An Experimental Study of the Turbulent Development of Rayleigh-Taylor and Richtmyer-Meshkov Instabilities

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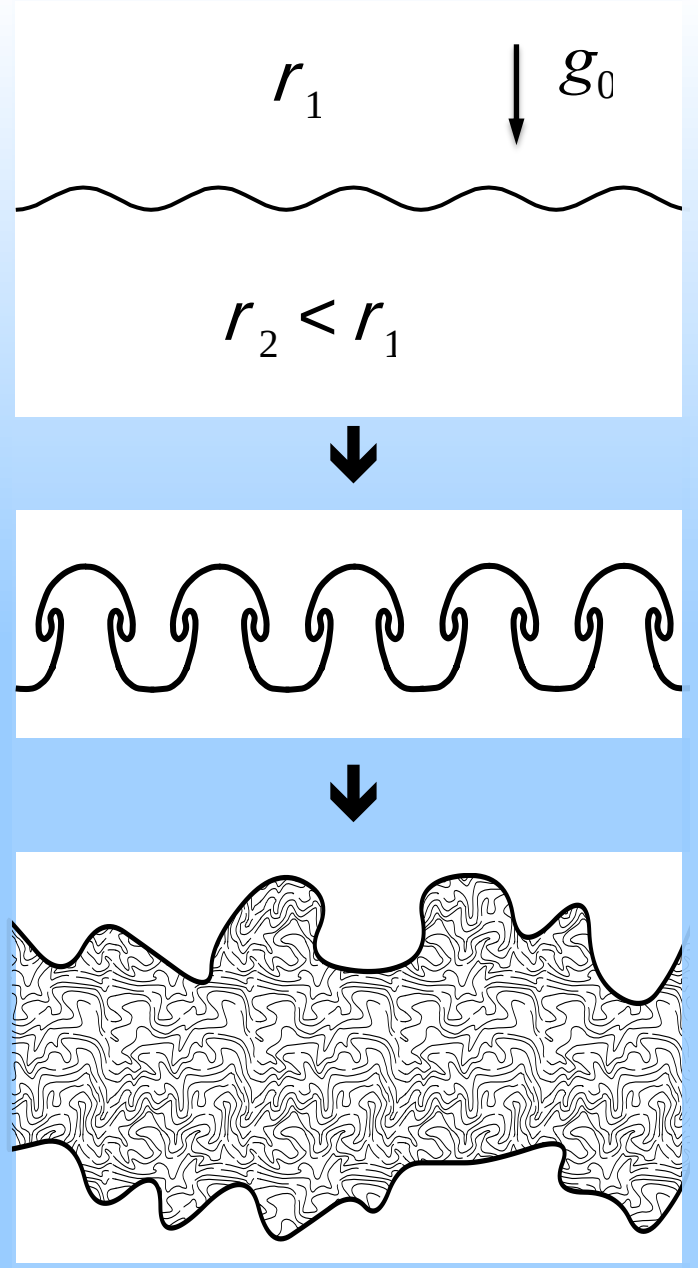
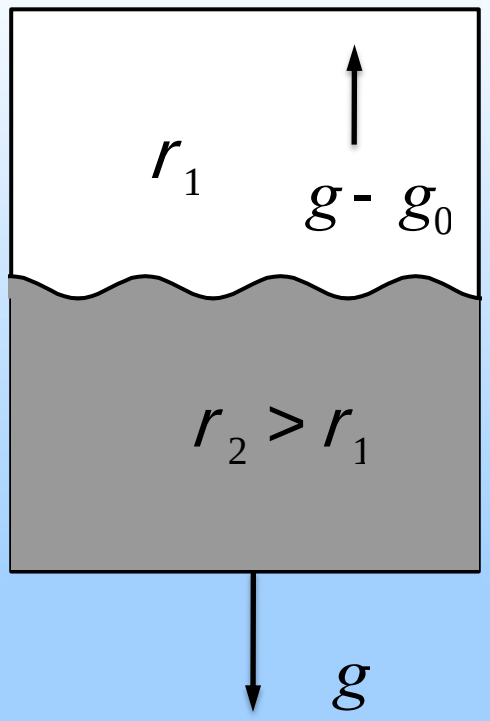
Rayleigh-Taylor Instability

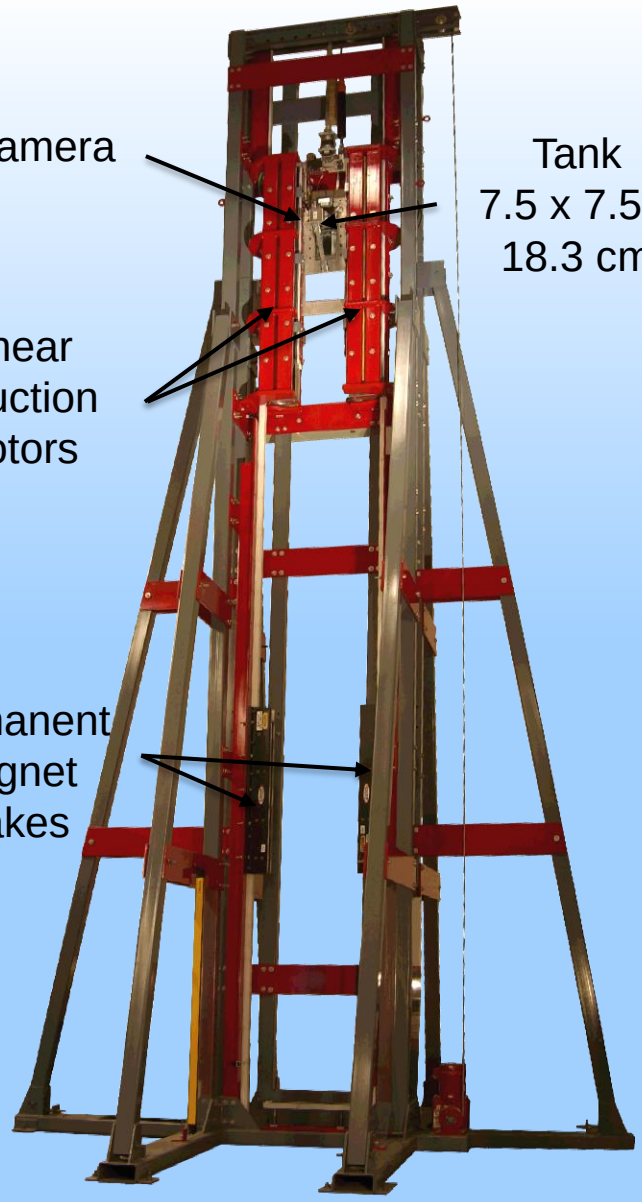


$$h \sim a A g t^2$$



$$A = \frac{r_2 - r_1}{r_2 + r_1}$$

Linear Induction Motor Apparatus



Net acceleration ≈ 15 g

Experimental Fluids

- Immiscible and miscible
  - Light fluid: Low viscosity silicone oil or alcohol
  - Heavy fluid: calcium nitrate water solution
  - Index matched with $A = 0.22$

