Comparison of fibre suspension flow measurements using UVP and MRI

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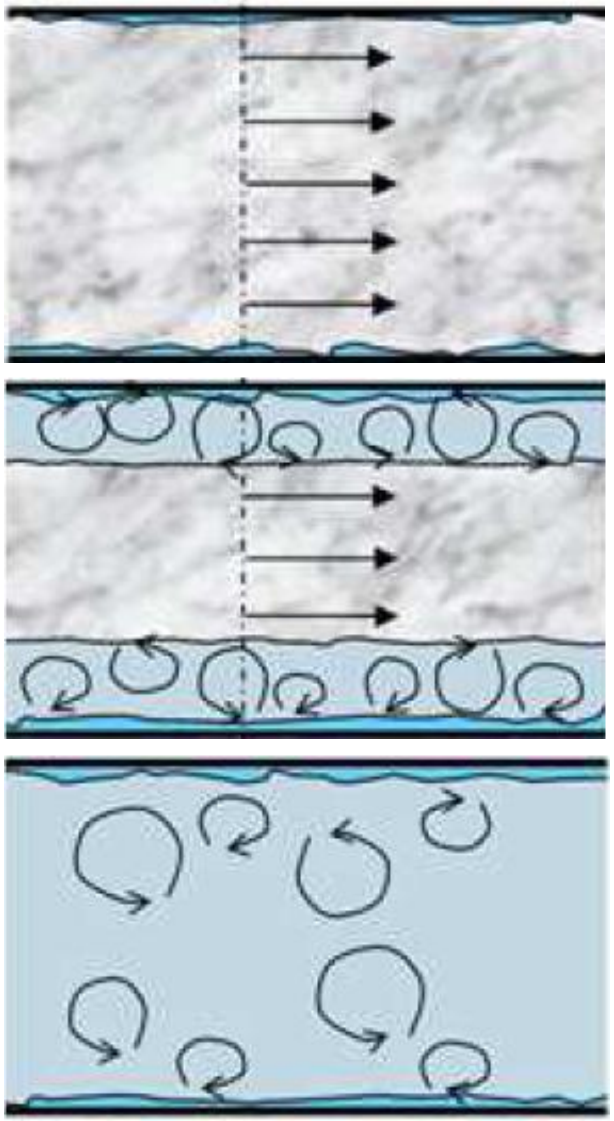
Fibre Suspension Flows

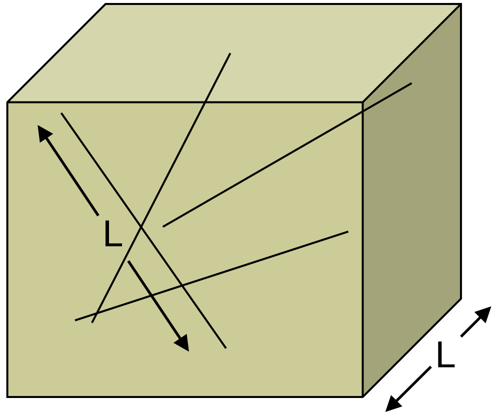
- Basic flow regimes in papermaking
  1. Plug:
     - Interconnected fibre network
     - Thin water layer near walls
  2. Mixed
     - Unstable wall layer
     - Turbulent Annulus
     - Plug begins to break up
  3. Turbulent
     - Flow is fully turbulent
     - Plug is fluidized and breaks apart

- Highly dependant on concentration, stock contents, and flow speed



Concentration Regimes

- Fibre type: Rayon (no water inside fibres lumen!)
- Average fiber length, L = 2 mm
- Average fiber diameter, d = 60 µm
- Fiber aspect ratio, r = L/d = 33



