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Title: The Bipolar Behavior in Richtmyer-Meshkov Instability (U)

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THE BIPOLAR BEHAVIOR IN RICHTMYER-MESHKOV INSTABILITY (U)

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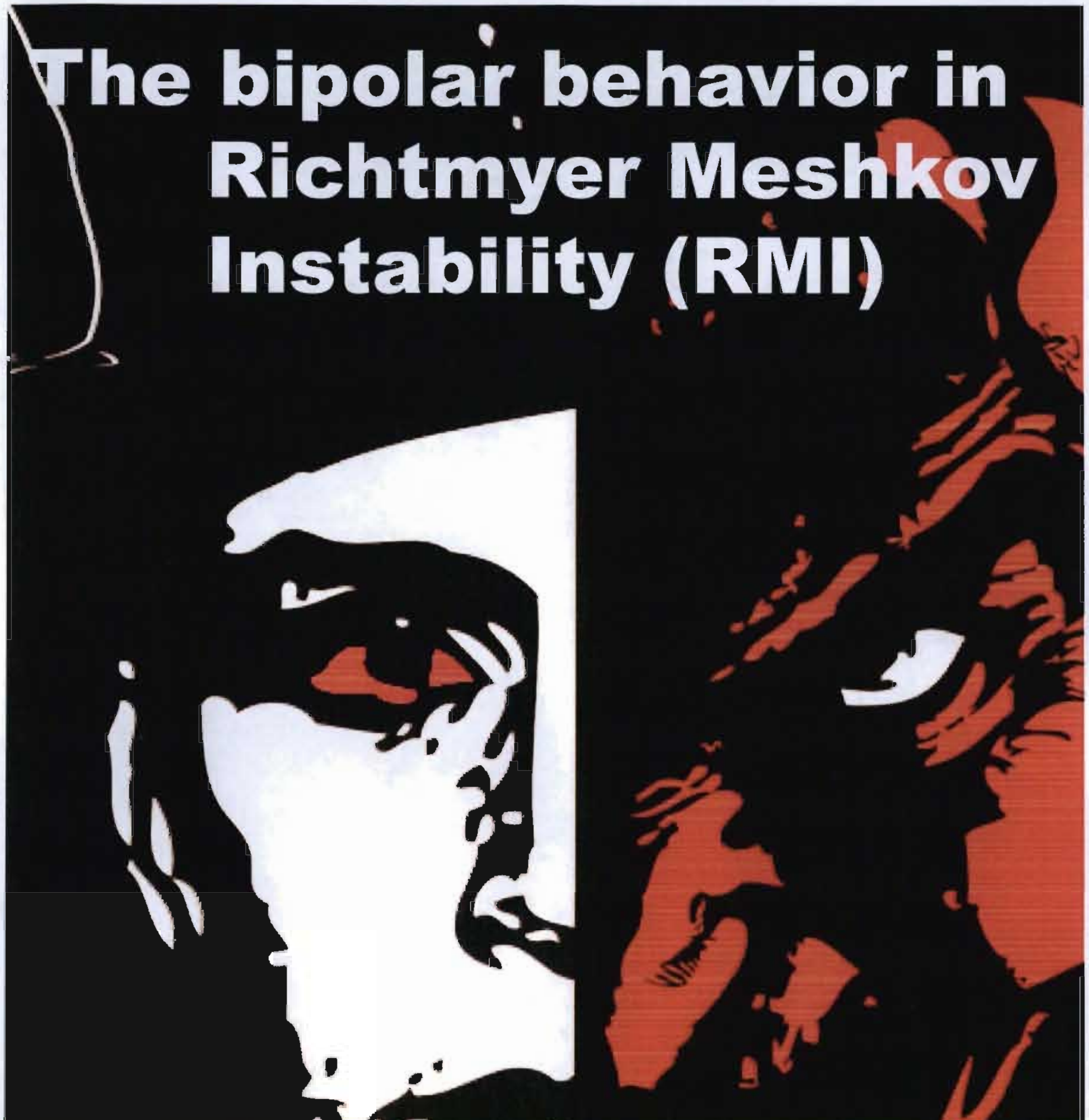
Abstract

A numerical study of the evolution of the multimode planar Richtmyer-Meshkov instability (RMI) in a light-heavy (Air-SF_6, Atwood number A=0.67) configuration involving a Mach number Ma=1.5 shock is carried out. Our results demonstrate that the initial material interface morphology controls the evolution characteristics of RMI, and provide a significant basis to develop metrics for transition to turbulence. Depending on the initial *rms* slope of the interface, RMI evolves into linear or nonlinear (mode-coupled) regimes, with distinctly different flow features and growth rates, turbulence statistics and material mixing rates. *Some of our findings are not consistent with heuristic notions of mixing in equilibrium turbulence.* The more turbulent the flow – as measured by spectral bandwidth – the higher the material mixing and, paradoxically, the smaller the turbulent kinetic energy and the slower the growth of the mixing layer. On the other hand, the least turbulent flow has more turbulent kinetic energy and higher mixing layer growth rate, with less material mixing.

The bipolar behavior in Richtmyer Meshkov Instability (RMI)



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Compressible Turbulence at the Intersection of Astrophysics and Engineering

April 25, 2011 - April 28, 2011, Santa Fe, NM

Outline

- Motivation
- Setup & Simulation
- Results
  - mixing width
  - turbulence metrics: k, w^2, Re_t ....
- Conclusion
- Future work

Motivation

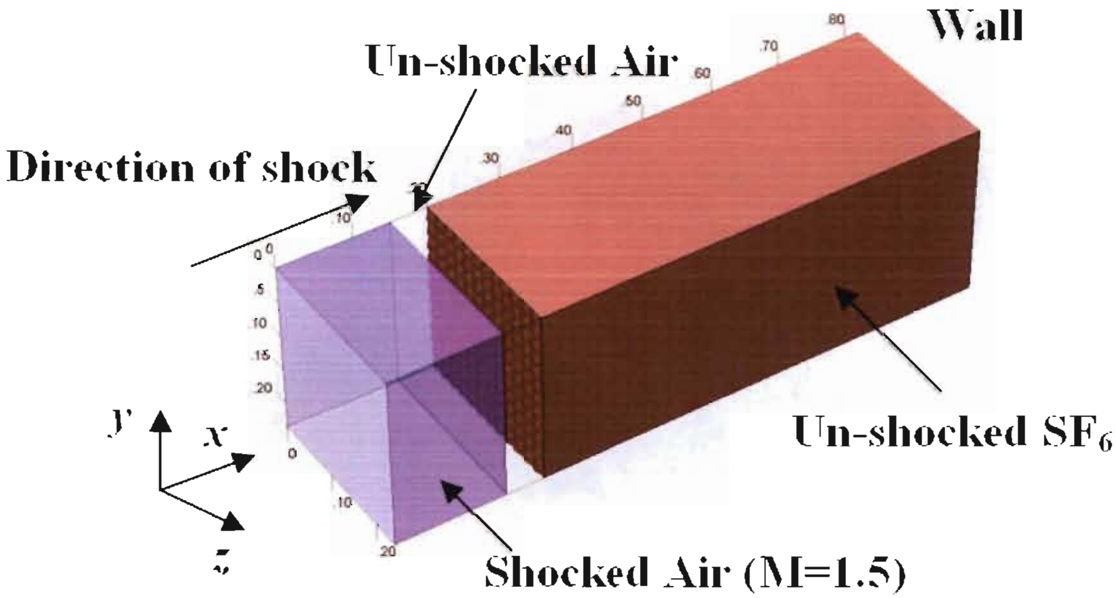
LDRD-DR *"Turbulence by Design"*
Effect of initial condition on late time turbulence
PI: Malcolm Andrews

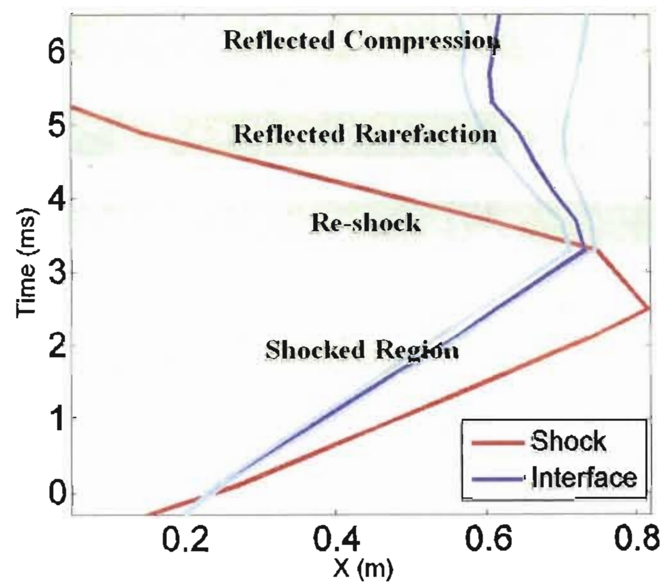
- **How does interfacial morphology control the evolution of RMI?**
- **Can turbulence transition be achieved with a single shock?**
- **Is there a controlling parameter in RMI?**