Planar laser induced fluorescence

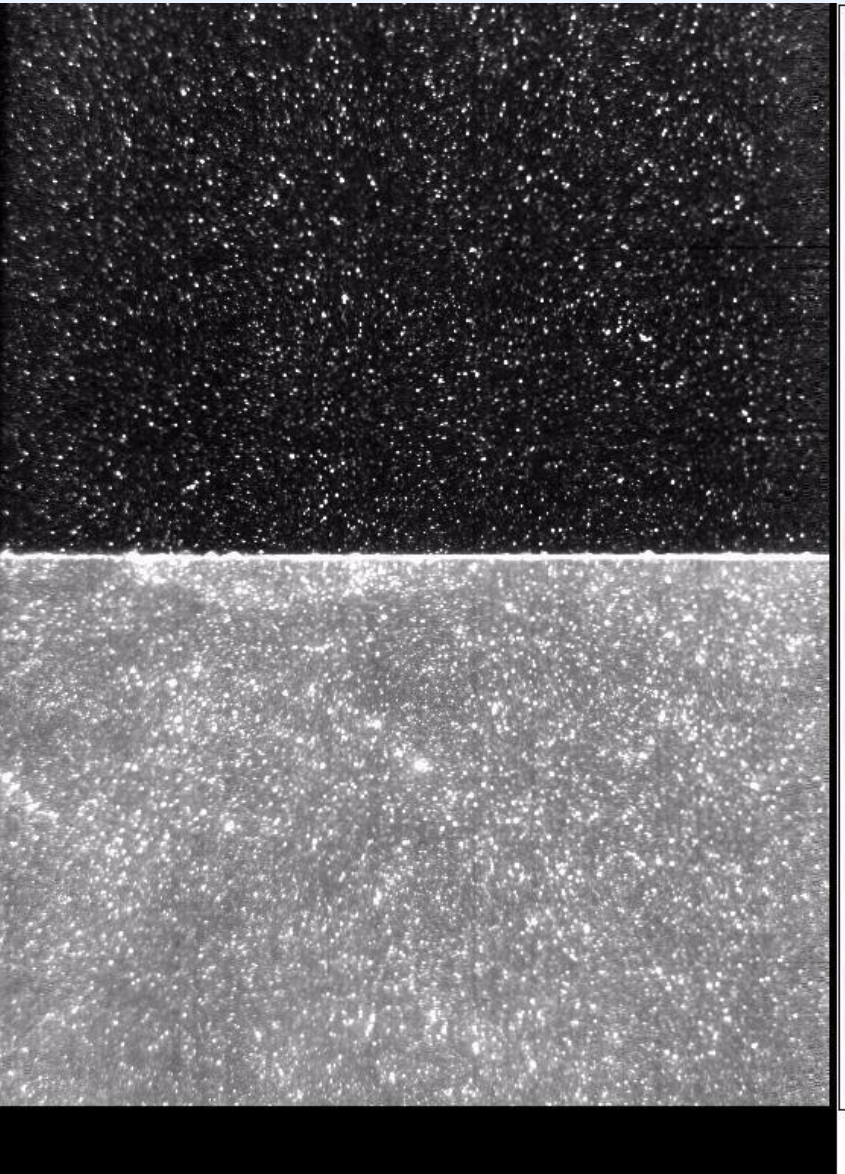
- Fluorescein added to bottom liquid
- 445nm, 1.2W laser diode
- Servo driven polygon mirror creates light sheet
- Laser sweep synchronized with camera shutter
- Camera: 800 x 600 resolution, 1200 fps

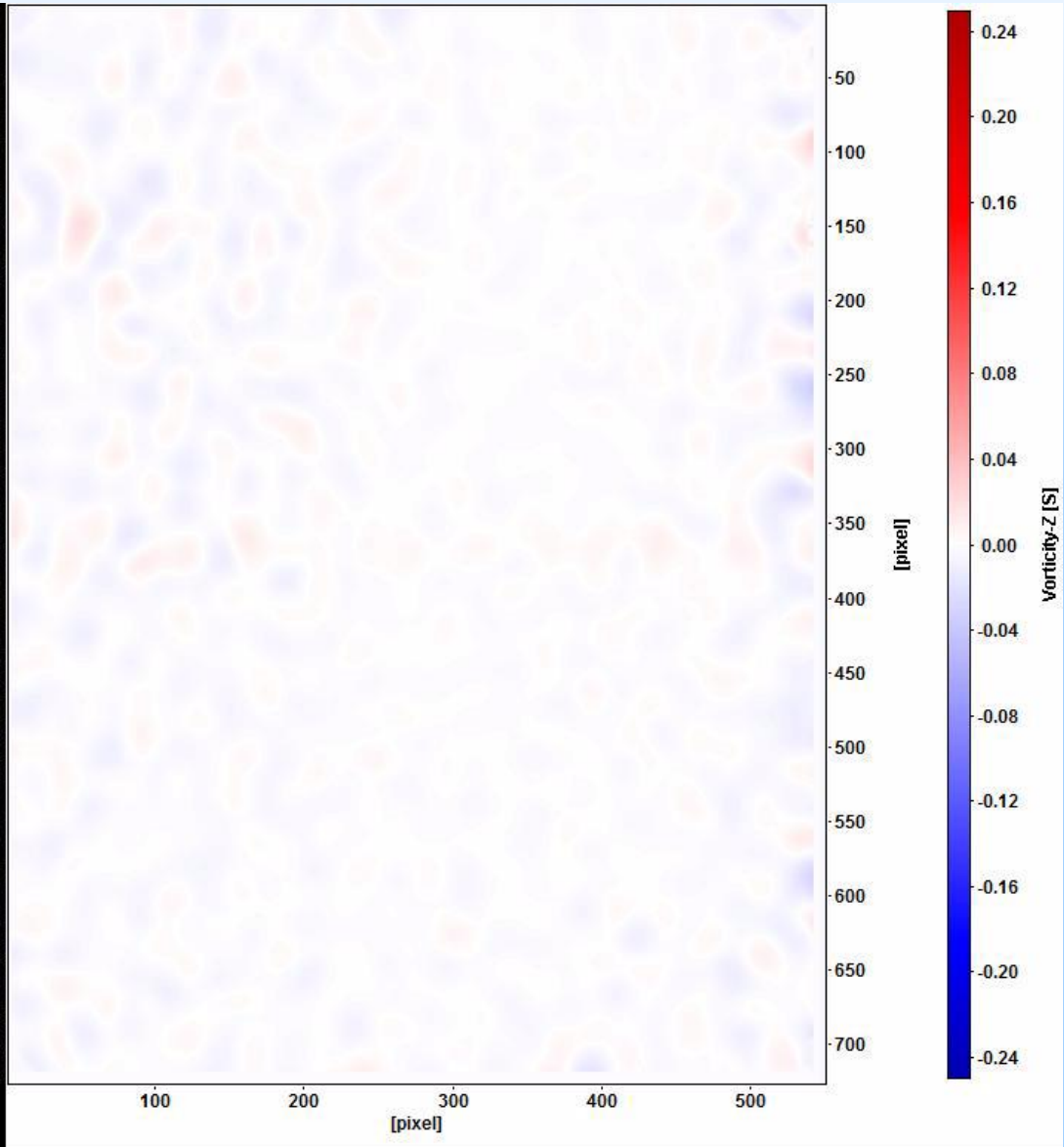
Particle Image Velocimetry

- Seeded with aluminum oxide ~ 3 μm particles
- Separate PIV from PLIF information using intensity threshold
- PIV processing using DaVis from LaVision

Particle Image Velocimetry

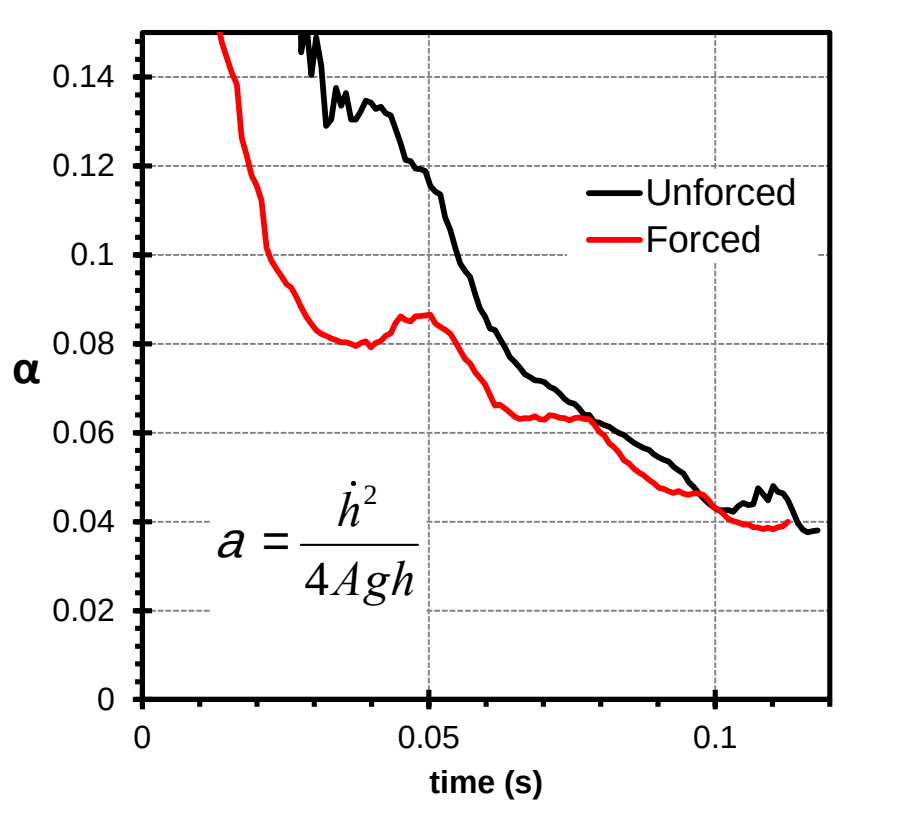
(4 passes, 32x32 window, round Gaussian weighting, 87% overlap)