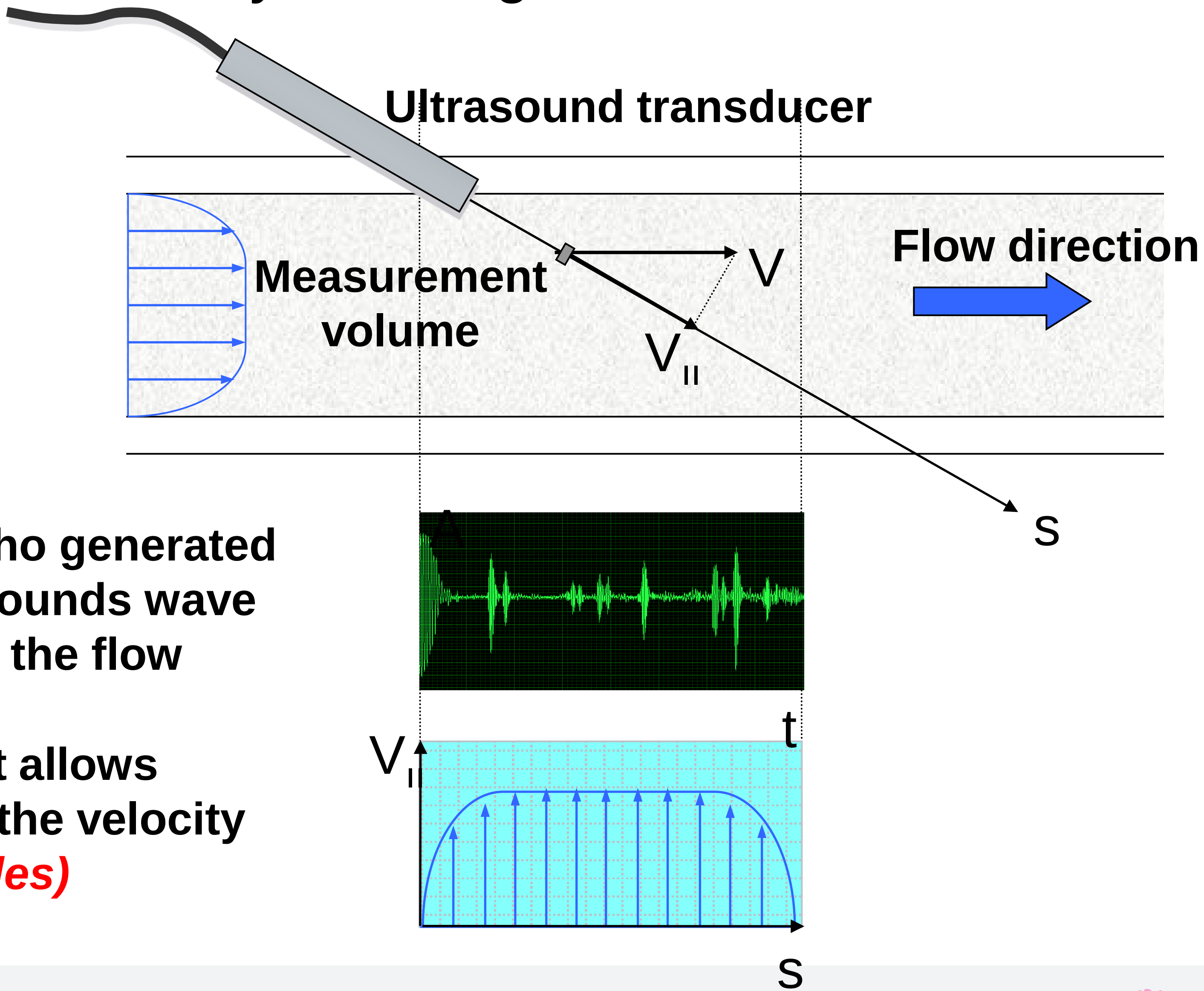
$nL^3 = 4$

$$nL^3 \leq 1$$ ***Dilute***

$$1 \leq nL^3 \leq r$$ ***Semi-dilute***

$$nL^3 \geq r$$ ***Concentrated***

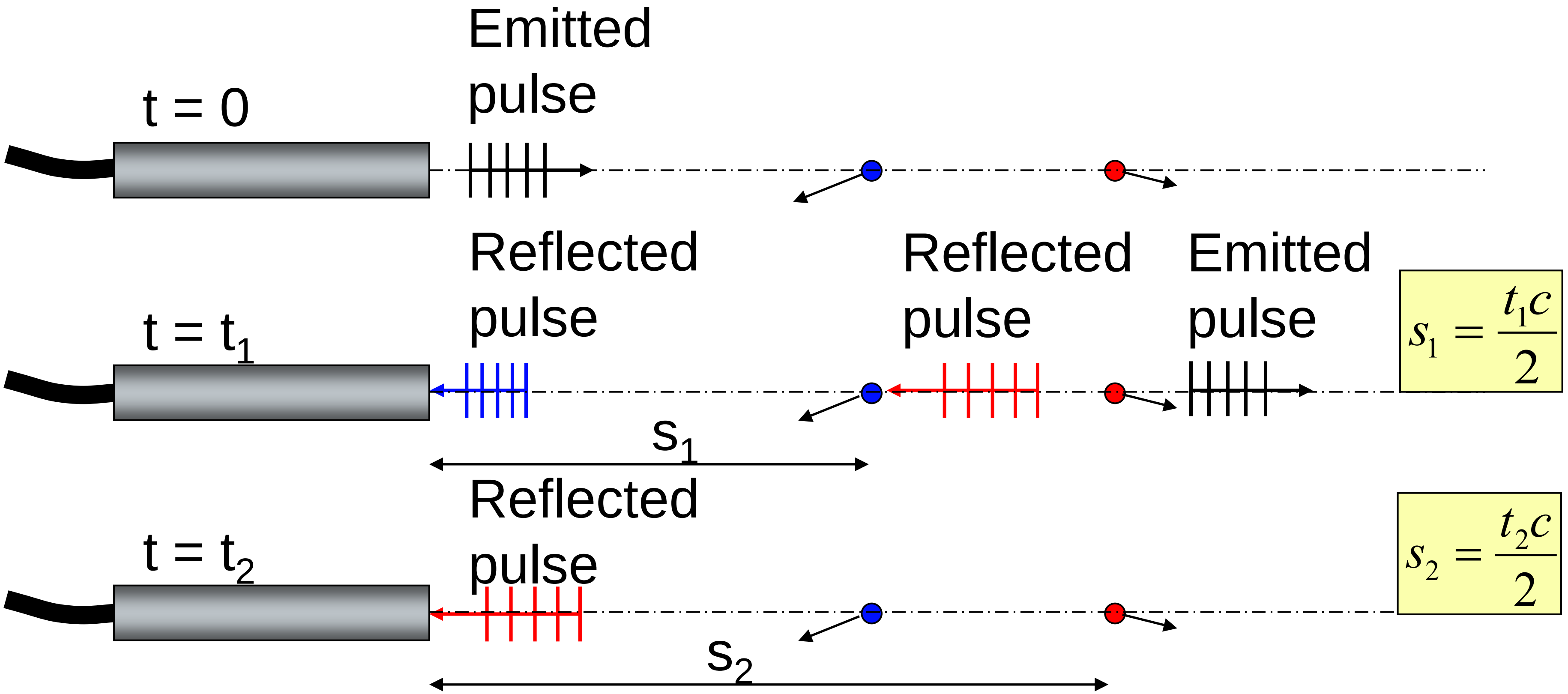
Utrasonic Velocimetry Profiling



Ultrasound echo generated by reflecting sounds wave off *particles* in the flow

Doppler effect allows estimation of the velocity profile *(particles)*

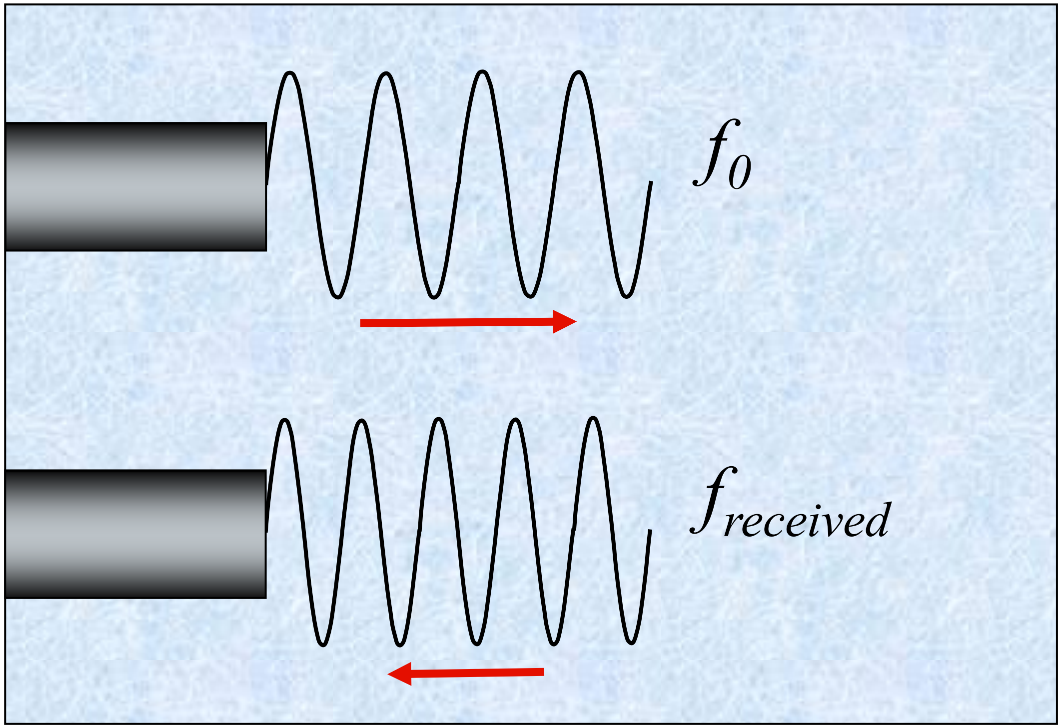
- Ultrasonic pulses emitted by a transducer are reflected by *particles* traveling in the fluid.
- The echo is Doppler shifted due to the *motion of the particles*.
- The same transducer switches to receiving mode and detects the echo as a function of time



$$s_1 = \frac{t_1 c}{2}$$

$$s_2 = \frac{t_2 c}{2}$$

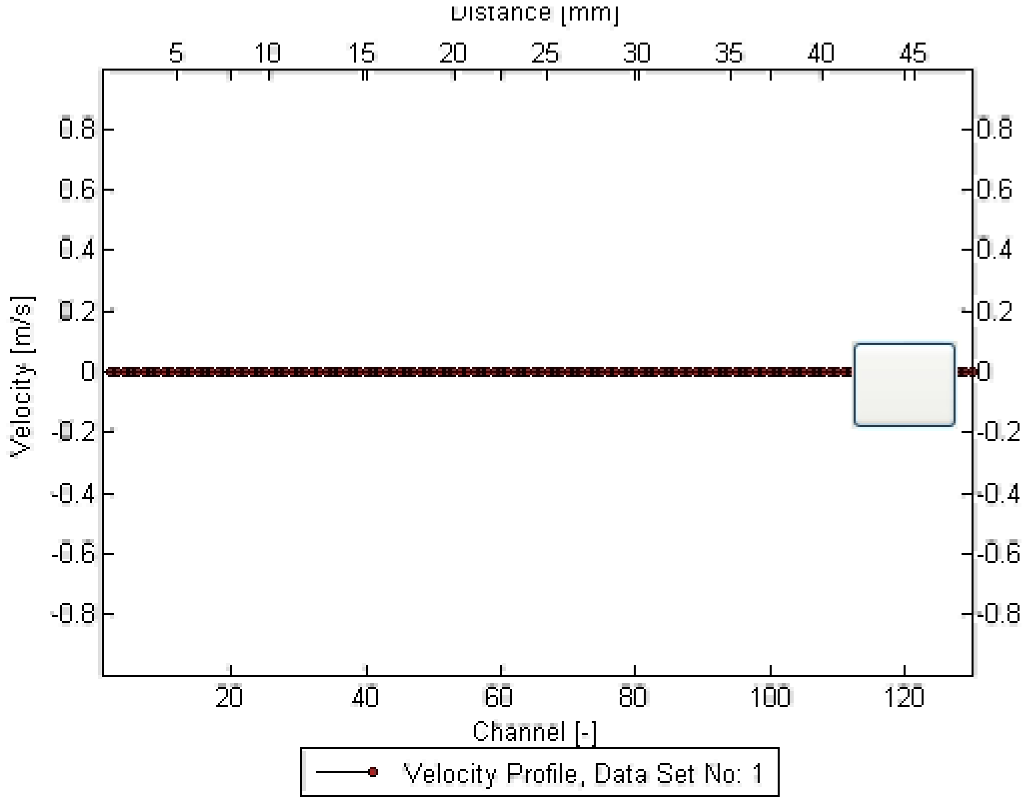
Doppler shift $\Delta f = f_0 - f_{received}$



- From the received Doppler shift frequency, the instantaneous beam-wise velocity component can be obtained as

$$v_{||} = c\,\frac{\Delta f}{2 f_0}$$

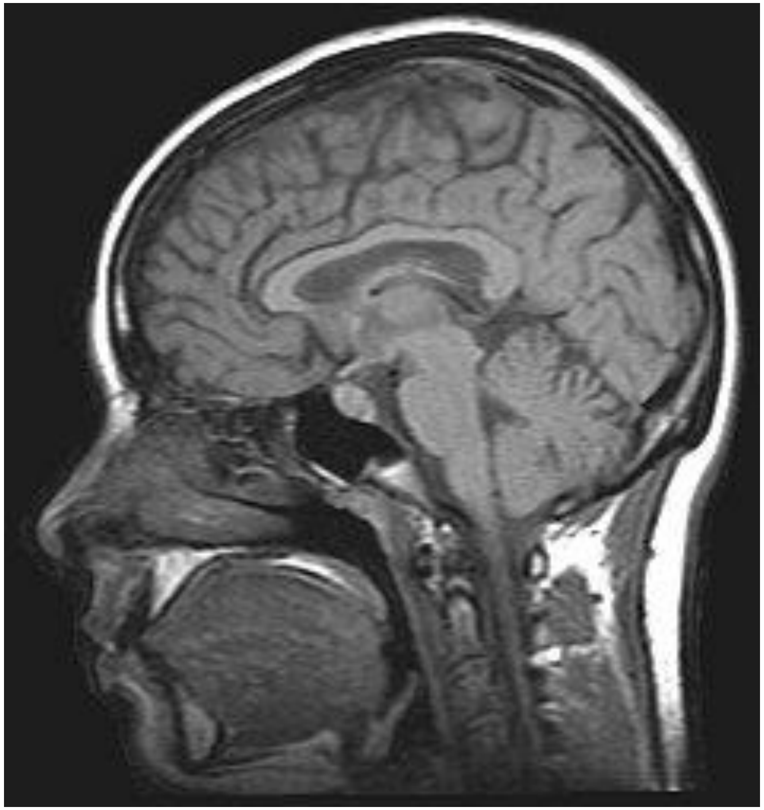
UVP Measurements of Pulp Flow



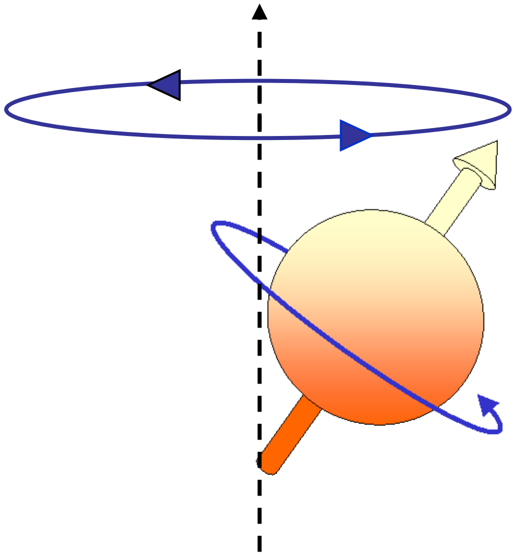
Nuclear Magnetic Resonance Imaging

- Most applications found in medical imaging.

- NMR can be used to measure a wide range of different parameters within a sample:
  - Hydrogen density
  - Relaxation time
  - Velocity, acceleration
  - Complex rheology
  - Diffusion coefficients



Precession and The Larmor Equation



$\omega_0 = -B_0 * \gamma$

ω_0- precession frequency

γ- gyro-magnetic ratio

B_0 – static magnetic field

$\gamma(^1H)$=42.57 MHz/Tesla

1 T: ω_0 =42.57 MHz
1.5T: ω_0 =63.86 MHz
3.0T: ω_0 = 128 MHz

Joseph Larmor
1857-1942

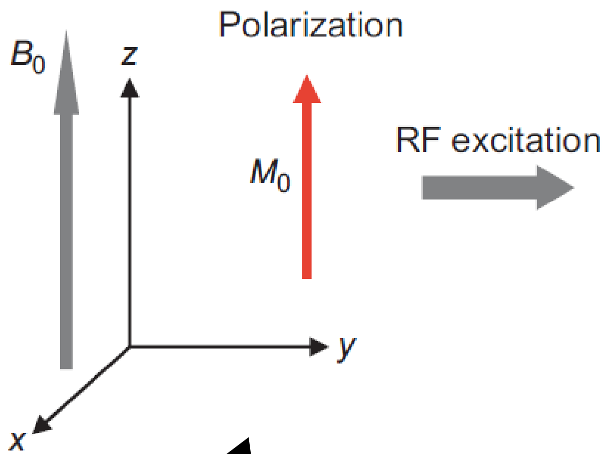
A quantum perspective of spins ½ in a magnetic field