Point in scientific process

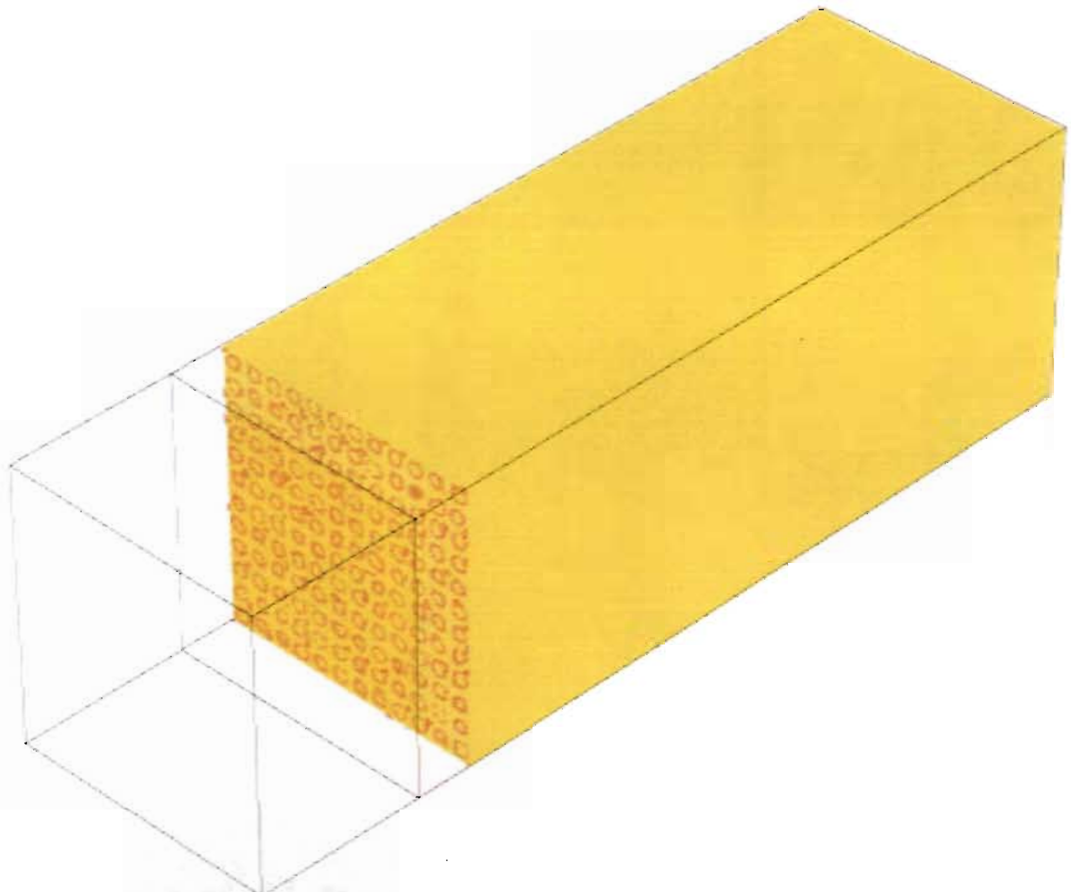
1. Data (numerical) collection
2. Observation
3. Hypothesis formulation
4. Hypothesis verification

Planar Richtmyer Meshkov Instability





Planar Richtmyer Meshkov Instability

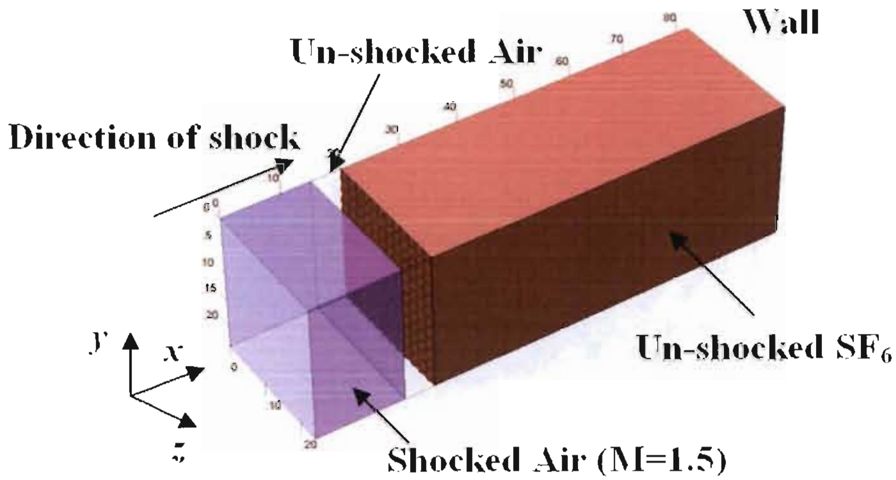


LANL's RAGE

Gittings et al. LA-UR Report 2006

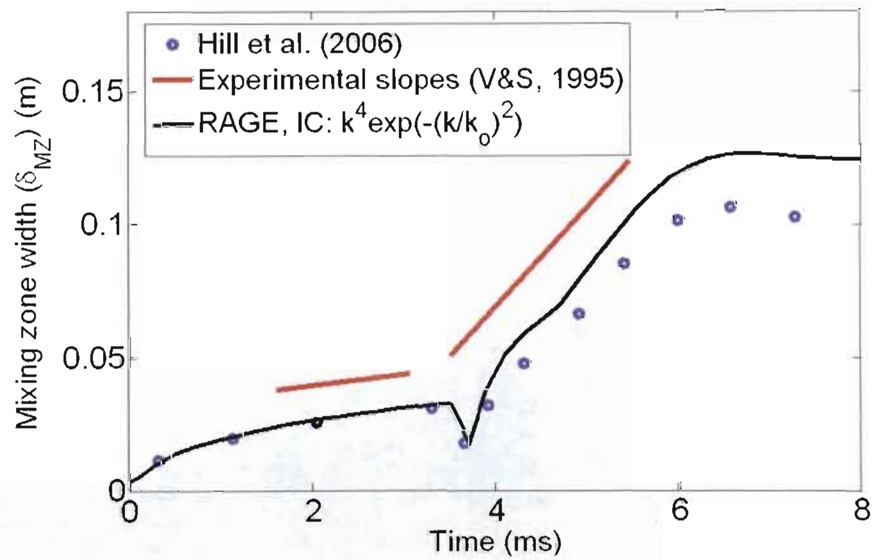
- **solves multimaterial compressible-Euler equations**
- **high resolution (2nd order) Godunov scheme**
- **ideal gas equation of state**
- **adaptive mesh refinement capability**
- **gradient terms (limiters) and interface treatment.**
  - **for the gradient:** min-mod (MM) ; **Van Leer (VL)**
  - **for the interface treatment:**
    - **(no IP) – monotonized centered VL limiter.**
    - (IP) interface preserver, width ~3 cells.

Problem Setup & Validation



3D RAGE simulation details
Domain Dimension: 82cm x 24cm x 24cm
Mach number: 1.5
Simulations with and without reshock performed
Grid Resolution: *dx=dy=dz* = 0.1cm (1 level AMR)
Periodic B.C. in *y* & z dir., inflow-wall in x dir.

Validation

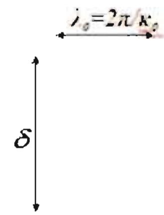


Does interfacial morphology control the evolution of RMI?

