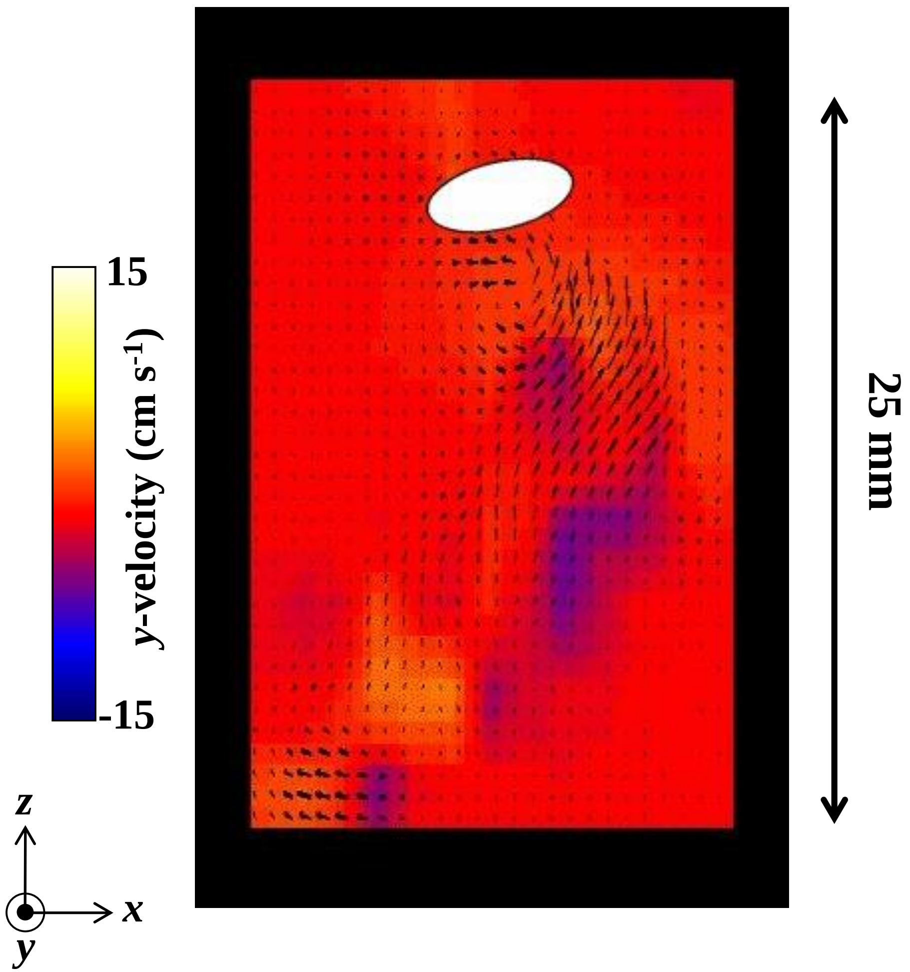


CS-Spiral velocity imaging of single bubbles

velocity images of water around a rising air bubble

- **single component velocity images in 5.3 ms**
- **3-component velocity images in 16 ms (63 fps)**
- **spatial resolution 390 μm × 586 μm**
- **field-of-view: 20 mm × 30 mm**

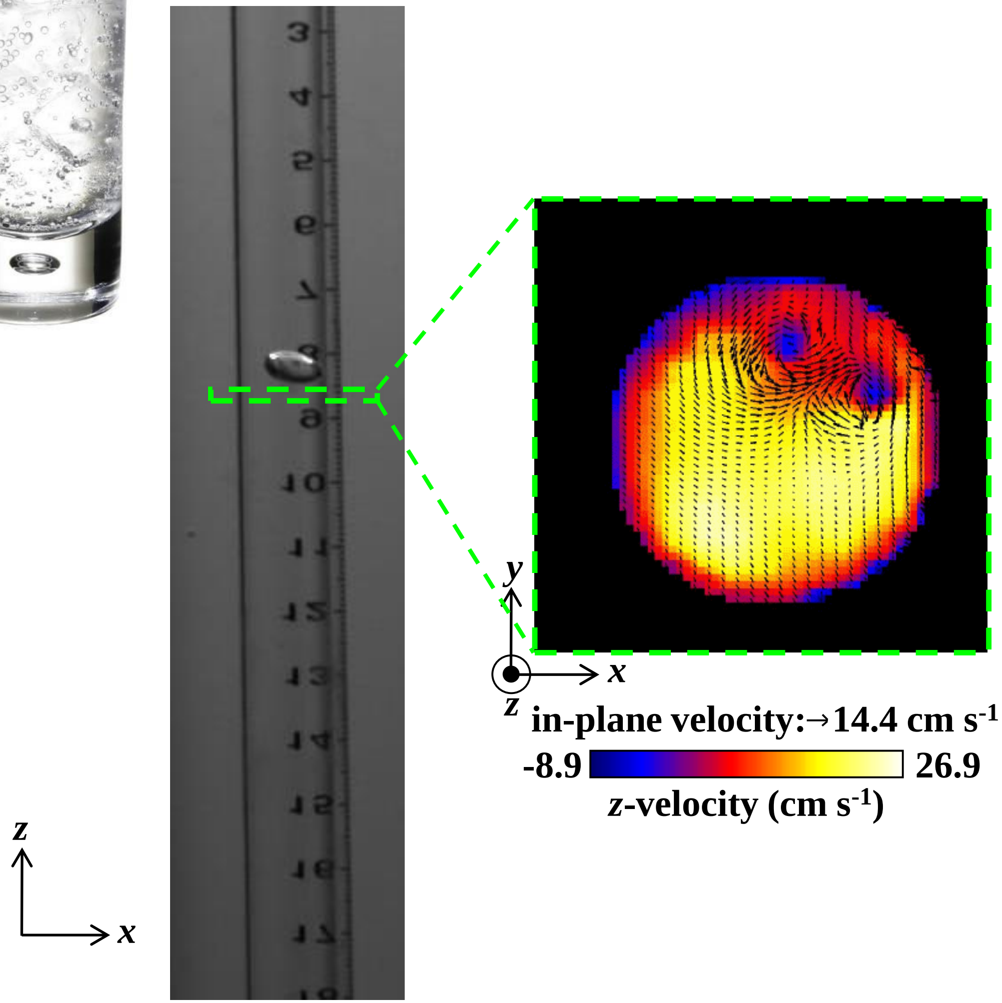
- **vortex shedding at a rate of 12.6 ± 1.1 Hz**
- **droplet rise velocity = 21 cm s^{-1}**

