EXPERIMENTAL STUDIES OF SHOCK-ACCELERATED GAS INTERFACES

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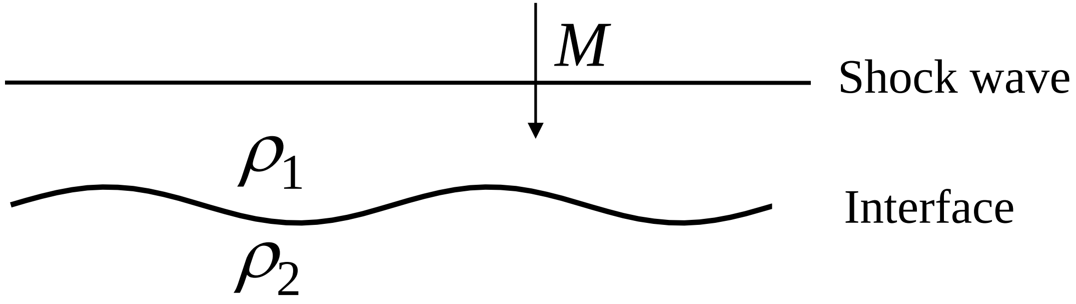
- Scientist: Jason Oakley
- Faculty: David Rothamer

Shock-interface interaction



Interface: between fluids with different densities

(more generally, different acoustic impedances, $\mathscr{R}=\rho a$)

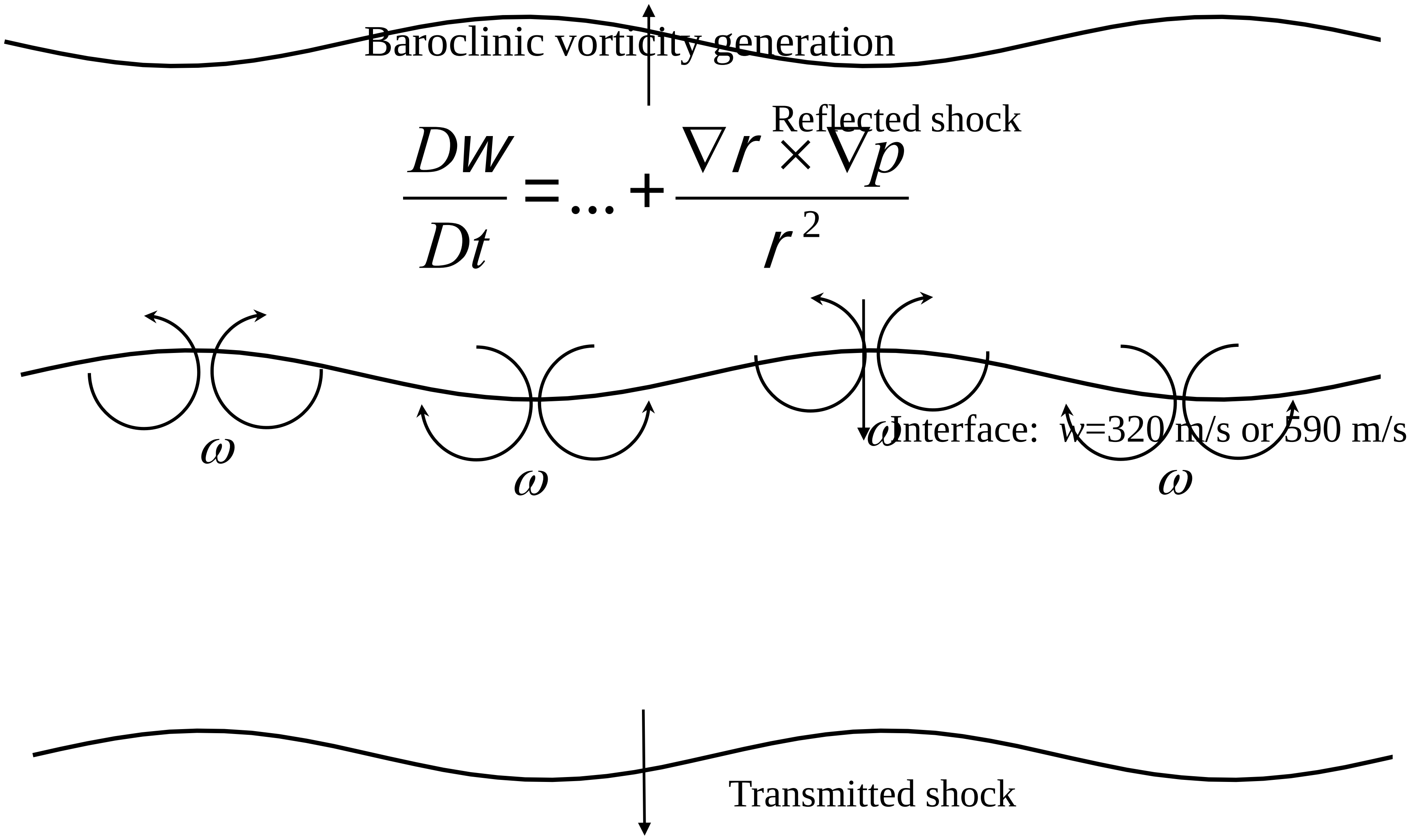
Shock refraction $\begin{cases} \text{Transmission} \\ \text{Reflection} \\ \text{Distortion by focusing/defocusing} \end{cases}$

Interface $\begin{cases} \text{Set into motion at “piston velocity”} \\ \text{Baroclinic vorticity generation} \\ \text{Distortion} \end{cases}$

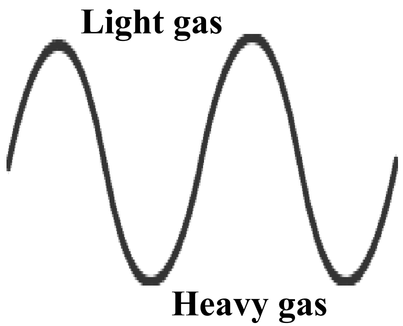
RMI physics

Baroclinic vorticity generation

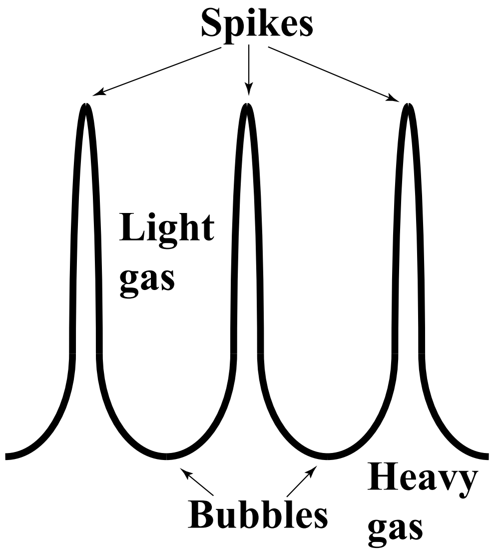
$$\frac{Dw}{Dt} = \ldots + \frac{\nabla r \times \nabla p}{r^{2}}$$

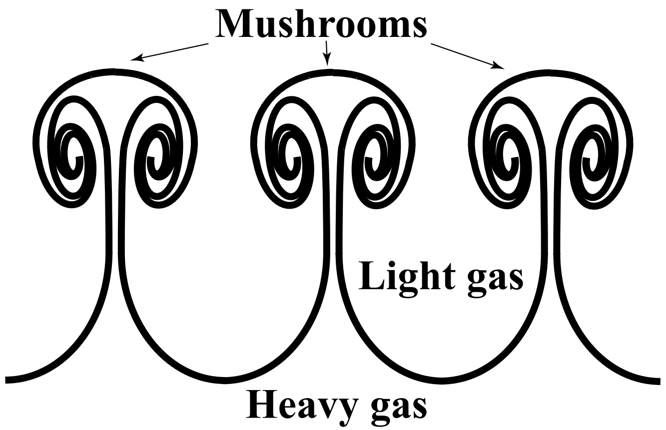


RMI stages



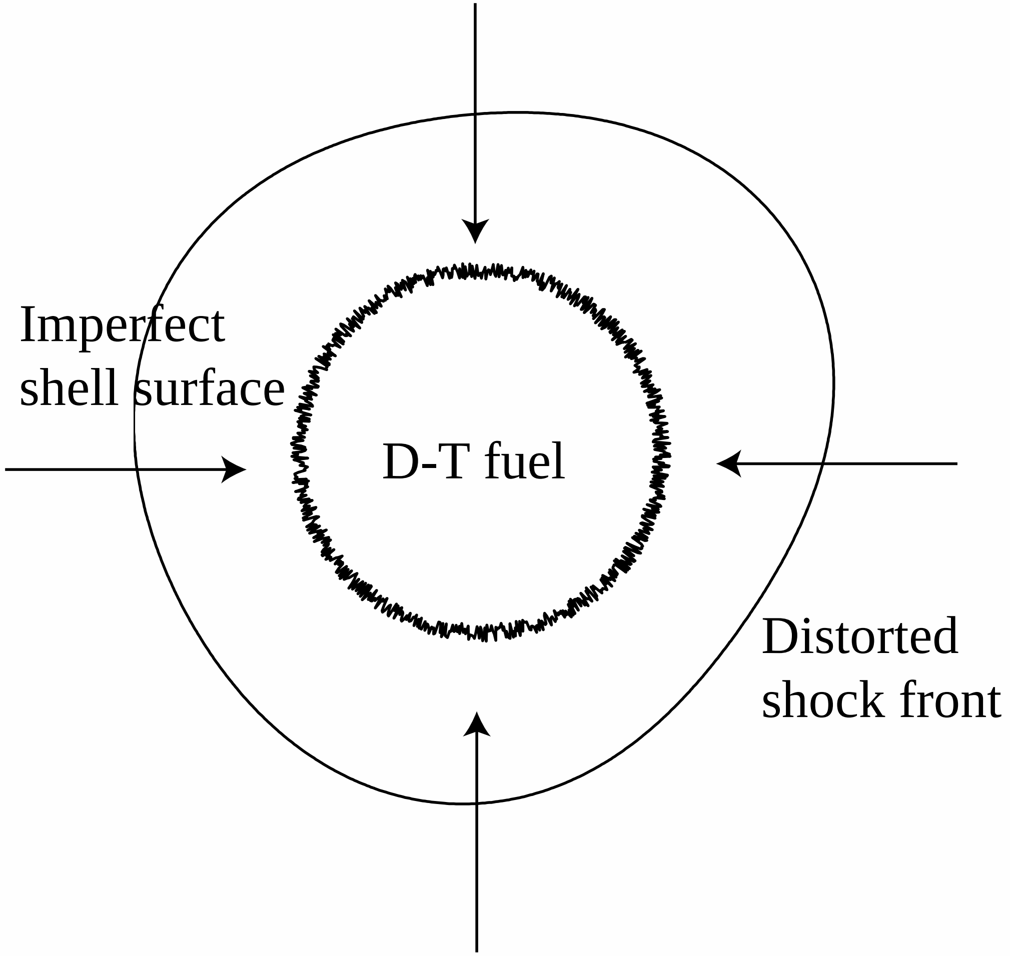
Sinusoidal shape, amplitude growth





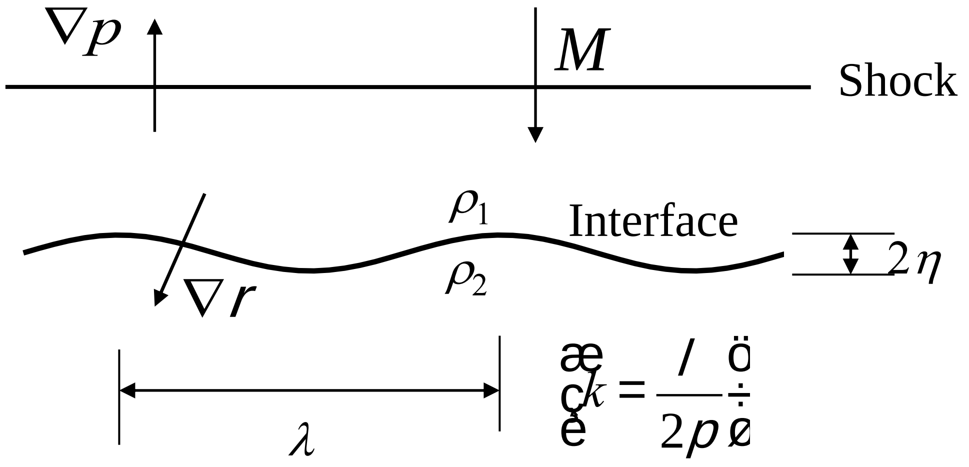
Turbulent mixing layer

Fluid dynamics of ICF s



- Imperfect shell
- Aspherical shock
- Shell ablates
- Shock traverses perturbed interface → RMI
- Shell material and fuel mix
- Fuel contamination → reduced yield or no ignition

The Richtmyer-Meshkov instability (RMI)



2D, single mode, sharp interface

Incompressible (ρ=const), linear analysis ($\eta << \lambda$)

$$\frac{d^2\eta}{dt^2} = kgA\eta \qquad g = [V]\delta(t) \qquad [V] = \text{velocity jump} \qquad A = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

$$\eta(t) = k[V]A\eta_0 t$$

Unstable for $A>0$ **AND** $A<0$!!