RMS Slope of the interface $\kappa_o \delta_o$ *or* η_o

if $X_s(y,z)$ is the interface, then

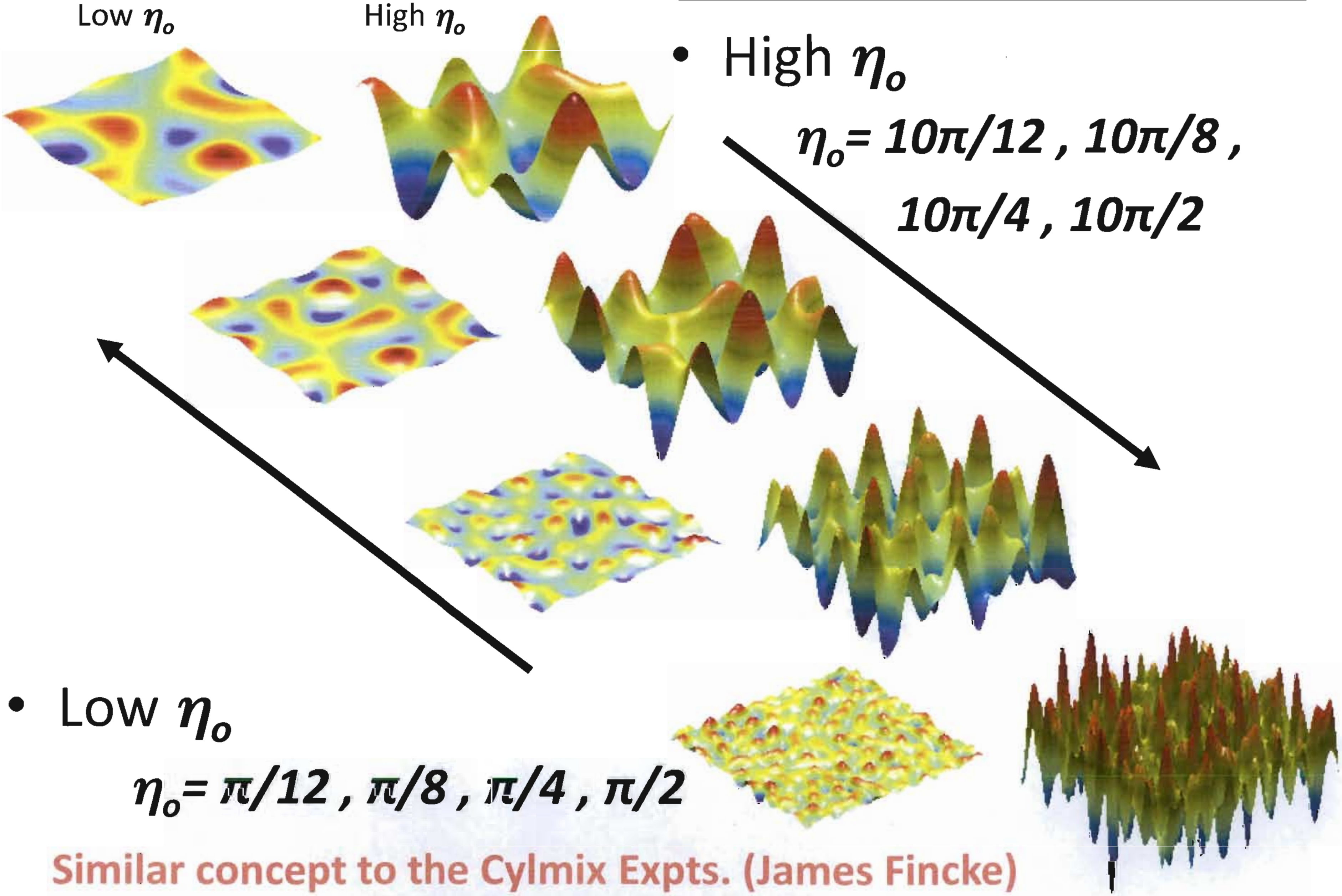
$$\eta_o = \kappa_o \delta_o = \langle \nabla X_s \nabla X_s \rangle^{1/2}$$



Low η_o

High η_o

Initial interface



- High η_o

  $\eta_o = 10\pi/12$, $10\pi/8$, $10\pi/4$, $10\pi/2$

- Low η_o

  $\eta_o = \pi/12$, $\pi/8$, $\pi/4$, $\pi/2$

Similar concept to the Cylmix Expts. (James Fincke)

Planar RMI: Low η_o

$$\langle f\rangle(x) = \frac{1}{A}\int f(x,y,z)dydz \quad , \quad A = \int dydz,$$

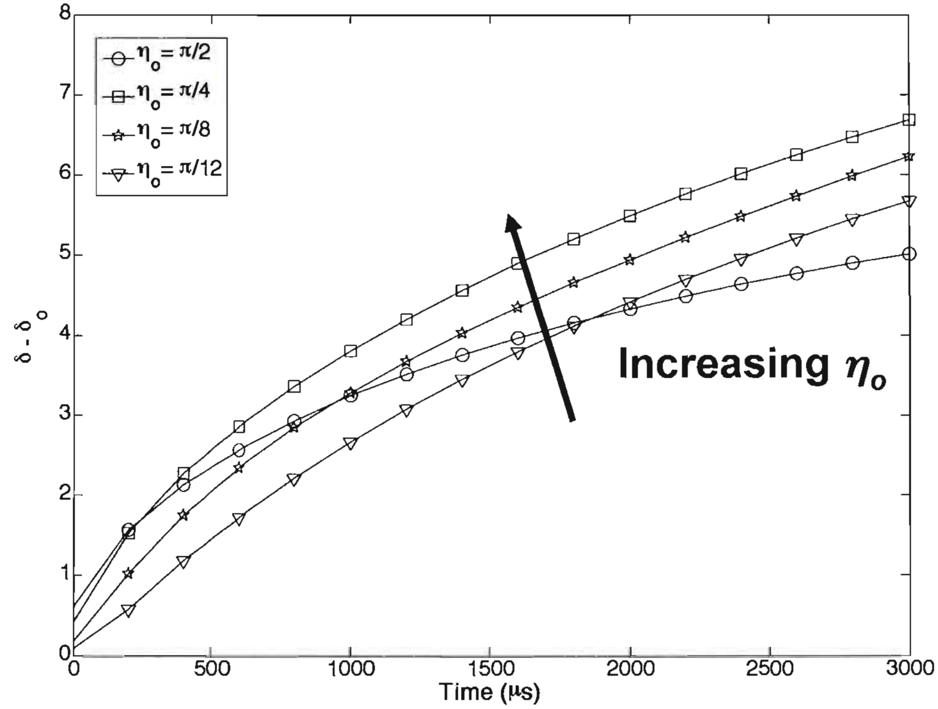
$$Y_{SF_6} = \rho_{SF_6} / \rho,$$

$$\theta = 4Y_{SF_6}[1 - Y_{SF_6}],$$

$$\psi(x) = \langle Y_{SF_6}\rangle,$$

$$M(x) = 4\psi(x)[1-\psi(x)],$$

$$\delta_{MZ} = \int M(x)dx,$$



Richtmyer 1960 theory for *low* η_o

$$V = A\Delta U\eta_o$$

$$\delta = A\Delta U\eta_o t + \delta_o$$

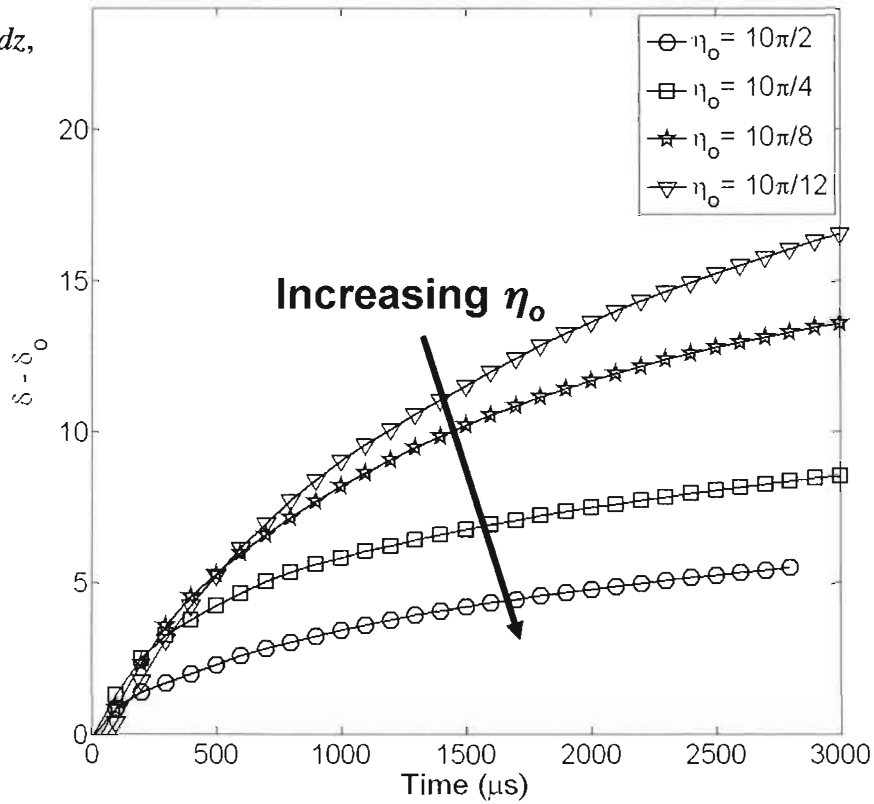
$$\delta - \delta_o = A\Delta U\eta_o t$$

For relatively low value of η_o, the Richtmyer's theory (growth is proportional to κ_o) is valid, however for the case $\eta_o = \pi/2$, the Richtmyer's theory is valid for a very short time after the first shock and soon the growth rate drops.

Consistent with Classical RMI theory!