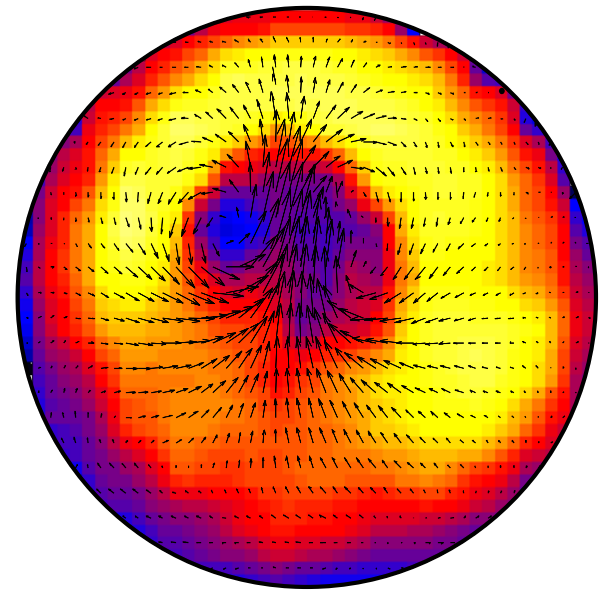


in-plane (x-z) velocity: ⟶ 26.7 cm s^{-1}

Tayler Phys. Rev. Lett. (2012)

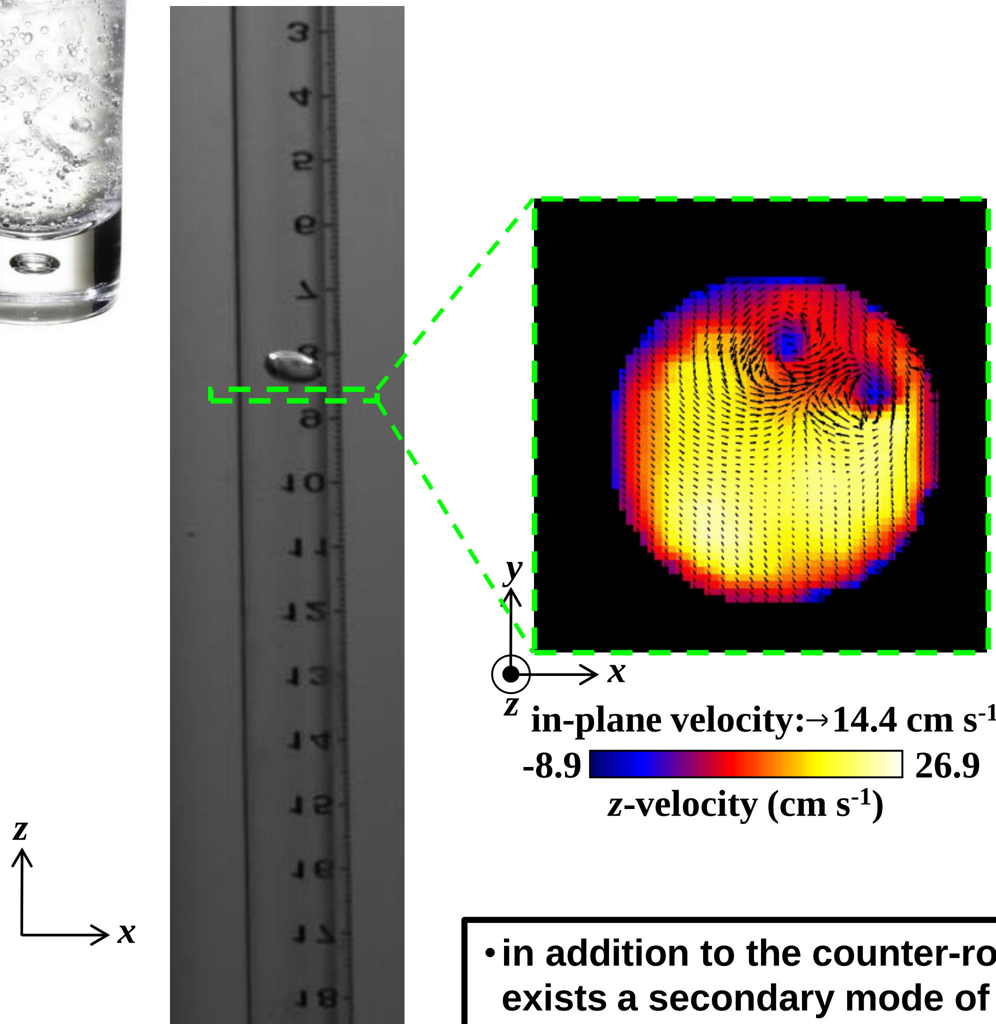
Why do bubbles wobble?