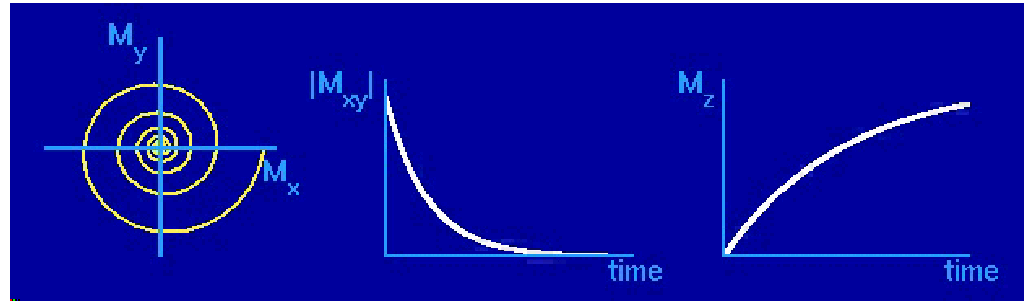
Energy level diagram for spin ½ :

$\boldsymbol{B_0} = 0$ $\boldsymbol{B_0} \neq 0$

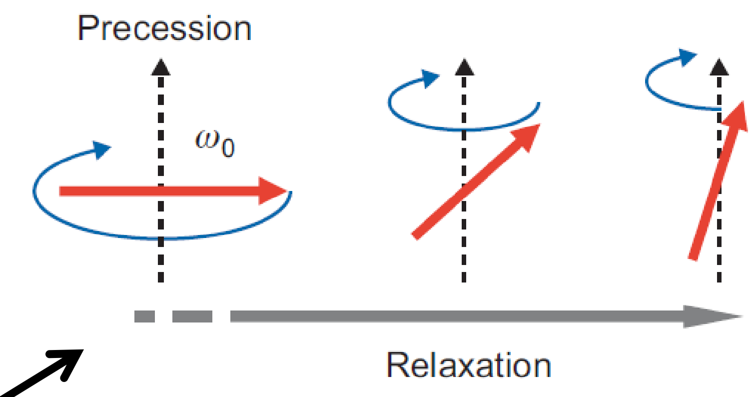
N_α and N_β are the number of spins at each respective level

NMR Basics





Precession Decay (T2) Recovery (T1)



***At equilibrium* the magnetization vector is aligned with the external field (along Z)**

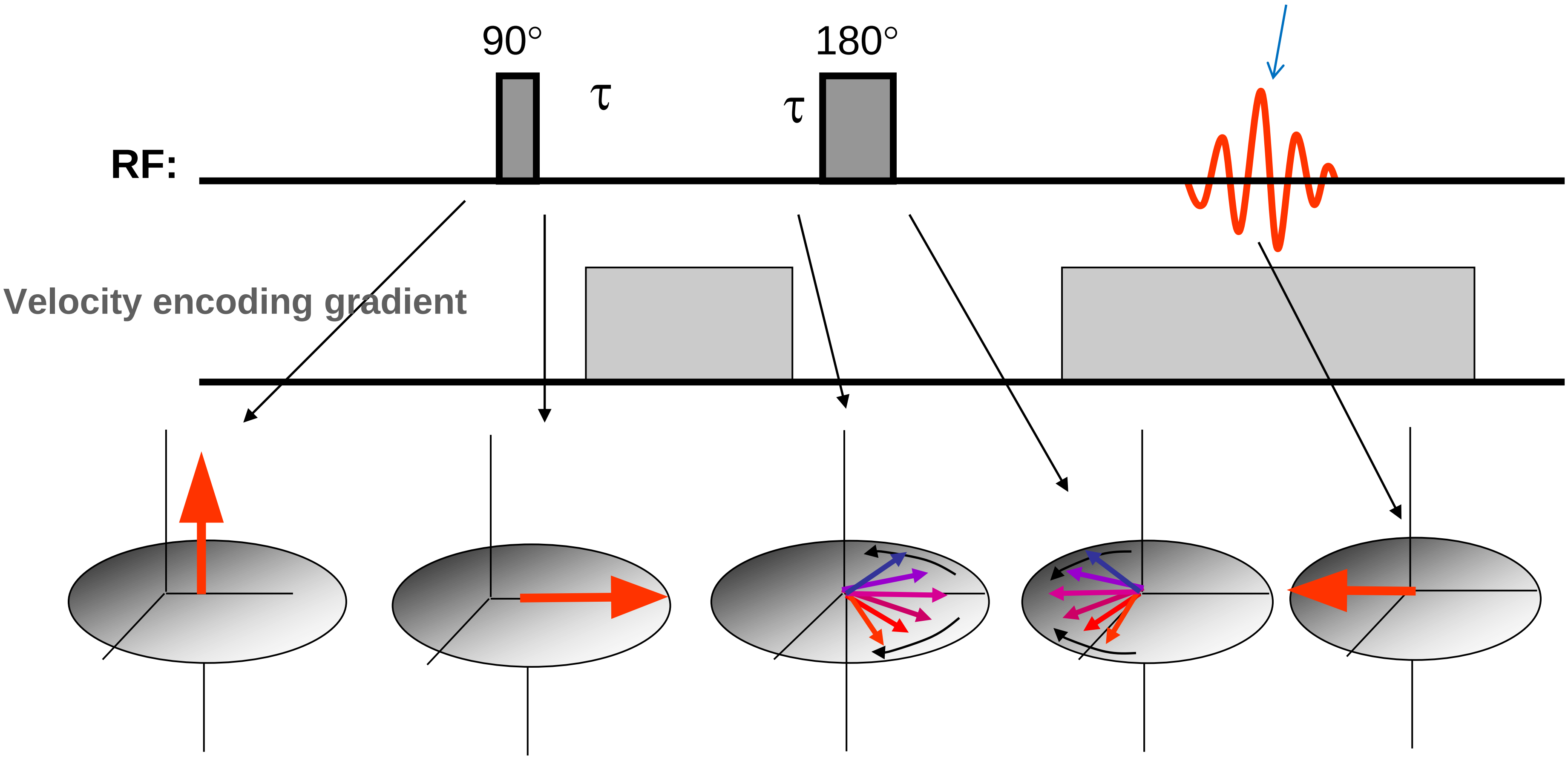
***After absorbing energy*, the magnetization vector is tilted away from the Z-axis**

Magnetization returns exponentially to equilibrium:

- Longitudinal recovery time constant is T1

- Transverse decay time constant is T2

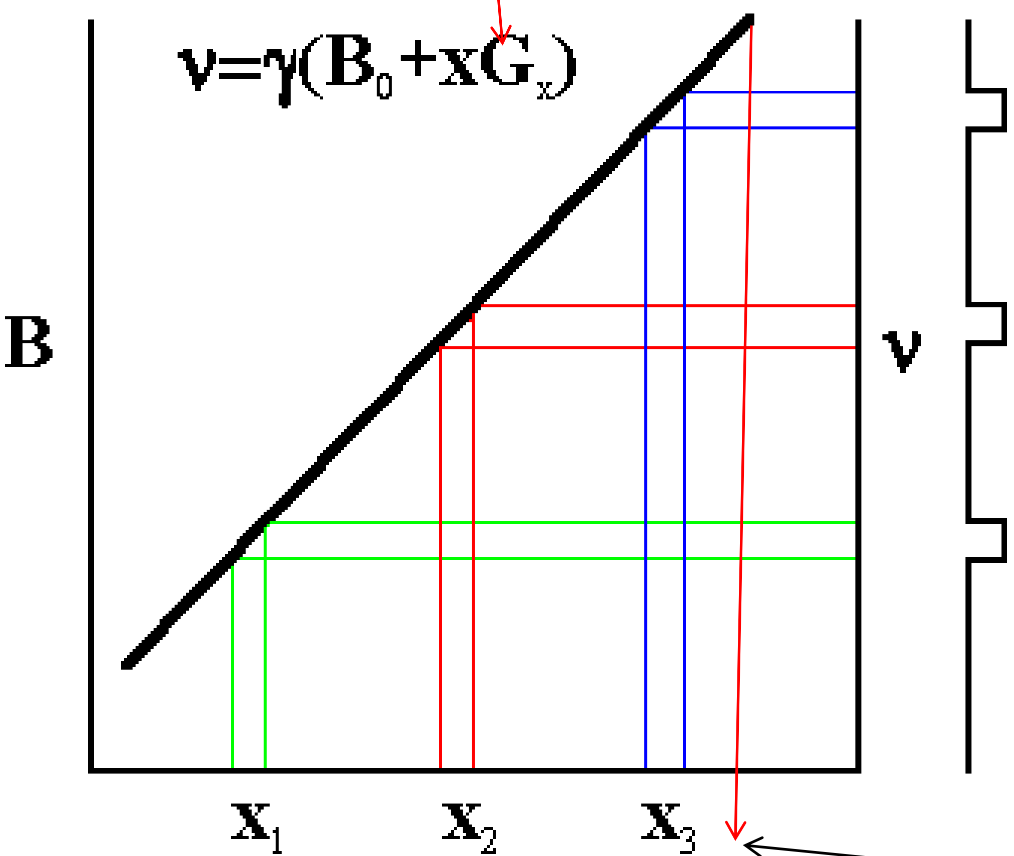
NMR and Flow: Pulse Sequences



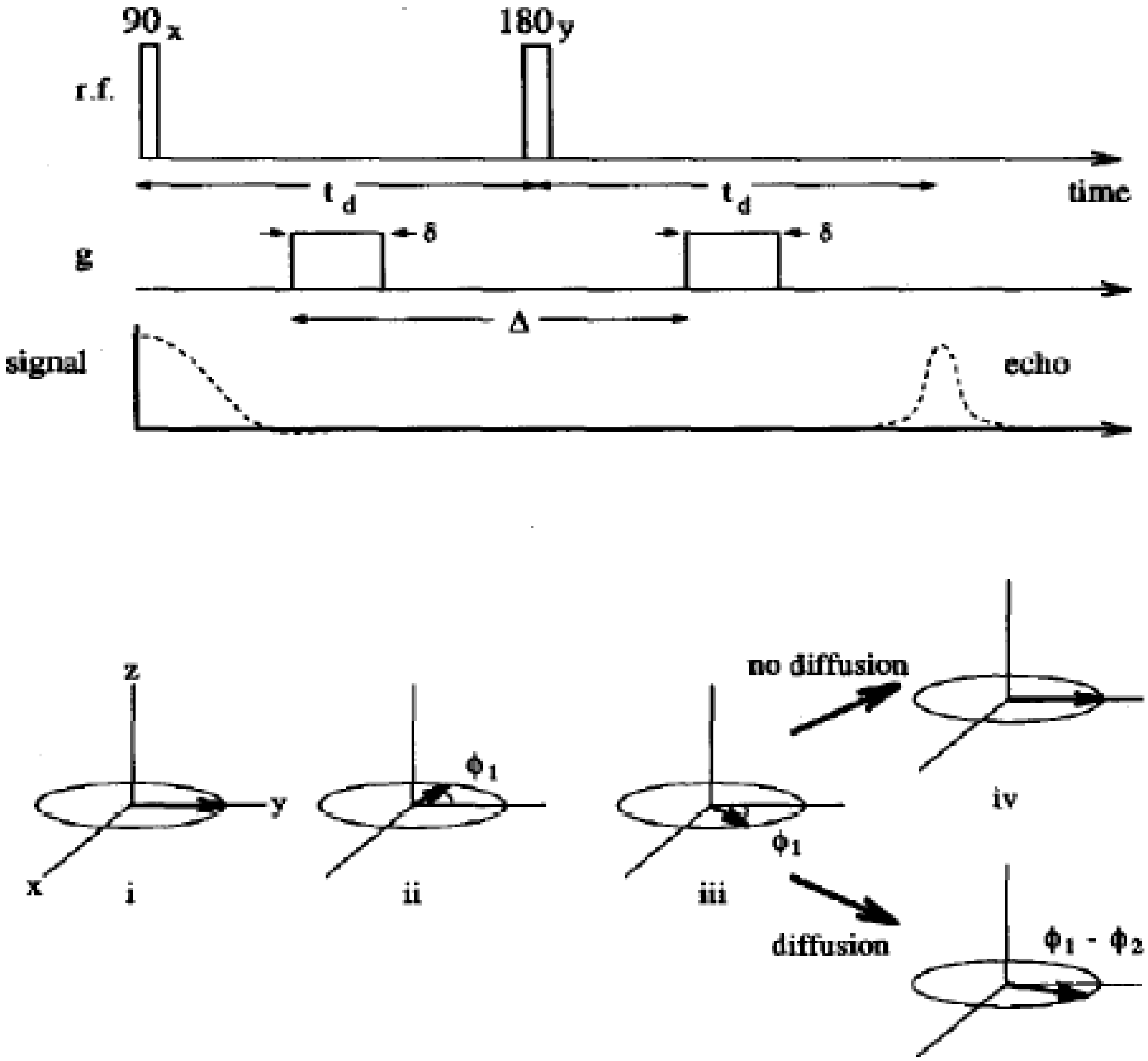
Spatial Resolution: Magnetic Gradients

Gradient **converts** ***phase*** **to** ***position.*** ***Every position now is assigned a unique phase.***

Bandwidth of pulse ($2f_0$) and gradient determine the slice thickness



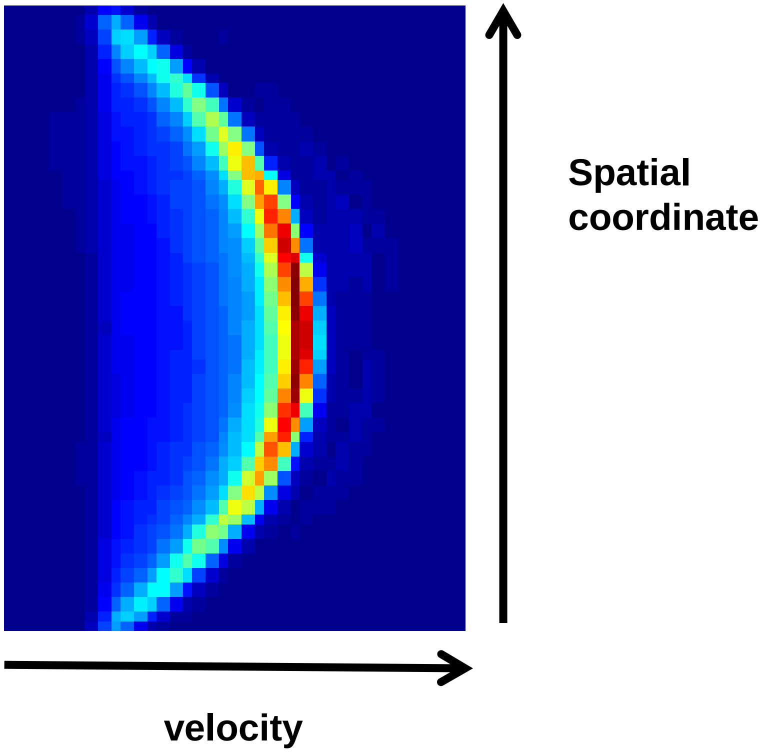
Carrier frequency of pulse (ν_0) determines slice position


90 x
180 y
r.f.
time
t d
t d
g
δ
δ
Δ
signal
echo
z
y
x
i
ii
iii
iv
ϕ1
ϕ1
no diffusion
diffusion
ϕ1 - ϕ2

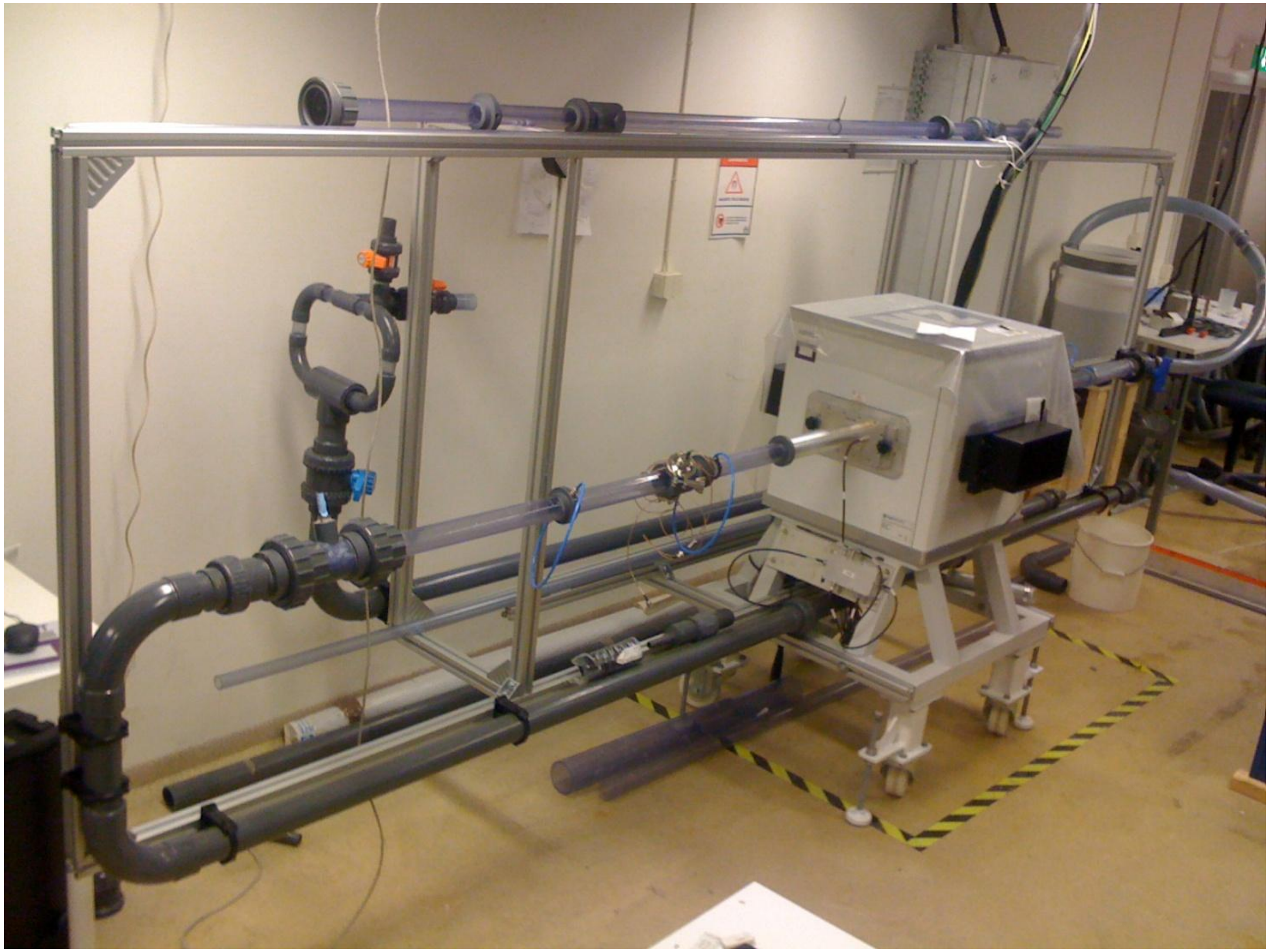
Magnetic Resonance Imaging of Velocity

A (linear) magnetic phase gradient is applied over the measurement domain to provide spatial resolution

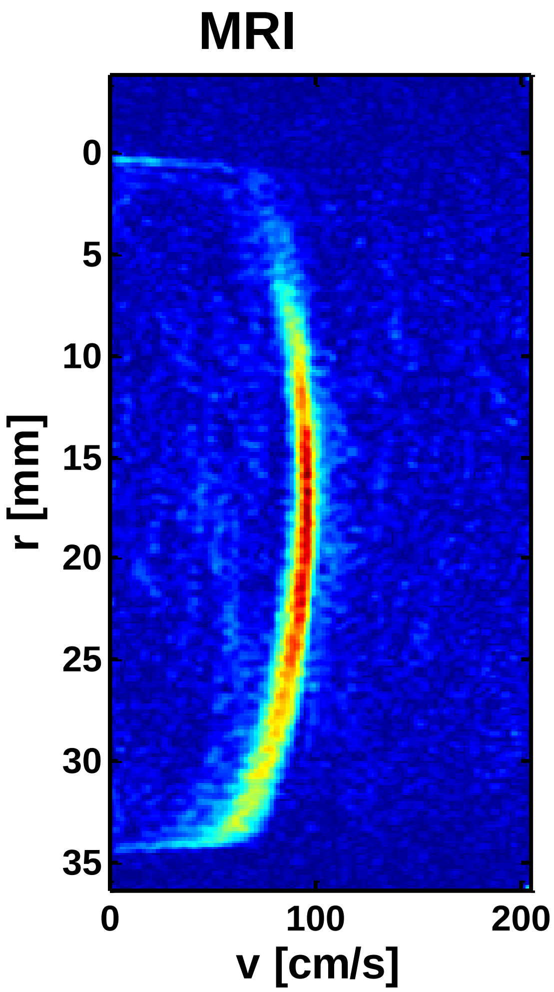
Velocity is encoded as an *additional 'dimension',* and the local velocity 'spectrum' is obtained by a separate FT along this dimension