Planar RMI: High η_o

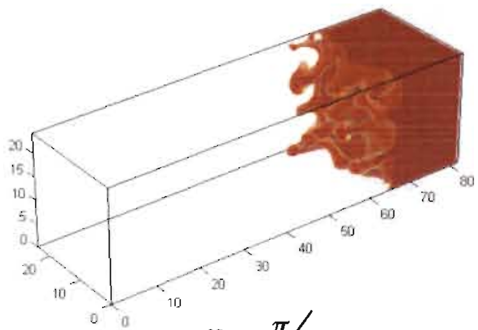
$$\langle f\rangle(x) = \frac{1}{A}\int f(x,y,z)dydz \ , \ A = \int dydz,$$
$$Y_{SF_6} = \rho_{SF_6} / \rho,$$
$$\theta = 4Y_{SF_6}[1 - Y_{SF_6}],$$
$$\psi(x) = \langle Y_{SF_6} \rangle,$$
$$M(x) = 4\psi(x)[1 - \psi(x)],$$
$$\delta_{MZ} = \int M(x)dx,$$



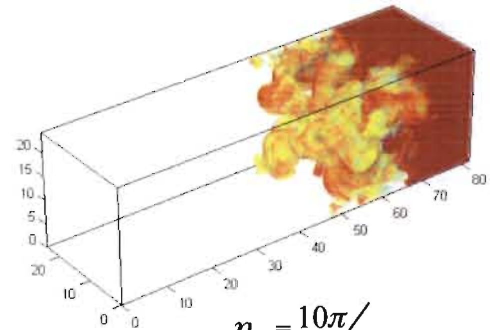
At very short time, for all the cases, the Richtmyer's theory (growth is proportional to κ_o) is valid. Soon after, the growth is actually **INVERSELY** proportional to κ_o.

NOT consistent with Classical RMI theory!

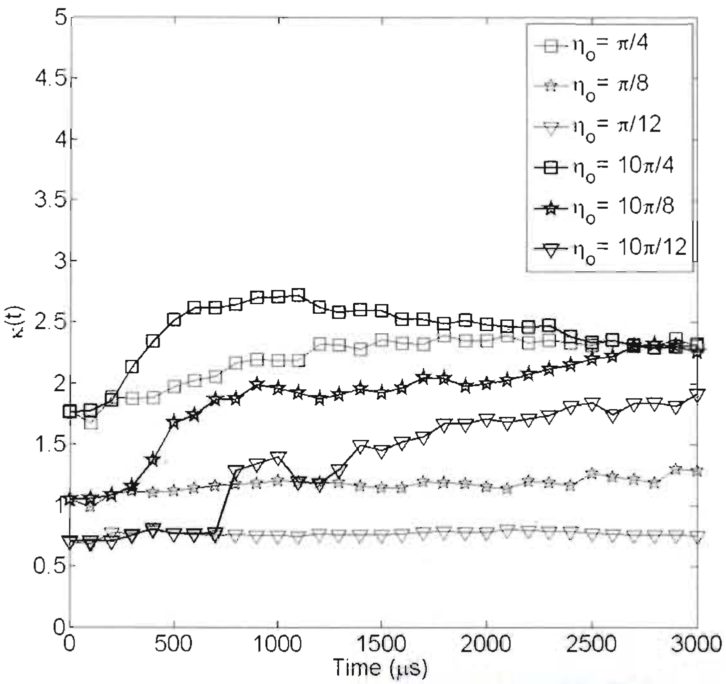
Planar RMI: Effect of η_o



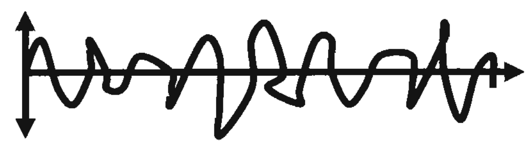
$\eta_o = \pi/12$



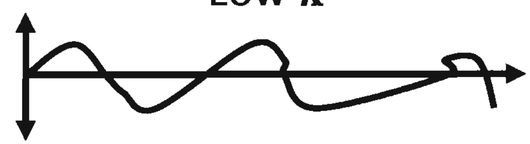
$\eta_o = 10\pi/12$



High κ



Low κ



κ is the zero crossing wavenumber of the density field

- ***Higher κ – smaller the small scales, flow is more "turbulent"***
- ***Higher η_o produces more small scales***

Planar RMI: Theory

$$\chi = \frac{\delta}{2}\sin(\kappa_o y)$$

Richtmyer 1960 theory for *low* $\kappa_o\delta$

$$V = A\Delta U\eta_o$$

$$\delta = A\Delta U\eta_o t + \delta_o$$

$$\delta - \delta_o = A\Delta U\eta_o t$$

Case I: Low η_o ***(***$\eta_o \ll \pi$***) - Jekyll***

- increasing η_o --> more baroclinic vorticity is deposited --> higher growth.
- growth is mostly *ballistic* (no mode coupling)
- **Higher the** η_o **higher the growth**

Case II: High η_o ***(***$\eta_o > \pi$***) - Hyde***

- increasing η_o, growth saturates due to secondary instabilities …
- flow becomes more turbulent (non linear, chaotic, mode coupling)
- **Higher the** η_o **lower the growth**

Planar RMI evolves into different class of flows

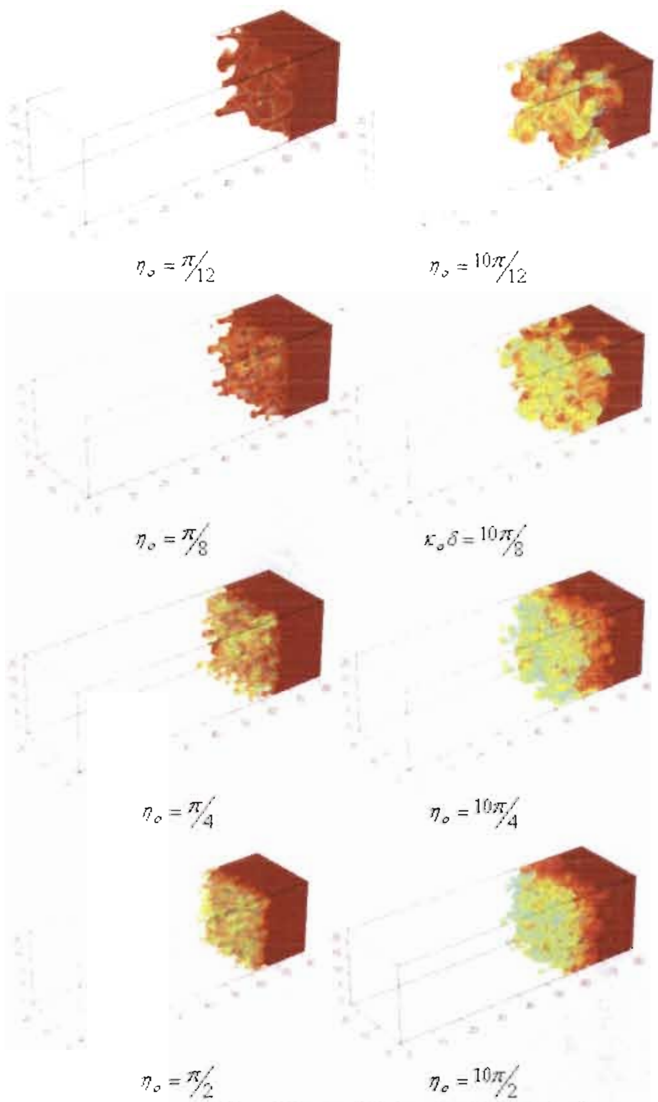
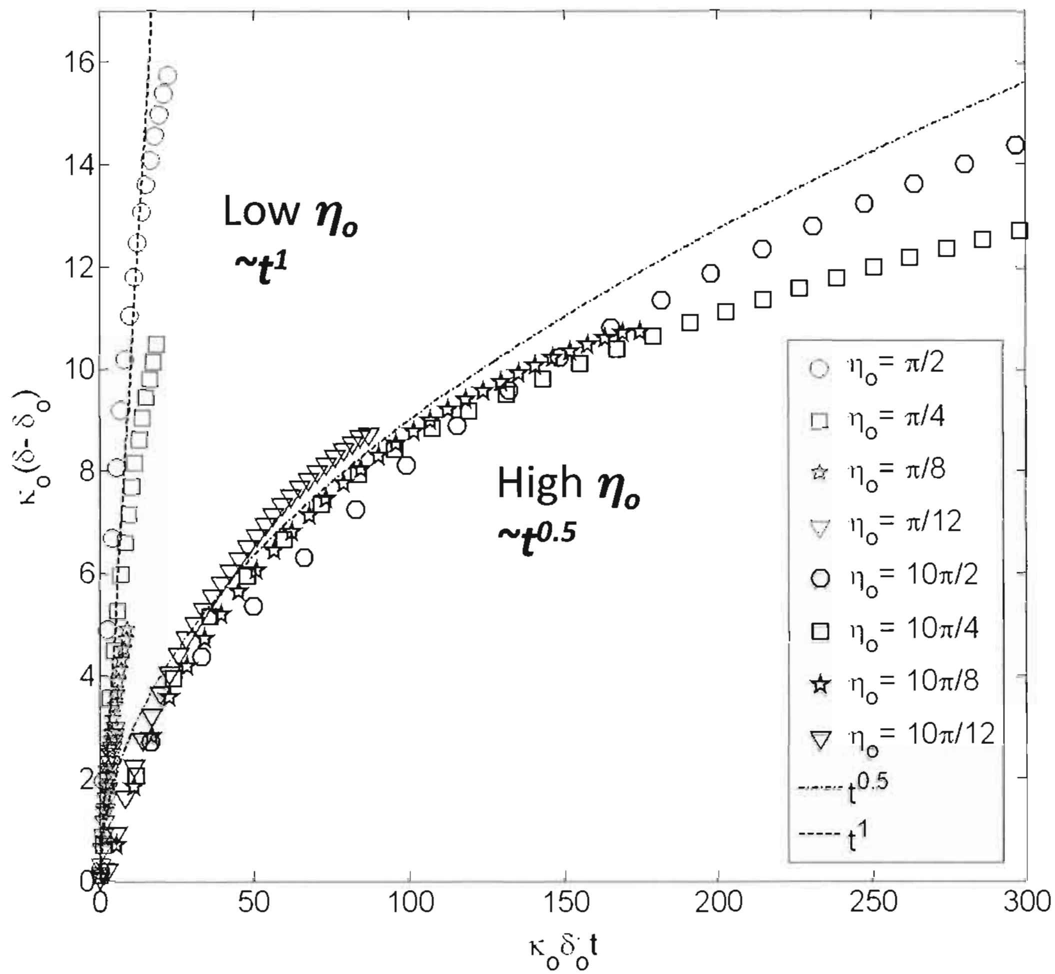