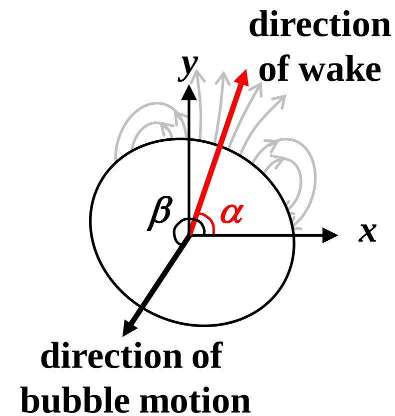


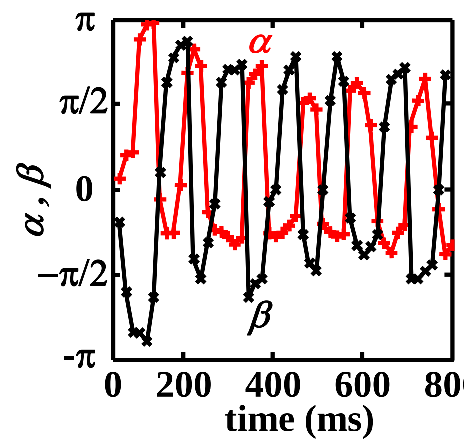


Phys. Rev. Lett. 108 (2012) 264505

Why do bubbles wobble?



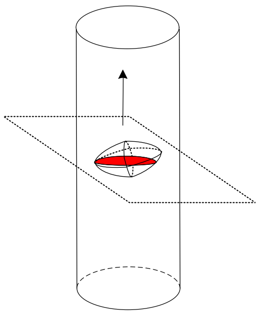


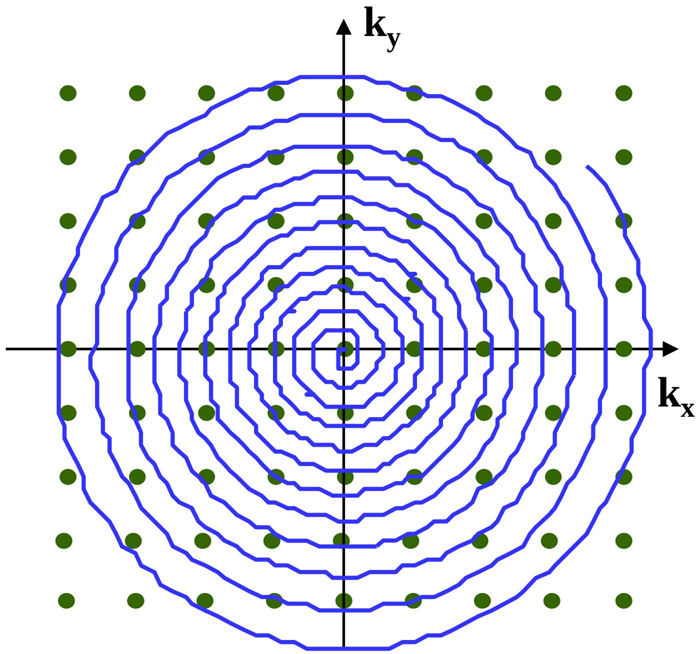


- in addition to the counter-rotating vortices in longitudinal plane, there exists a secondary mode of vorticity in the horizontal plane
- direct coupling between direction of bubble path and secondary vortex; secondary vortices reverse direction following every shedding event

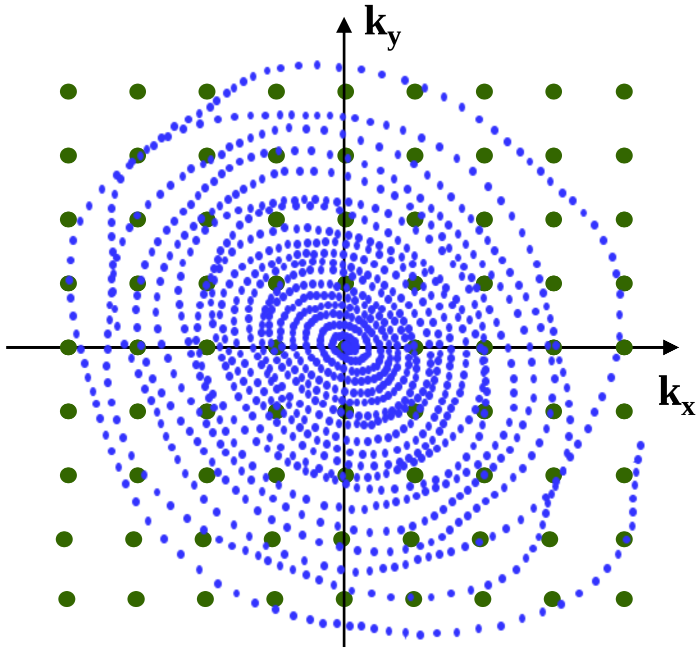
Can we extend this to liquid-liquid flows?