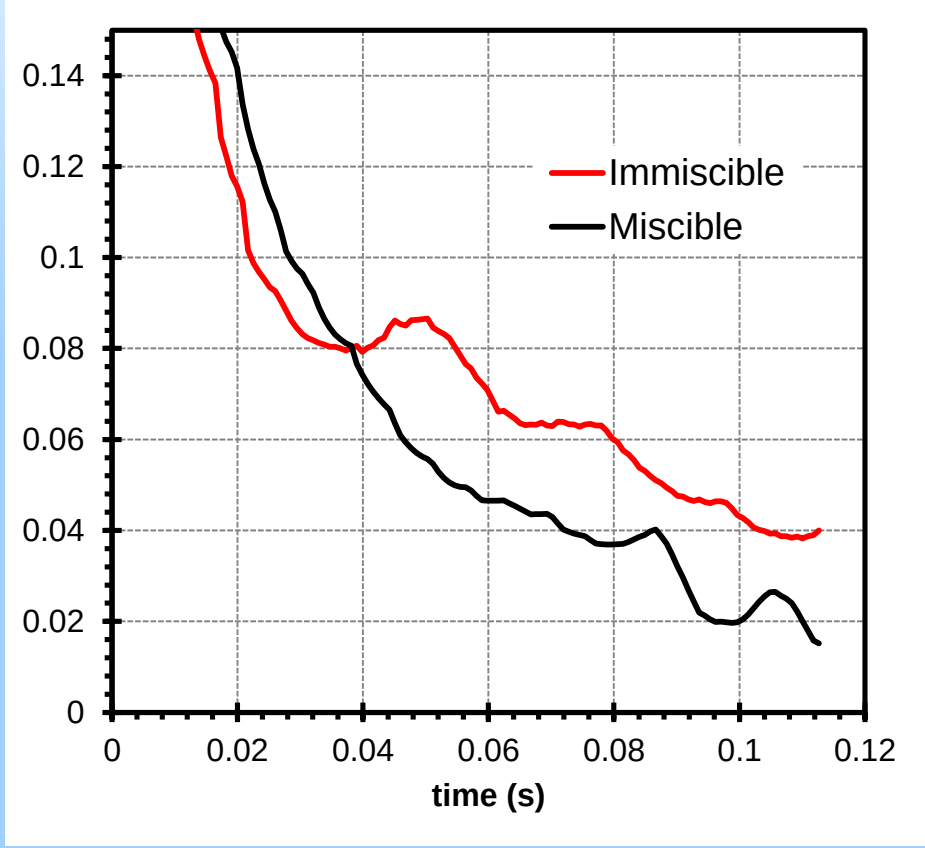
Alpha Measurement

Ensemble average of 15 immiscible experiments



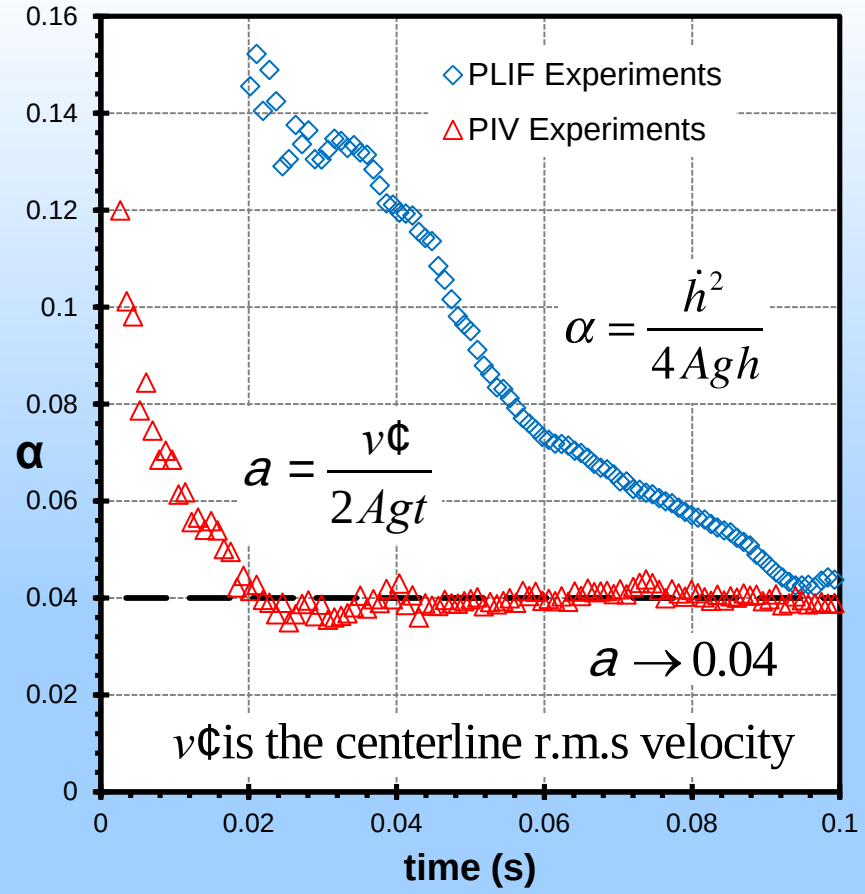
$$a \rightarrow 0.04$$

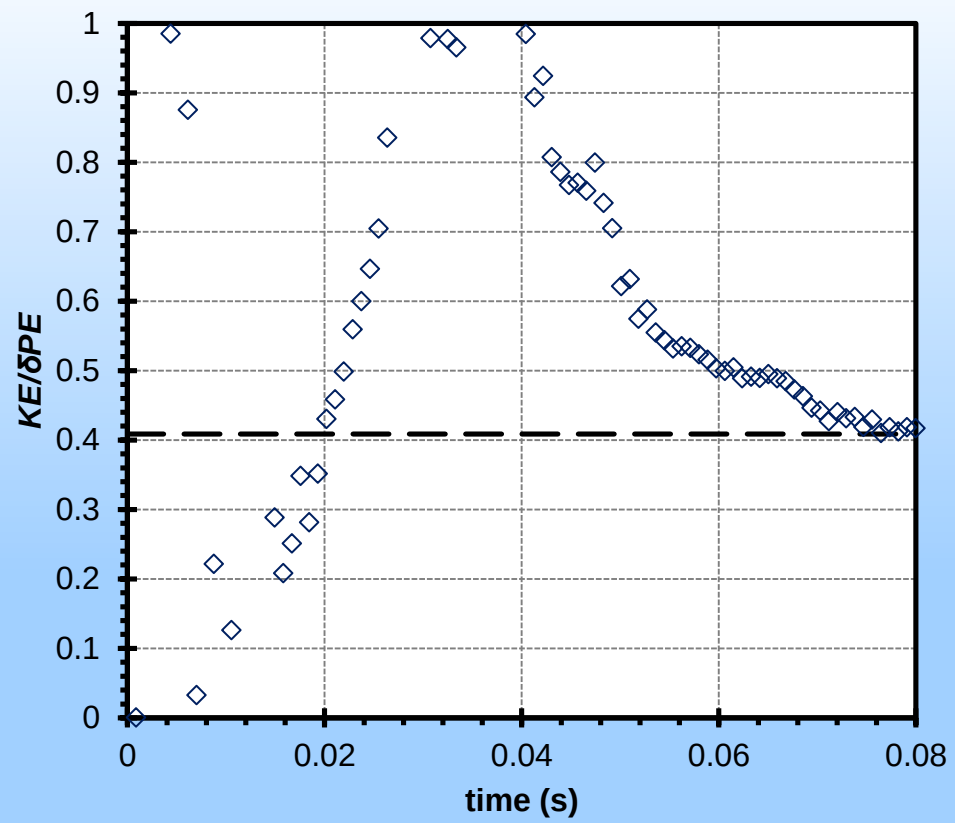
Ensemble averages of 15 forced immiscible and 9 forced miscible experiments



$$a_{\text{immiscible}} \rightarrow 0.04 \quad a_{\text{miscible}} \rightarrow 0.02$$