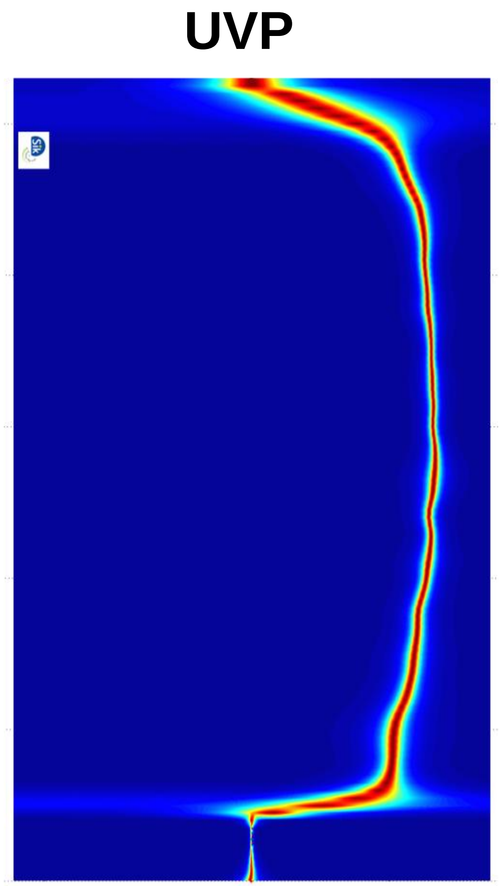


The Flow Loop



Comparison of Flow Images





Results and possible discussion

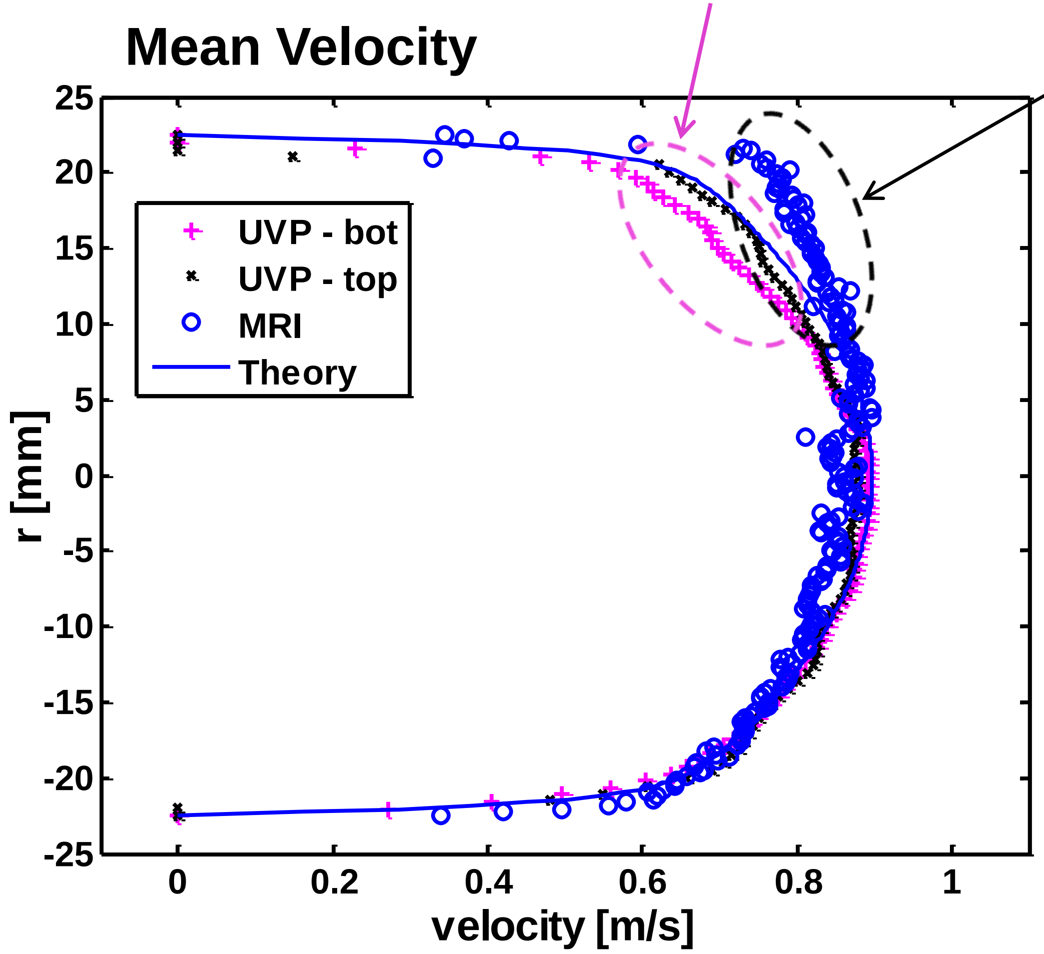
- What can we really measure?
  - Mean velocity
  - RMS
  - Distributions / moments
  - Dispersion / Turbulence…..

- Pros and cons of different techniques
  - UV: echo / near wall
  - UVP: mechanical signal -> attenuation in high concentration
  - MRI Resolution: Time -> low, Spatial -> moderate
  - MRI: Coherence issues
  - MRI: Non trivial development