- **Chemical shift differences between peaks in spectra lead to extra signal dephaseing**
  - **chemical shift artefacts**
- **Similar proton densities**
  - **difficult to distinguish phases**





k-space raster
sparse spiral sampling

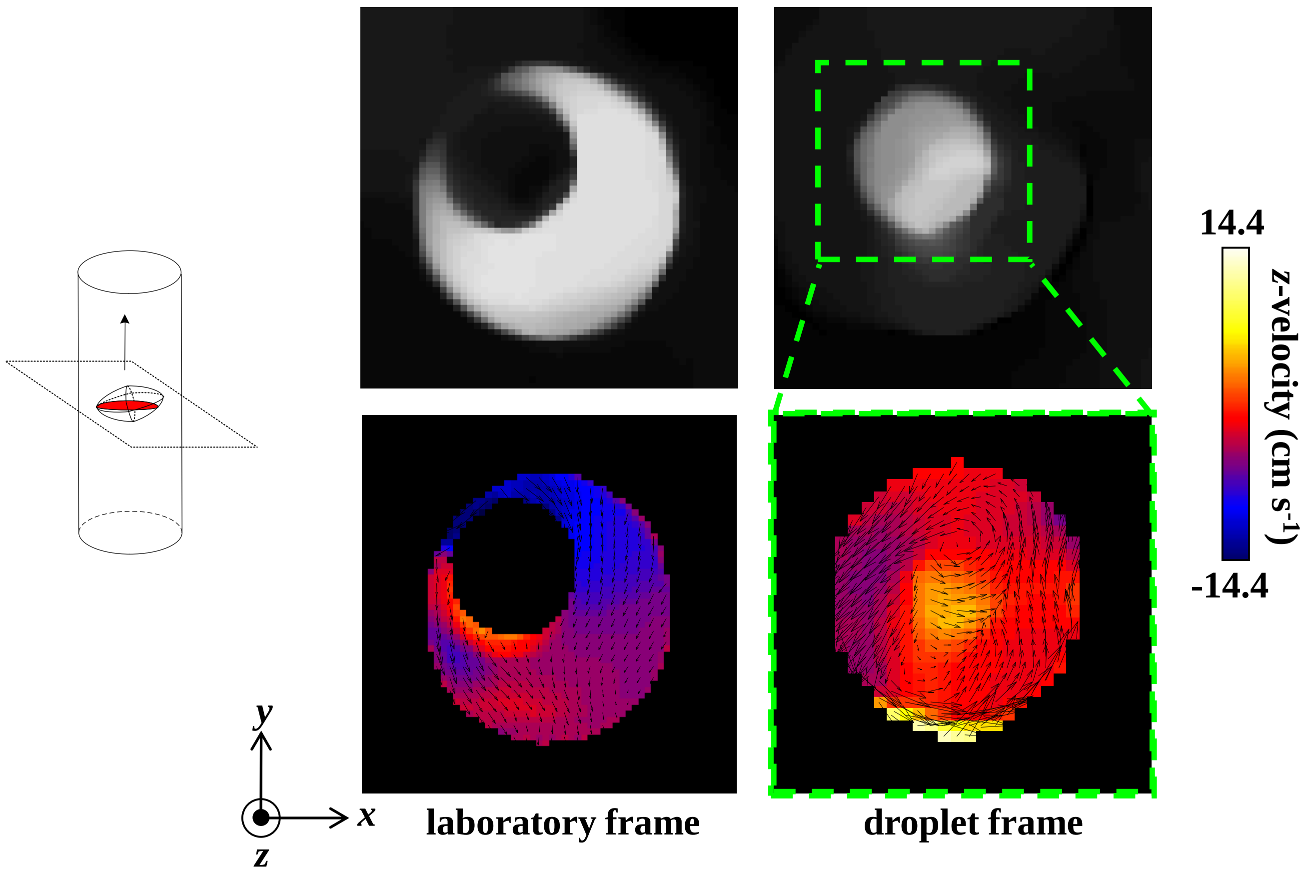


k-space raster
sparse perturbed spiral sampling

Simultaneous measurement of oil and water flow fields

50 cSt PDMS droplet rising through water

Tayler et al. *Phys. Rev. E* 89 (2014) 063009



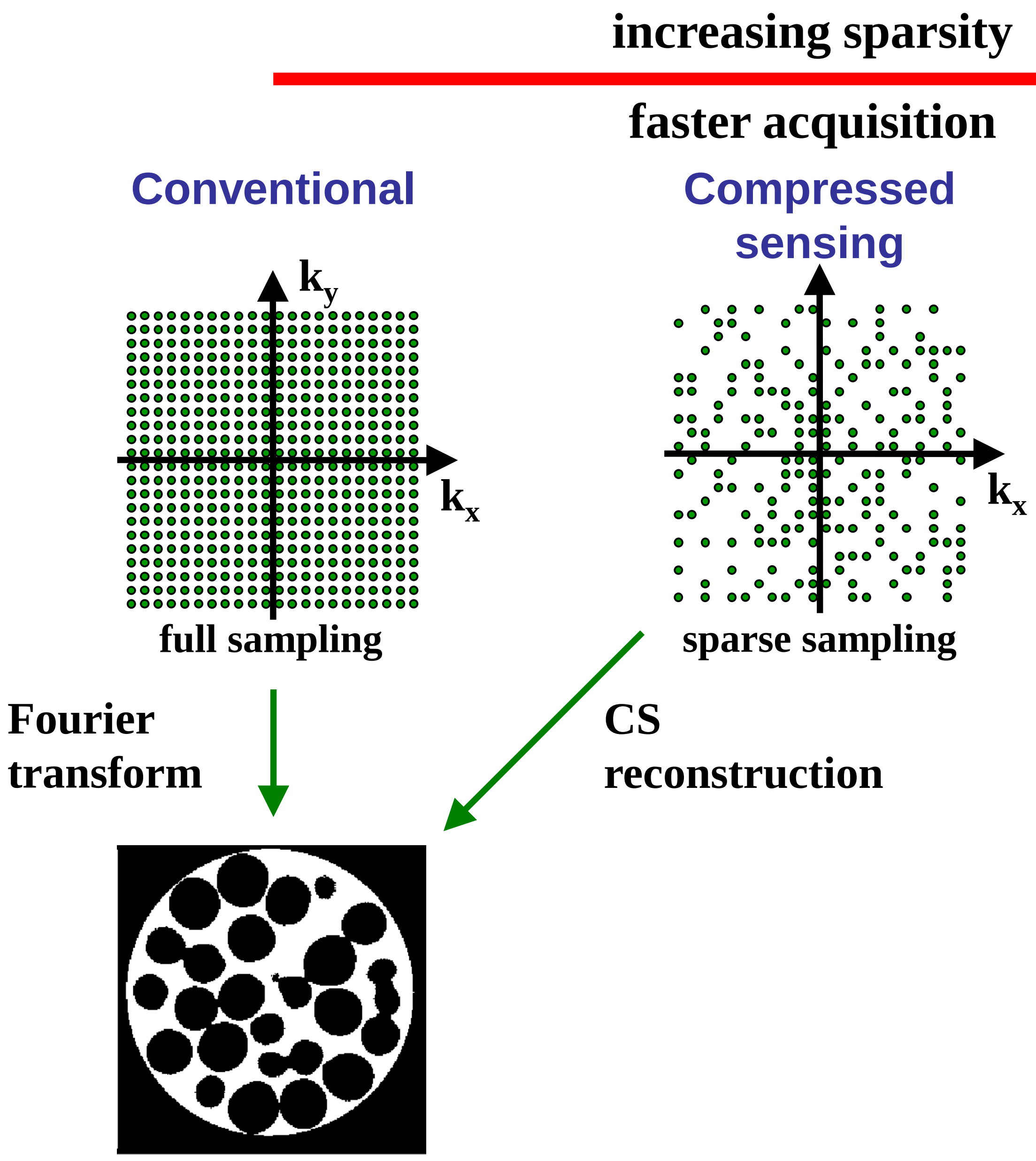
in-plane velocity — droplet frame: → 14.4 cm s^{-1}; laboratory frame: → 7.2 cm s^{-1}