Unforced Results





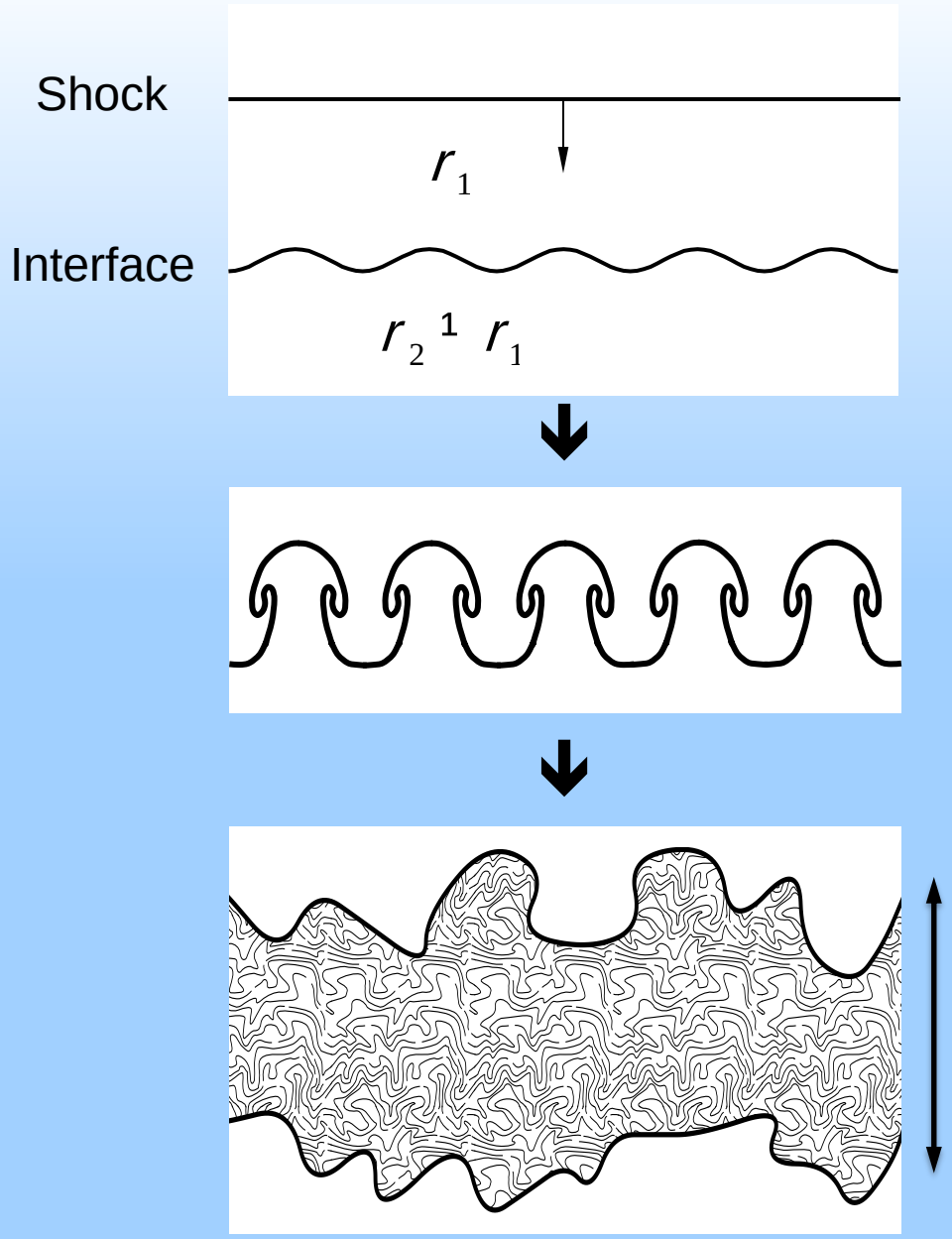
Slightly lower than typically measured

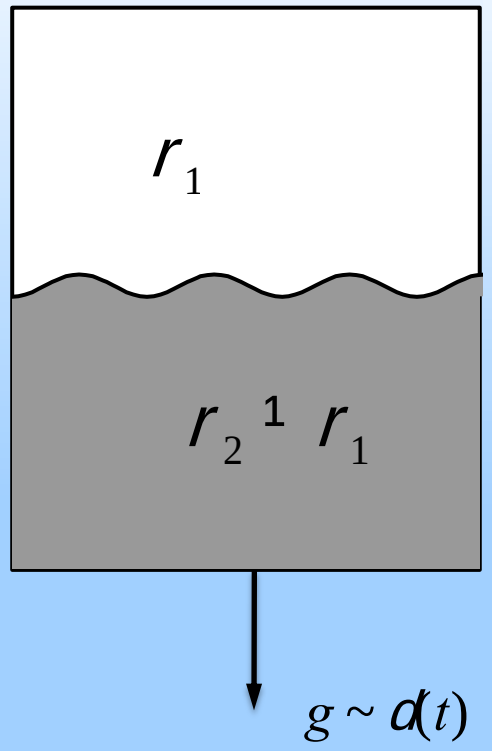
Kinetic energy: $KE = \frac{1}{2}\int_A \rho (v¢^2 + 2u¢^2)\,dA$

Potential energy released: $dPE = \int_A (\rho_{t=0} - \rho_t)\,gz\,dA$

$KE / dPE \rightarrow 0.41$ similar to Cabot and Cook (2006)

Richtmyer-Meshkov Instability





Shock Tube

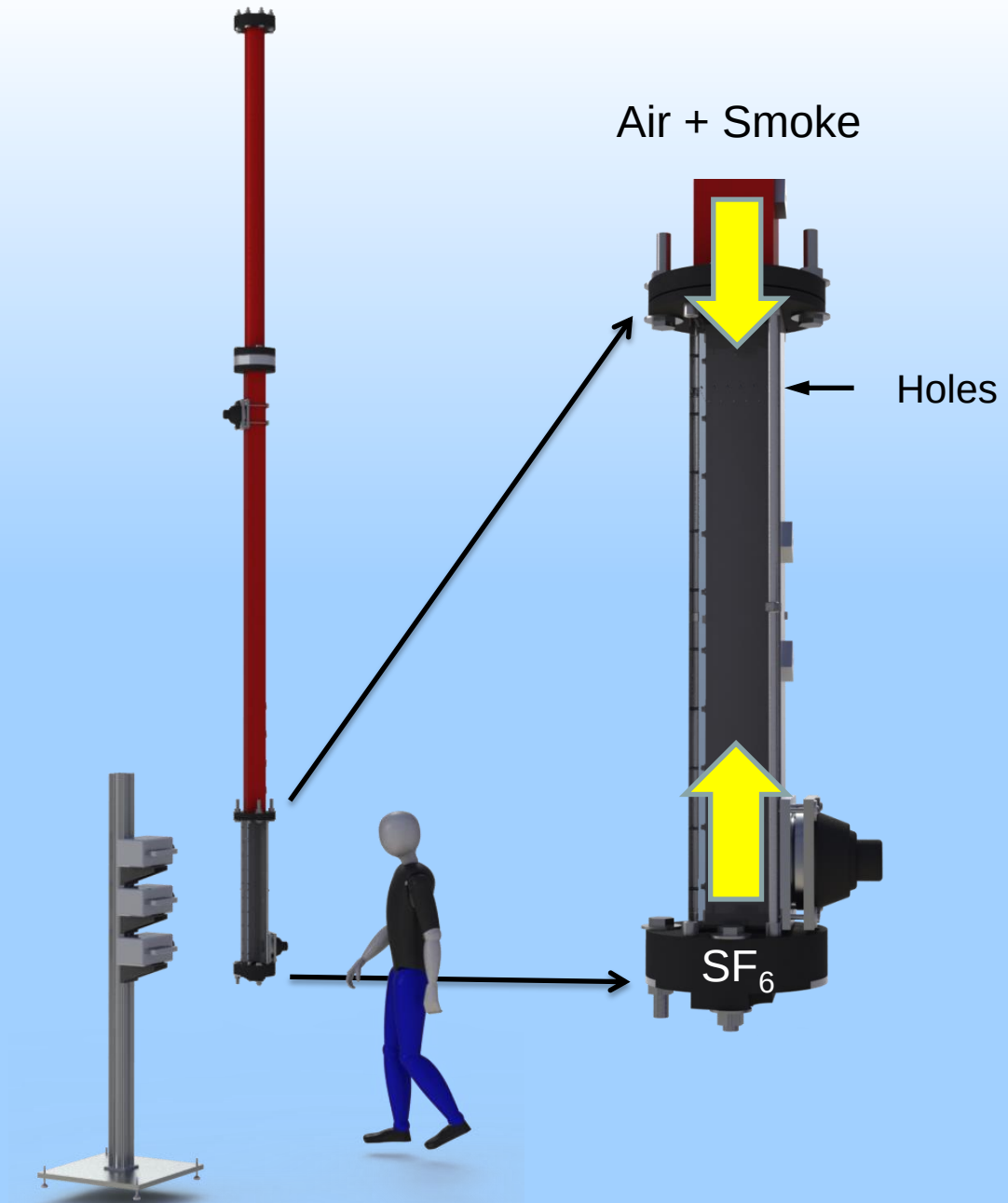
Shock tube:

- 5 m long
- 0.86 m long test section
- 89×89 mm cross section
- Shock Mach number = 1.2

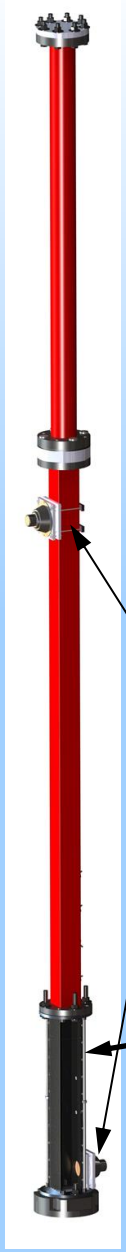
$$A = \frac{r_2 - r_1}{r_2 + r_1} = 0.67$$

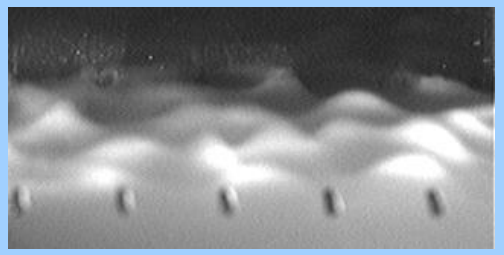
Planar Mie Scattering Movies:

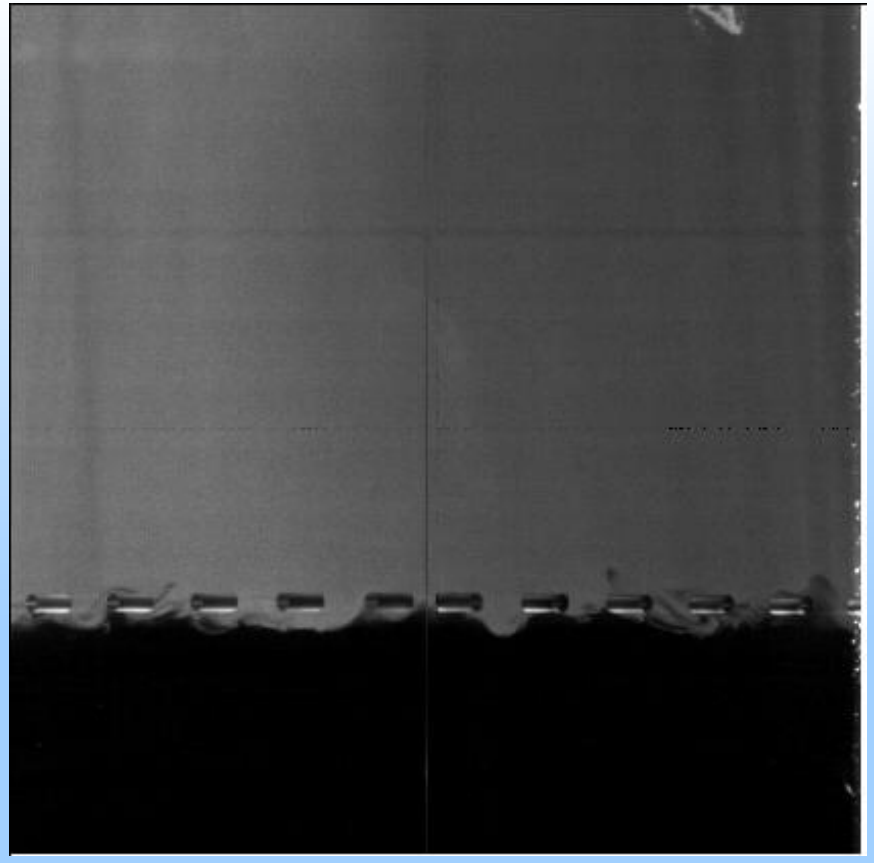
- Nd:YLF laser
- 1 to 3 High-speed cameras (6,000 pps)
- 1024 x 512 images are stitched together



Faraday Wave Initial Perturbation



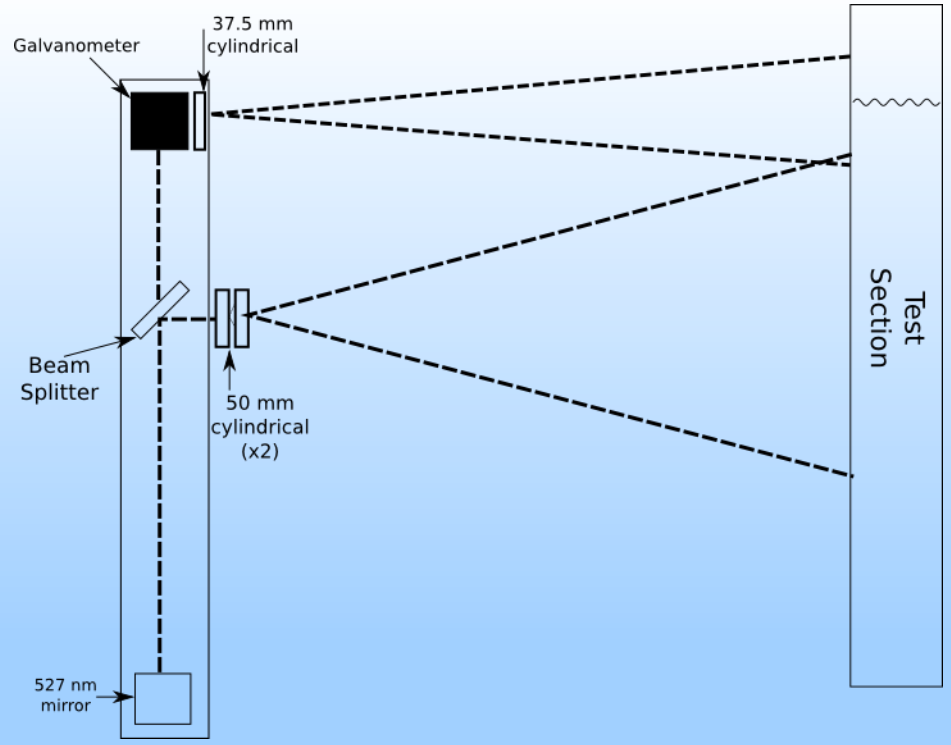




Faraday waves

- Frequency = 32.5 Hz
- Wavelength = 3 to 7 mm
- Amplitude = 2 to 4 mm

3D Interface Scanning



Laser: Photronix 75W 527 nm Nd:YLF Pulsed Laser

- Optics used to split beam path
  - One path redirected by the galvo
  - One path illuminates lower test section