If $A>0$, immediate growth

If $A<0$, phase reversal, followed by growth

Broader view

More representative initial conditions

- Multimode
- Three-dimensional
- Diffused

Challenges

- Linear superposition only if $\eta << \lambda$ for ALL λs
- $\eta \sim \lambda$ very quickly for high wavenumbers
- New growth laws
- Non-linear mode-coupling
- Saturation

Laser-driven *vs.* shock tube experiments

	ICF	Shock tube
T-scale	10^6 K	10^2-10^3 K
L-scale	10^{-9}-10^{-3} m	10^{-6}-10^{-2} m
t-scale	10^{-12}-10^{-6} s	10^{-6}-10^{-3} s
ρ-scale	10^3 kg/m^3	10^0 kg/m^3
M	~5-10	≤ 5
A	[-1,1]	[-1,1]

Objectives

- Contribute to understanding of the physics
- Develop database for code benchmarking/calibration/validation

General objectives

Physical quantities of interest

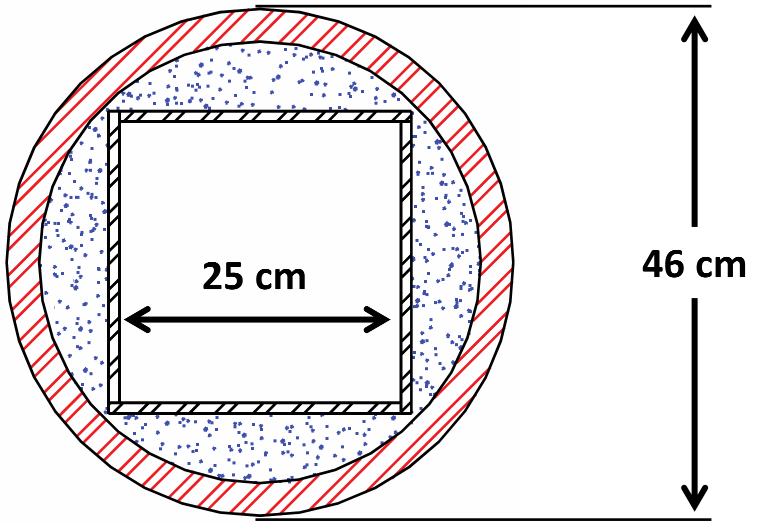
- Fields: velocity, density, temperature (I wish …)
- Geometrical [amplitude (η), thickness (h)]
- Statistical quantities
- Spectra

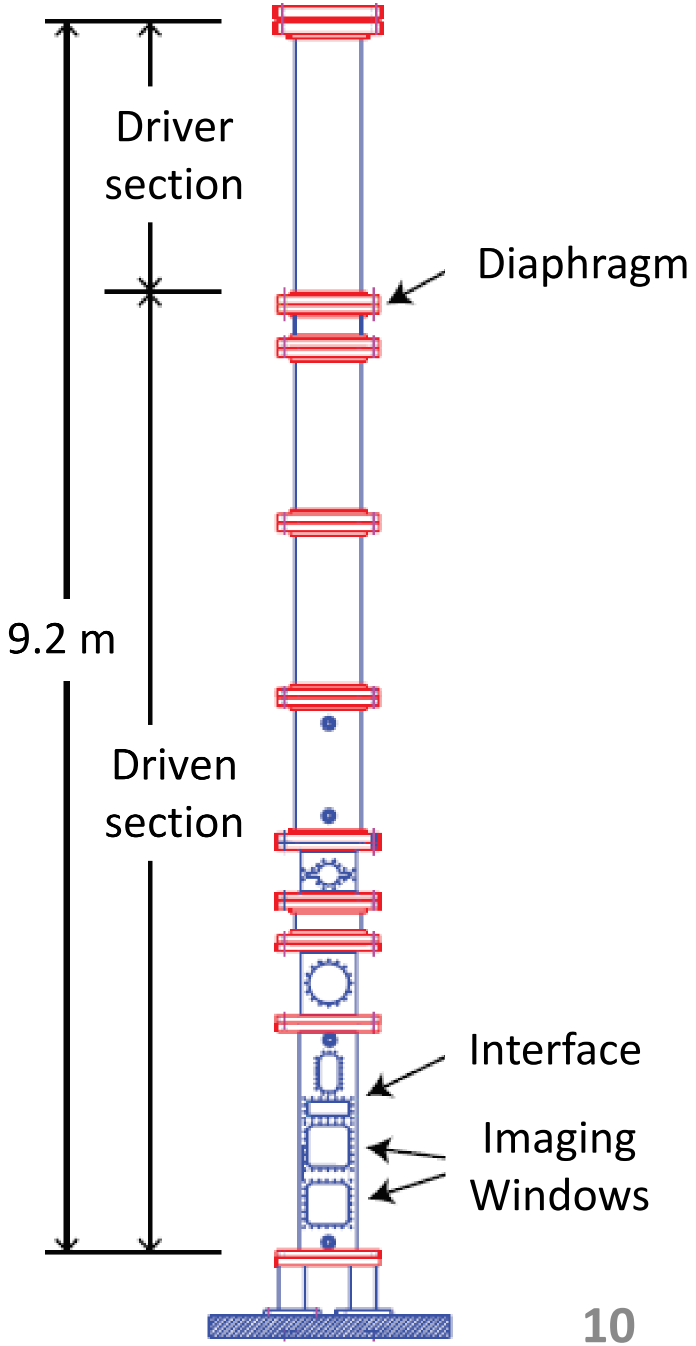
Understanding

- Mixing/dissipation processes
- Effects of IC (initial shape, A, M)

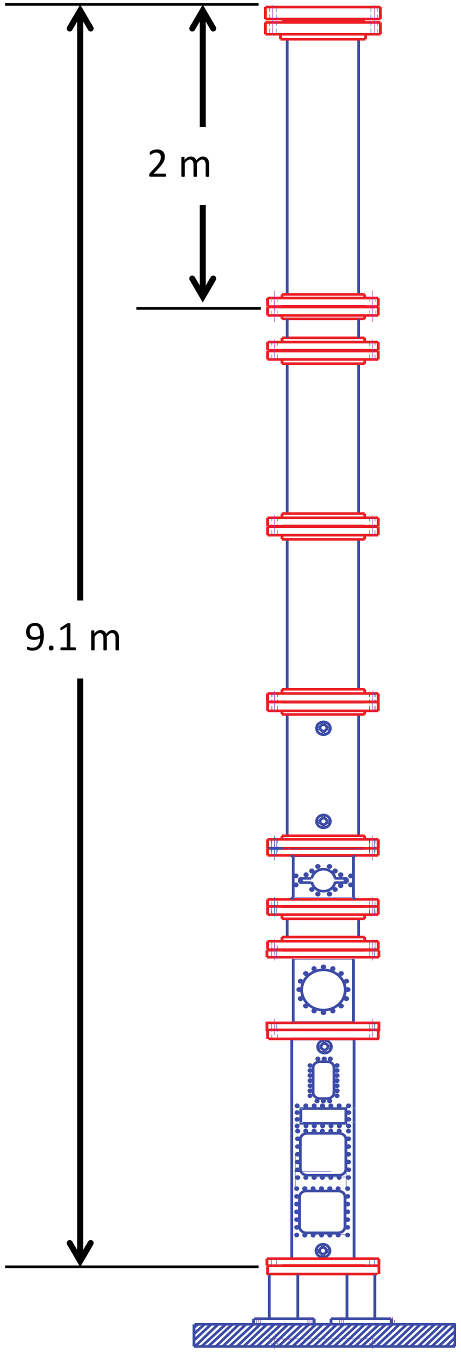
Shock Tube Facility

- Vertical
- Large internal cross-section (25 cm square)
- Total length 9.13 m, driver length 2 m
- Pressure load capability: 20 MPa
- Modular driven section