pipe diameter = 2 cm; droplet rise velocity = 7.1 cm s^{-1}

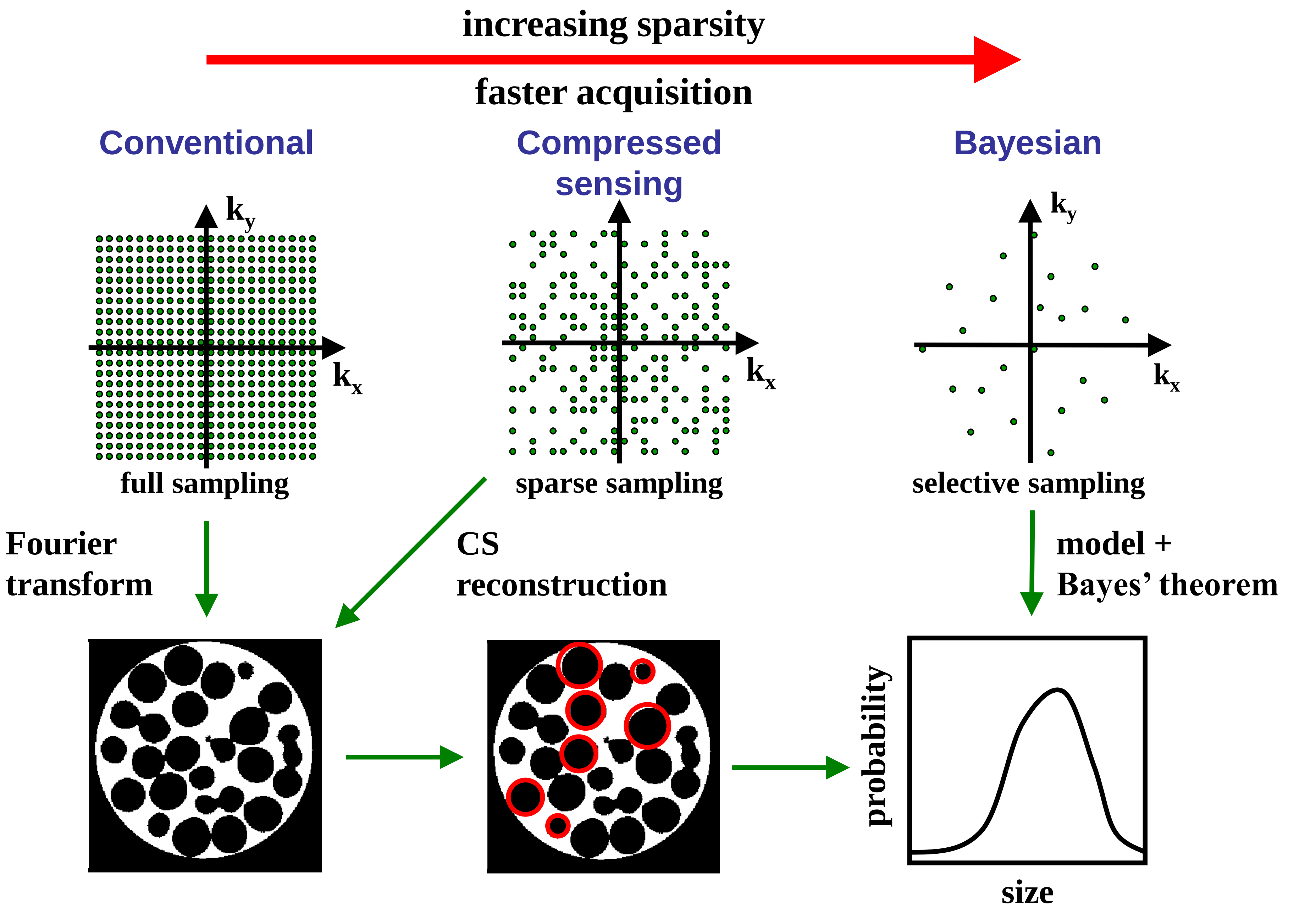
data acquisition time = 31.8 ms

spatial resolution = 540 μm × 540 μm; image slice thickness = 500 μm

Why take an image? – A Bayesian approach



