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Title: Simulations of Richtmyer-Meshkov Instabilities in Planar and Gas-Curtain Shocktube Experiments (U)

Author(s): Fernando F. Grinstein, Akshay Gowardhan, and Ray Ristorcelli

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Simulations of Richtmyer-Meshkov Instabilities in Planar and Gas-Curtain Shocktube Experiments

F.F. Grinstein, A.A. Gowardhan, and J.R. Ristorcelli

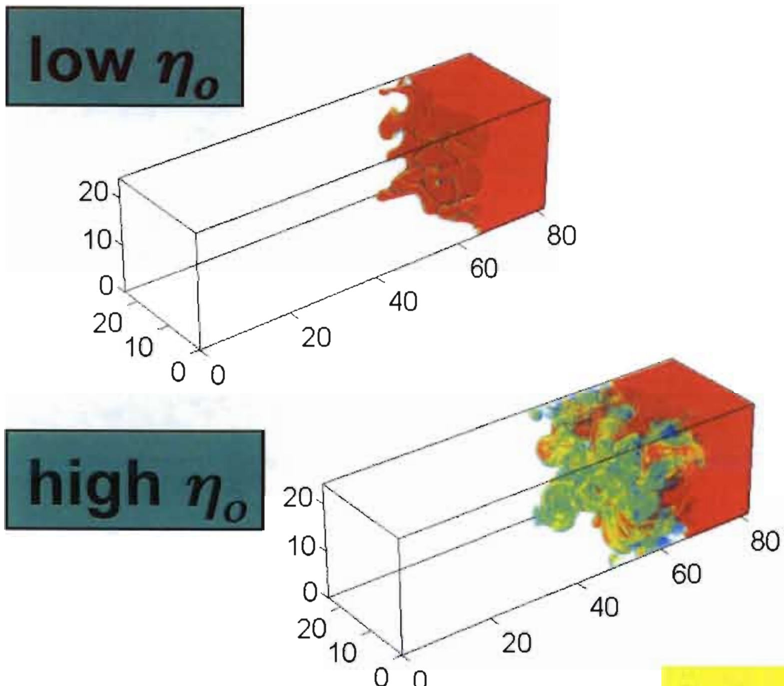
Los Alamos National Laboratory, Los Alamos, NM 87545, USA

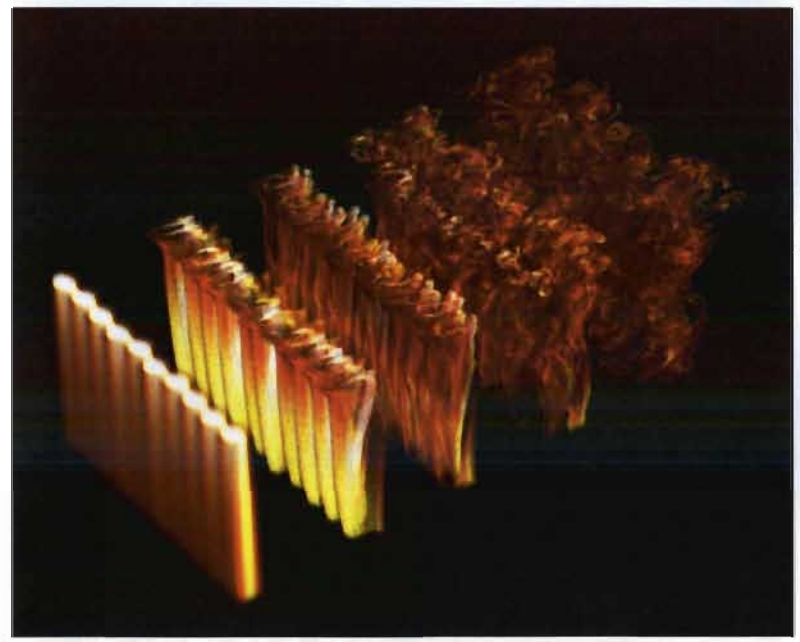
Abstract

Our particular focus in this presentation is devoted to initial material interface characterization impact on shock-driven turbulent material mixing. Progress in addressing relevant issues of initial condition effects in studies of mixing driven by Richtmyer-Meshkov instabilities in planar and gas-curtain shock-tube laboratory experiments is reported.

Simulations of Richtmyer-Meshkov Instabilities in Planar and Gas-Curtain Shocktube Experiments

Fernando F. Grinstein (simulations), Akshay A. Gowardhan (post-doc), J. Ray Ristorcelli (theory)





instantaneous material mixing

LANL LDRD-DR Program on "Turbulence by Design"

Simulations of Initial Condition Effects on Shock-Driven Turbulent Mixing

Background, Motivations

- Understand effects of initial material interface conditions
- Assess predictability of simulation models

The (single-interface) planar RM experiment

- Challenges to Moment Closures: ***the bipolar RM behavior***

→ ***Reshock effects (on mix & transition) on first-shock***

The (two-interface) Gas Curtain RM experiment

- Initial 3D GC characterization and modeling issues
- Sensitivity of shocked / reshocked GC to ICs
- Data reduction and **bipolar RM behavior**

→ ***Opportunities for defining a RM test case***

Conclusions

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Shock-Driven Turbulence Simulations

shocks and turbulence must be emulated

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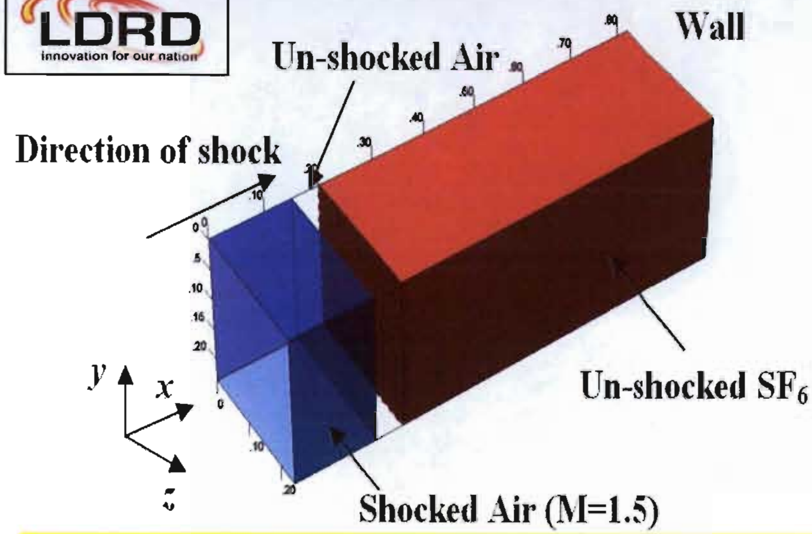


- shocks and turbulence, unsteady
- wide range of length and time scales, non-linear interactions
- Implicit Large Eddy Simulation (ILES), e.g., ILES book, 2nd printing: 2010

- Richtmyer '60; **planar shocktube expts.** (**V&S '95**, Poggi '97, Leinov '09, …); **LANL P-23 gas curtain expts.**, ….
- **hybrid WENO / classical LES, …,** Pullin et al. – *JFM* 2006, …, 2011
- **ILES** , 2002 – 2011: Cohen et al. (FV-PPM), …, Schilling et al. (FD-WENO), Leinov et al. (FV-ALE), Thornber-Drikakis-Youngs-Williams et al. (FV-Godunov), …
- ***ILES-RAGE***; FV-Godunov, van Leer limiter, no interface treatment, AMR

  planar V-S expts., *P. Scripta* 2010, IWPCTM12; ***PoF*** **March 2011**;

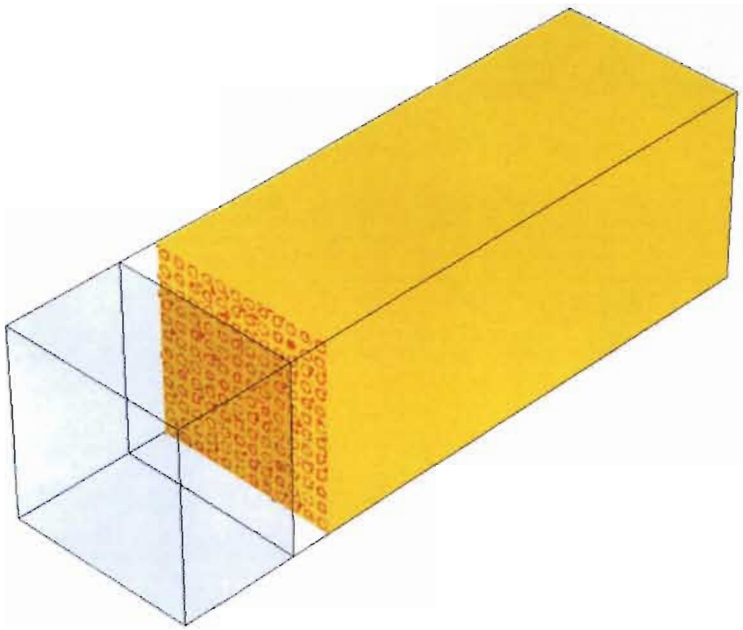
  planar Bipolar RM, ***PoF*** **Letters July 2011**; AIAA-Hawaii-2011 / ETC13 → **PoF**

  shocked (double interface) **gas-curtains**, ***J. Turbulence*** **2011**, in press.