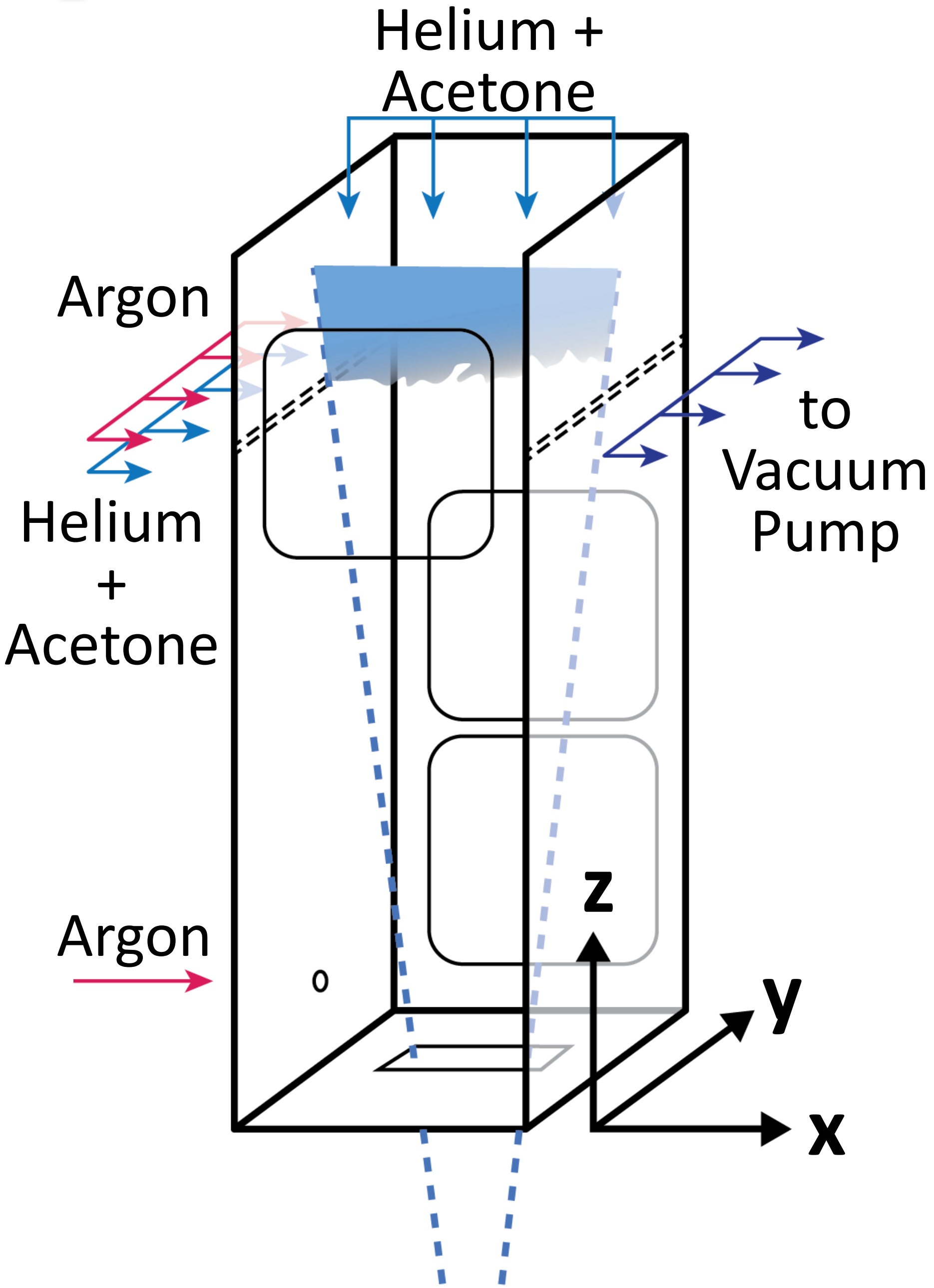


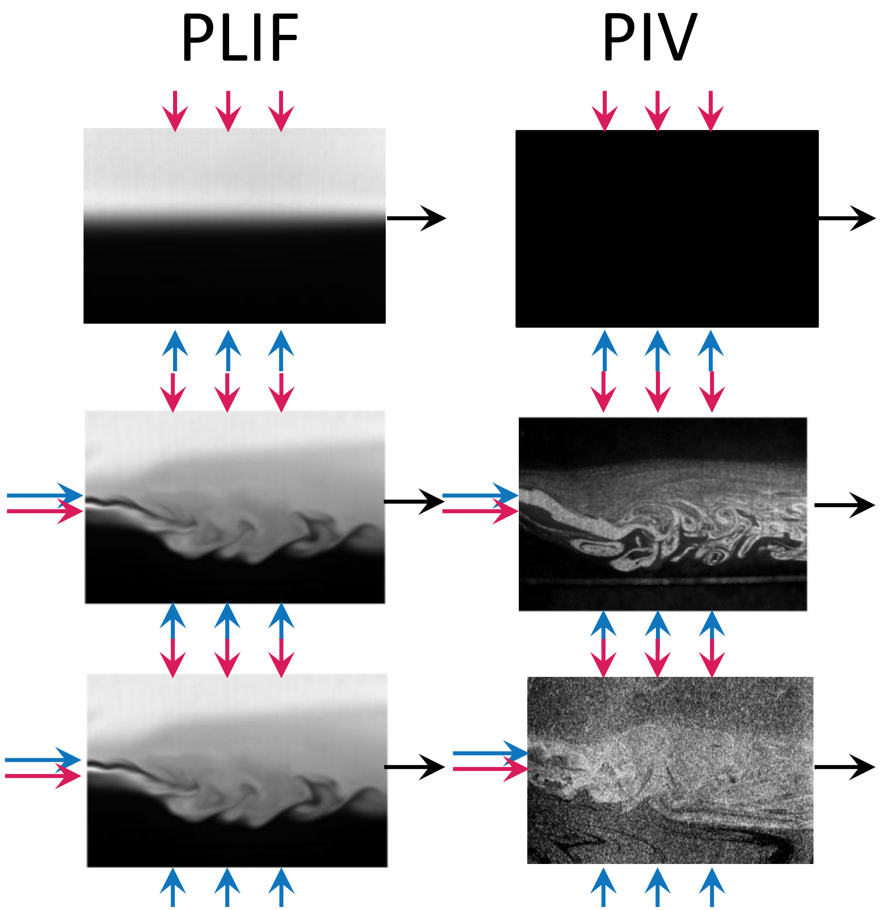


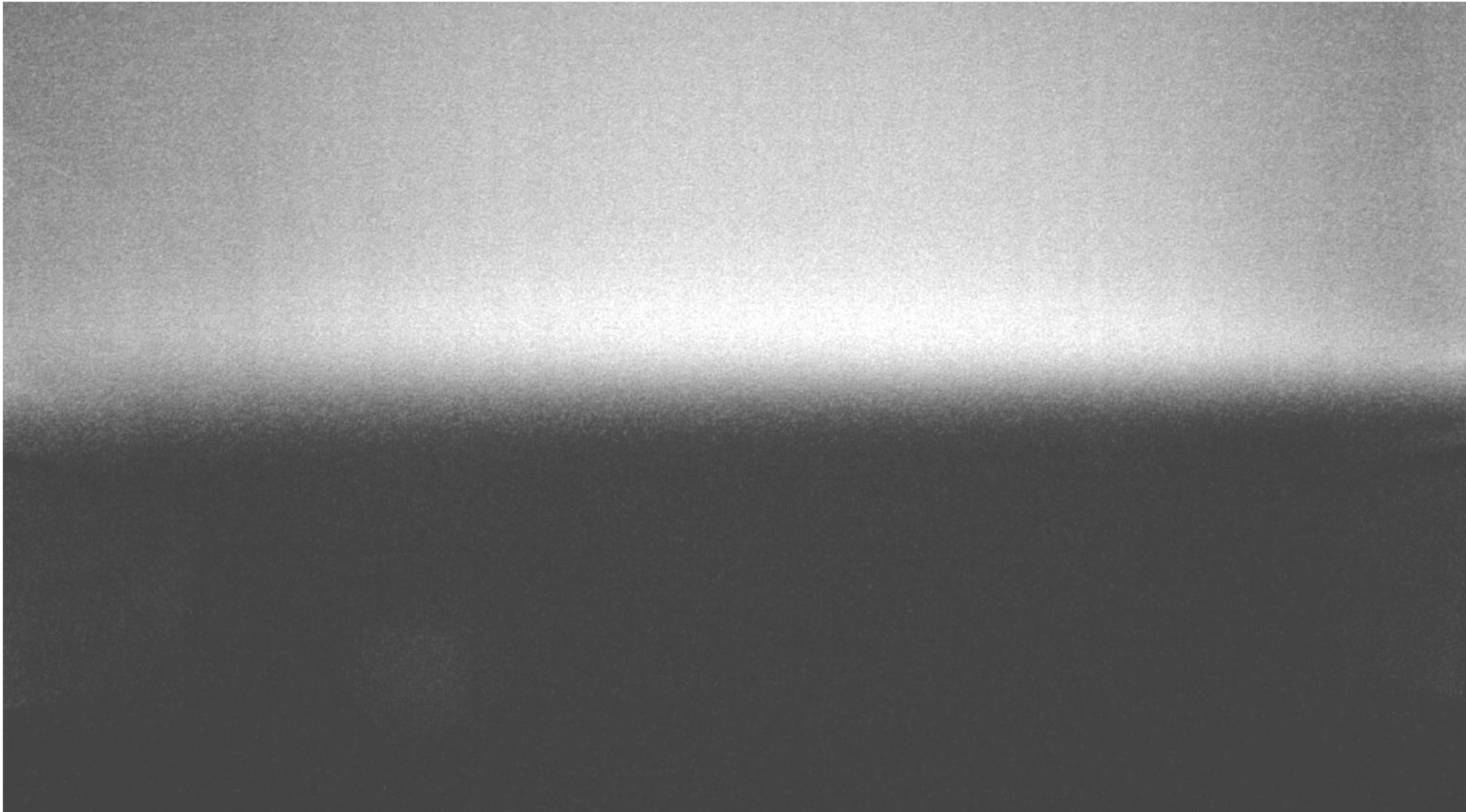
Shock tube facility



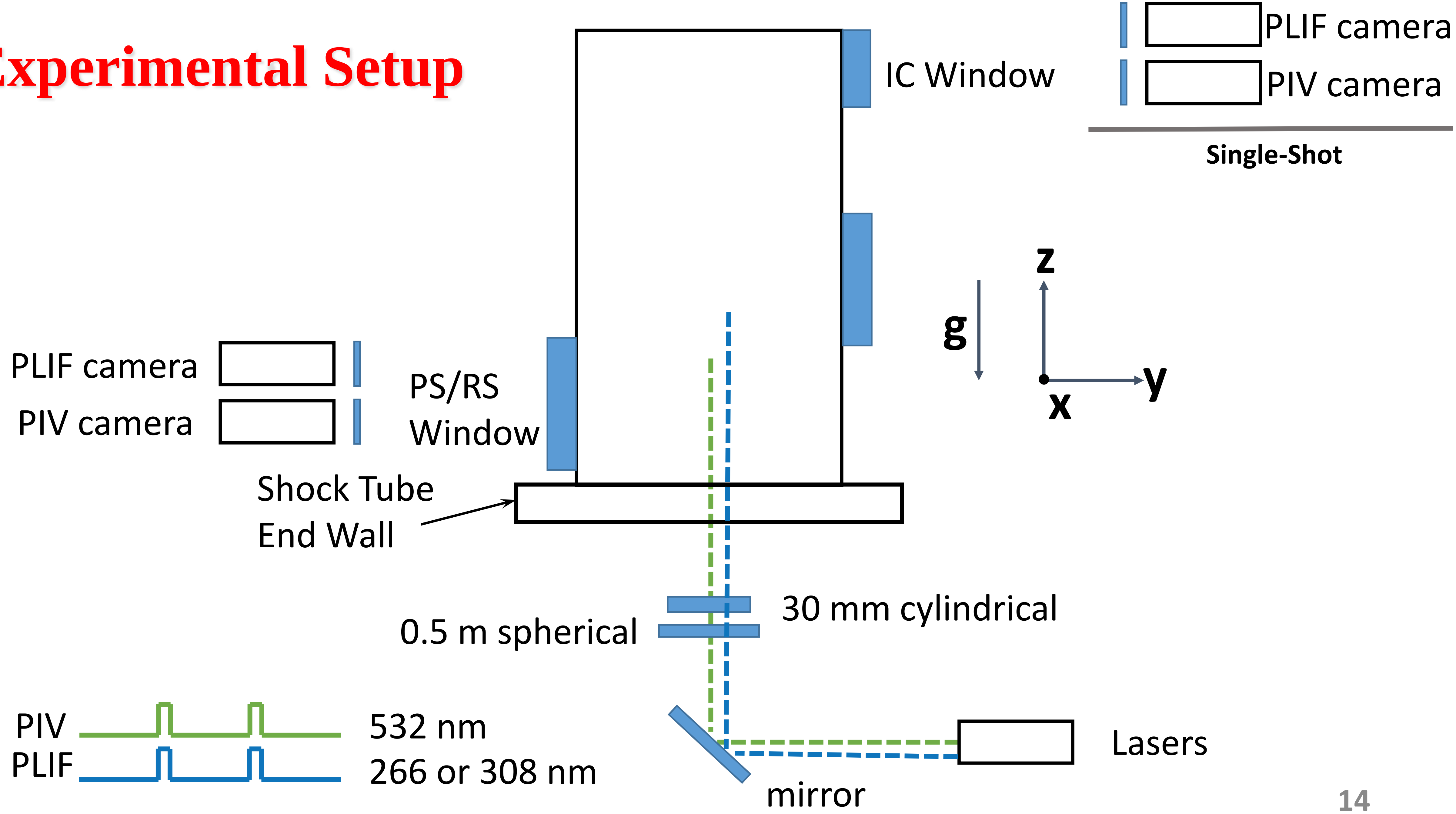
Experiment Details: Initial Condition Setup