Why take an image? – A Bayesian approach



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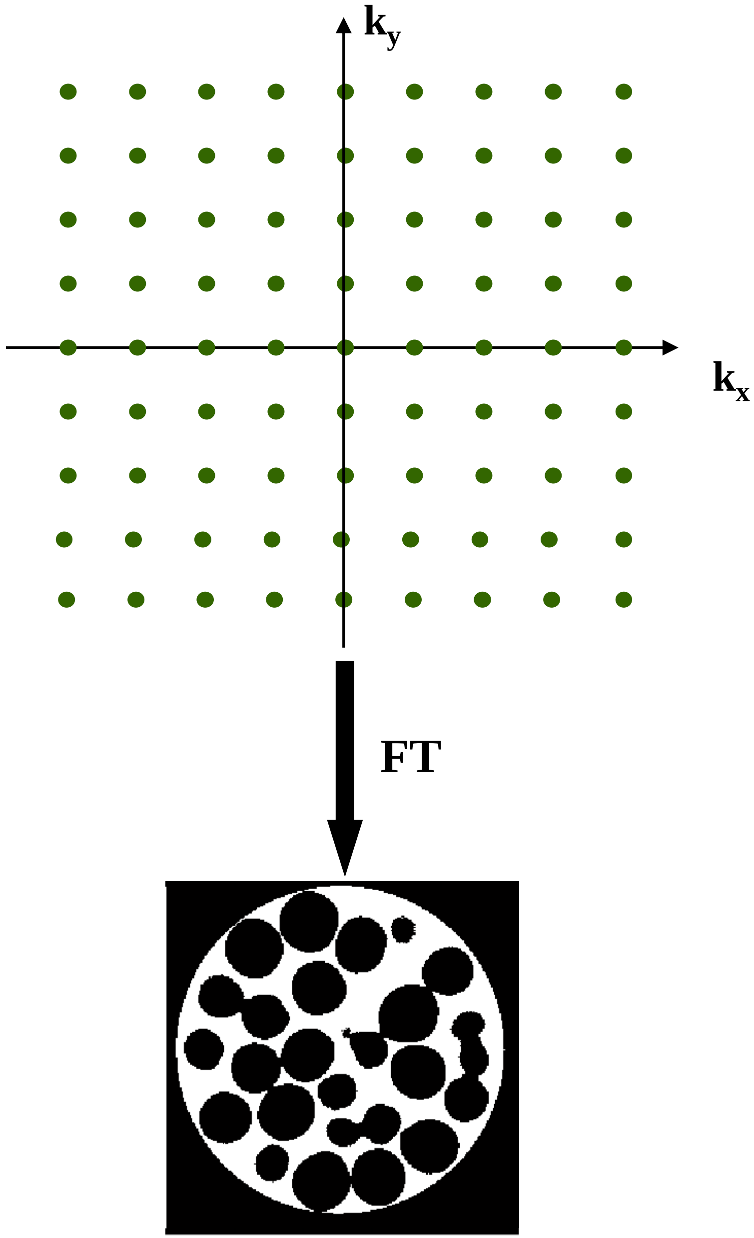
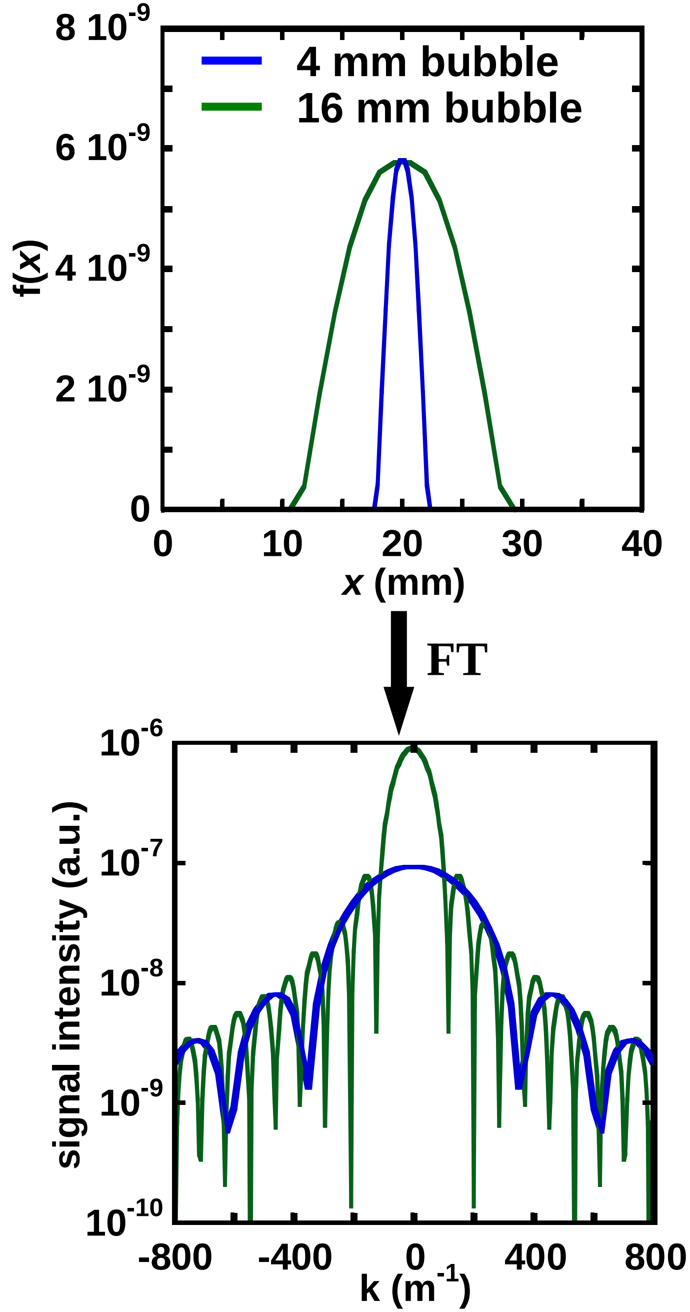
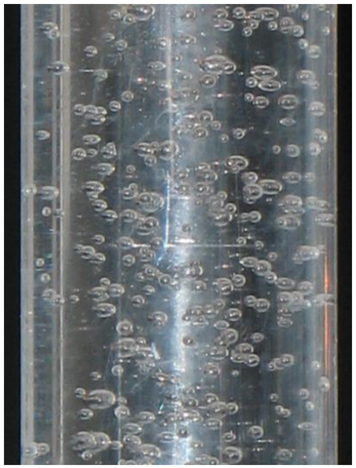