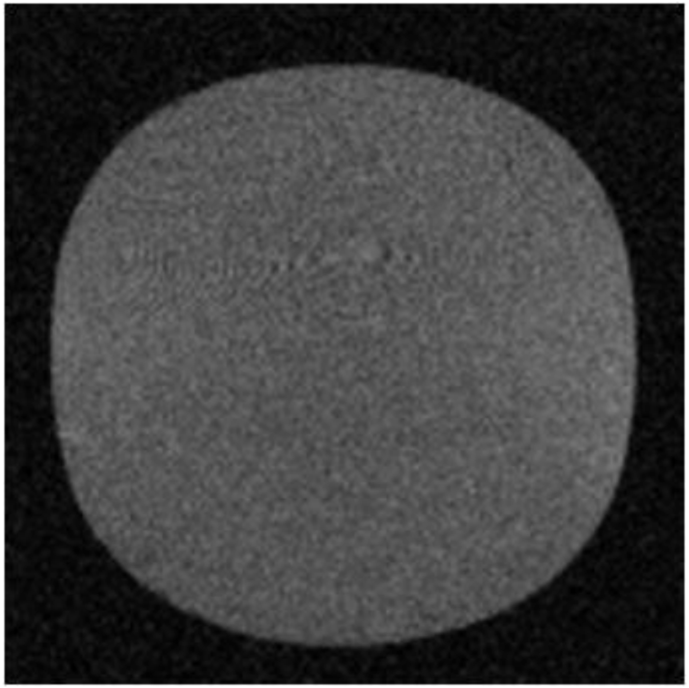
Comparison – H_2O

UVP bottom probe under-estimate

MRI Over-estimate

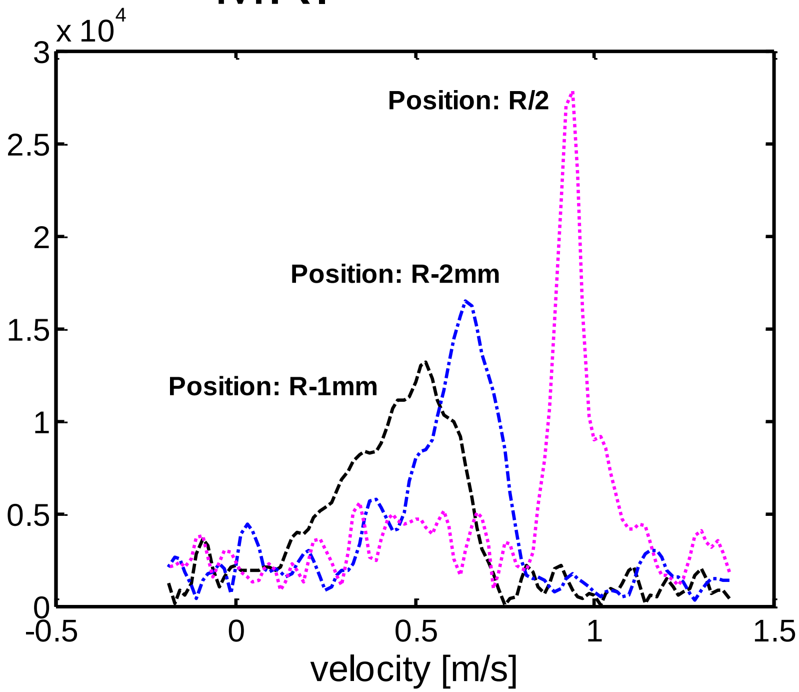


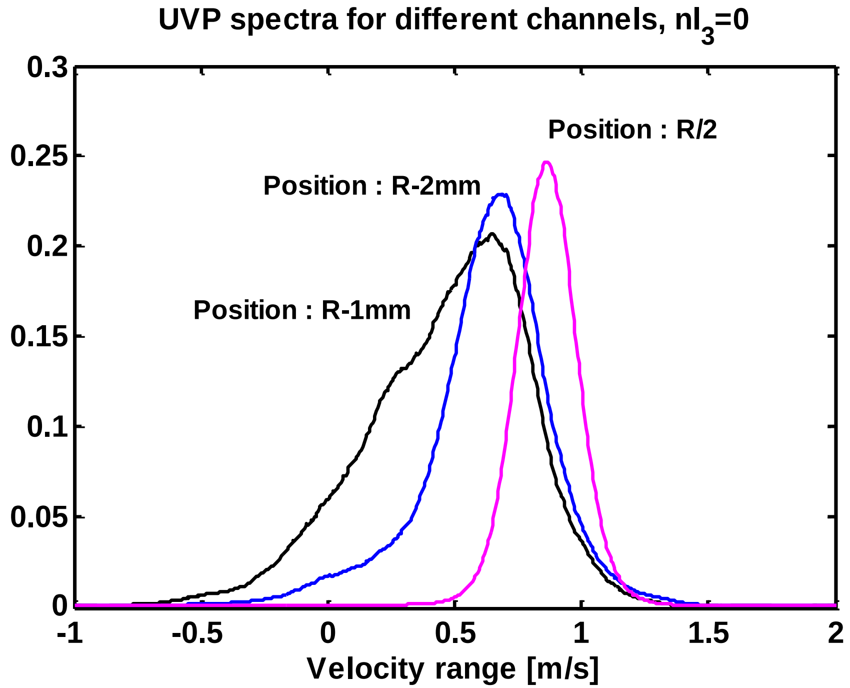
Spin Echo of the Pipe



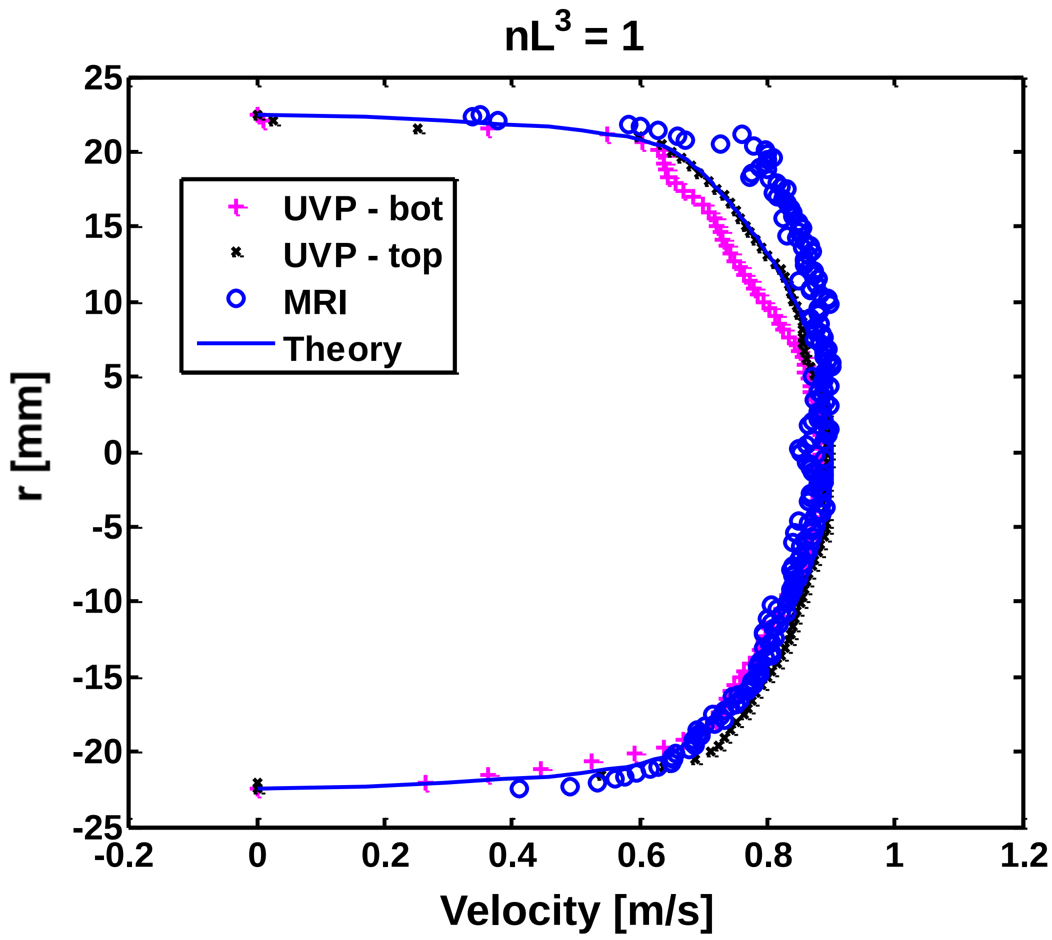
Velocity Spectra Comparison – H_2O

MRI





$nL^3 = 1$, v ~ 0.9 m/s



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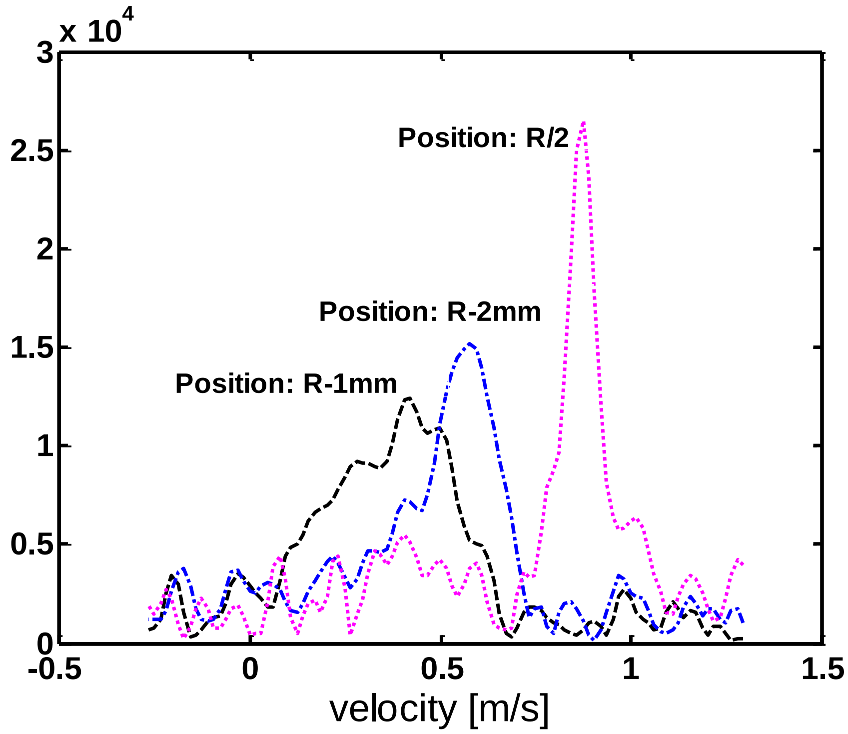
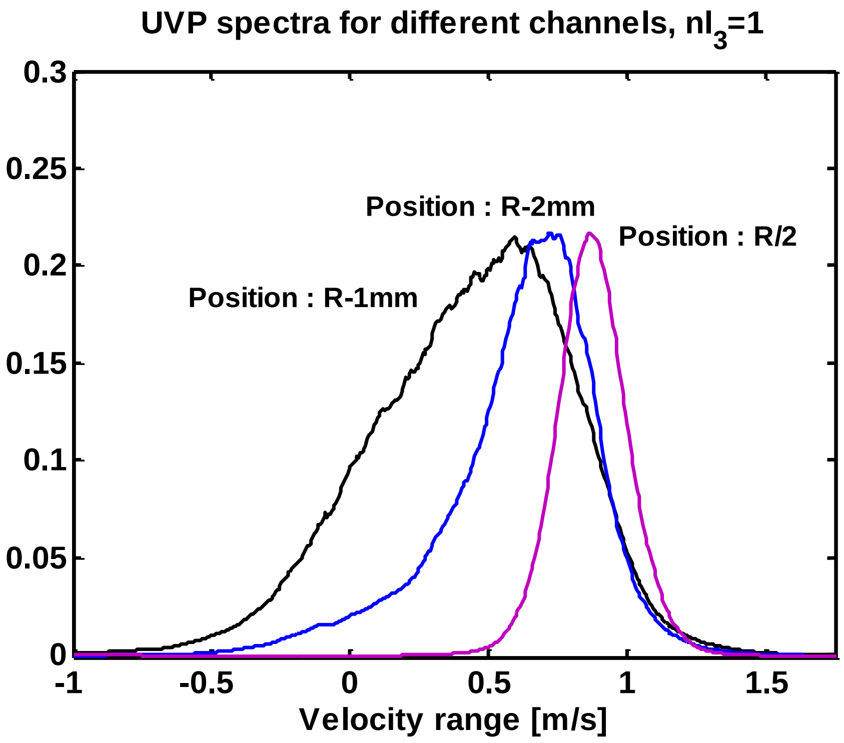
$nL^3 = 1$, v ~ 0.9 m/s

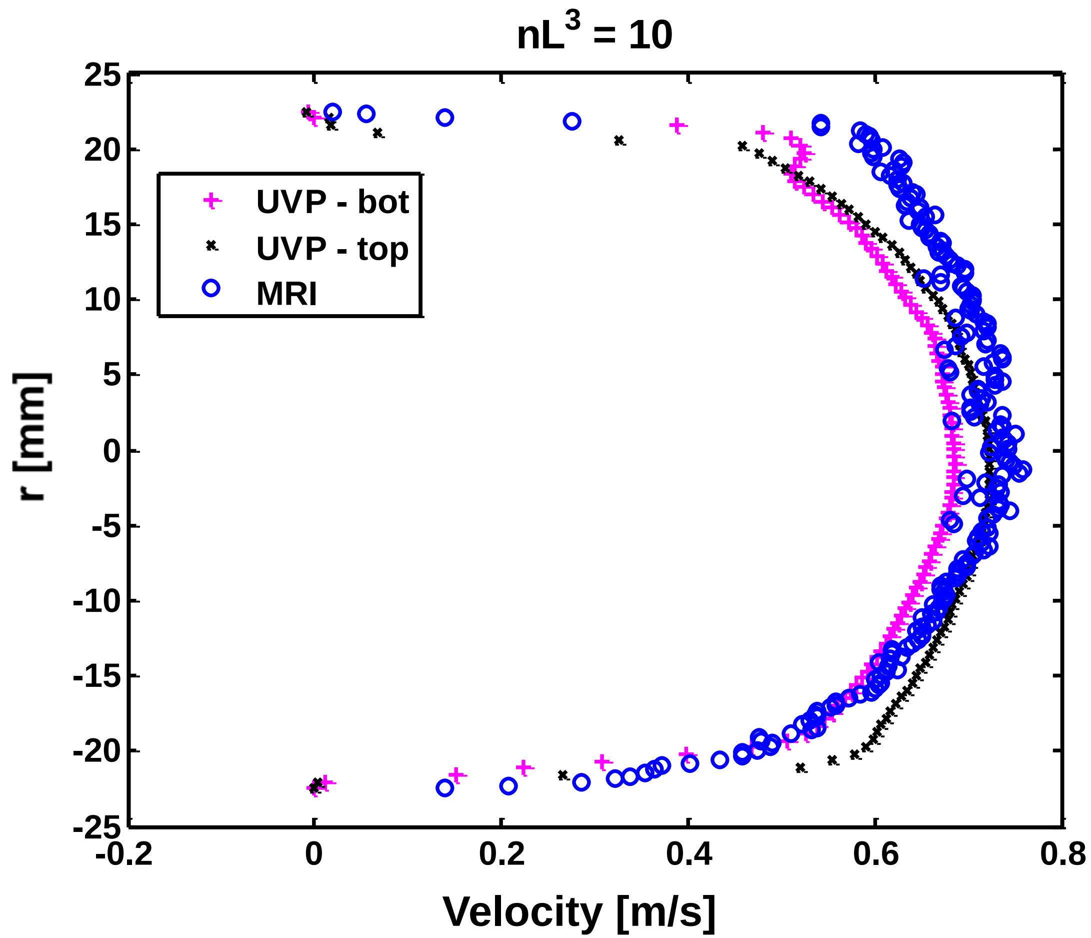


x 10^4
3
2.5
2
1.5
1
0.5
0
-0.5
0
0.5
1
1.5
velocity [m/s]
Position: R/2
Position: R-2mm
Position: R-1mm