Experimental Setup



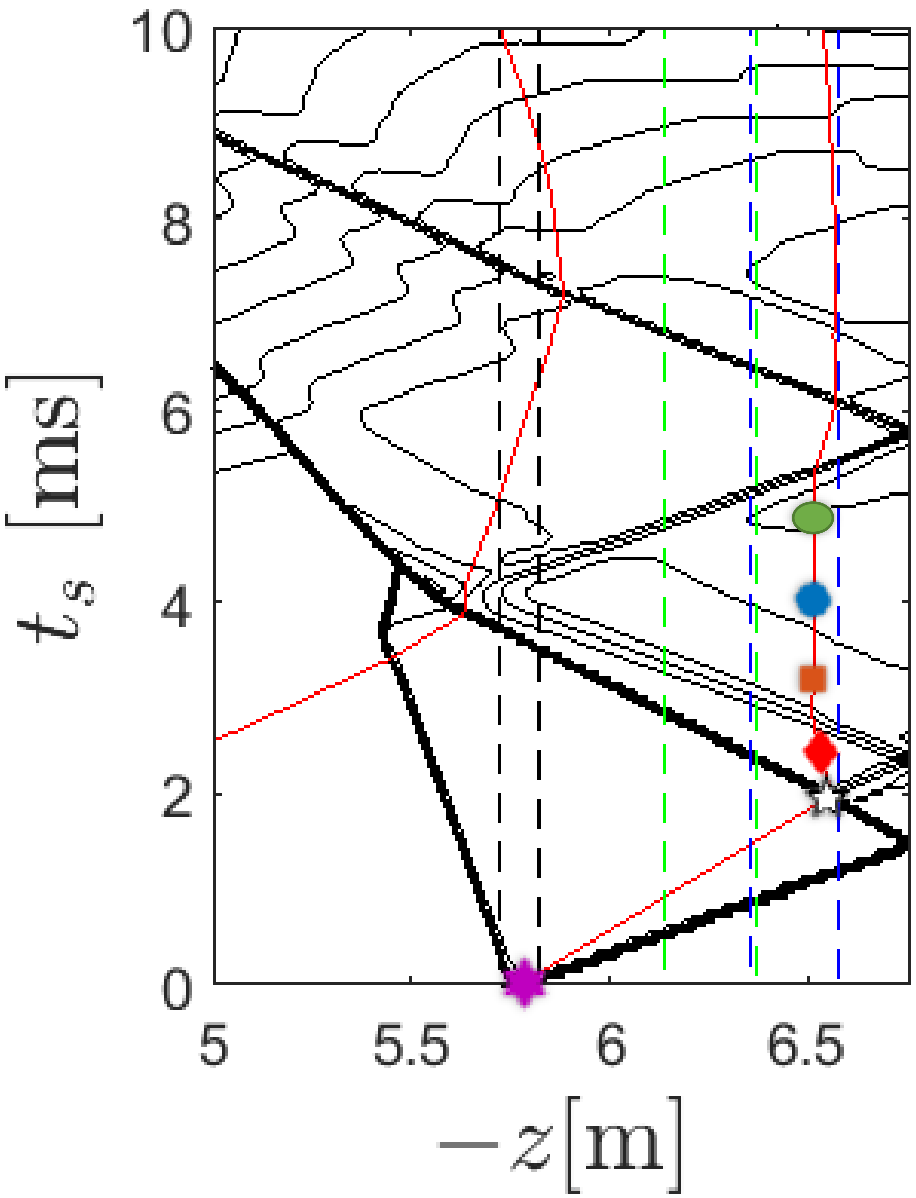
Performed so far

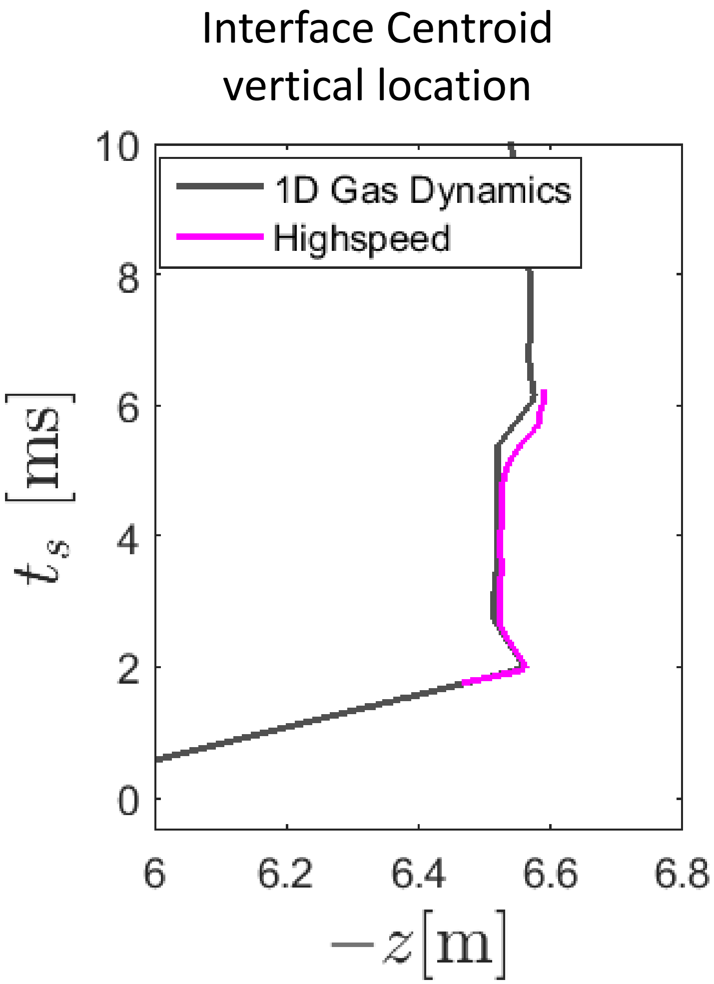
- Single-shot PLIF
- Single-shot PIV
- Concurrent single-shot PLIF/PIV
- High-speed (20 kfps) PLIF

Experiment Details: Interaction Times

M_s	1.9±0.04
M_{rs}	1.7±0.01
A_i	0.43±0.01
A_s	0.27±0.04
A_{rs}	0.23±0.04

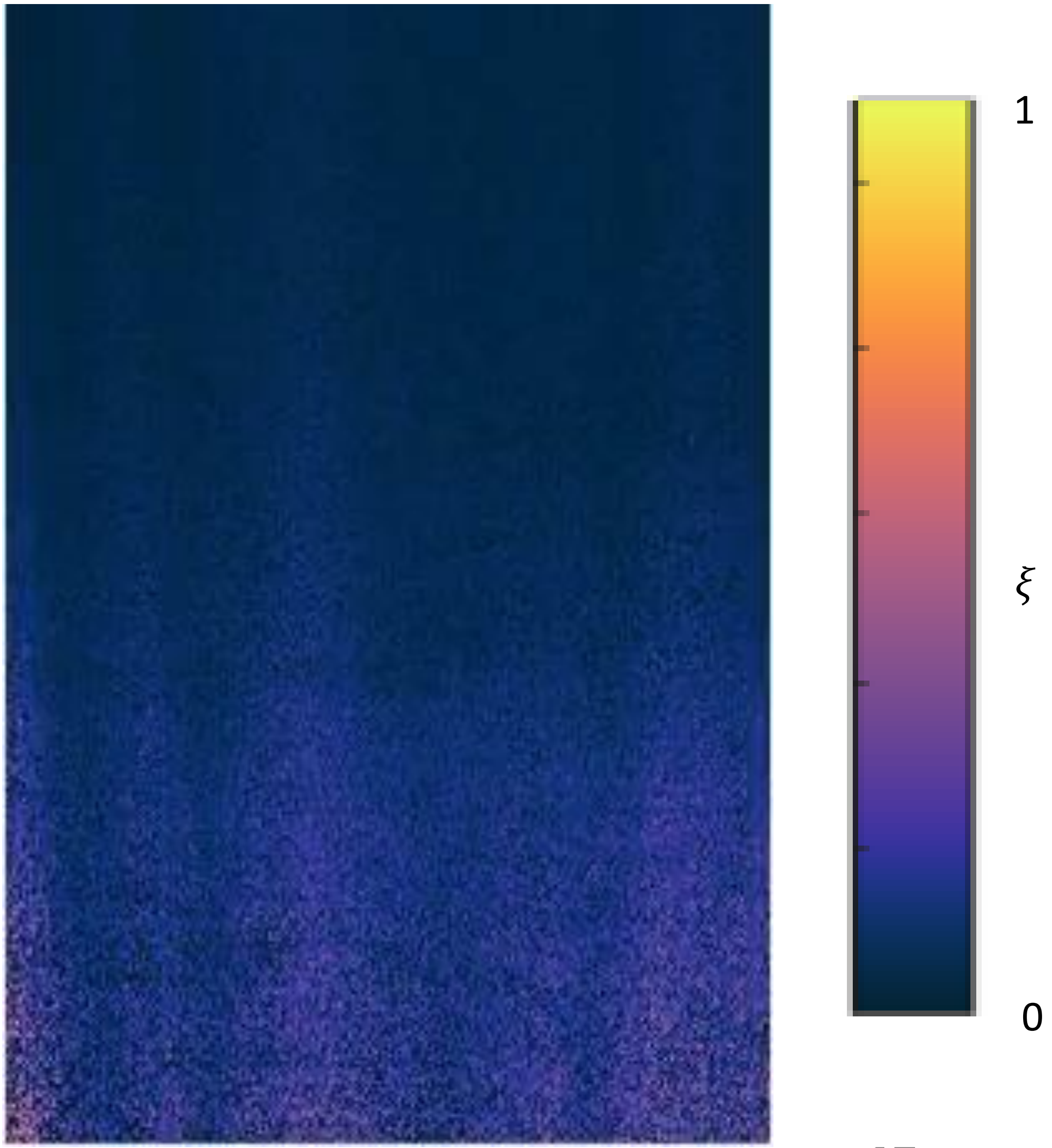
	t_s [ms]	t_{rs} [ms]	Sym
IC	0	-	✶ (magenta)
PS3	2.16	-	☆
RS1	2.3	0.26	◆ (red)
RS2	3.07	1.14	■ (orange)
RS3	3.87	1.92	● (blue)
RS4	4.7	2.75	⬮ (green)





Experiment:
High-Speed PLIF

Evolution of 2D He-concentration field, ξ
(20 kfps)



Numerical Simulations

MIRANDA code (LLNL)

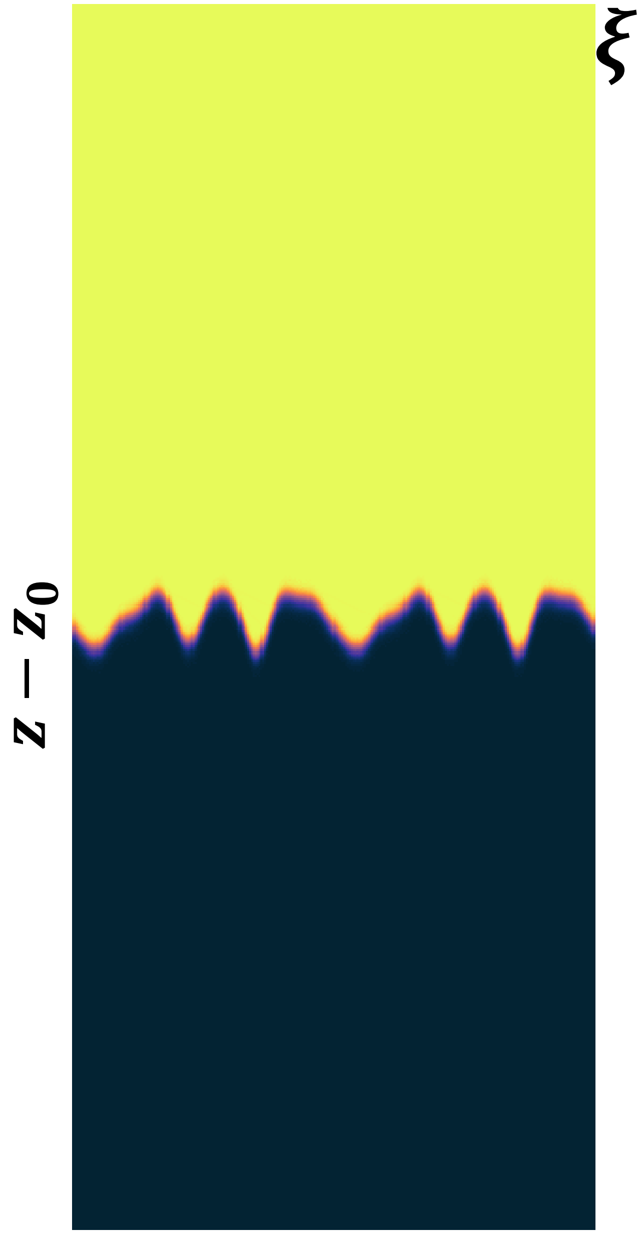
3D multi-mode RMI simulation

M = 1.8, Helium/**Argon**

1280 x 128 x 128 cells

IC=random field of Gaussian perturbations

Periodic BC in the x- and y-directions



Evolution of 2D He-concentration field, ξ
(mid plane of calculation volume)

Experimental Results: Definitions

Light Gas Mole Fraction: ξ

Spanwise average: $\bar{\xi}$

Mixing Thickness: $\boldsymbol{h = 4\int_{-\infty}^{\infty}\bar{\xi}(1-\bar{\xi})\,dz \quad h = h(t)}$ [1]