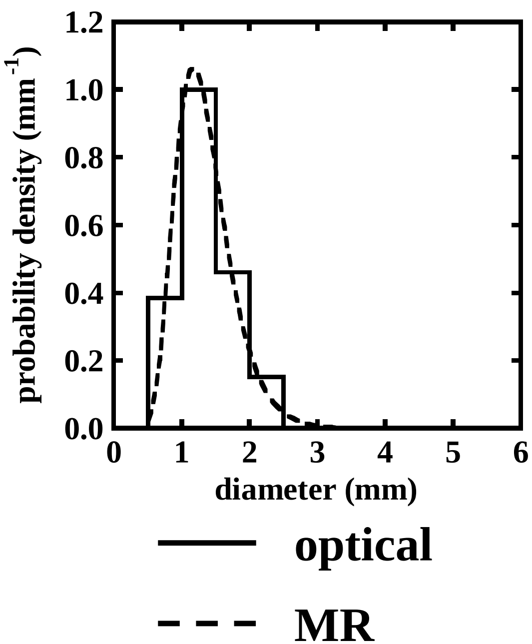


Bayesian bubble size measurement

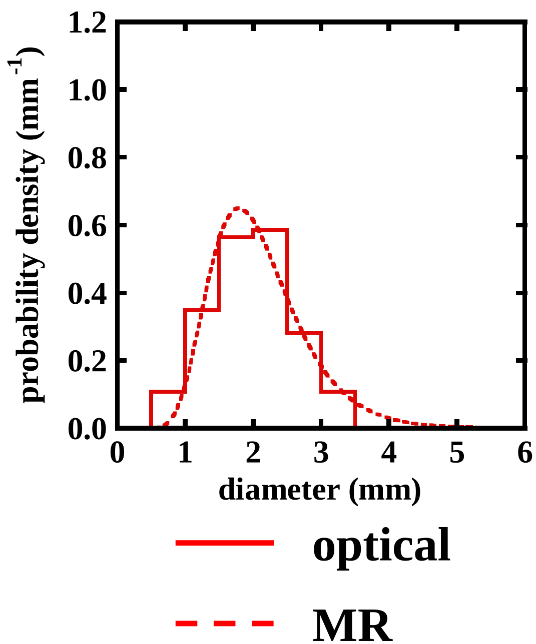
comparison with optical measurements

Distribution I

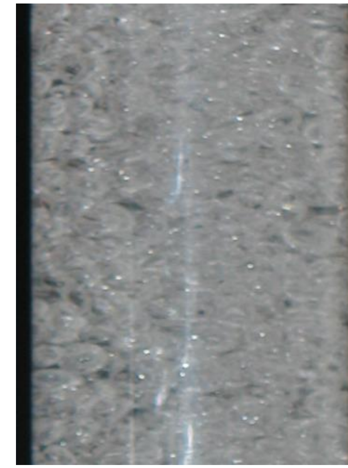


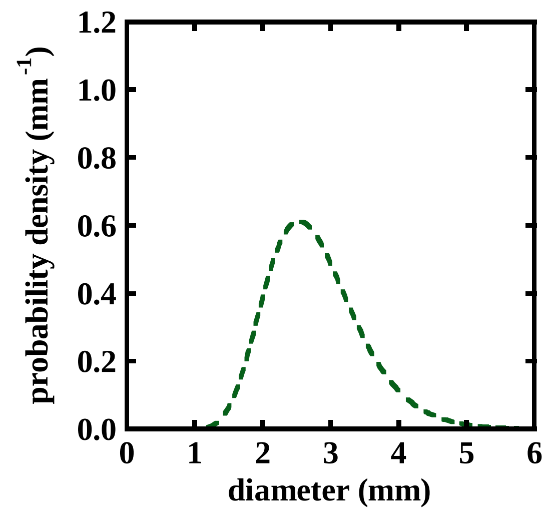


Distribution II



Distribution III

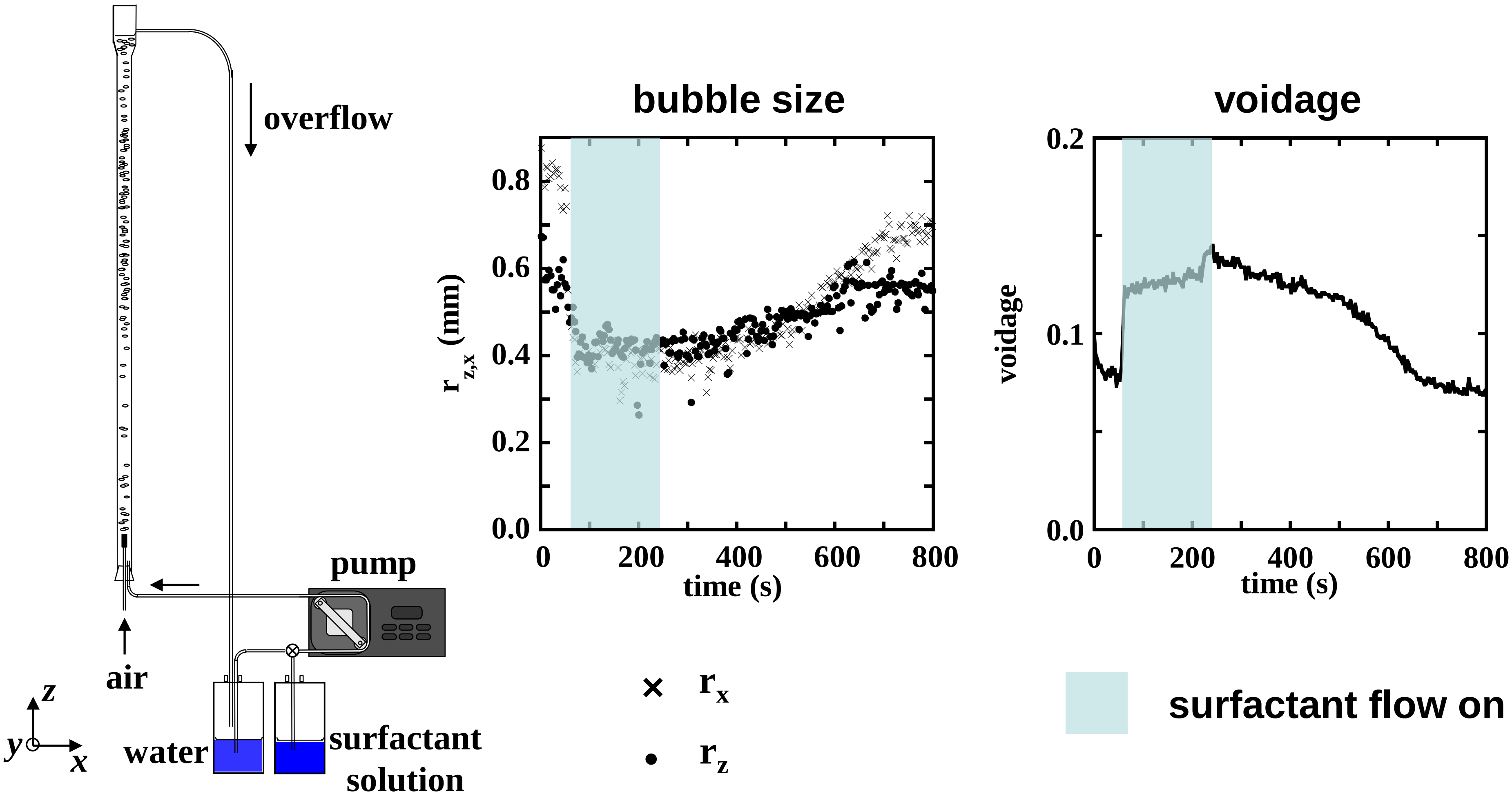




Optical techniques cannot be used at high voidage

Time resolved result

- Surfactants decrease the surface tension and, therefore, the bubble size
- Change in bubble size tracked in real time as a pulse of surfactant is injected at the base of a bubble column
- Bubble size monitored every 3 s



Summary

- **MRI velocity imaging can be used to develop the understanding of many dynamic processes**

- **More 'intelligent' data acquisition and reconstruction can help to increase imaging speeds**
  - **image acquisition times as short as 5 ms**

- **Sometimes the important information can be obtained without the need for an image**
  - **Bayesian analysis**