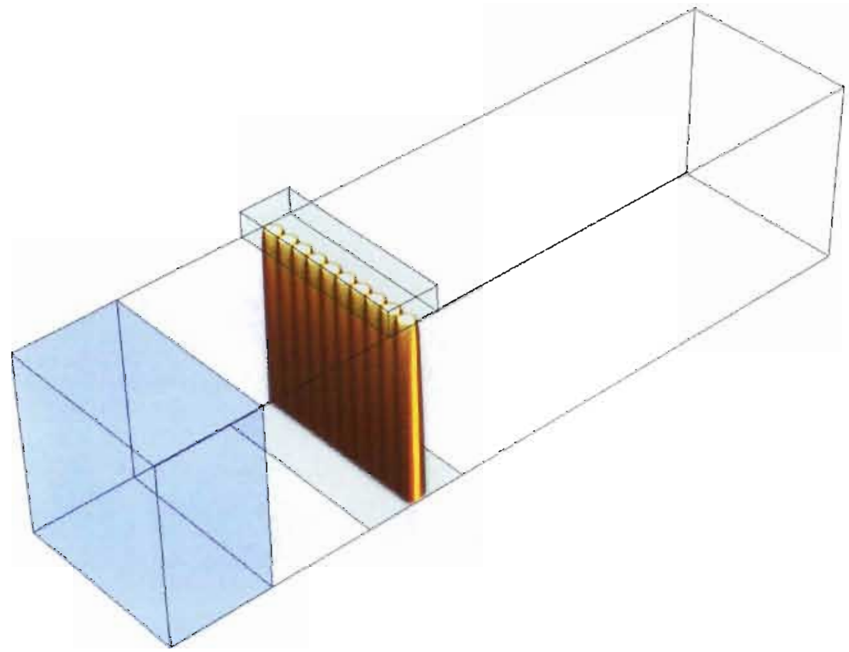
Shock-Driven Turbulent Mixing Experiments

Effects of shocks and turbulence must be addressed

ILES RAGE simulations (SF_6 mass fraction distributions)



planar single-interface (V&S, Caltech)



gas-curtain two-interface (P-23)

- Understand Effects of Initial Material Interface Conditions
- Practical Goal: control (promote or inhibit) RM instability

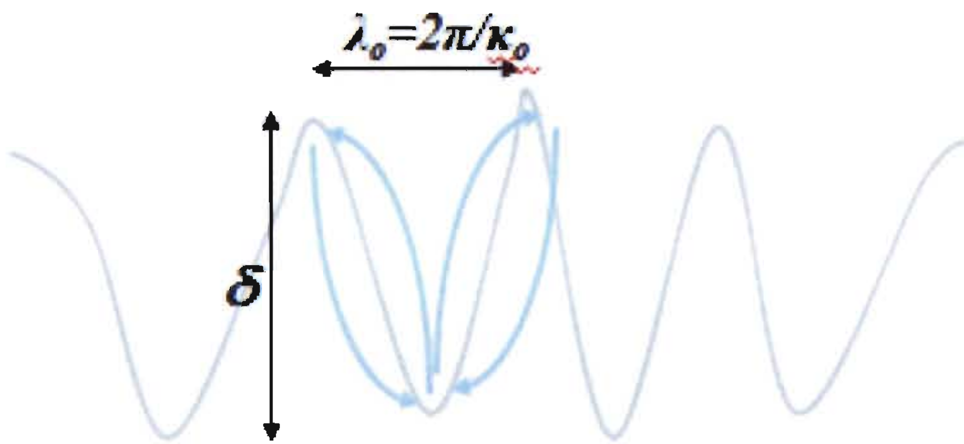
How does interfacial morphology control the evolution of RM ?

if $X_s(y,z)$ ***describes the material interface,***

then, we define the rms slope of the interface "η_o"

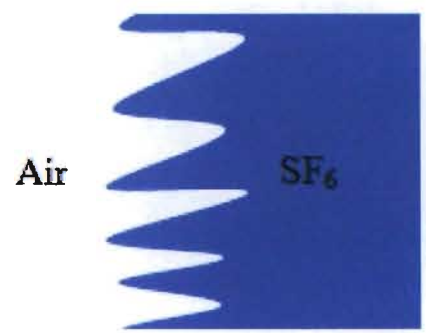
$$\eta_o = \kappa_o \delta_o$$

$$\sim \langle \nabla X_s \nabla X_s \rangle^{1/2}$$



low η_o

$(\kappa_o \delta_o << \pi)$



high η_o

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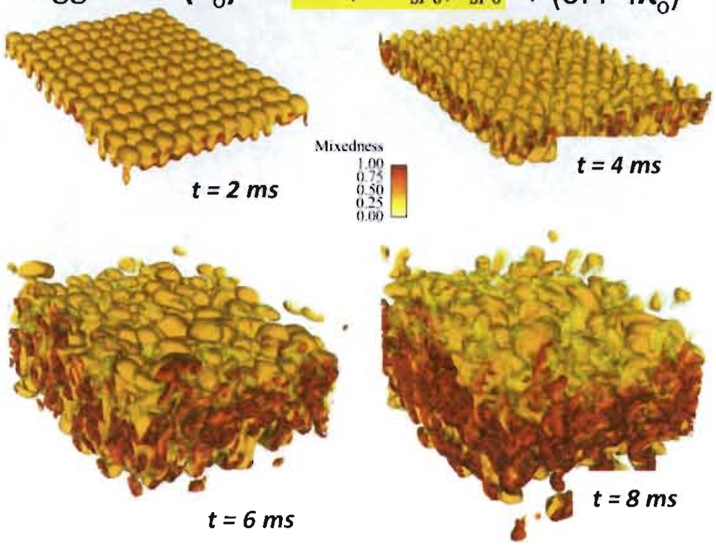
ILES RAGE – Planar RM Expts.

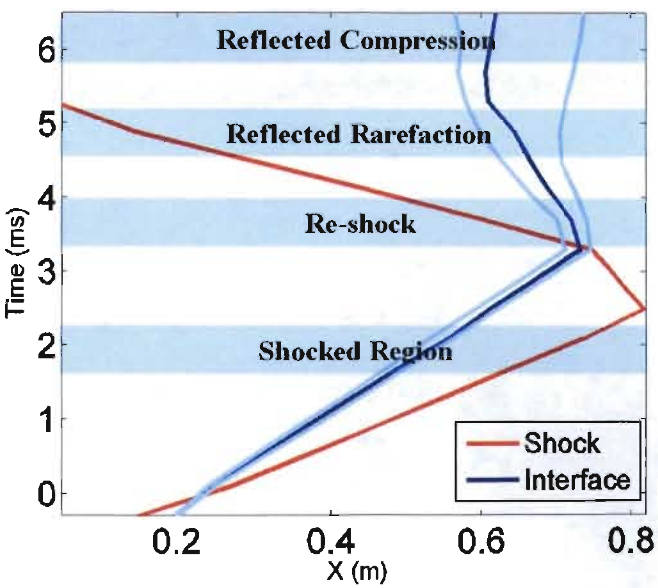
Spectral IC effects on material mixing

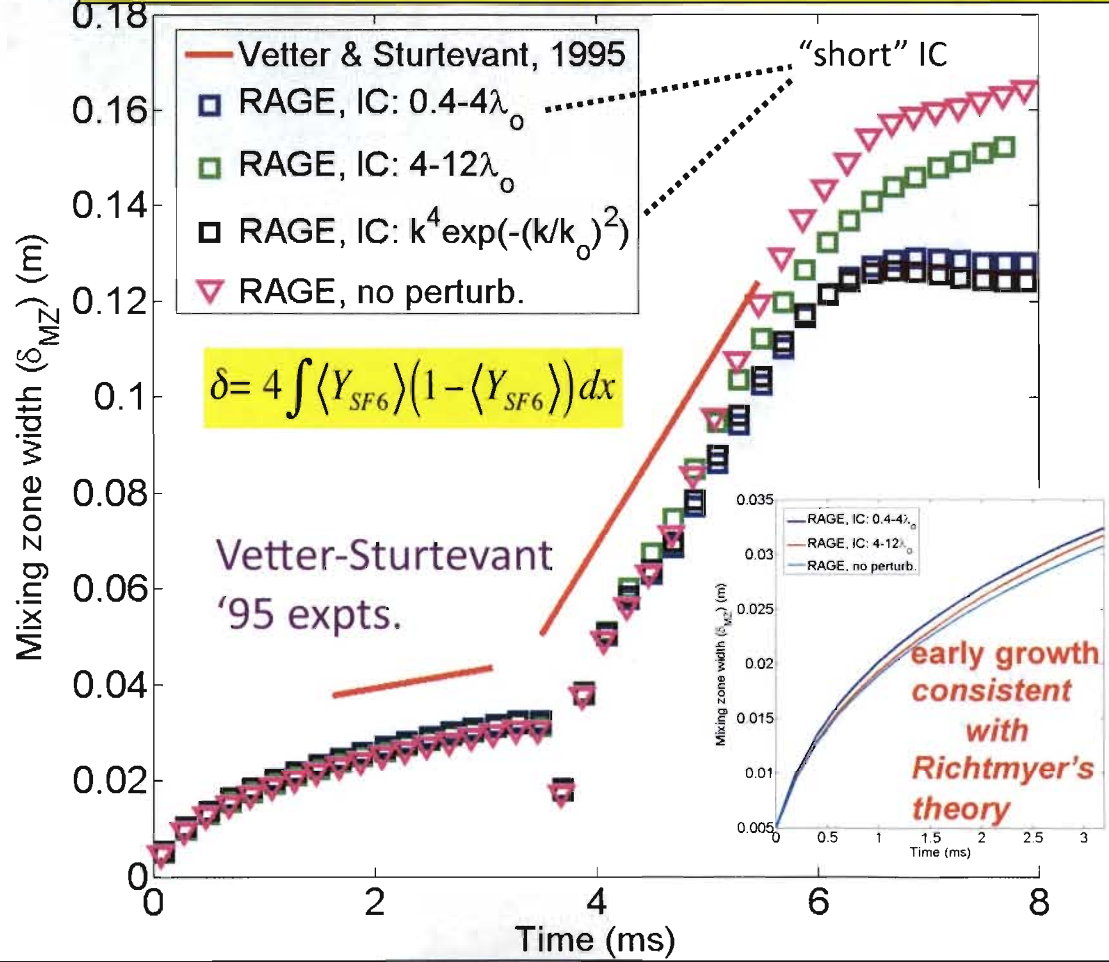
Grinstein, Gowardhan, and Wachtor, *PoF*, March 2011

egg crate (λ_o) $\theta = (1 - Y_{SF6})Y_{SF6}$ + (0.4-4λ_o)