Figure 4. Volume visualization of Y_{SF6} at time t = 3000 μs after the first shock.

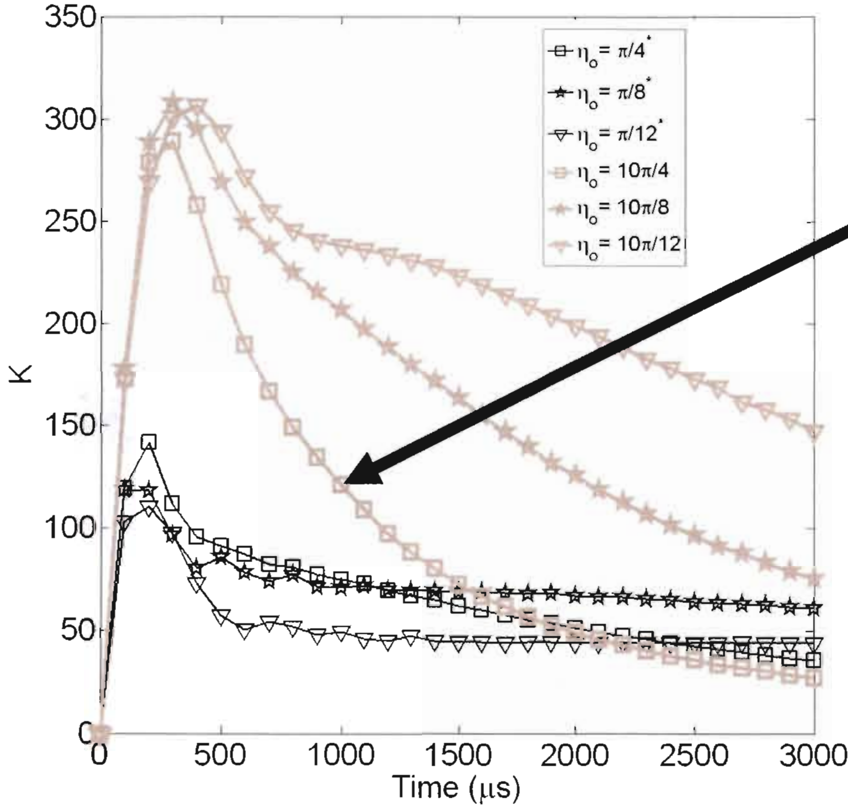


Low η_o : ***Linear***

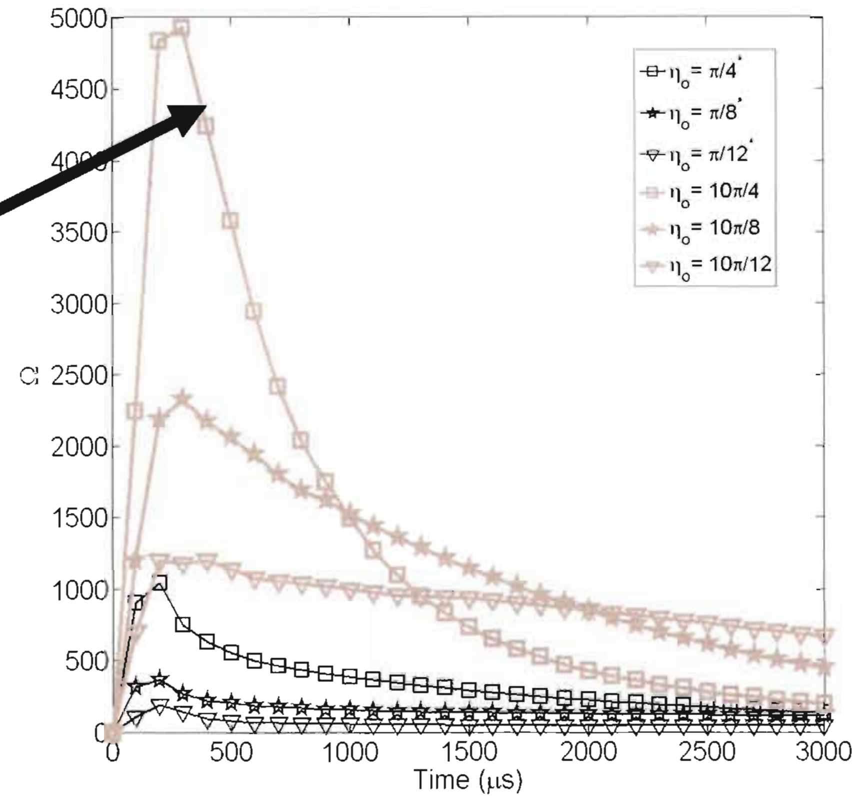
High η_o : ***Non-linear***

Turbulence metrics....

Turbulent kinetic energy



Enstrophy

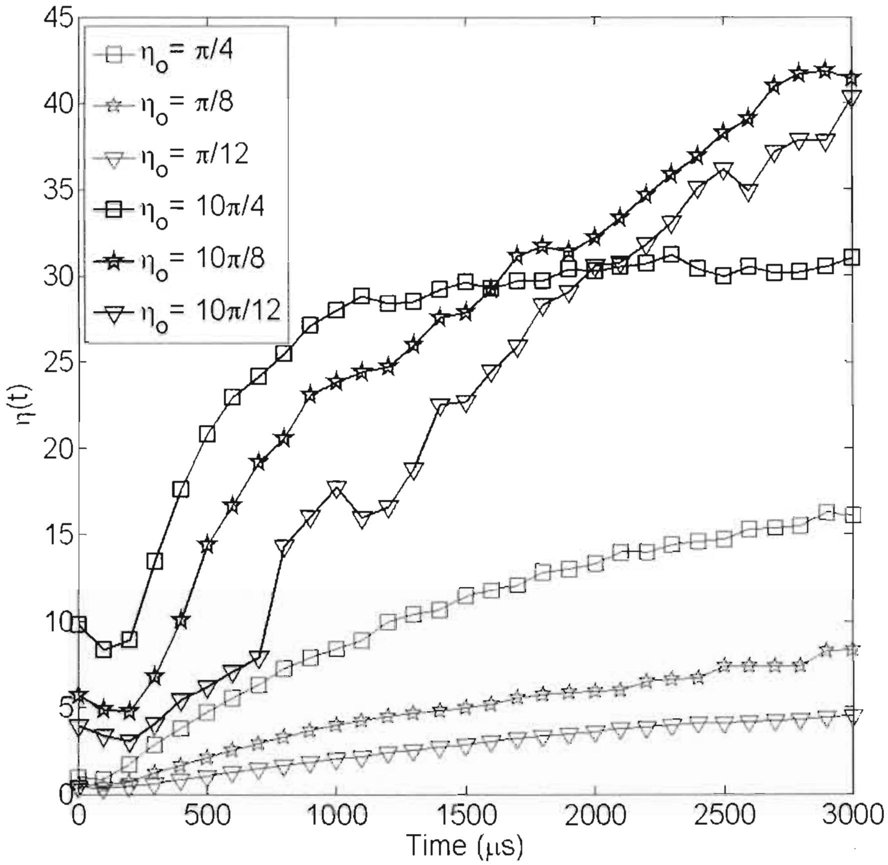


more enstrophy - less energy

"Spectral Bandwidth"

$$\eta_o = \frac{\delta}{\lambda} = \frac{Integral\ lengthscale}{Taylor\ lengthscale}$$

Spectra bandwidth can be thought of as a measure of how turbulent the turbulence is, loosely!