2 x Photron Fastcam APX-RS Cameras

- One pointed at interface region
- One oriented along test section

Images captured at 6 kHz

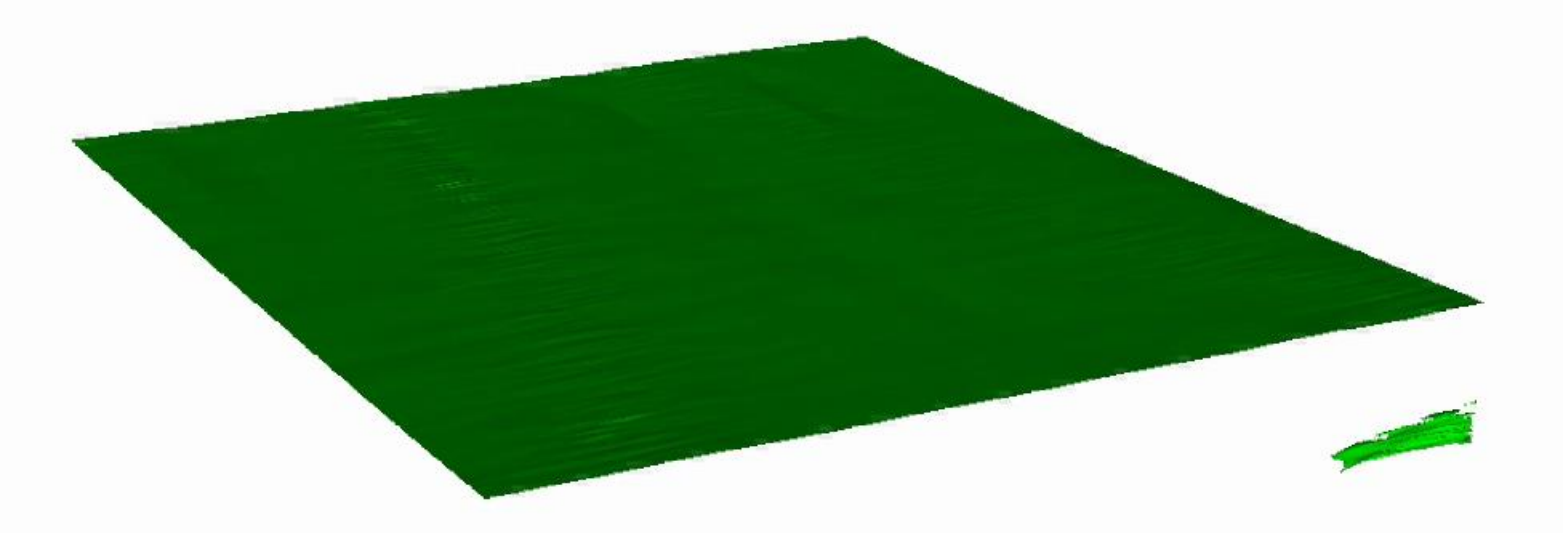
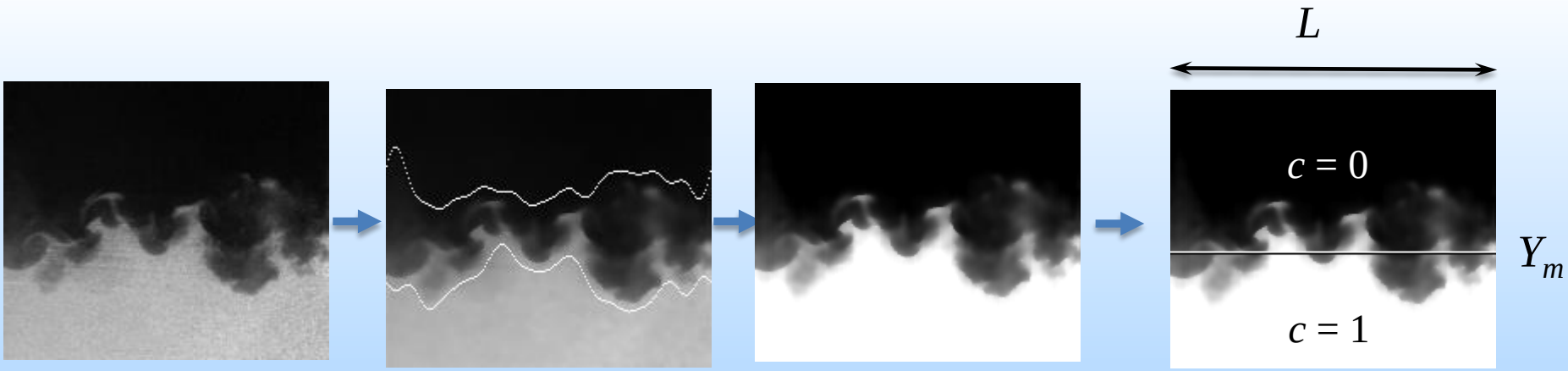


Image Processing



Original → Filter + edge detection → Normalize concentration → Find mid-plane location, Y_m

Integral width

$$\langle c(y,t)\rangle = \frac{1}{L}\int_0^L c(x,y,t)\,dx$$

$$W_{b,s} = 4\int_{-\infty,Y_m}^{Y_m,+\infty} \langle c\rangle\left(1-\langle c\rangle\right)dy$$

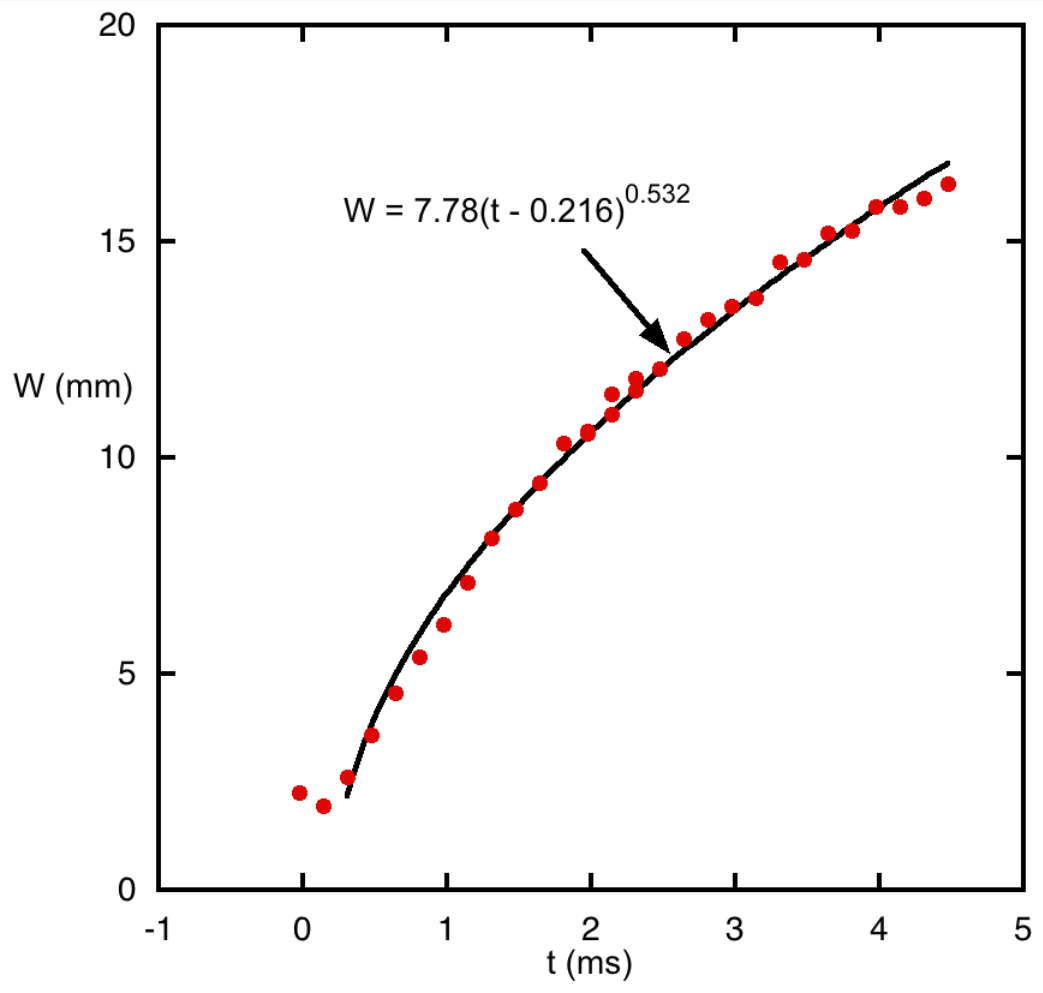
$$W = 4\int_{-\infty}^{+\infty} \langle c\rangle\left(1-\langle c\rangle\right)dy$$

$$\int_{Y_m}^{+\infty}\int_0^L c(x,y)\,dx\,dy = \int_{-\infty}^{Y_m}\int_0^L (1-c(x,y))\,dx\,dy$$