Initial thickness $\boldsymbol{h_0 = h(t=0)}$

Mole Fraction Weighted Centroid: $\boldsymbol{z_0 = \frac{4}{h}\int_{-\infty}^{\infty} z\bar{\xi}(1-\bar{\xi})\,dz \quad z_0 = z_0(t)}$

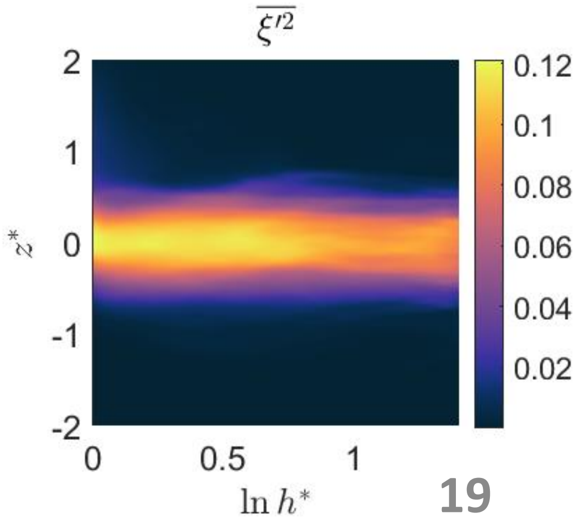
Normalised Mixing Width: $\boldsymbol{h^* = \frac{h}{h_0}}$ Normalised $z-$ coordinate: $\boldsymbol{z^* = \frac{z - z_0}{h}}$ Normalised time: $\tau = t\frac{\dot{h}_0}{h_0}$

$\dot{h}_0$ - Mikaelian mixing width linear growth rate $\dot{h}_0 = C\Delta V A_{rs}$

$C \approx 0.28$ – based on RTI experiments [2]
≈ 0.38 – for 3D multi-mode RMI [3]
≈ 0.57 – estimate from current data

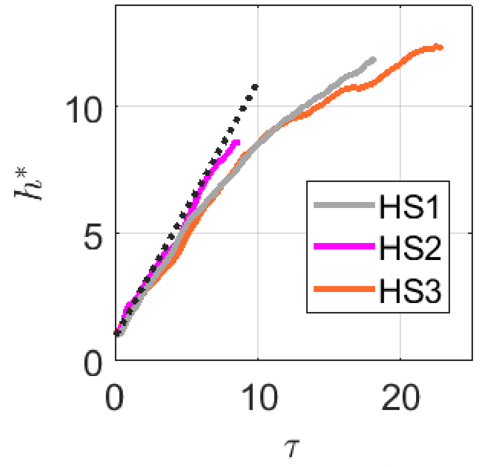
[1] – Lombardini, 2012
[2] – Read, 1984
[3] – Ukai et al, 2011
[4] - B. E. MORGAN ET AL (2017)

Number of Generations: $\boldsymbol{\ln(h^*)}$ [4]

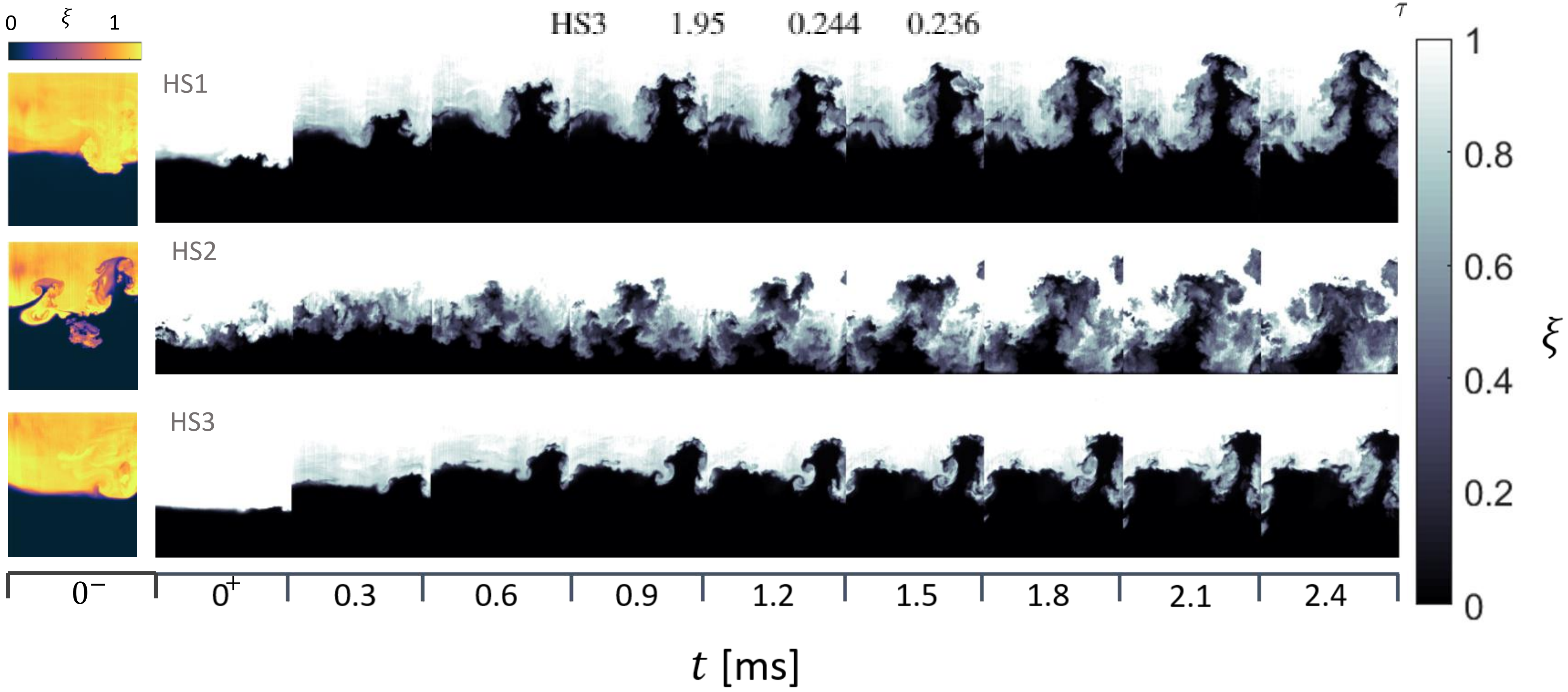


Experiment Results:

Post-reshock high-speed PLIF



	M_s	A^+	A^{++}
HS1	1.94	0.253	0.247
HS2	1.90	0.306	0.312
HS3	1.95	0.244	0.236



Experimental Results: Taylor Microscale

Taylor microscale, λ_T, is the length scale at which viscosity starts affecting the flow.
It can be found using two methods:

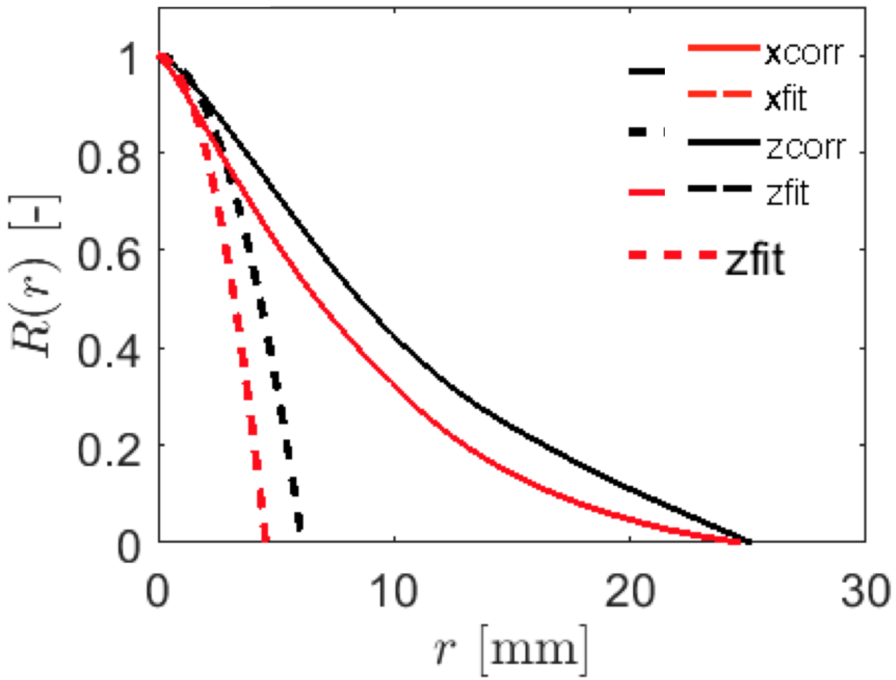
Autocorrelation Method

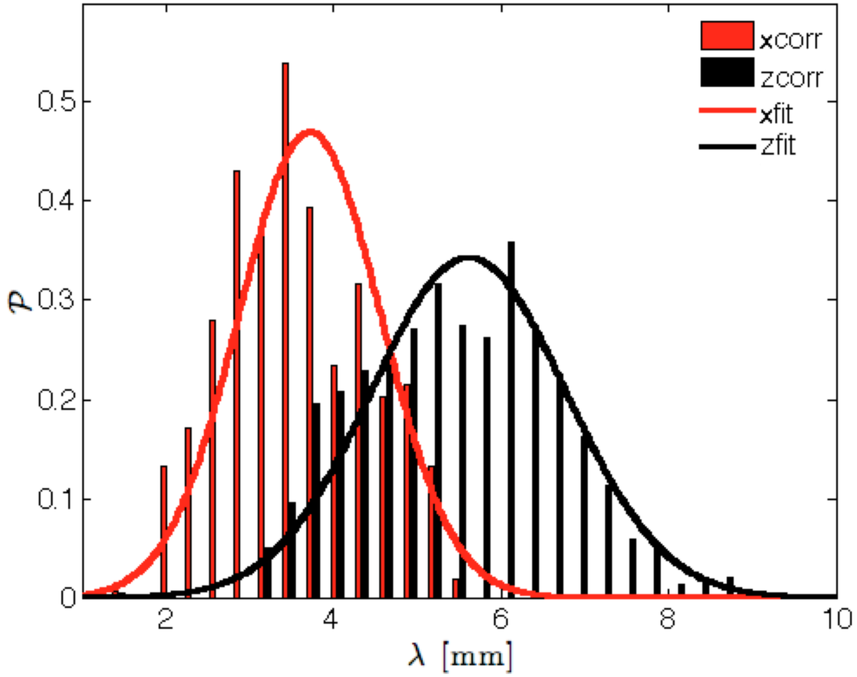
$$R(r) = \frac{\langle u(x)u(x+r)\rangle}{\langle u^2\rangle}$$

$$\lambda_T = \left[-\frac{1}{2}\frac{d^2R(0)}{dr^2} \right]^{-1/2}$$

Variance Method

$$\lambda_{T,x} = \left[\frac{2\langle u^2\rangle}{\left\langle \left(\frac{\partial u}{\partial x}\right)^2 \right\rangle} \right]^{1/2} \qquad \lambda_{T,z} = \left[\frac{2\langle w^2\rangle}{\left\langle \left(\frac{\partial w}{\partial z}\right)^2 \right\rangle} \right]^{1/2}$$