10% IC perturbation added to mode (λ_o)

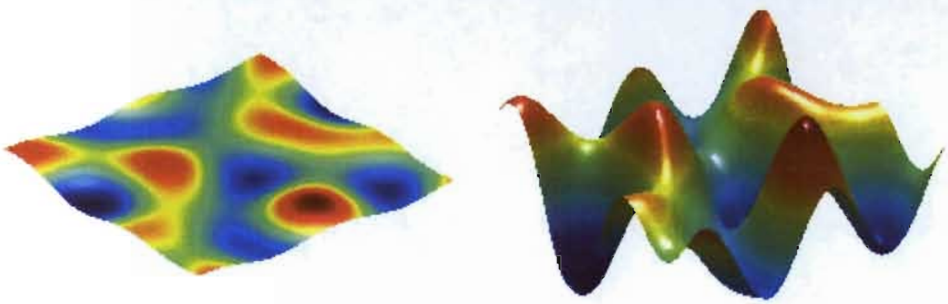




- **results for "thin" low η_o initial material interface**
- **early-time** (t<~5ms) **growth fairly IC insensitive**
- **late-time sensitive to ICs** (more so for "longer" IC
- **IC resolution issues … separate discussion req'd …**

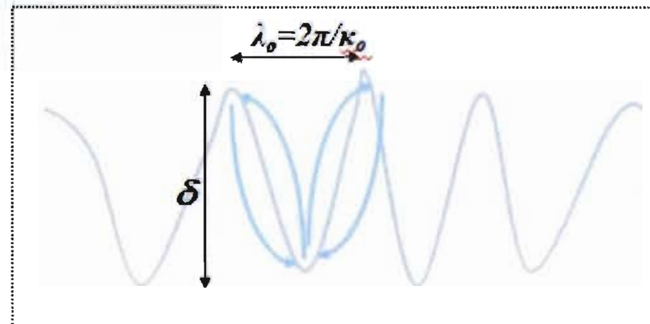
Initial (single) **material interface parameterization**

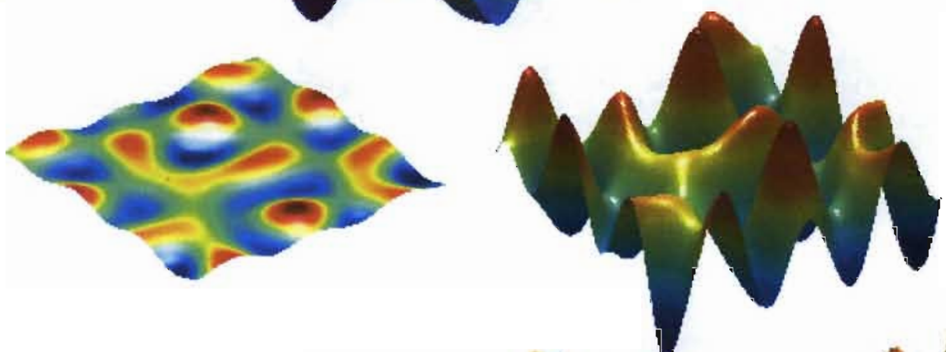
focus first on: no "egg-crate", no reshock…



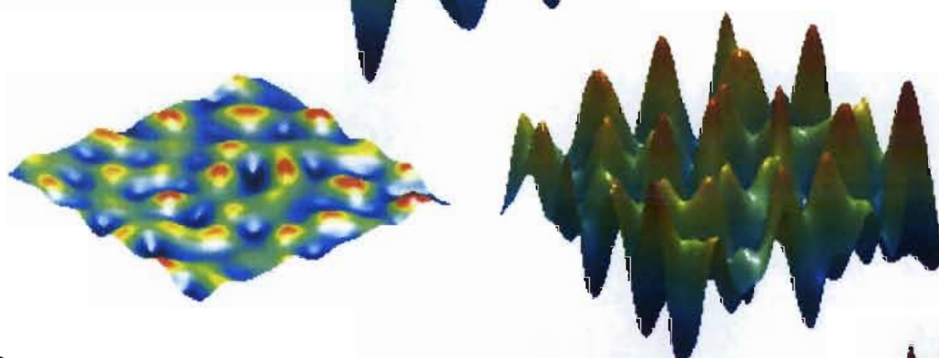
high η_o ***class*** $(\kappa_o\delta_o > \pi)$

η_o= 10π/12 , 10π/8, 10π/4 , 10π/2





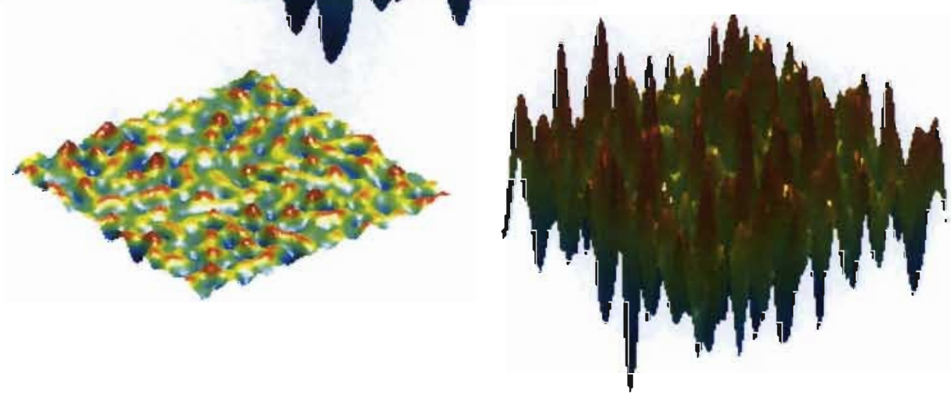
$$\eta_o = \kappa_o\delta_o$$



low η_o ***class***

η_o= π/12 , π/8 , π/4 , π/2

$(\kappa_o\delta_o << \pi)$



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Bipolar Behavior of planar RM

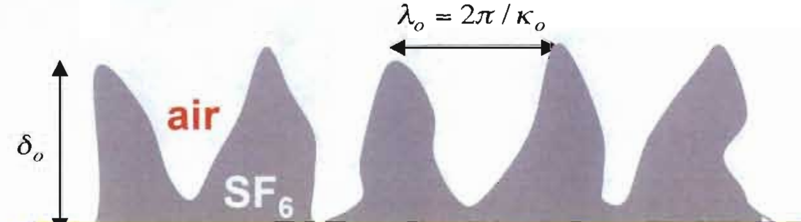
Ma=1.5, air/SF_6 – **no** egg-crate, **no** reshock

Gowardhan, Ristorcelli and Grinstein; *PoF* Letters, July 2011

Impact of *rms* slope $\eta_o = \kappa_o \delta_o$ of Initial Material Interface

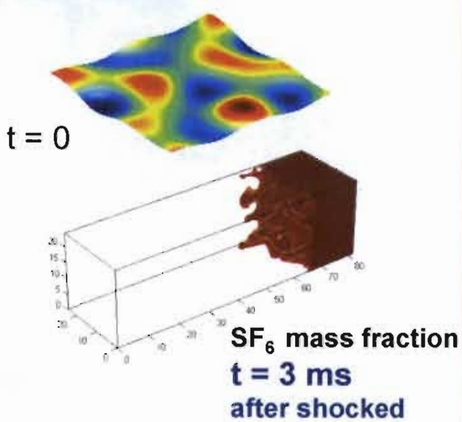
Beyond Richtmyer (growth = constant × η_o):

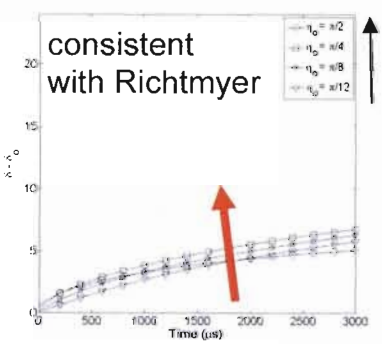
- → ***bipolar RM behavior vs. IC morphology***
- → ***different instability mechanisms & late-time flow***