Mixedness

$$Q = \frac{\int_{-\infty}^{+\infty}\langle c(1-c)\rangle\,dy}{\int_{-\infty}^{+\infty}\langle c\rangle\left(1-\langle c\rangle\right)dy}$$

Integral Width Measurements



Several self-similar models predict

$$W \sim t^q$$

Fitting a function of the form:

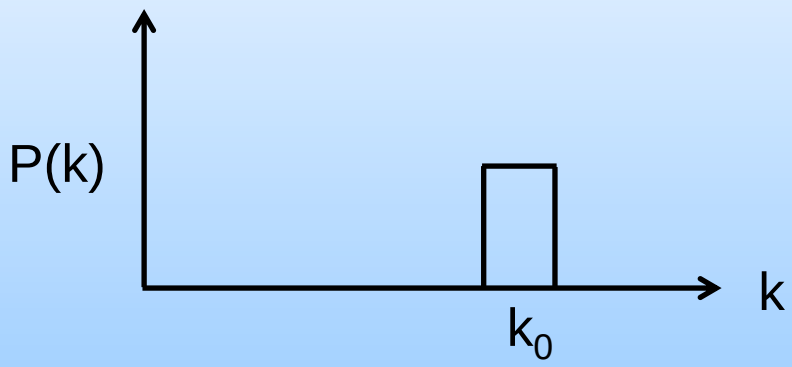
$$W = C(t - t_0)^q$$

gives $\theta \sim 1/2$

There have been a number of numerical simulations that find $\theta \sim 1/4$
But most experiments have very different initial perturbations

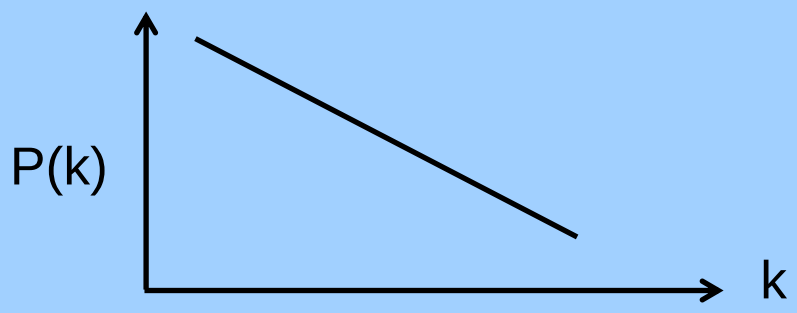
Spectral Dependence of Initial Conditions

Most numerical simulations showing self-similar behavior are initiated with narrowband initial spectra



where $2\pi/k_0 \ll$ computational domain

Most shock tube experiments have more broadband initial spectra



Youngs (2004)

Youngs (2004) showed that for a narrowband initial perturbation and assuming self-similarity

$$W = C(t - t_0)^q$$

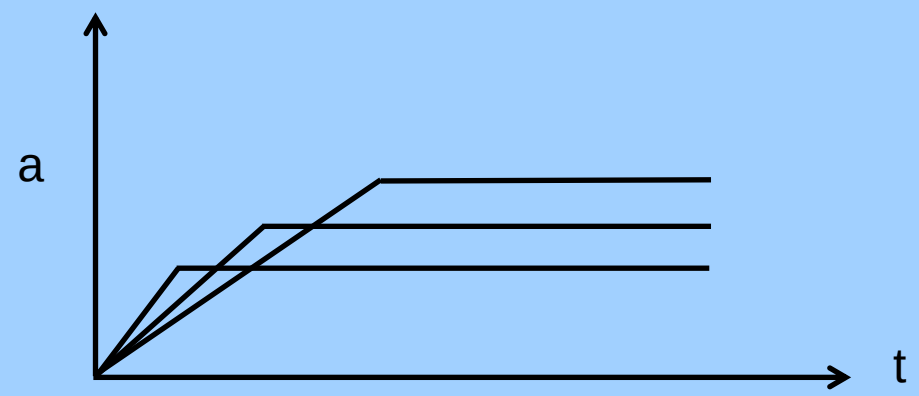
where θ is independent of the initial perturbation and depends on the dissipation rate.

For broadband perturbation power spectrum of the form

$$P(k) = C\,k^s$$

Youngs used the behavior of the collection of an infinite set of non-interacting modes, assuming each mode grows following Richtmyer's formula until reaching saturation at $a = \lambda$.

to obtain $W \sim \left\{ C^{1/2} \mathrm{D} U t \right\}^{\frac{2}{s+5}}$

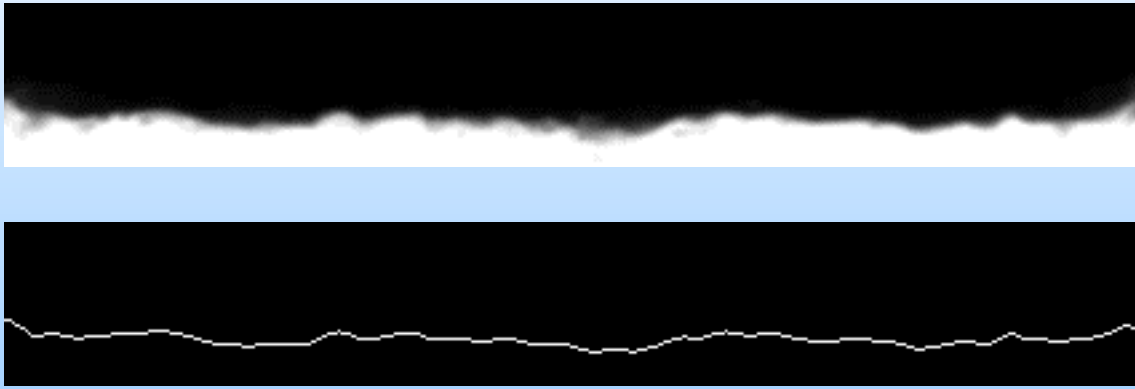


Spectra Measurement

Two methods were used to find the initial spectra

Interfacial method

- Apply edge detection to find a single-valued function for the interface elevation.
- Then find the DFT of this function.