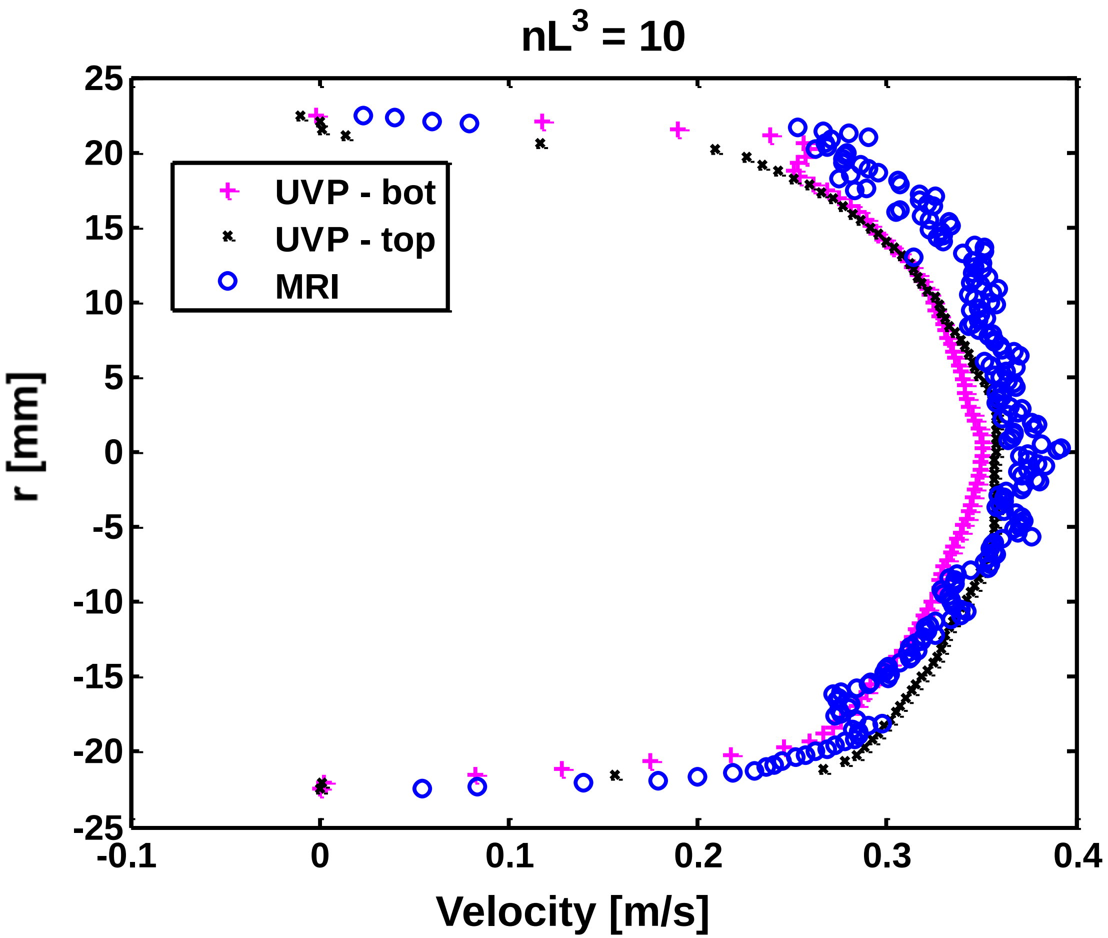
UVP spectra for different channels, nl3=1
0.3
0.25
0.2
0.15
0.1
0.05
0
-1
-0.5
0
0.5
1
1.5
Velocity range [m/s]
Position : R-2mm
Position : R/2
Position : R-1mm

$nL^3 = 10$, v ~ 0.7 m/s



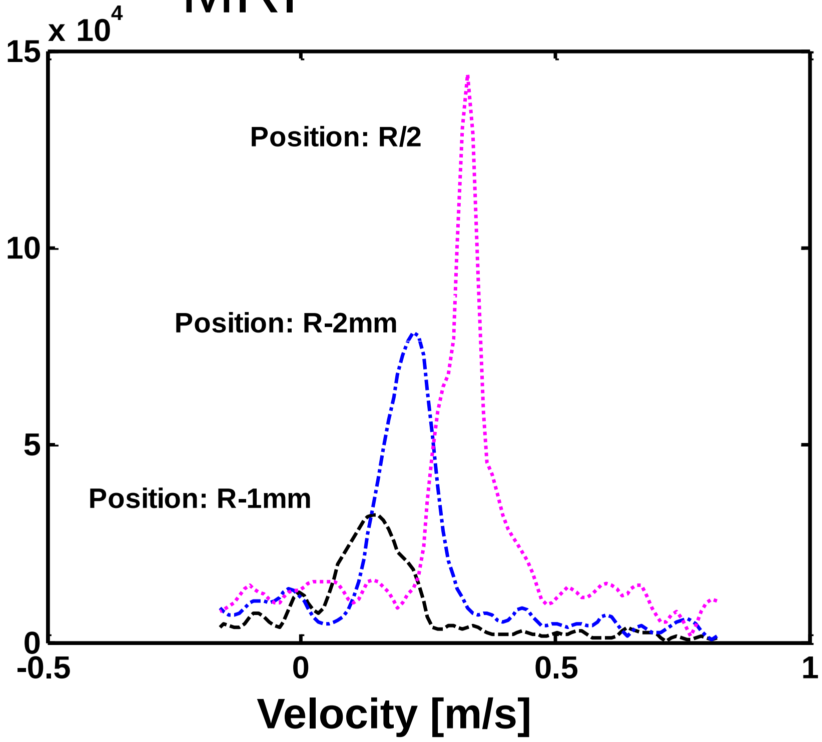
nL3 = 10
UVP - bot
UVP - top
MRI
r [mm]
Velocity [m/s]
25
20
15
10
5
0
-5
-10
-15
-20
-25
-0.2
0
0.2
0.4
0.6
0.8