Dimensional **results**

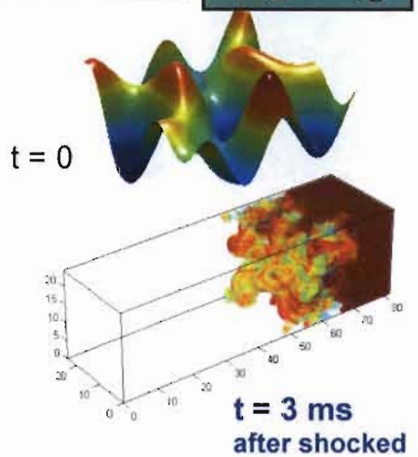
low η_o

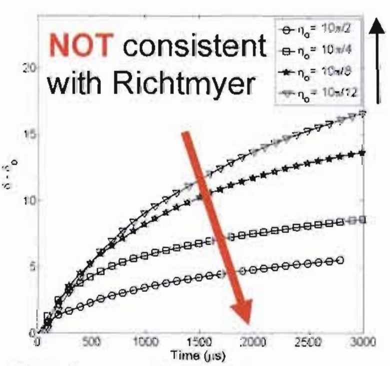




Mixing width **increases** with increasing η_o

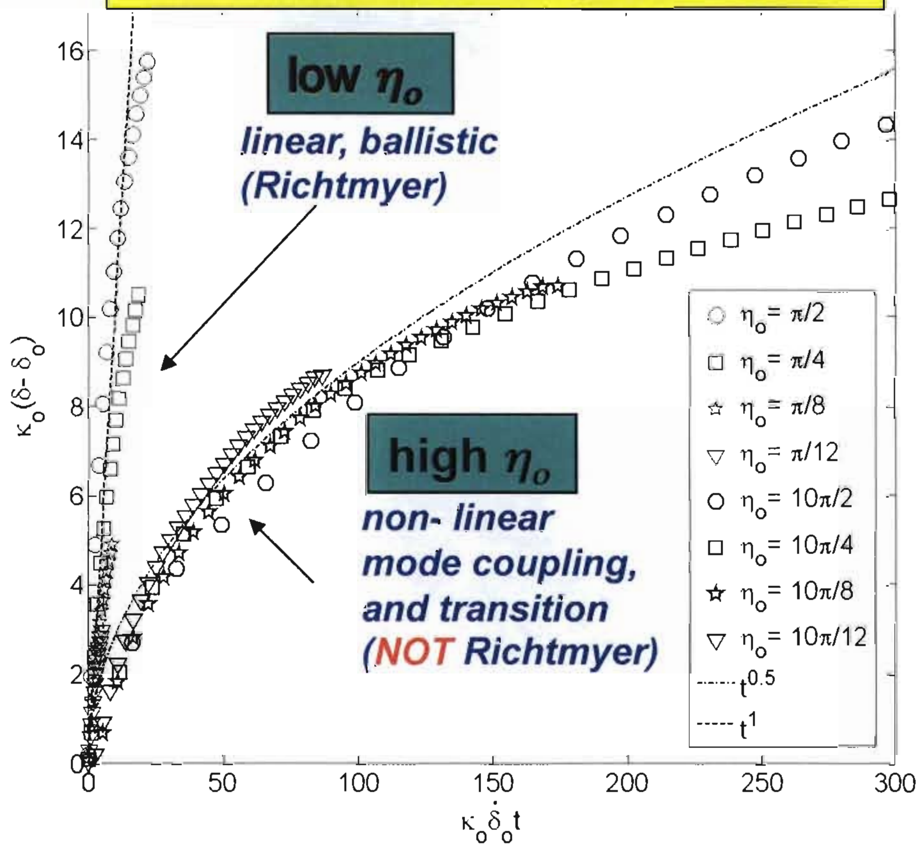
high η_o





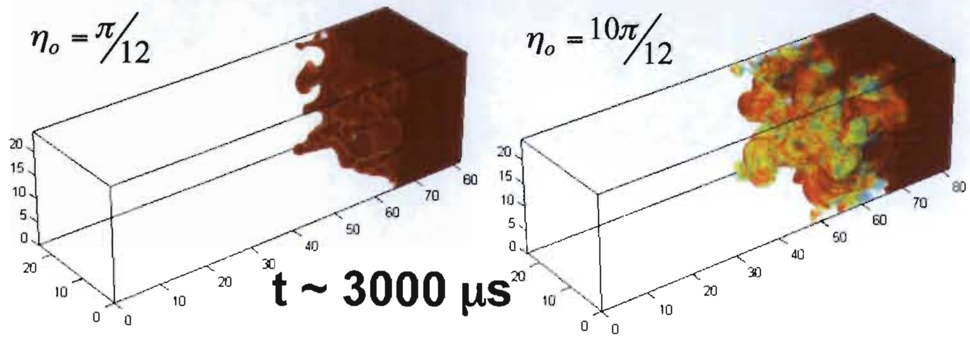
Mixing width **decreases** with increasing η_o

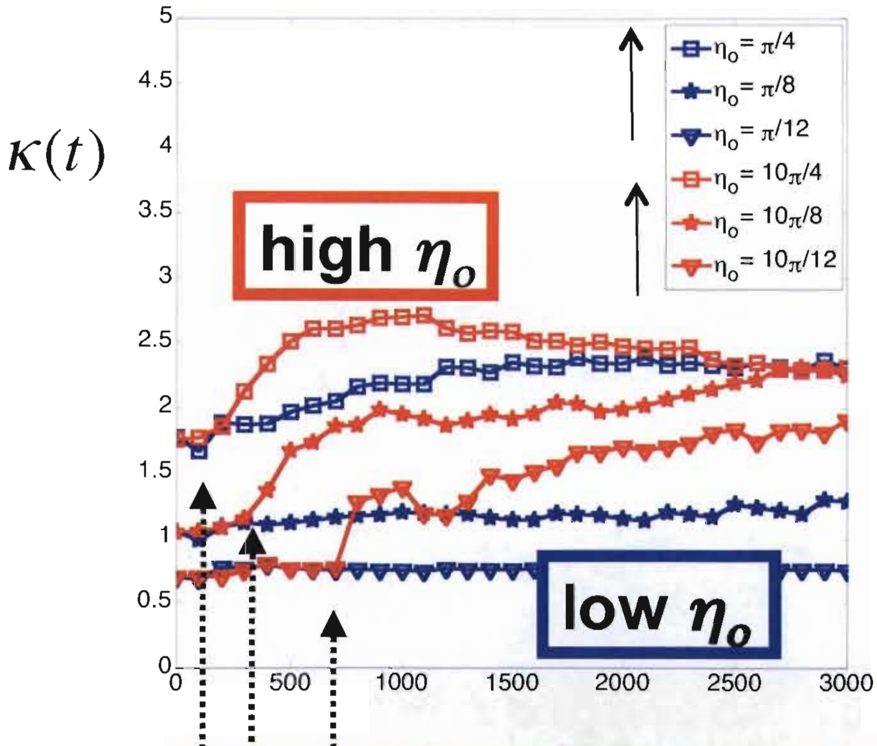
Non-Dimensional "Bipolar" **results**



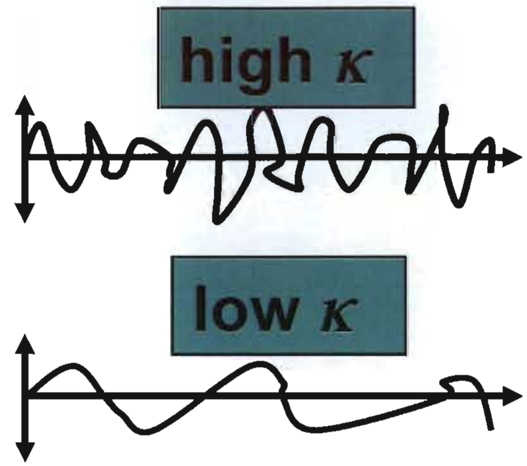
Characterizing Small-Scale Production

→ zero-crossing wavenumber κ (e.g., Sreenivasan et al. JFM '83)





"transition" process indicated by rapid increase of κ



κ is the "zero crossing" wavenumber of the mass density fluctuation

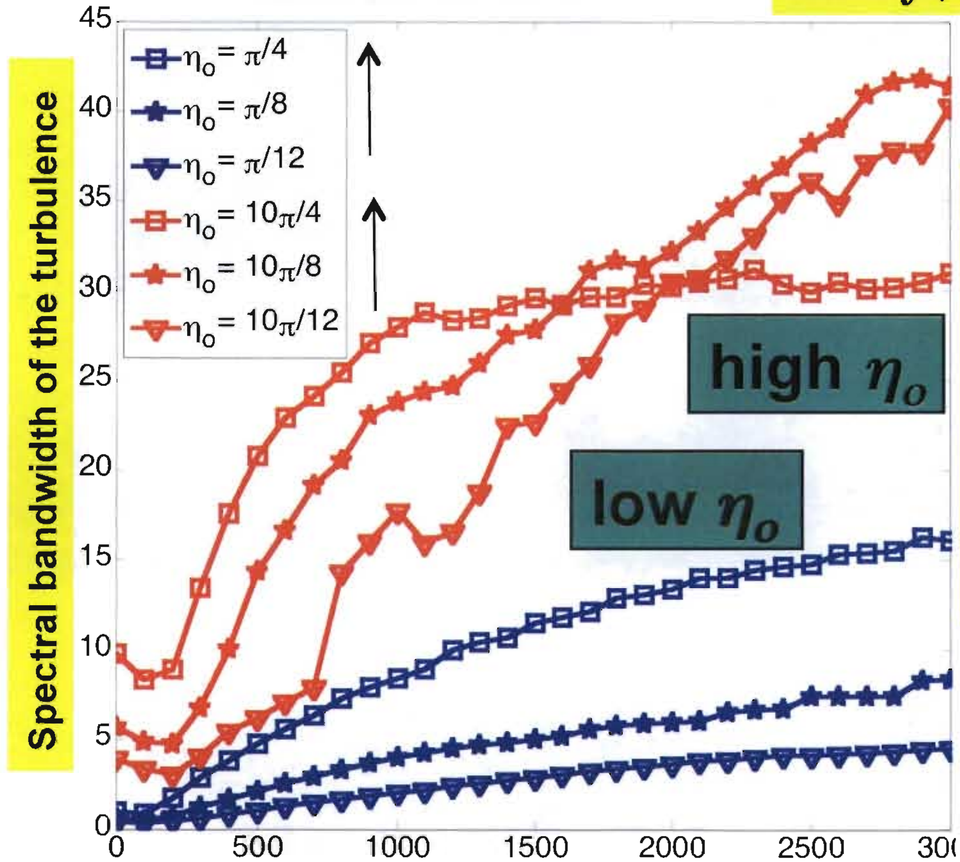
$$\kappa(t) \sim \frac{1}{\lambda(t)} = \frac{1}{Taylor\ length\ scale}$$