High initial η_o leads to high value at late times, until the decay is far enough along…

Rate Decay of TKE

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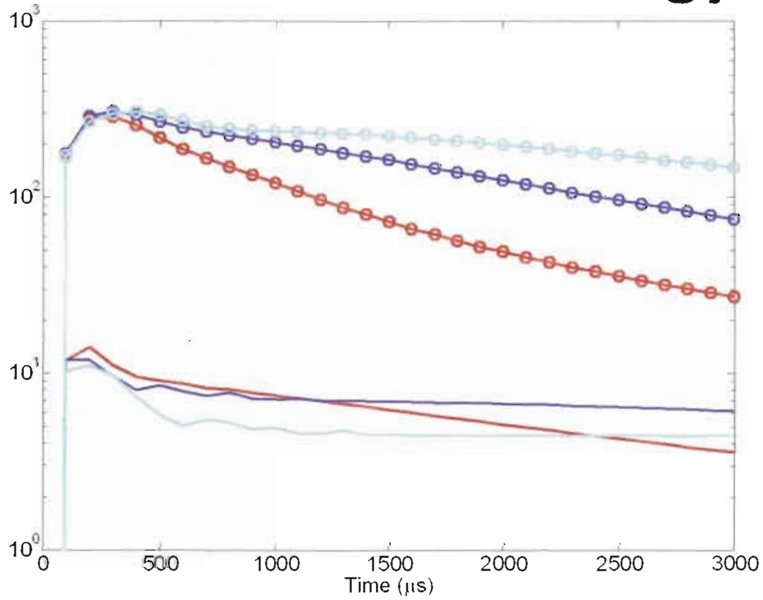
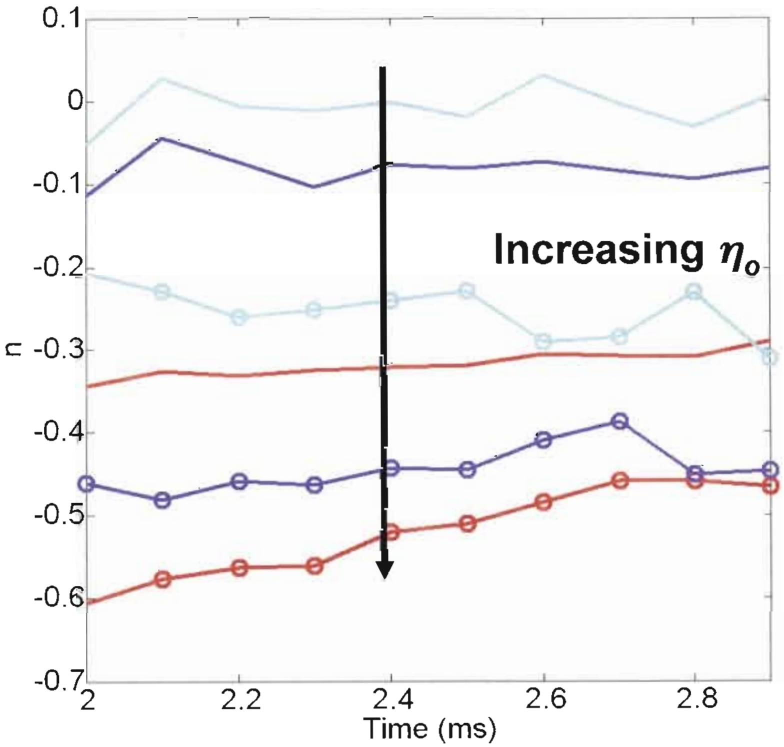
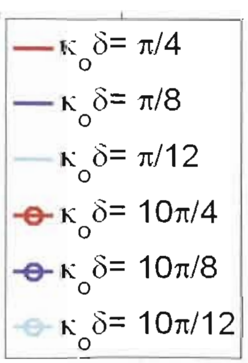
Turbulent kinetic energy



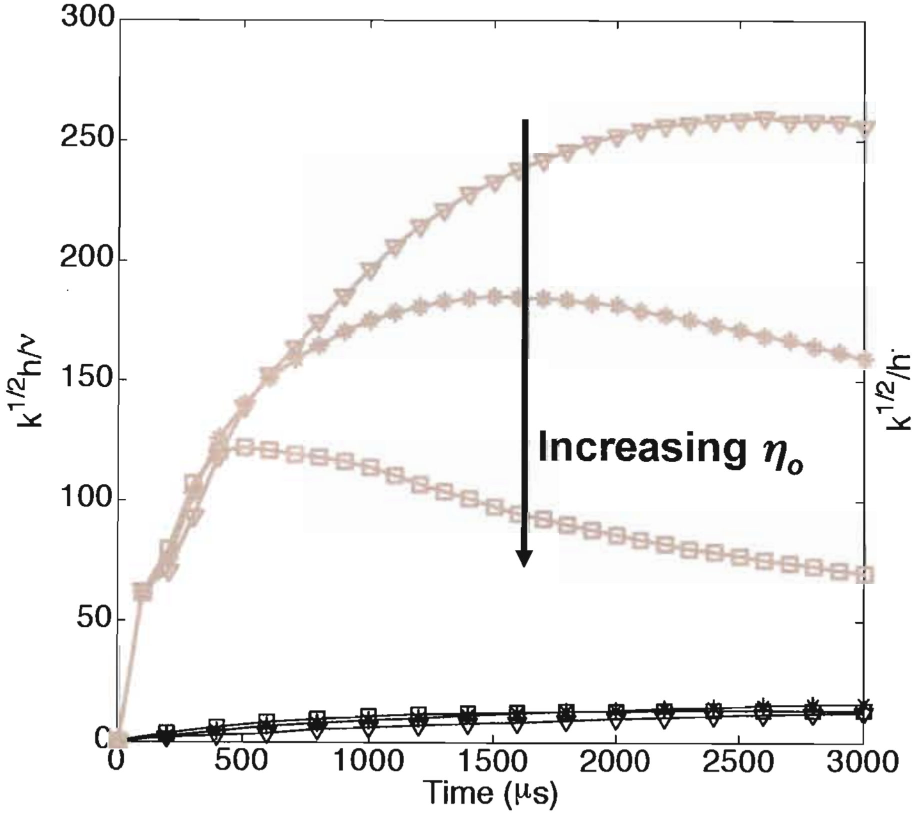




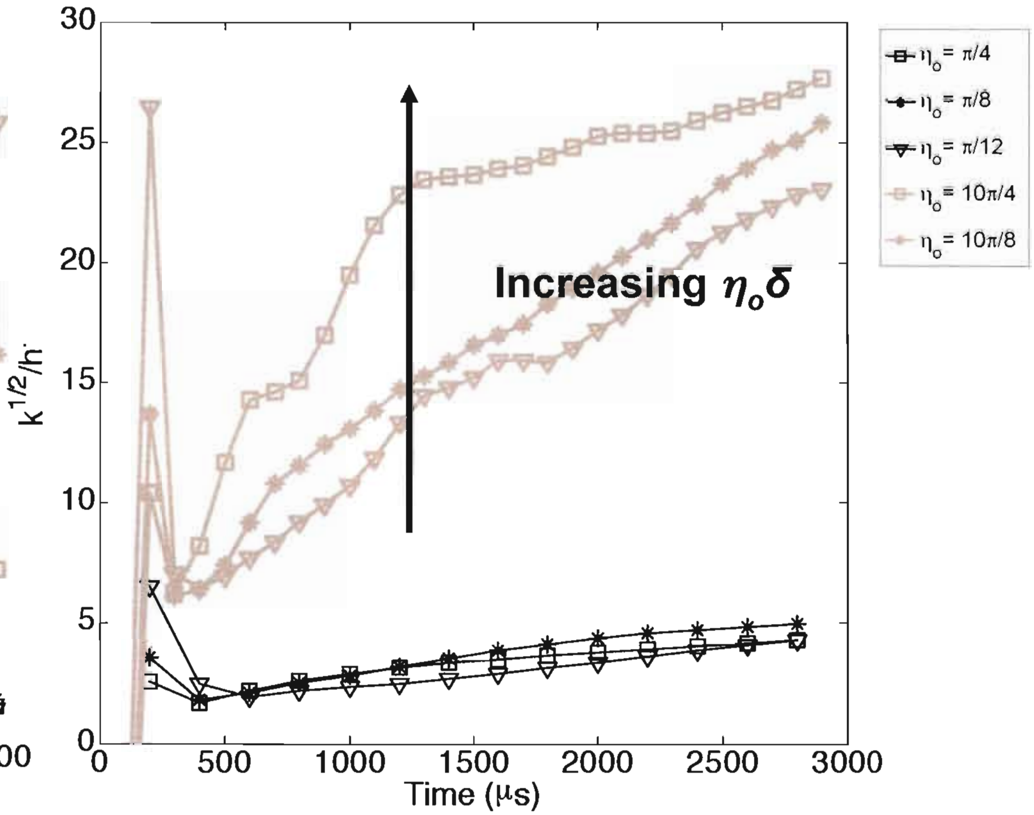
Decay rate, $k \sim t^n$, of TKE depends on $\kappa_o\delta$

Turbulence metrics....