Volume method

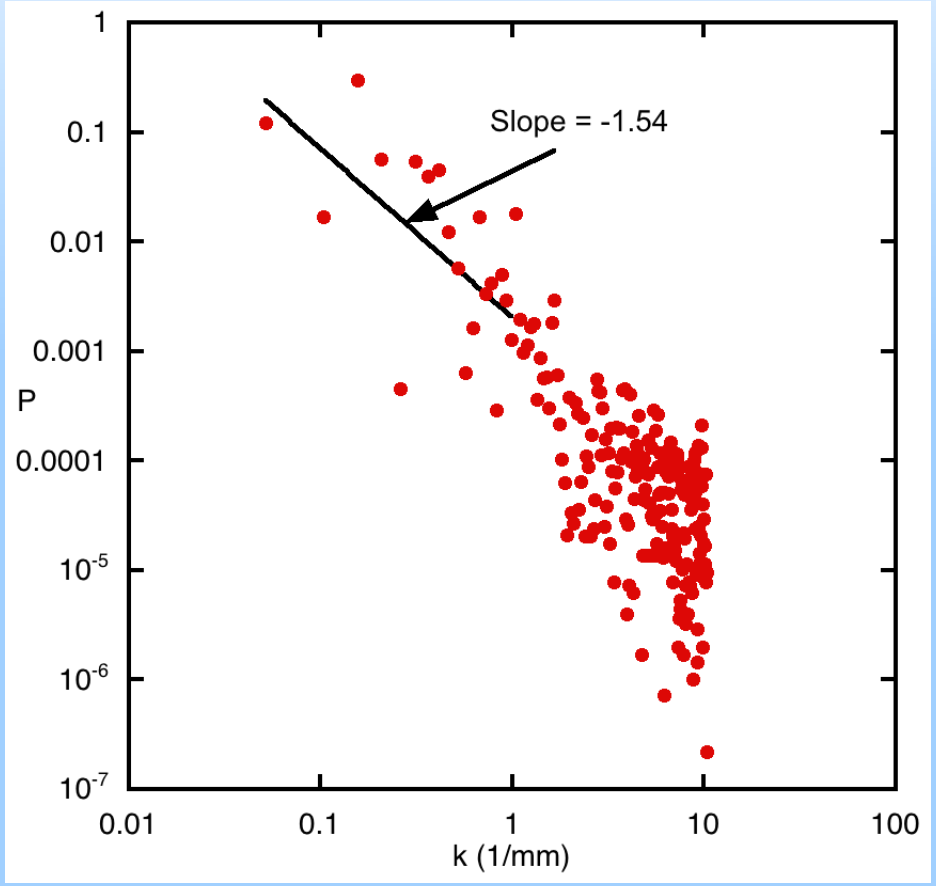
- Find the DFT for the normalized heavy gas concentration of each row in the region where

$$\langle c \rangle \left(1 - \langle c \rangle\right) > 0.3$$

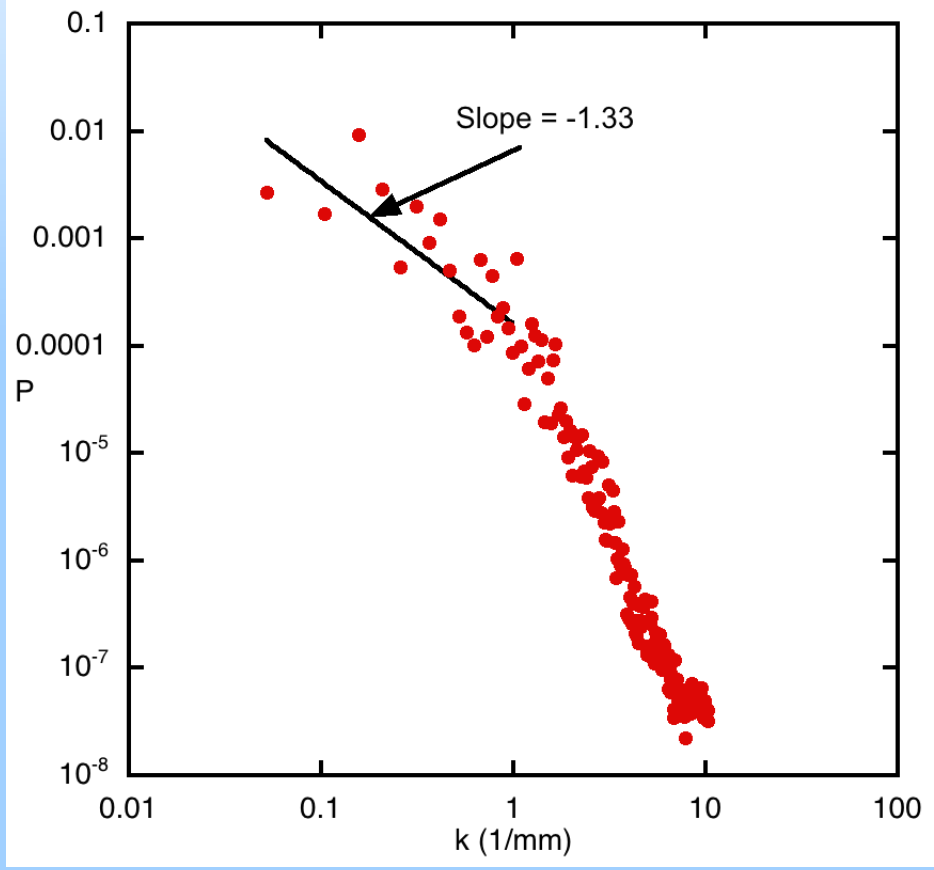
- Then average these spectra as in Olson & Greenough (2014).

Initial Spectra

Interfacial

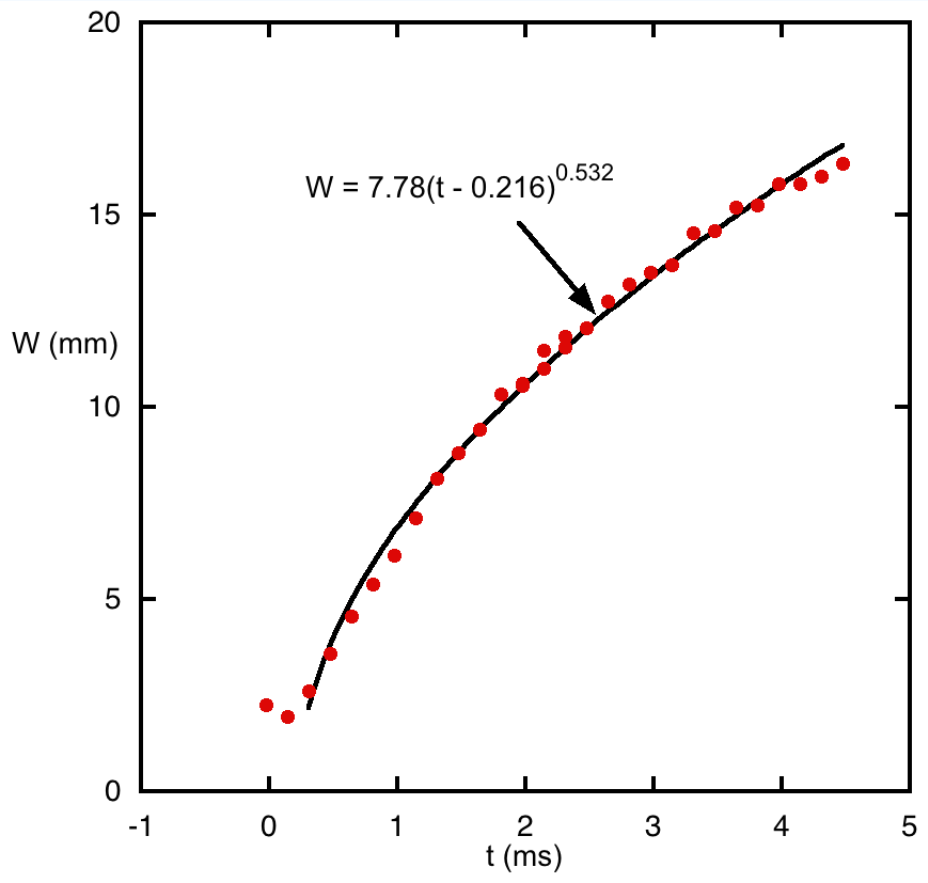


Volume



Done for both pre- and post-shock perturbations

Integral Width Measurements



$$q = \frac{2}{s+5} = 0.54$$

Exp #	s-	s+	θ-	θ+	Measured
1	-2.31	-2.06	0.74	0.68	0.47
2	-1.18	-0.86	0.52	0.48	0.56
3	-1.51	-1.21	0.57	0.53	0.33
4	-1.54	-1.33	0.58	0.54	0.53
5	-1.19	-0.98	0.52	0.50	0.30

Findings/Future Work

- Major Findings
  - Miscibility produces significantly reduced α values in incompressible RTI experiments.
  - Youngs' (2004) model for the initial perturbation dependent growth exponent θ produces reasonable agreement with our shock tube RM experiments.
  - It will difficult for shock tube experiments to obtain the self-similar values of θ.
- Future Work
  - Further explore the effects of initial conditions in RMI experiments.
  - Implement PIV and eventually combined PLIF/PIV in shock tube RMI experiments.
  - Use the LIM drop tower to for incompressible RMI experiments.