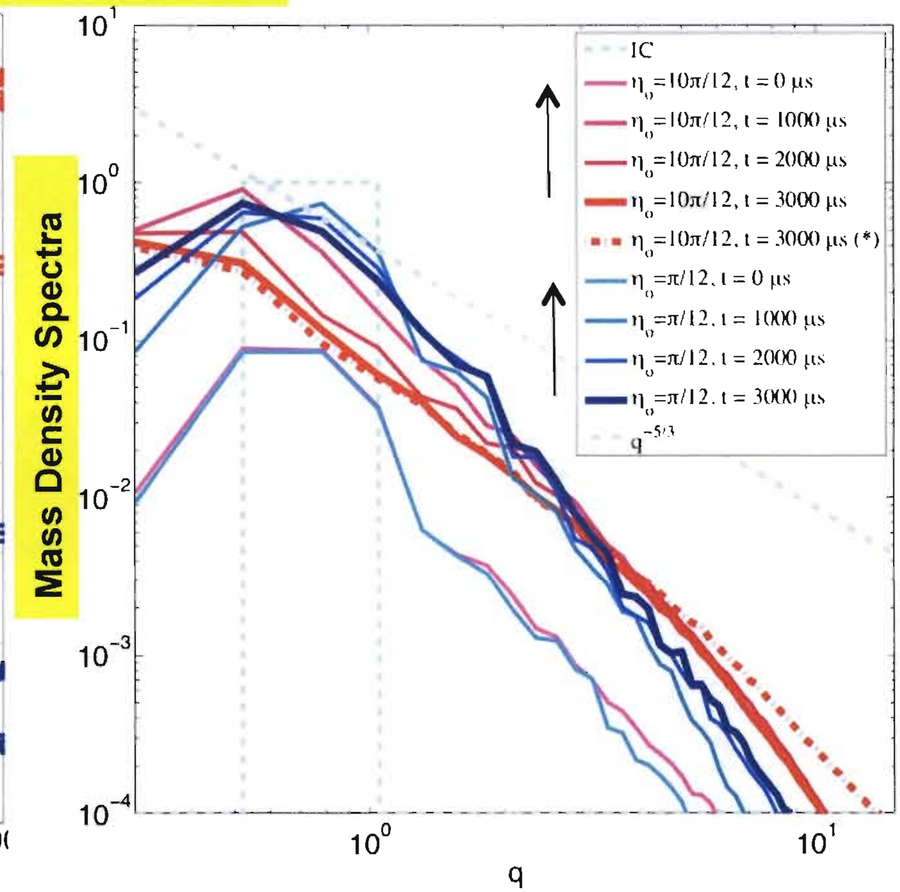
Spectral bandwidth of the turbulence

Spectral bandwidth proxy provides a measure of how "turbulent" the flow is

$$\eta(t) = \kappa(t)\delta(t) = \frac{\delta(t)}{\lambda(t)} \sim \frac{Integral\ scale}{Taylor\ length\ scale} \sim \mathrm{Re}_\lambda$$

$$\delta(t) = 4\int \langle Y_{SF6}\rangle \left(1 - \langle Y_{SF6}\rangle\right) dx$$

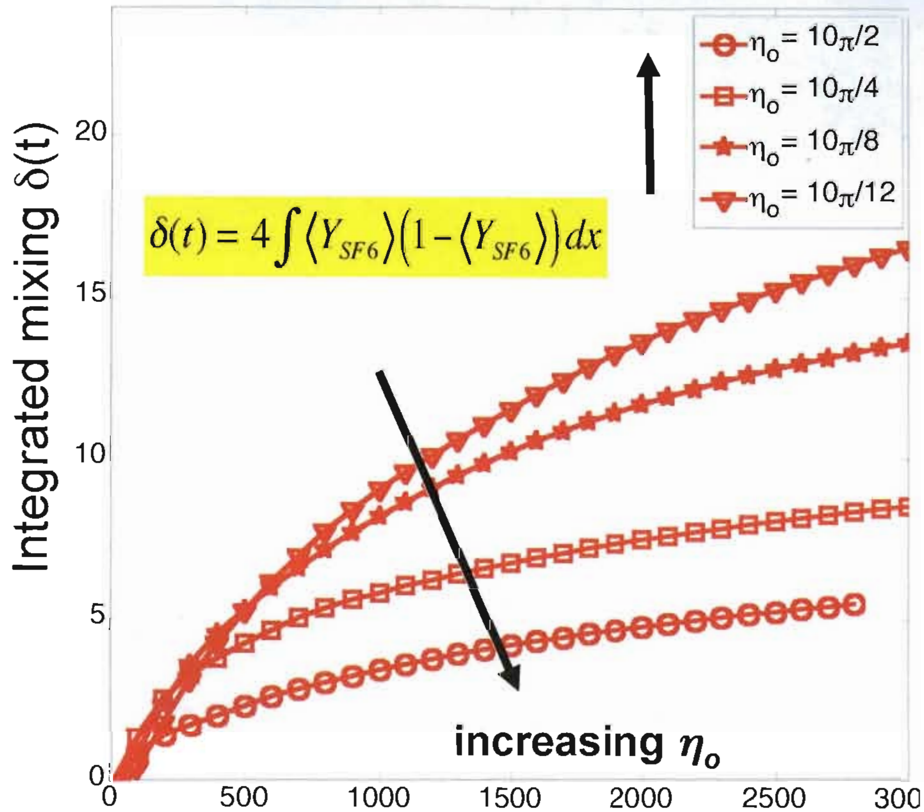


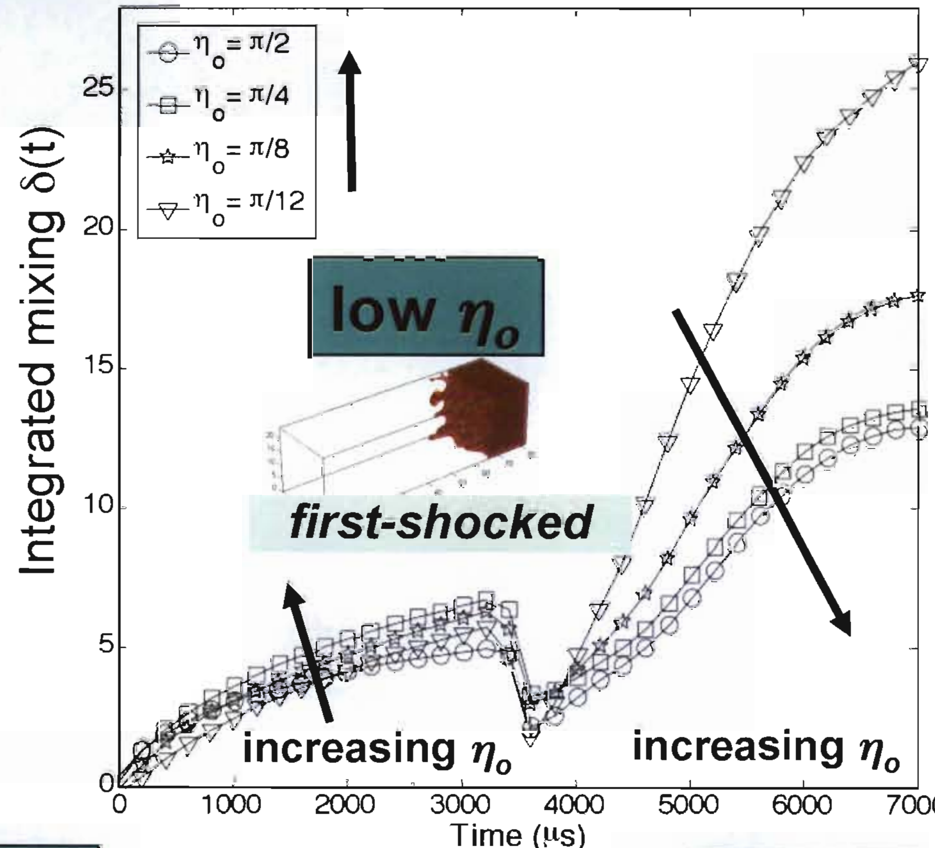


Higher initial η_o ***leads to higher*** $\eta(t)$ ***at late times***

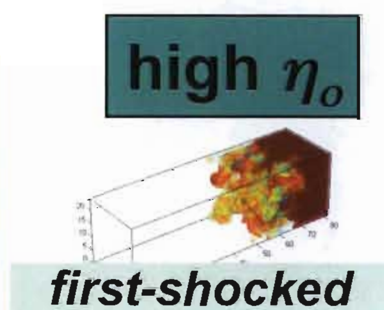
Consequences of Bipolar RM Behavior

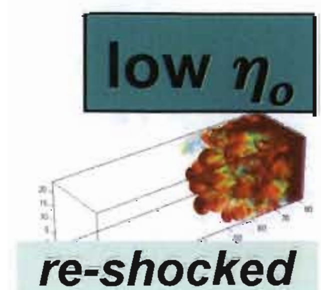
low η_o ***reshock effects*** ~ **high η_o** ***first shock effects***





Y_{SF6} visualizations at
t ~ 3000 μs
after first-shock
(or after reshock)