Turbulent *Re*



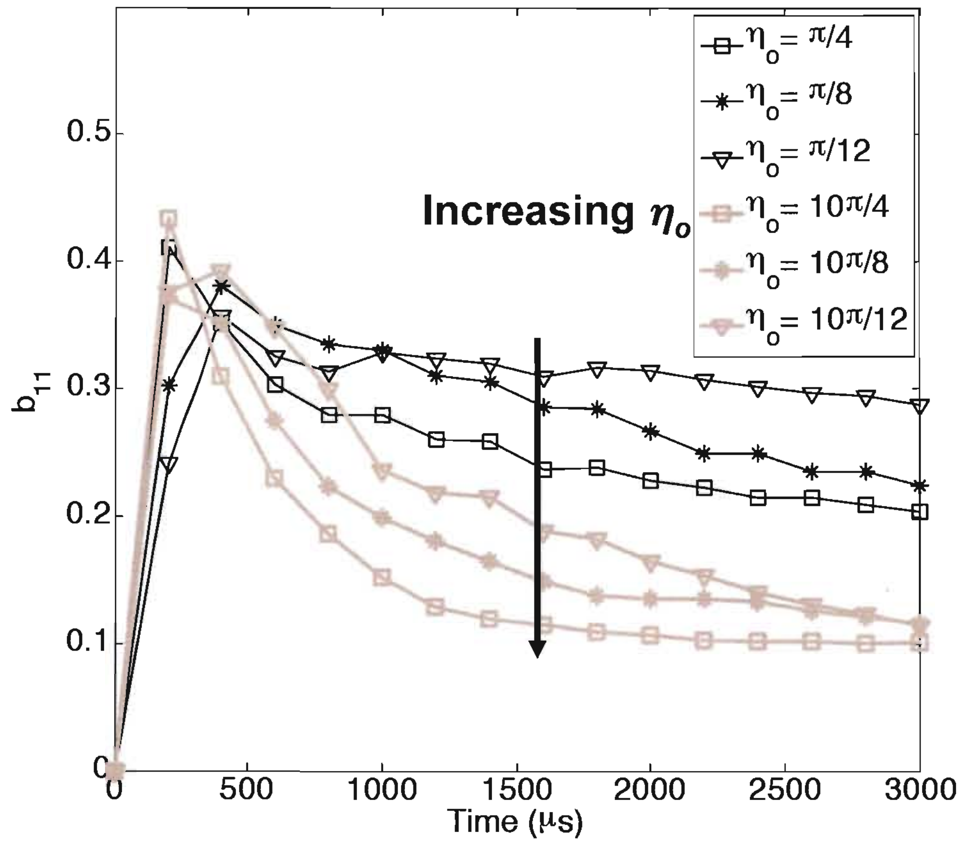
Turbulence intensity



Higher η_o – smaller Turbulent Re number, BUT higher turbulent intensity

Turbulence metrics....

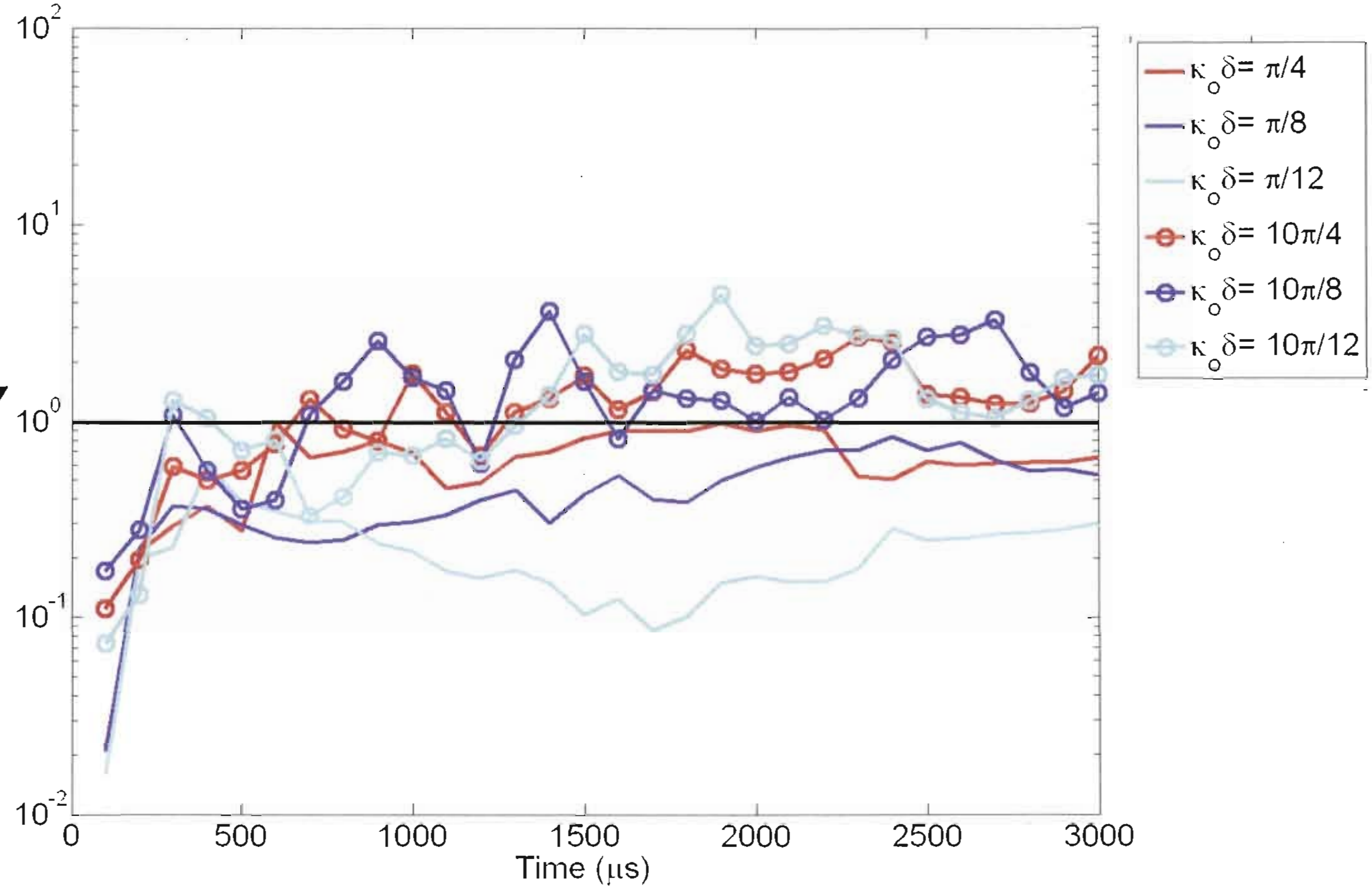
Anisotropy $b_{11} = \frac{\langle u_1 u_1 \rangle}{2k} - \frac{1}{3}$



Higher η_o – more mixing, more isotropy

Ratio of enstrophy generation mechanisms

stretching / baroclinicity



- *Baroclinicity is important at all times for enstrophy production*
- ***Higher η_o produces more enstrophy by "stretching"***
- ***Baroclinicity is much higher initially***

Can turbulence transition be achieved with a single shock?