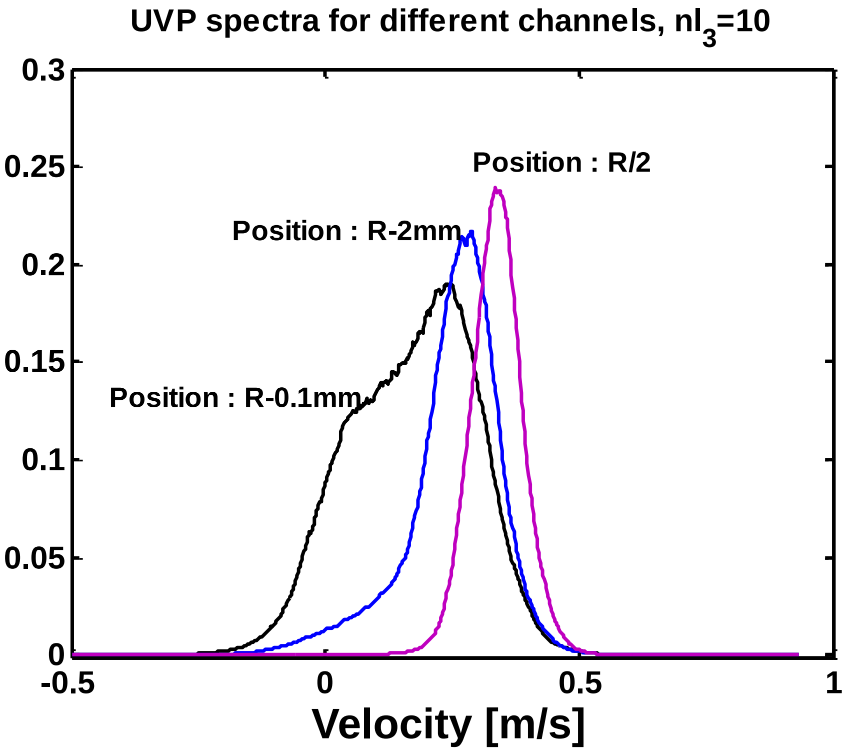
$nL^3 = 10$, v ~ 0.35 m/s



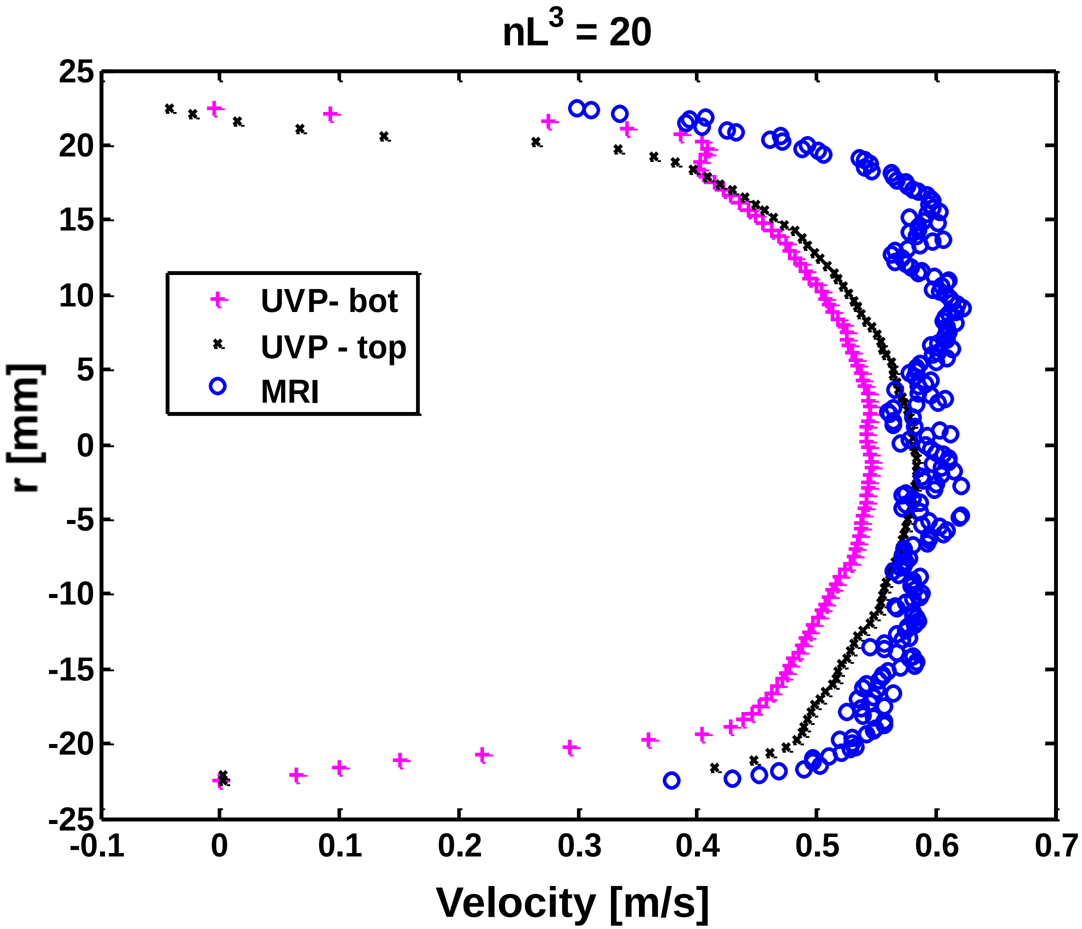
nL^3 = 10, v ~ 0.35 m/s

MRI

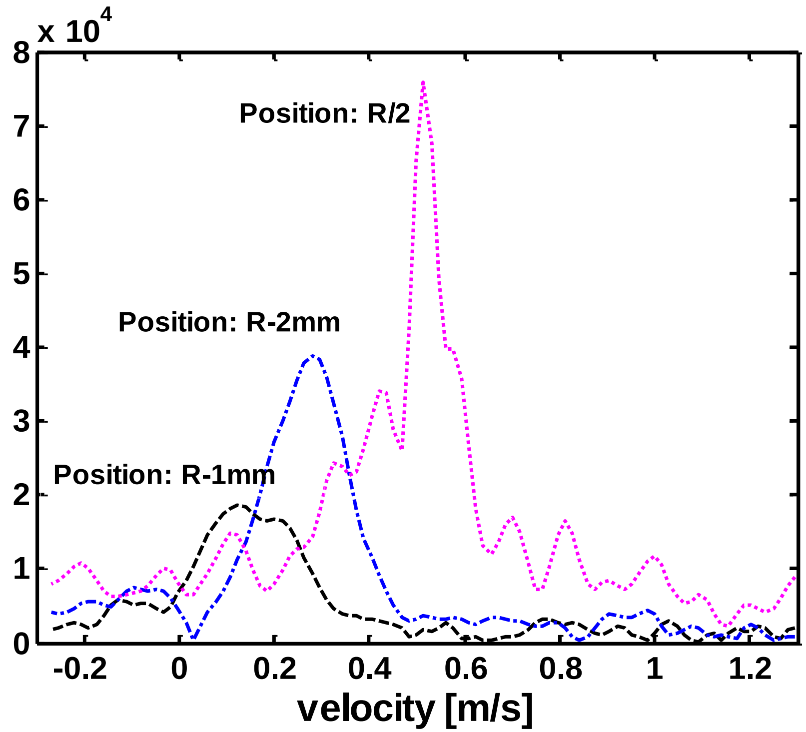


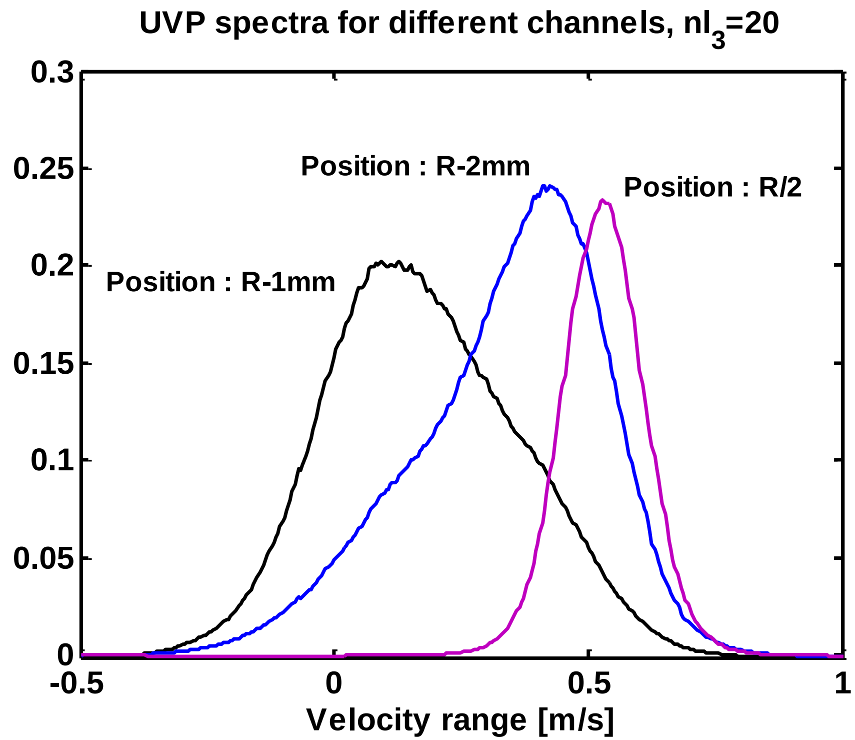


$nL^3 = 20$, v ~ 0.55 m/s

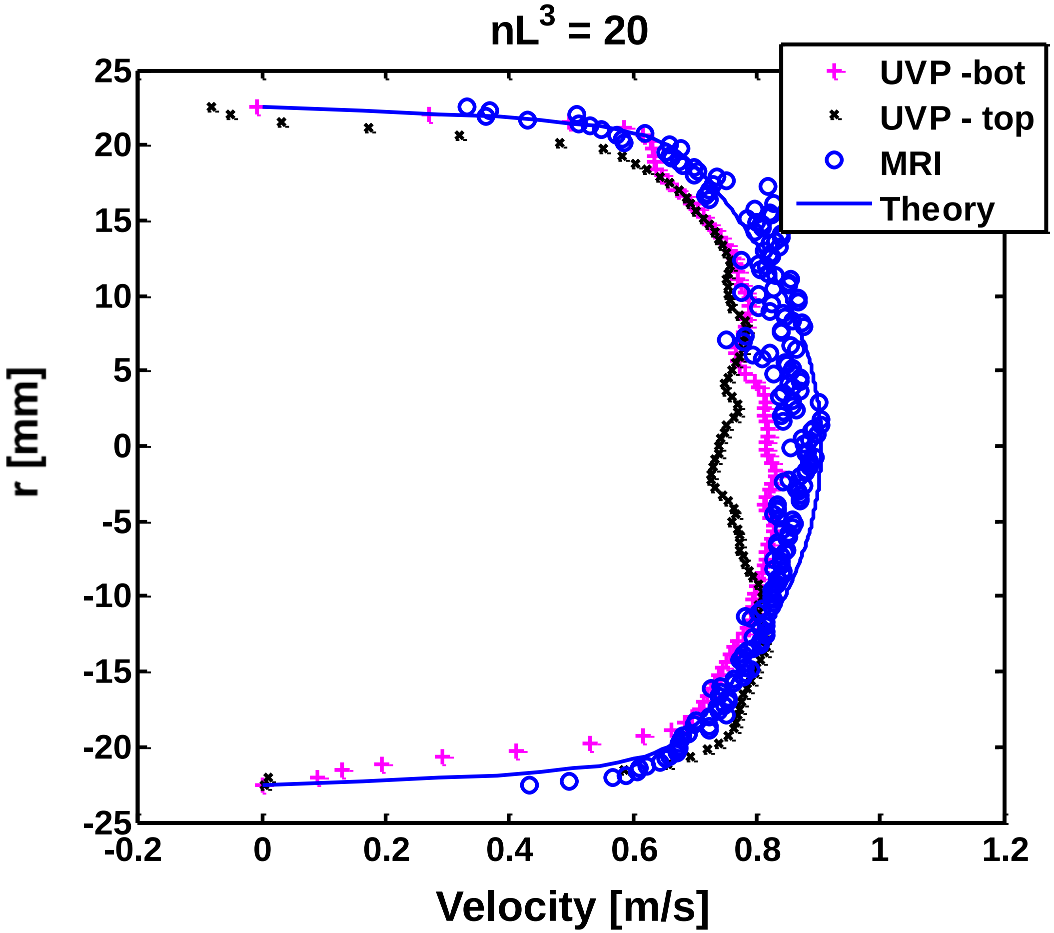


$nL^3 = 20$, v ~ 0.55 m/s

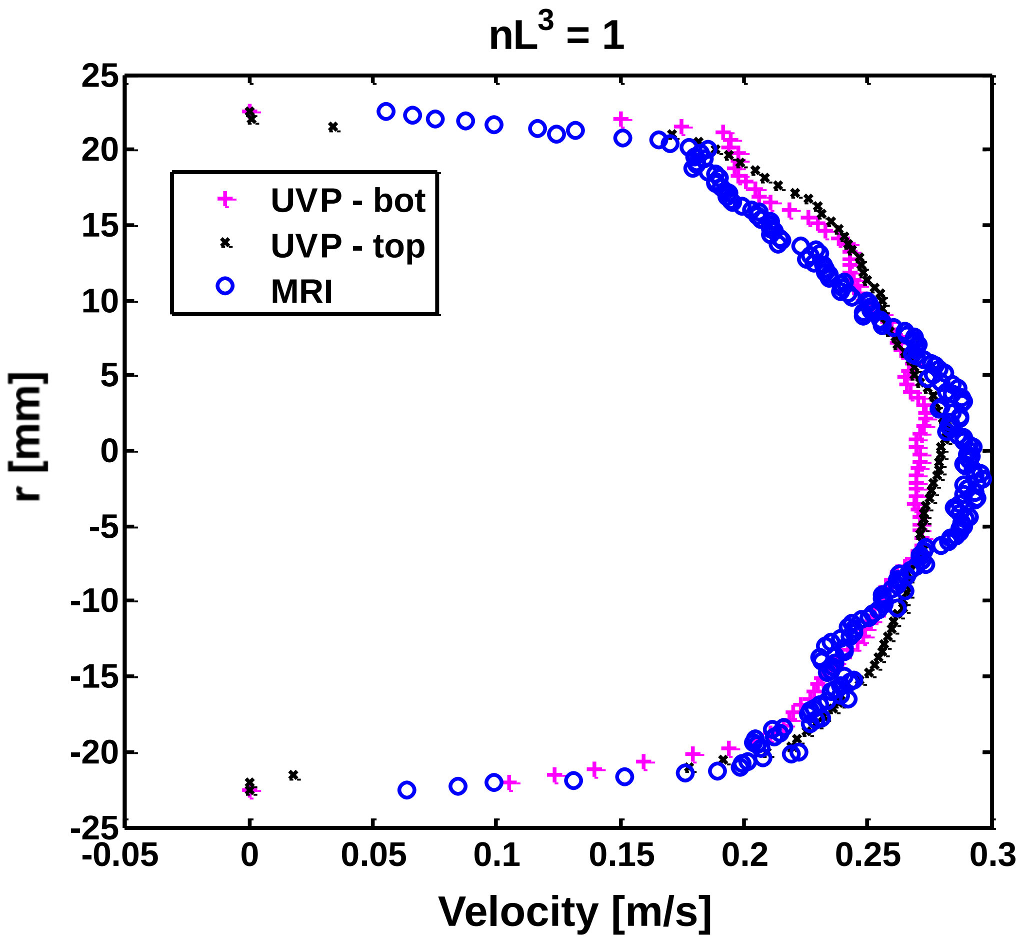




nL^3 = 20, v ~ 0.85 m/s



$nL^3 = 1$, v ~ 0.3 m/s



nL3 = 1
UVP - bot
UVP - top
MRI
r [mm]
25
20
15
10
5
0
-5
-10
-15
-20
-25
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
Velocity [m/s]

Conclusions

- NMR provides a robust, non-invasive technique for measuring flow of water through complex geometries *with arbitrary stock contents and concentrations*.
- UVP provides a robust non-invasive techniques for measuring flow of particles.
- Measurements agree well for low concentration and/or high velocity flow.
- Differences in fluid/fibre flow observed as velocity decreases and/or concentration increases, expect to see differences:
  – > Differences in velocity = fcn(c,v)

- Together, MRI and UVP give a more complete picture of fibre suspension flow.
- The gap between what is possible and what is routinely done with NMR is still large! The field is still open to many new applications.