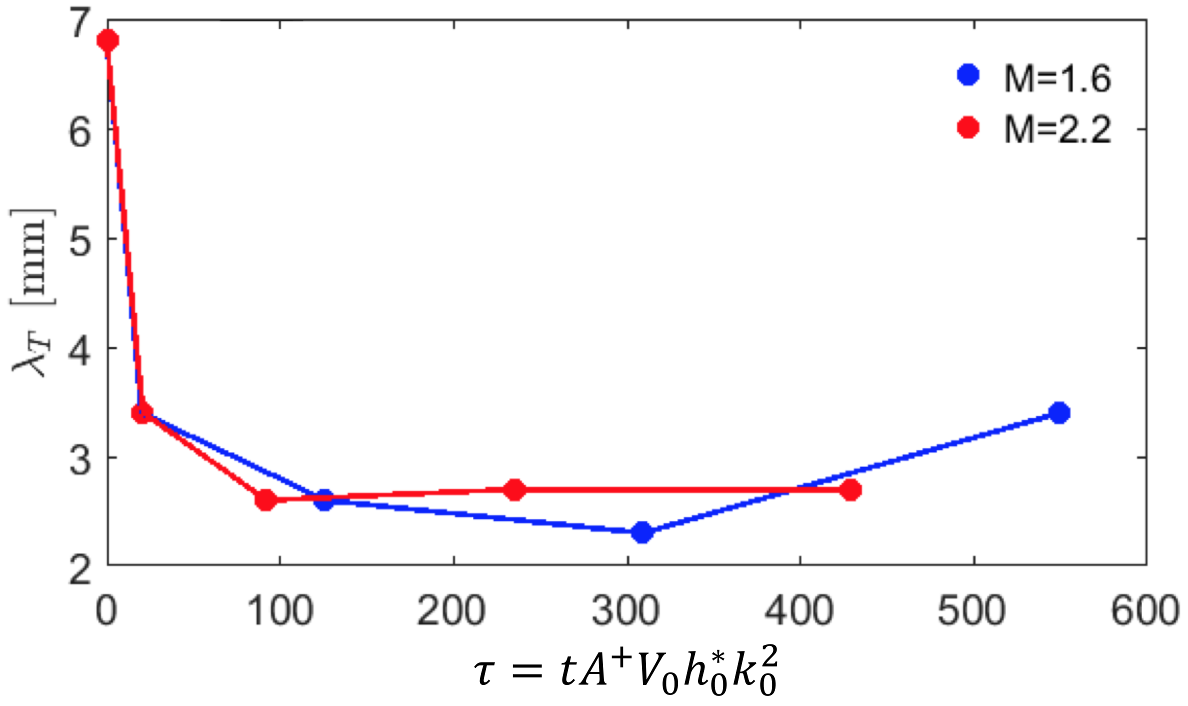


Experimental Results: Taylor Microscale Continued

For nearly all cases, $\lambda_{T,z} < \lambda_{T,x}$

For each method (autocorrelation or variance): $$\boldsymbol{\lambda_T = \sqrt{\lambda_{T,x}^2 + \lambda_{T,z}^2}}$$

Averaging results from the 2 methods gives final λ_T



λ_T ~ const. for M=2.2 suggests flow isotropy

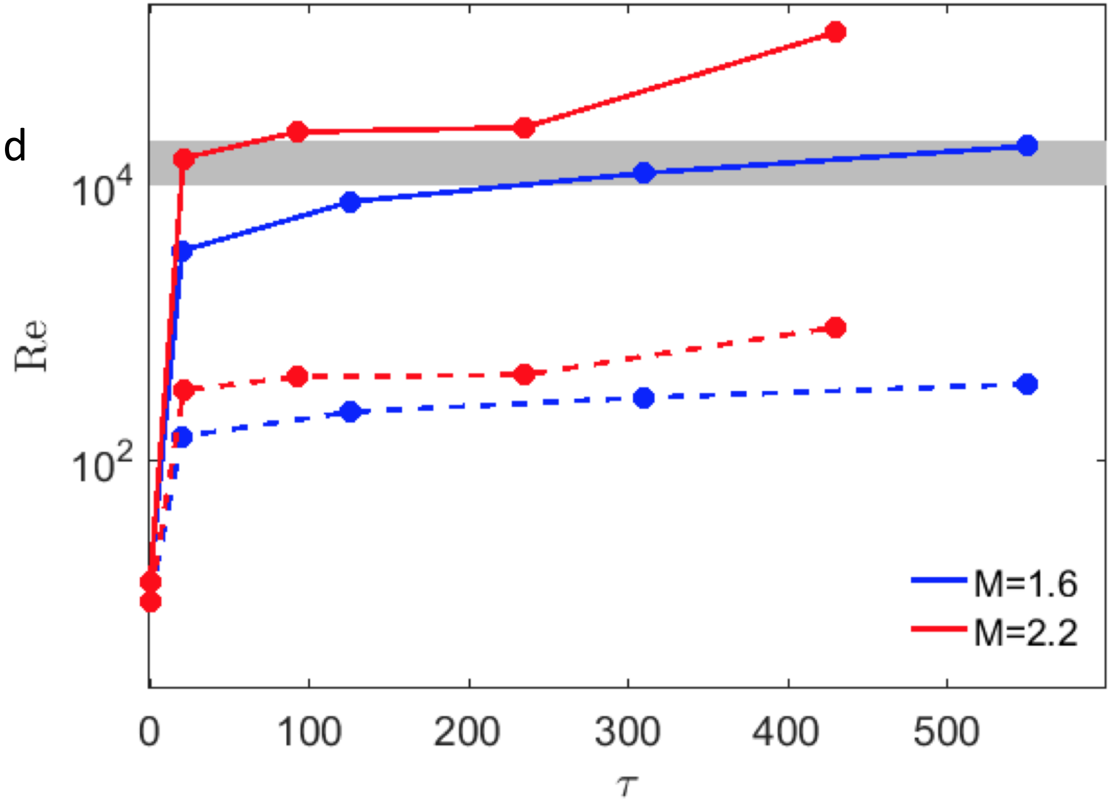
Experimental Results: Reynolds Number

With the Taylor microscale and RMS velocity, estimate Reynolds numbers:

$$Re_\lambda = \frac{V_{RMS}\lambda_T}{\nu} \rightarrow Re = \frac{3}{20} Re_\lambda^2$$

$$V_{RMS} = \sqrt{\langle u'^2 \rangle}$$

Mixing transition threshold
(Dimotakis, *JFM*, 2000)



$\tau = tA^+V_0h_0^*k_0^2$

Experimental Results:

Structure Functions and Exponents

$$S_{\xi,p}(r_x^*, z^*, h^*) = \overline{\left(\xi(x^* + r_x^*, z^*, h^*) - \xi(x^*, z^*, h^*)\right)^p}$$

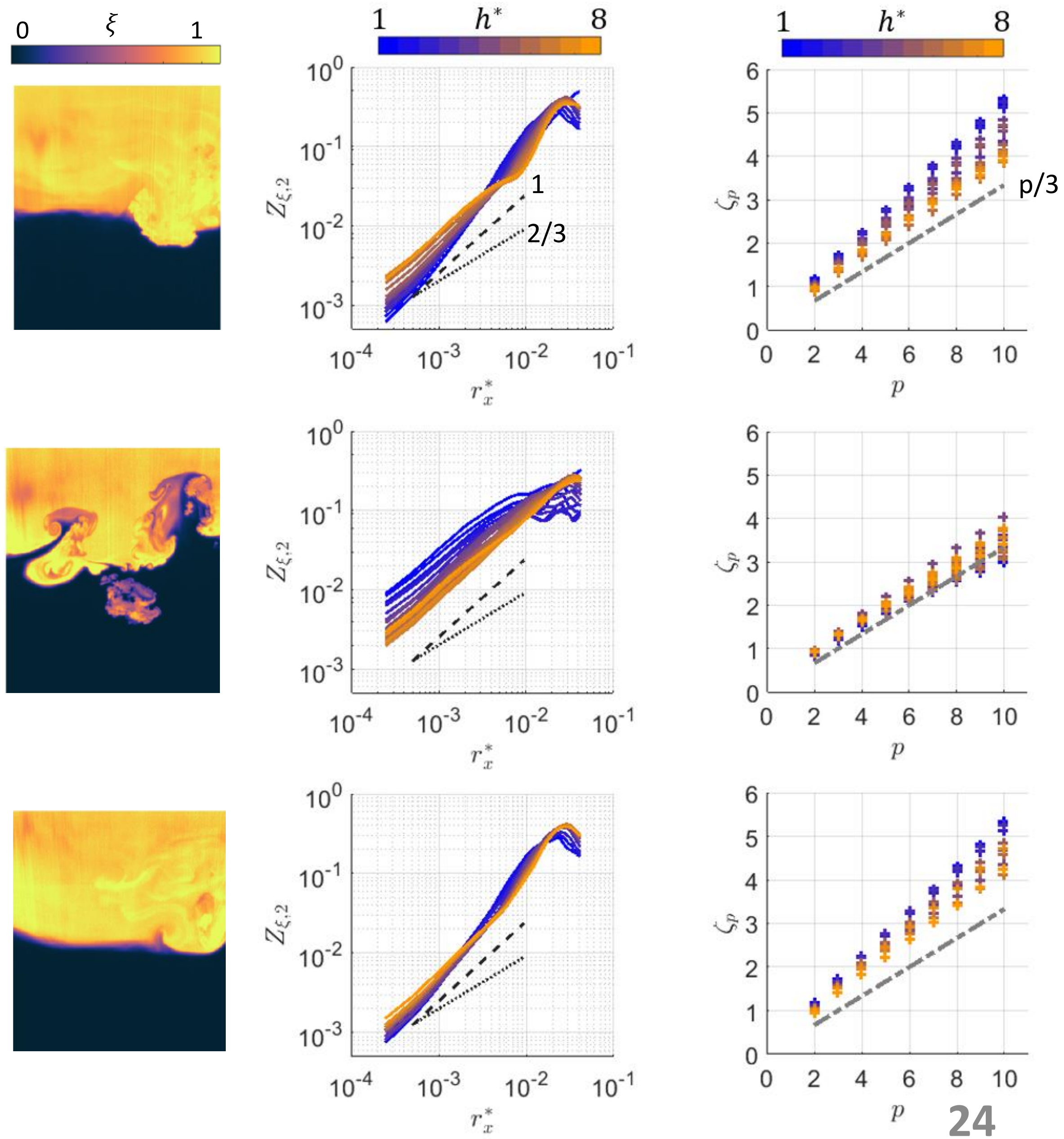
$$Z_{\xi,p}(k_x^*, h^*) = \int_{-\infty}^{\infty} S_{\xi,p} dz^* \qquad \zeta_p = \frac{\partial ln Z_{\xi,p}}{\partial ln r_x^*}$$

KOC scaling: $\zeta_p = \frac{p}{3}$ (homogeneous turbulence)

Kraichnan scaling: $\zeta_p = \frac{1}{2}\left[\sqrt{6p+4} - 2\right]$

$$\lim_{p \to \infty} \zeta_p \propto \sqrt{p}$$

Scaling - KRAICHNAN (1994)



Experimental Results:

Power Spectra

Fourier transform: $\hat{\xi}$ Complex-conjugate: $\hat{\xi}^{\times}$

$$E_\xi(k_x^*, z^*, h^*) = \hat{\xi}\hat{\xi}^{\times}$$

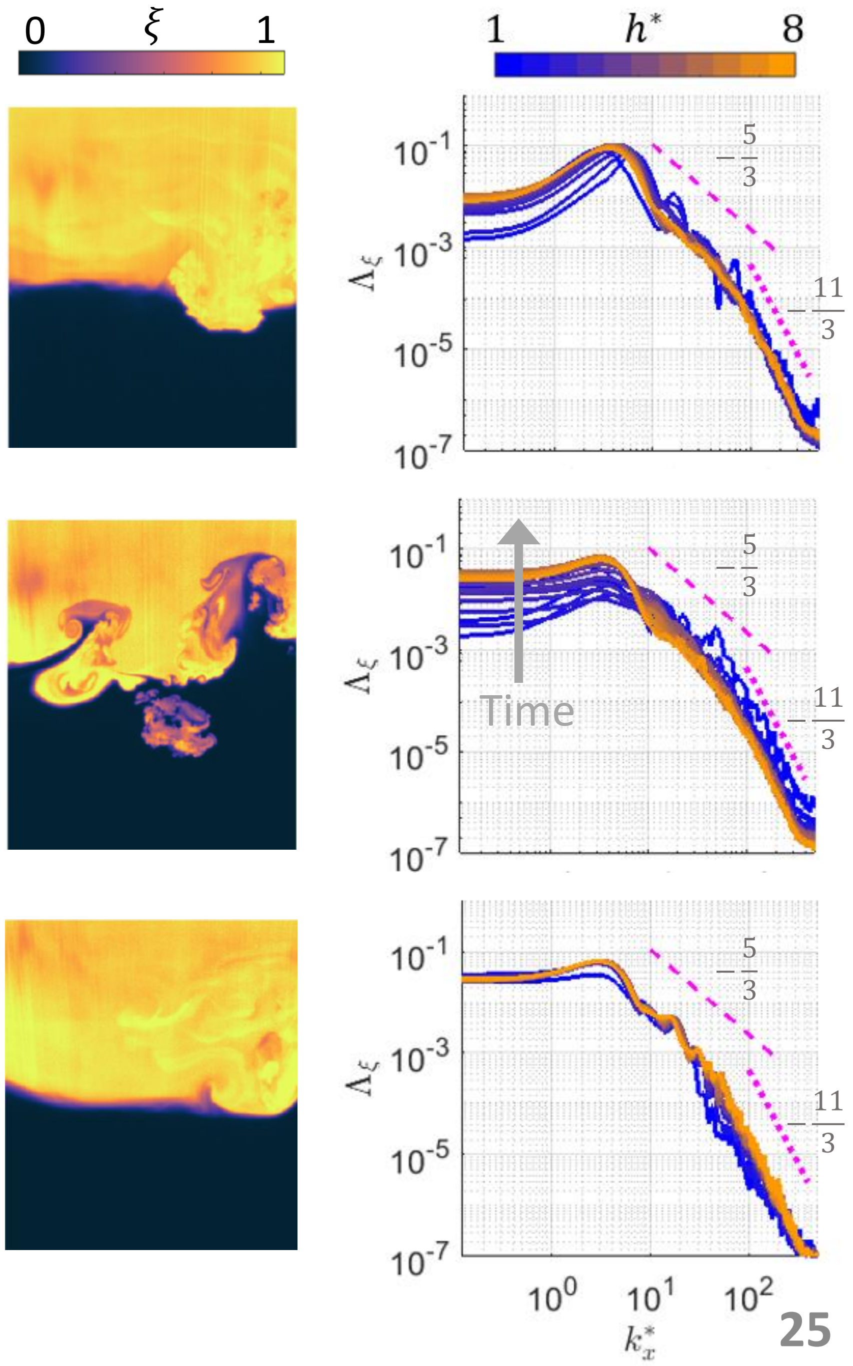
$$\Lambda_\xi(k_x^*, h^*) = \int_{-\infty}^{\infty} E_\xi \, dz^*$$

Inertial Range (Kolmogorov-Obukhov-Corrsin) scaling: $-\frac{5}{3}$

Inertial - Diffusive Range (Batchelor) Scaling: $-\frac{17}{3}$ $(Sc \ll 1)$

In present experiments, dominant scaling: $-\frac{11}{3}$ $(Sc \sim 0.1)$

Scaling ranges – SREENIVASAN and KATEPALLI (2019)
Inertial – diffusive scaling – BATCHELOR *et al* (1959)



“Generalized” Energy Transport Equation

E is “some” descriptor of the energy content

Focus here

Time evolution of the energy at a given scale

Scale to scale energy transport

Molecular diffusion in scale space

Molecular dissipation

$$\frac{\partial E}{\partial \tau} - \mathcal{P} - \frac{\partial \pi_l}{\partial l} + \frac{\partial \pi_z}{\partial z} = D_l + D_z - \chi$$

Production of energy

Transport of energy in inhomogeneous direction

Molecular diffusion in inhomogeneous direction

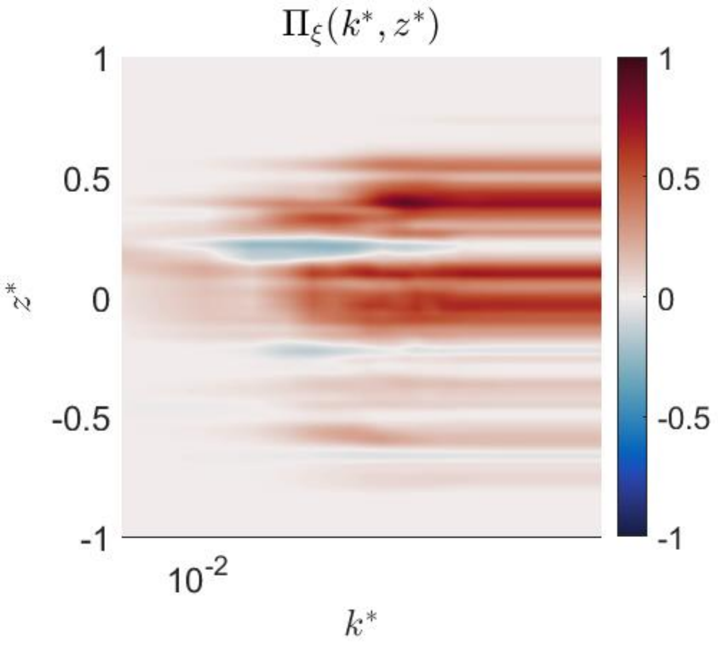
Spectral Transport: Results from simulations

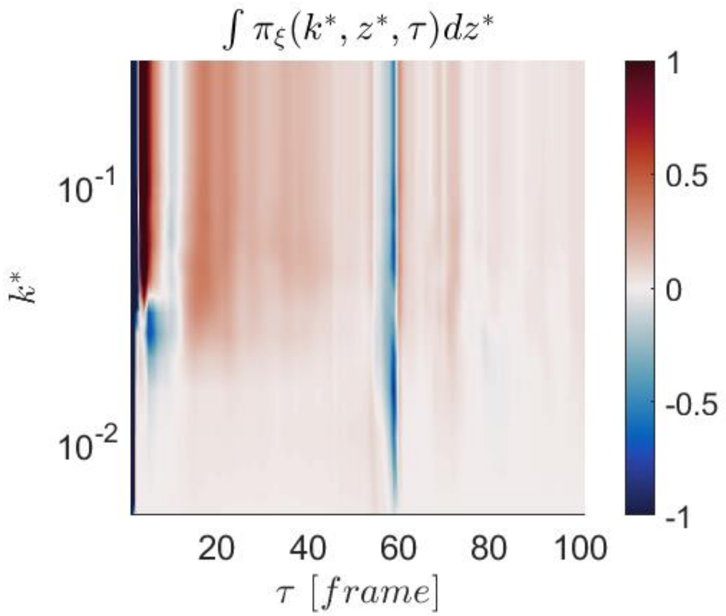
$$\frac{\partial \pi_\xi}{\partial k^*} = ik\left(\widehat{u\xi}\hat{\xi}^\times - \widehat{u\xi}^\times\hat{\xi}\right) = k^*\sqrt{E_{u\xi}E_\xi}\,\sin\left(\frac{1}{2}\left(\phi_{u\xi} - \phi_\xi\right)\right)$$

$\phi_{u\xi}, \phi_\xi$: phases of the spectra

$$\pi_\xi(k^*, z^*, \tau) = \int \frac{\partial \pi_\xi}{\partial k^*}(k^*, z^*, \tau)\,dk^*$$

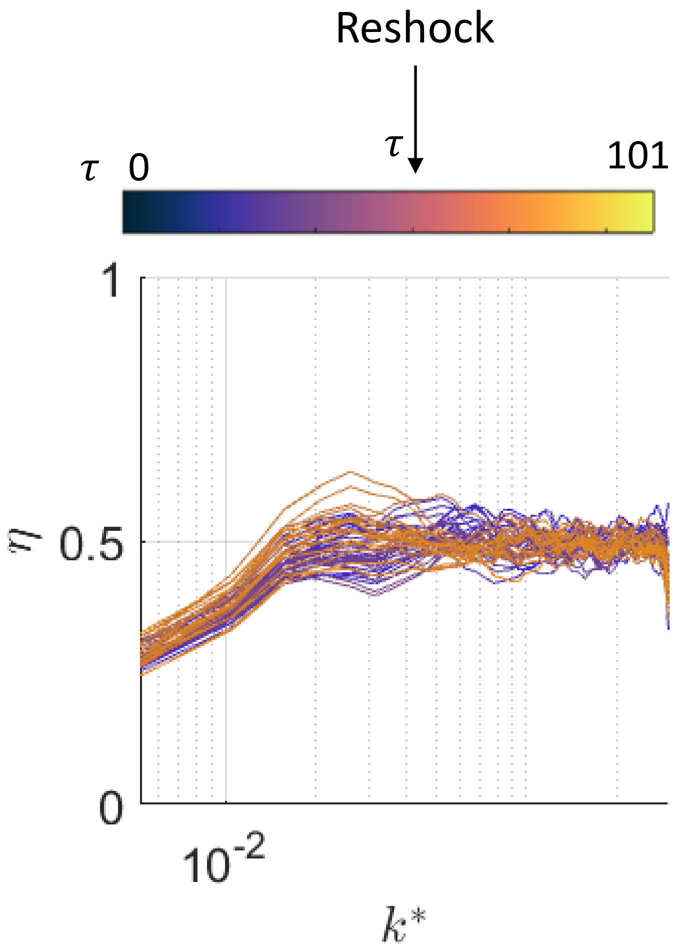
$$\Pi_\xi(k^*, z^*) = \int_{frame\ 20}^{frame\ 50} \pi_\xi(k^*, z^*, \tau)\,d\tau$$ (entirely pre-reshock)





Efficiency

$$\eta_{\pi_\xi} = \frac{\int \sqrt{E_{u\xi} E_\xi} \sin\left(\frac{1}{2}(\phi_{u\xi} - \phi_\xi)\right) dz^*}{\int \sqrt{E_{u\xi} E_\xi}\, dz^*}$$



Spectral Transport:
Single-shot experiments

$$T_{\xi\xi}(K,Q) = \int \xi_K (\boldsymbol{u}\cdot\nabla)\xi_Q \, dx^2$$

$$\hat{\xi} = \mathcal{F}[\xi']$$

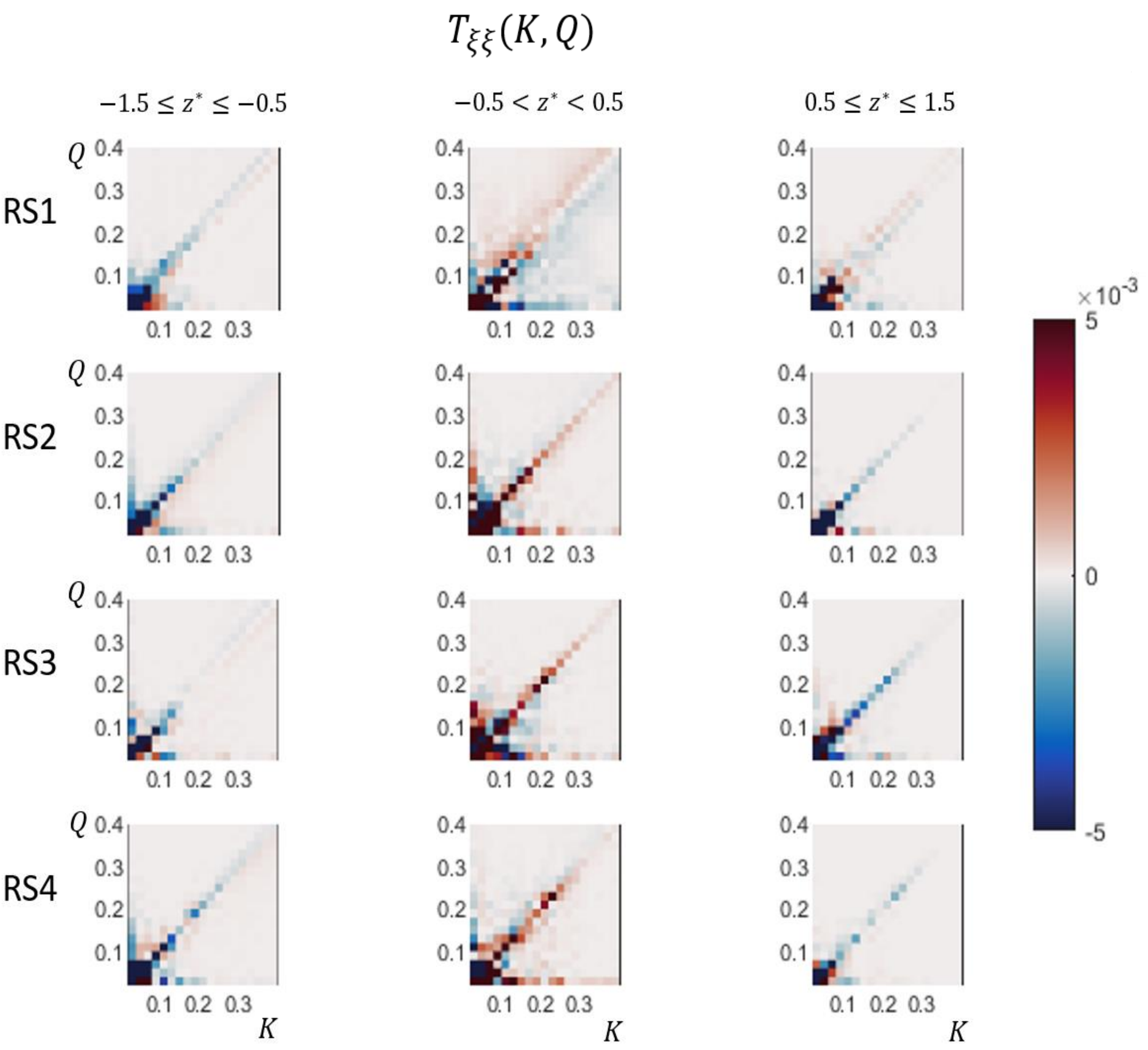
$$\hat{\xi}_K = \begin{cases} \hat{\xi} \; for \; k = [K-\delta, K+\delta] \\ 0 \; for \;\; k \neq [K-\delta, K+\delta] \end{cases}$$