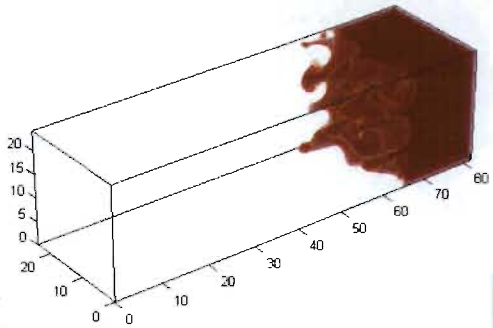




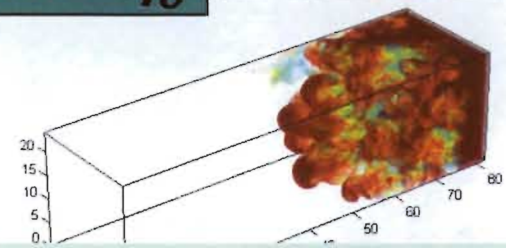
Consequences of Bipolar RM Behavior

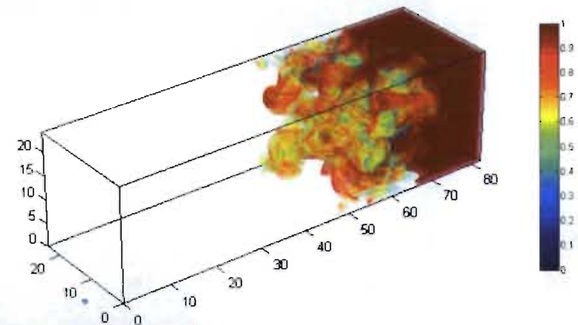
low η_o *reshock effects* ~ high η_o *first shock effects*

low η_o *re-shocked*



instantaneous material mixing





low η_o *first-shocked*

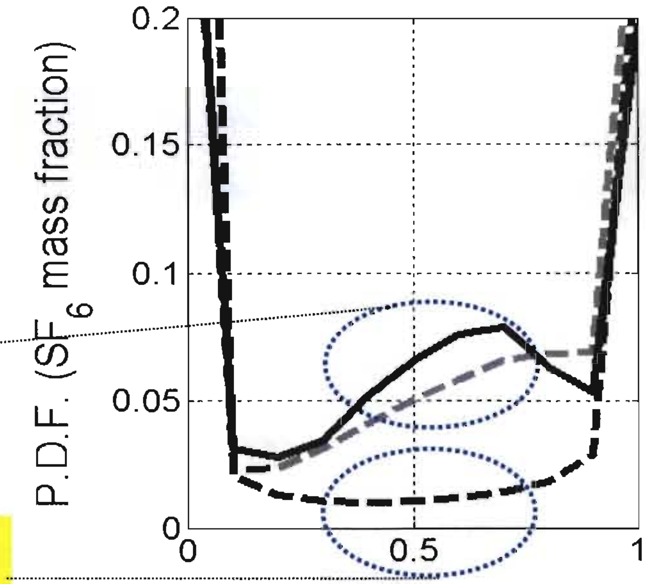
high η_o *first-shocked*

t ~ 3000 μs after first-shock
(or after reshock)

low η_o *reshocked* **mixed**

high η_o *first-shocked* **mixed**

low η_o *first-shocked* **unmixed**



Planar Shock-Driven Turbulence

Grinstein, Gowardhan, and Wachtor, *PoF*, 2011; Gowardhan, Ristorcelli and Grinstein; *PoF* Letters, 2011
Shocked (double interface) Gas Curtain → Gowardhan and Grinstein, *J. of Turb.* 2011, in press

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- **RM bipolar behavior:** **switch for $\eta_o = \kappa_o \delta_o \sim 1$**

low η_o : *linear, ballistic, mix-width $\delta \sim t$*

high η_o : *non-linear, mode coupling , mix-width $\delta \sim t^{1/2}$*

→ *transition to turbulence suggested*

→ more material mixing & smaller scales

- **Reshock effects on first shock, if $\eta_o > 1$**

- **The modeler's (initial condition) challenge**
  - **two different instabilities & growth trends**

low η_o $\rightarrow$ as $\eta_o \uparrow$ enstrophy $\uparrow$ isotropy $\uparrow$ TKE $\uparrow$ $\delta \sim t \uparrow$ ALL GROW with η_o

high η_o $\rightarrow$ as $\eta_o \uparrow$ enstrophy $\uparrow$ isotropy $\uparrow$ GROW with η_o

TKE $\downarrow$ $\delta \sim t^{1/2} \downarrow$ DECREASE with η_o

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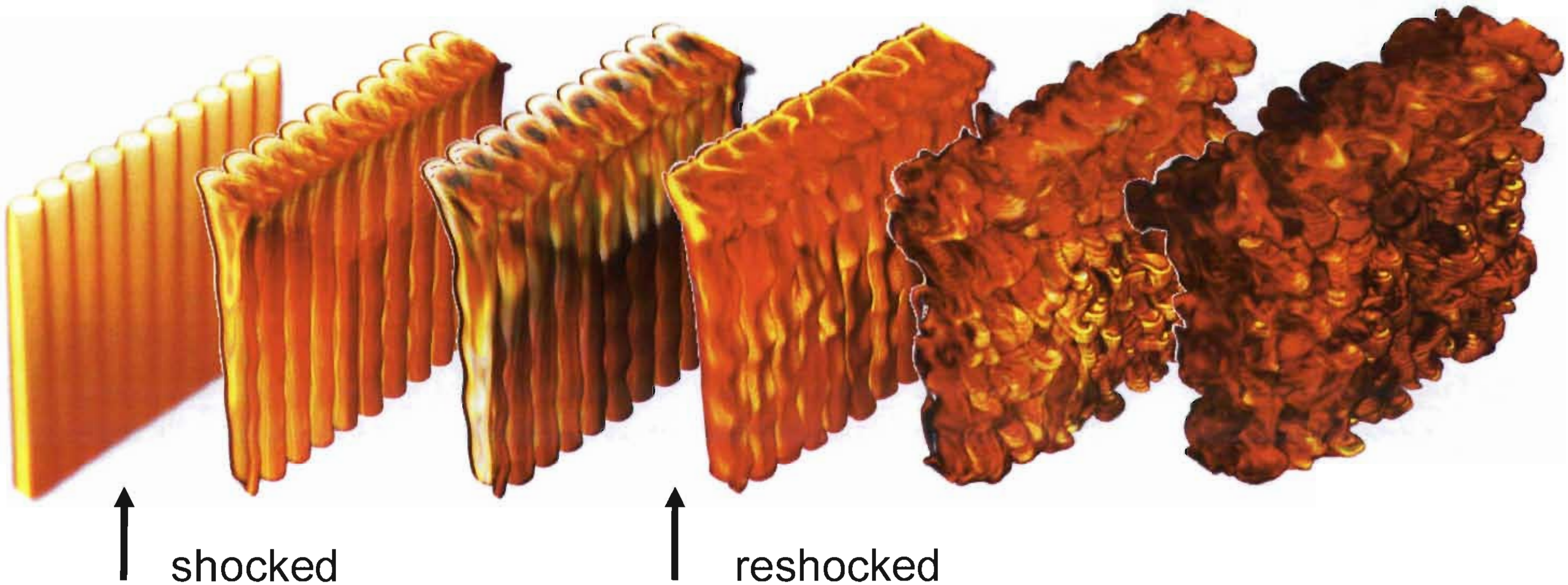
possible first "generalization" : η_o → η_o A Ma

RAGE Simulations of Shocked (two-interface) Gas-Curtains

Gowardhan & Grinstein, JoT 2011, under review

Thanks to K. Prestridge, S. Balasubramanian, B.J. Balakumar (P-23, LANL)
for stimulating discussions and for sharing information and data from their experiments.



- Initial 3D GC characterization and modeling
- Sensitivity of turbulence characteristics to ICs
- Data reduction and bipolar RM behavior

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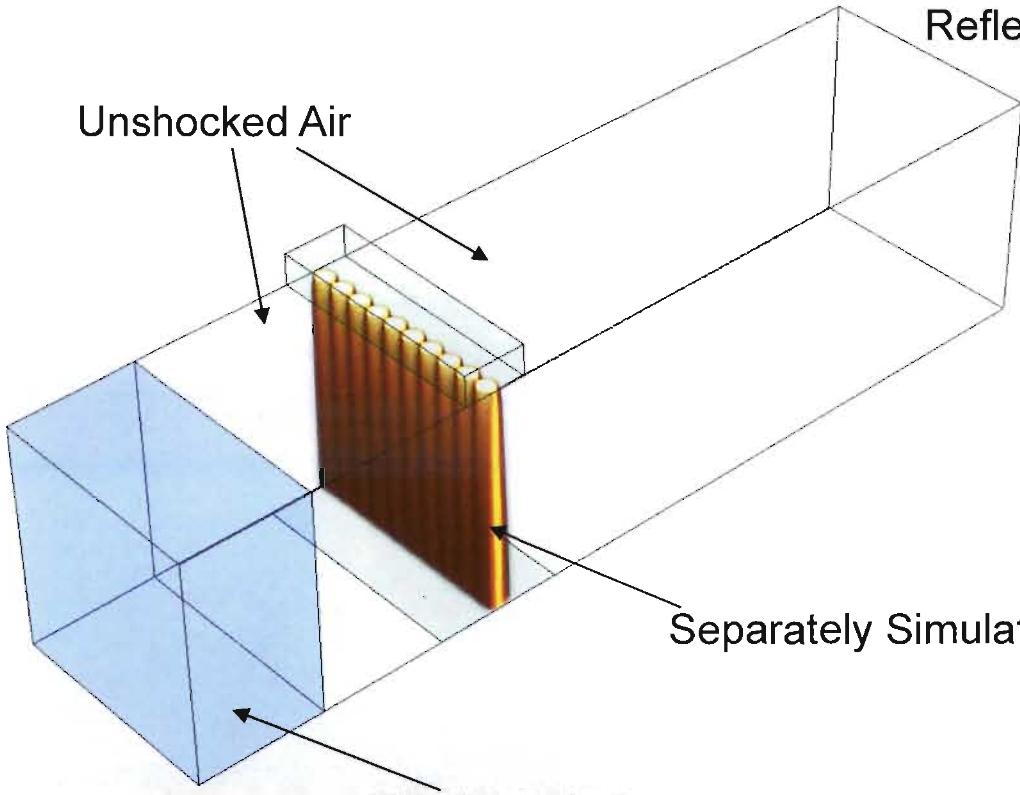
Shocked Gas Curtain