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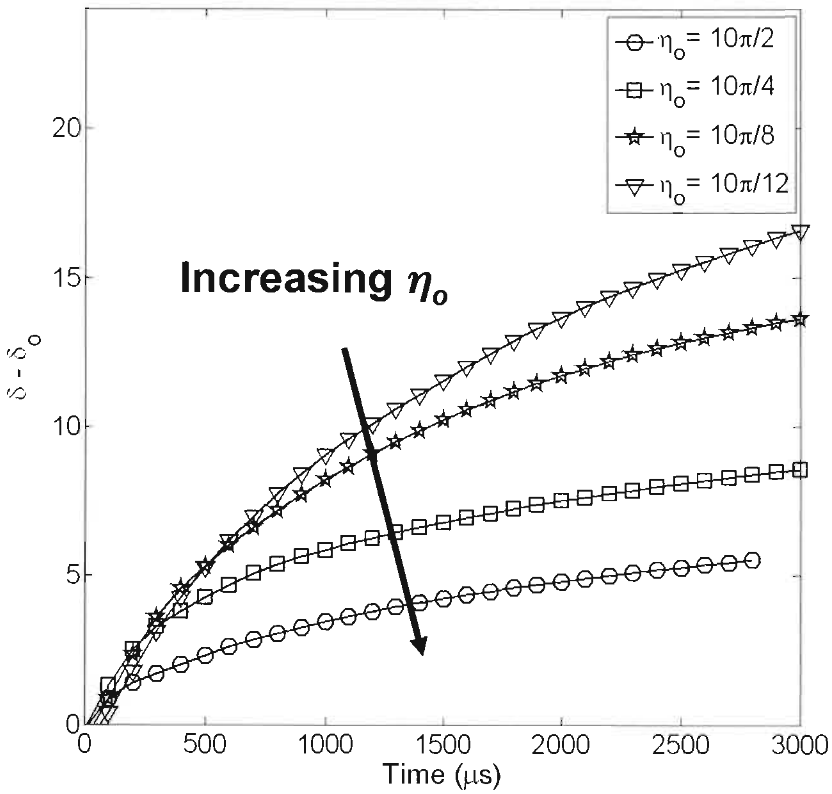
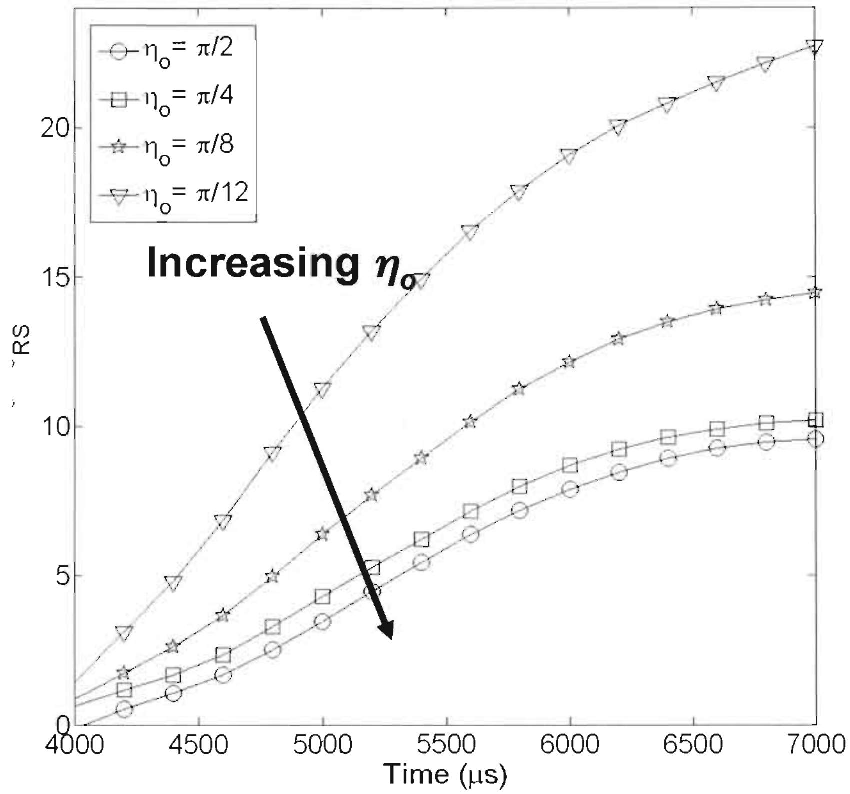


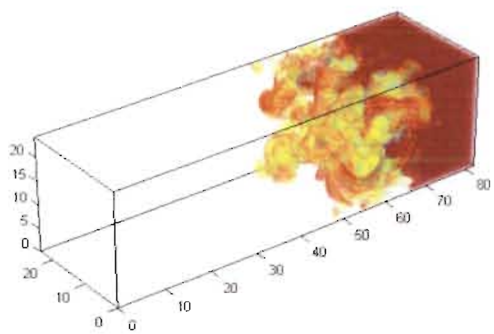
High η_o *before reshock*



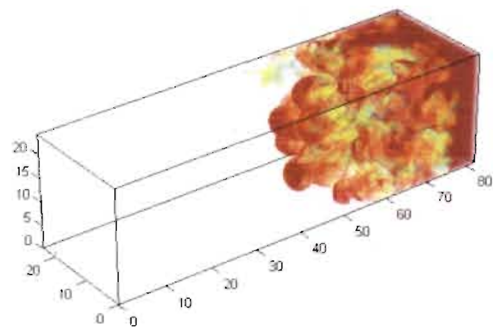
Low η_o *after reshock*

Shocked high η_o *case behaves like reshocked low* η_o *case*

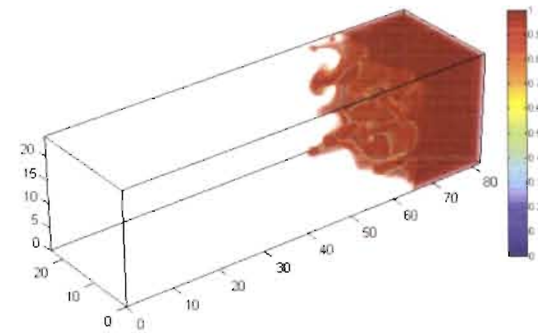
Can turbulence transition be achieved with a single shock?



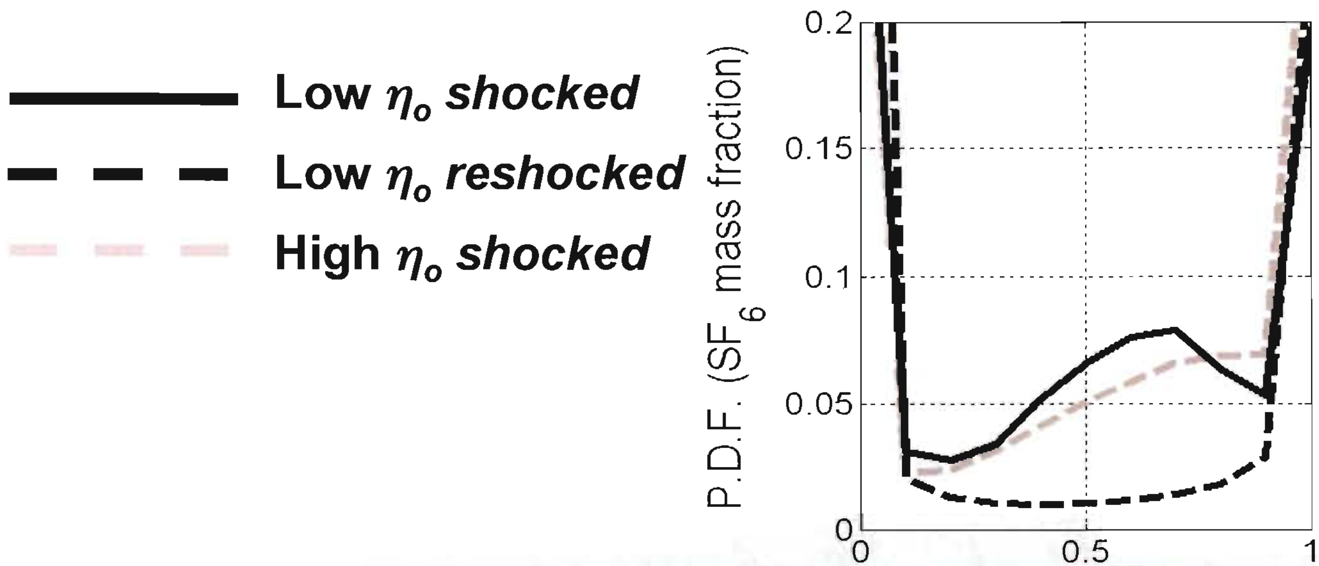
High η_o *shocked*



Low η_o *reshocked*



Low η_o *shocked*



Shocked high η_o *case behaves like reshocked low* η_o *case*

Questions answered

- Does interfacial morphology control the evolution of RMI?
  - Yes
- Can turbulence transition be achieved with a single shock?
  - Yes
- Is there a controlling parameter in RMI?
  - $\kappa_o \delta$

Conclusion

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- RMS slope η_o of the interface affects the evolution of RMI
- Reshock effect can be achieved with single shock, if $\eta_o > 1$.
- Higher η_o behaves like the reshock problem
- Higher η_o leads to faster dissipation of TKE because of presences on more small scale structure

Counter-intuitive results

- In non-linear regime, higher η_o leads to more material mixing, has smaller scales and is more isotropic

BUT

1. Lower TKE
2. Lower Re_T
3. Smaller mix width

Future work

- Study the effect of Mach number and Atwood number
- Identify scaling parameters ($\kappa_o \delta_o$ or $\kappa_o^{\alpha} \delta_o^{\alpha}$?)
- Enstrophy and TKE budget
- Identify parameters which can predict the transition to turbulence