$$\xi_{\mathrm{K}} = \mathcal{F}^{-1}[\hat{\xi}_K]$$

$$\frac{\partial \int \pi_\xi dz^*}{\partial K} = \int T_{\xi\xi} dQ$$

Alexakis, Mininni, Pouquet, Phys. Rev. E (2005)

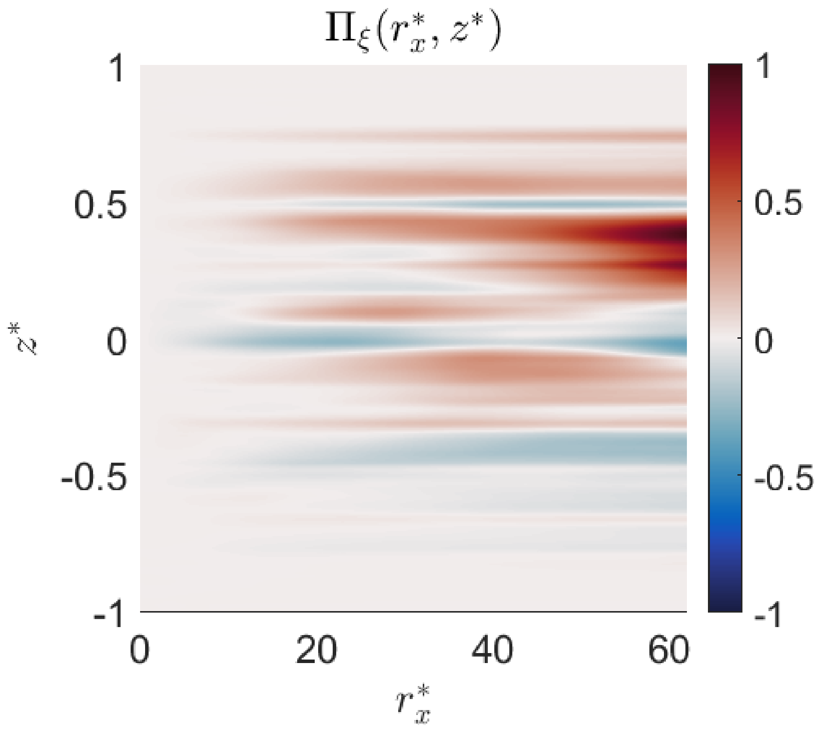
(This paper is about intervariable energy transfer in MHD)

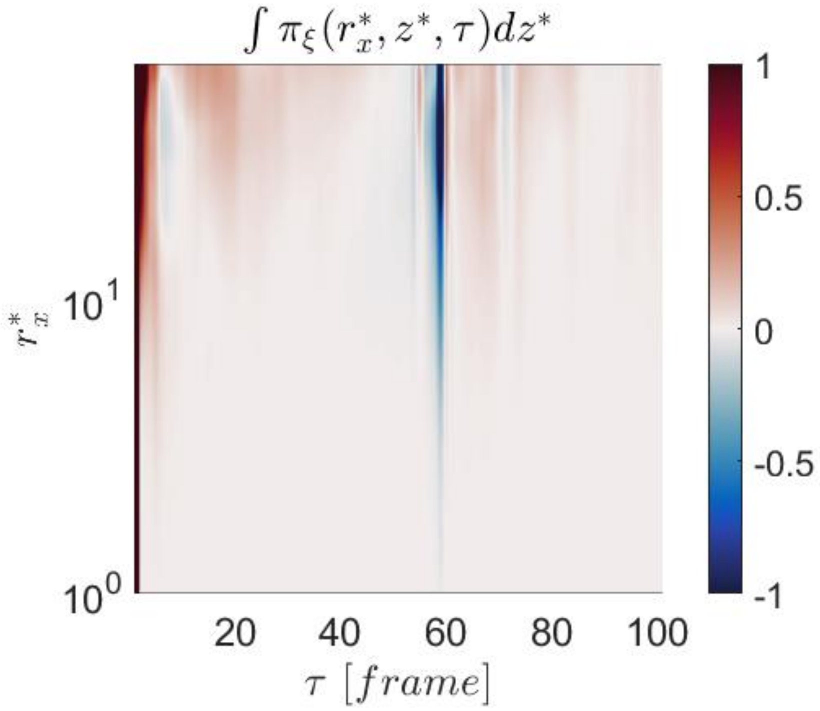


Scale Transport: Results from simulations

$$E = S_2(r^*, z^*, \tau) = \overline{\delta\xi^2} = \overline{\left(\xi(x^* + r^*, z^*, \tau) \; - \xi(x^*, z^*, \tau)\right)^2}$$

$$\frac{\partial \pi_\xi}{\partial r^*} = 2\overline{\delta\xi \frac{\partial \, \delta u\xi}{\partial r^*}}$$





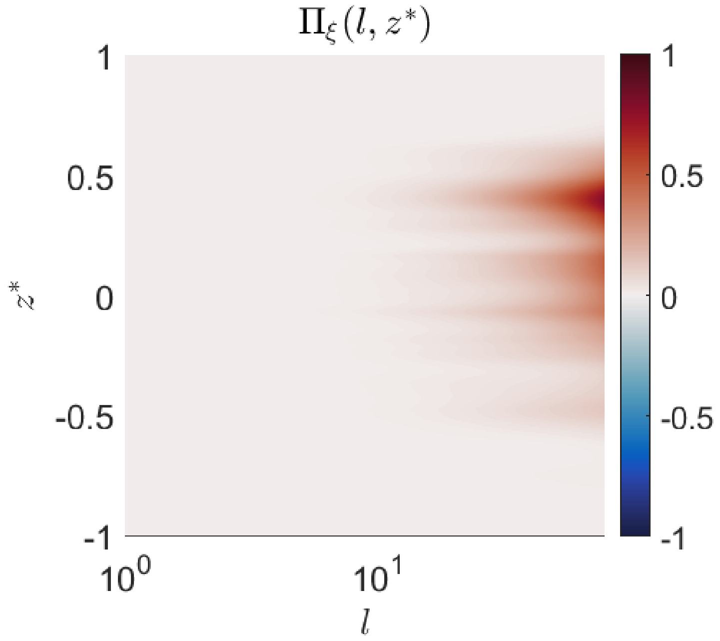
Lai, Chris C K ; Charonko, John J ;
Prestridge, Katherine. JFM (2018)

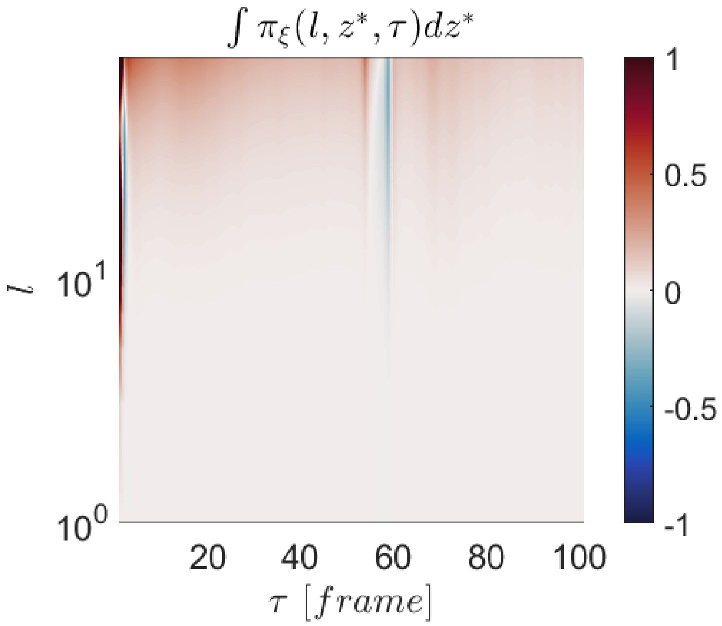
Filter Scale Transport: Results from simulations

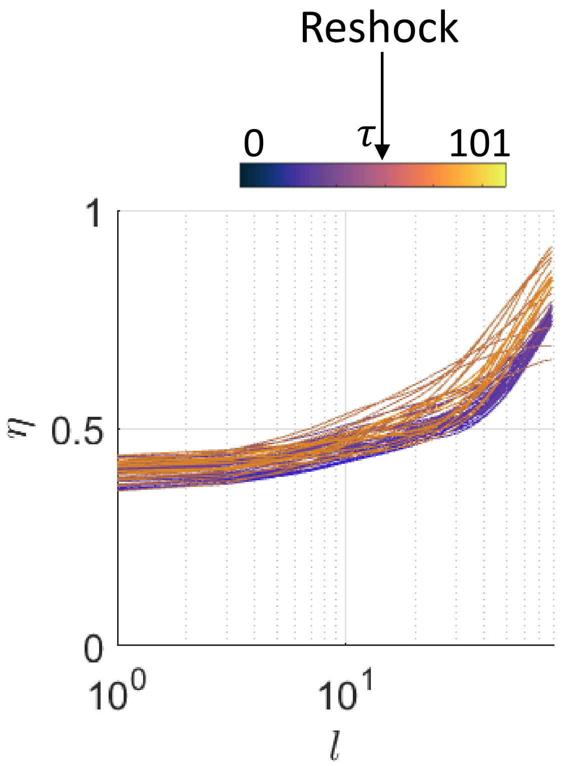
$$\bar{\xi}^l = \int G(x - x'; l)\xi(x)dx'$$ (A filtering operation similar to LES. Here use a gaussian shape.)

$$\frac{\partial \pi_\xi}{\partial l} = \left[\overline{u_i \xi}^l - u_i^l \bar{\xi}^l\right] \frac{\partial \bar{\xi}^l}{\partial x_i} = \sigma_i S_i$$ $\boldsymbol{\sigma}$: subgrid stress $\boldsymbol{S}$: grid-scale $\nabla\xi$

$$\eta = \frac{\sigma_i S_i}{|\sigma||S|}$$







Perry L. Johnson, PRL, (2020)

Summary

Growth rate of mixing layer thickness larger than previously reported

After first shock, *Re* approaches/crosses proposed threshold for turbulent mixing

After reshock, structure functions suggest isotropy not fully reached

After reshock, scale-to-scale energy transport from low to high wavenumbers

New frontier

Many terms in "generalized" energy transport equation contain both velocity and concentration fields. Need to resolve both spatially and temporally.

Need simultaneous high-speed PLIF and PIV

Available: pulse-burst laser (20 kp/s, 532/266 nm, 40/20 mJ/pulse)
high-speed CMOS cameras (1 MP, 16 kf/s @ full frame)

Already successfully performed high-speed PLIF

Main challenge: spatial resolution of high-speed CMOS camera inadequate to perform PIV over full field of view

QUESTIONS