ILES RAGE simulations – SF_6 mass fraction distributions



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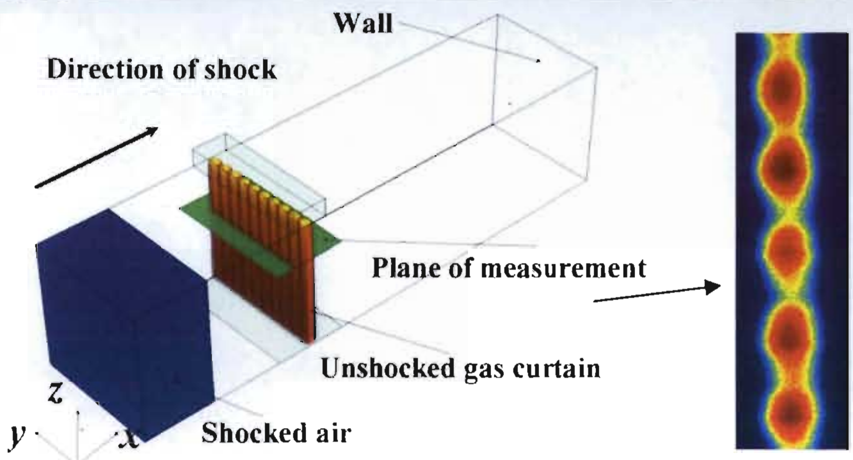
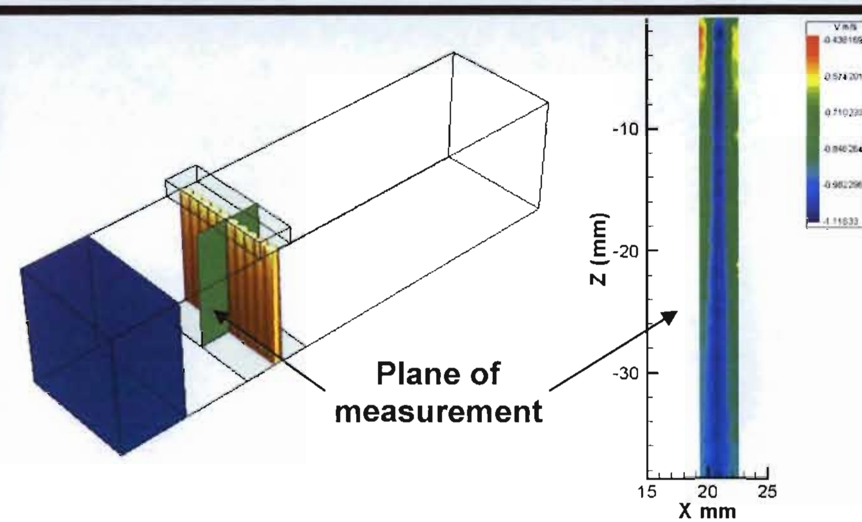
Initial GC Characterization ...



2D *PLIF* SF_6 intensities (C / C_{max}) in a horizontal plane 2 cm from nozzle exits



Vertical PIV @ center of GC, gives estimates of nozzle exit velocity (~100 cm/sec)

- Composition & fluctuations of SF_6 mixture at nozzle exits only estimated

  50-80% SF_6 – rest Acetone (used as a tracer for PLIF), and air;

- Uncharacterized co-flow and bottom suction used to stabilize the GC

P-23 lab info insufficient to fully characterize 3D initial GC conditions for *RAGE* simulations

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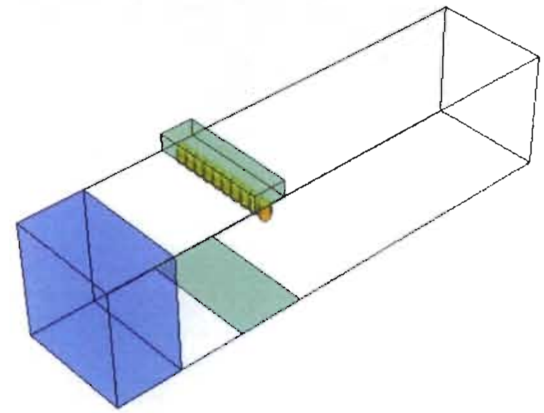
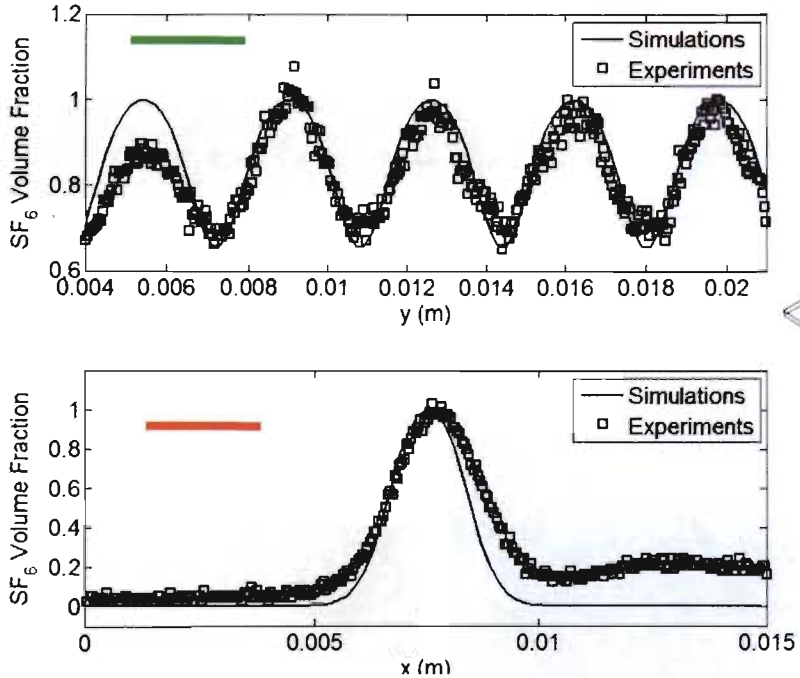
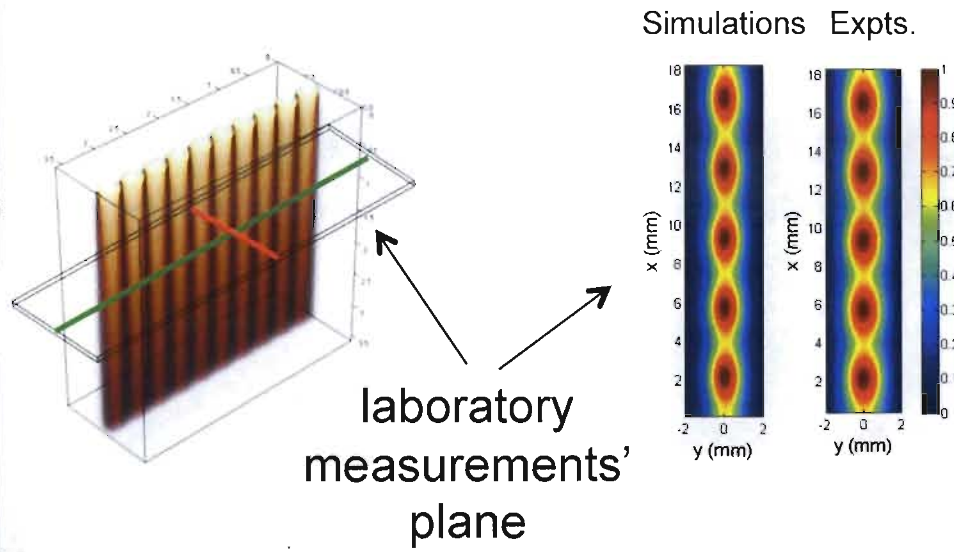
Simulated 3D Gas Curtain → Initial Conditions for RAGE

- separate laminar NS-Boussinesq simulation of SF_6 falling through nozzle arrangement
- **available info from lab. expts. used to constrain 3D GC simulation**
- no coflow, advective downstream BC
- 75% SF_6 – air (no acetone) at nozzle exits







Initial Mass-Density Variance Spectra

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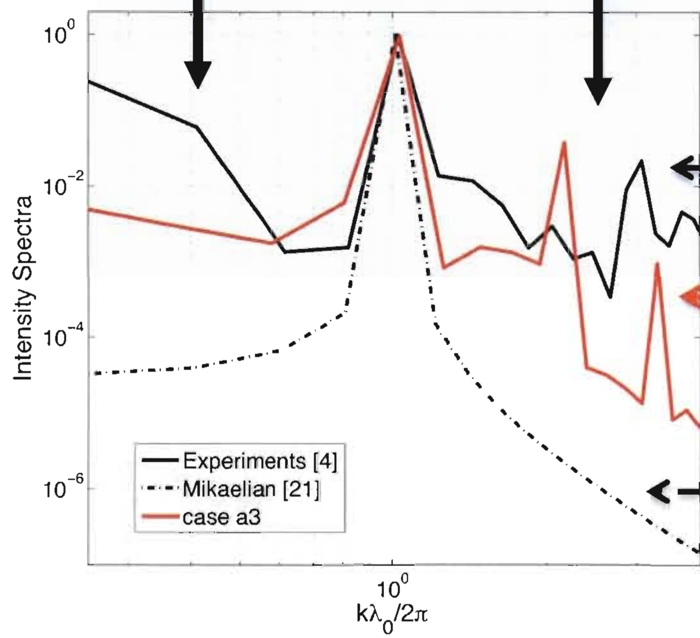
Large scale noise

Small scale noise



typical experiment

simulation with added noise

Mikaelian's 2D intensity model

$$I = \frac{A(1 + B\cos kx)}{1 + B} \exp[-y^2\alpha^2 / (1 + \beta \cos kx)^2]$$

Mass-density variance spectra of initial GC data indicates presence of *small* and *large* scale modes, in addition to 2D Mikaelian's dominant mode …

To mimic the noise present in the experiments, nozzle offsets and/or SF_6 concentration perturbations were added to baseline simulated GC …..

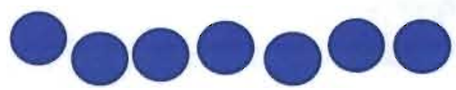
3D simulated GC "noise"
(Initial Conditions for RAGE)

Large scale perturbation: Achieved by slightly offsetting (randomly, <0.05R) the nozzles in the shock direction

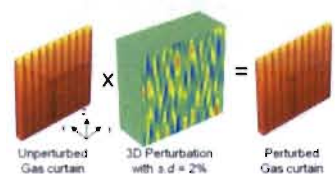
Small scale perturbation: Achieved by adding multimode 3D concentration perturbation (s.d. ~2%) to baseline 3D GC

a0: no perturbation (baseline)

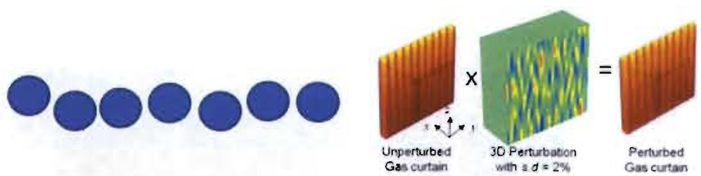
a1: nozzle offset



a2: 3D concentration perturb.



a3: nozzle offset and 3D conc. Perturb.



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ILES RAGE of Shocked SF_6 Gas Curtain
Multi-mode IC Effects on Mixing & Transition

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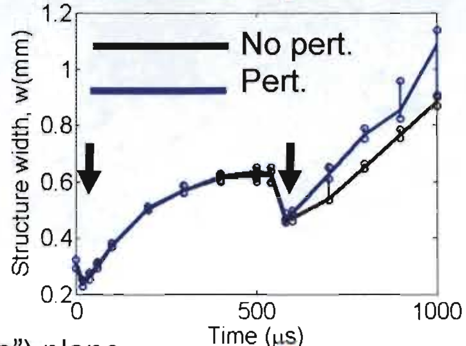
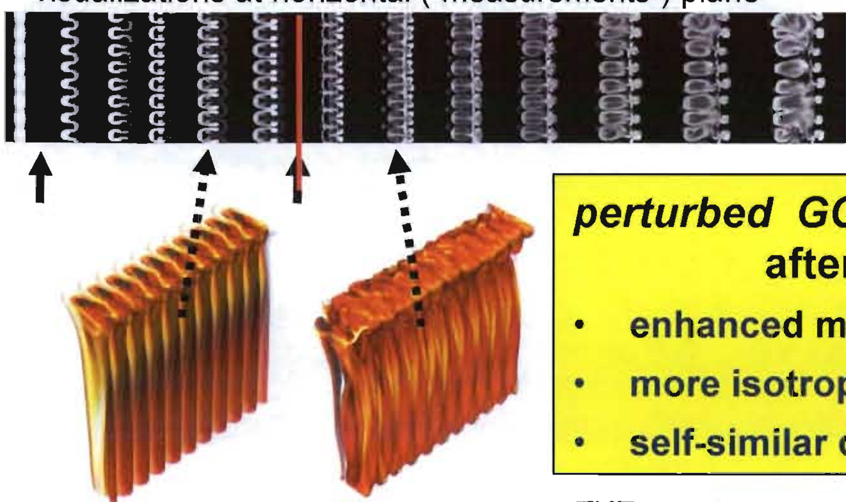


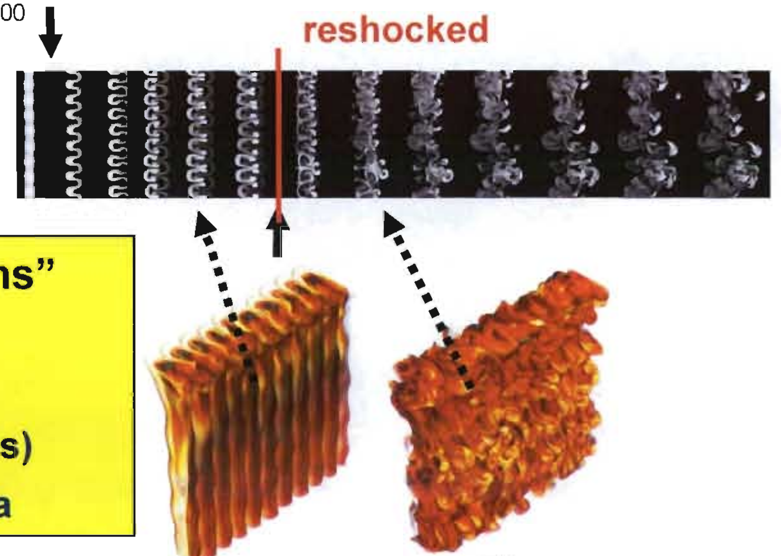
Gowardhan & Grinstein, JoT (2011), under review

non-perturbed GC
"ballistic" growth dominates

multi-mode perturbed GC
mode-coupling promoted

visualizations at horizontal ("measurements") plane

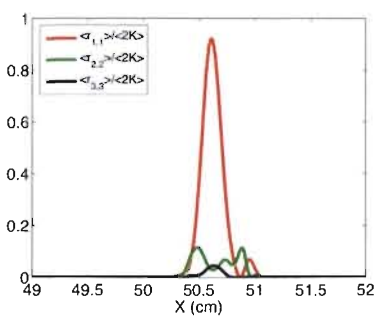




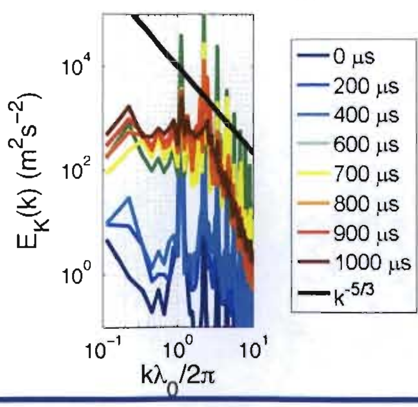
perturbed GC **"transitions" after reshock**

- **enhanced mixing**
- **more isotropic (late times)**
- **self-similar decay spectra**

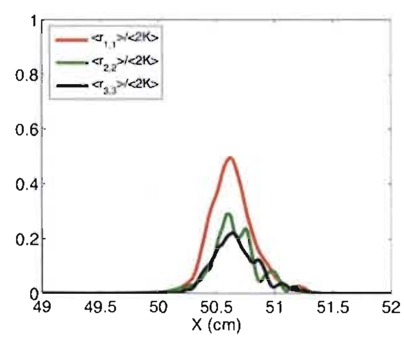
velocity variances @ t=1000μs



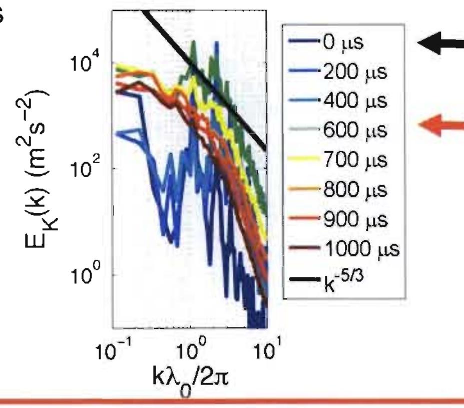
TKE spectra



velocity variances @ t=1000μs



TKE spectra



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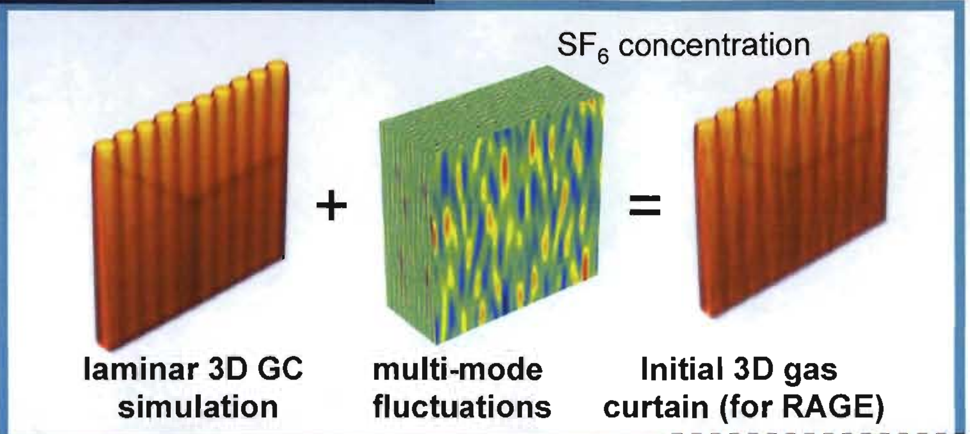
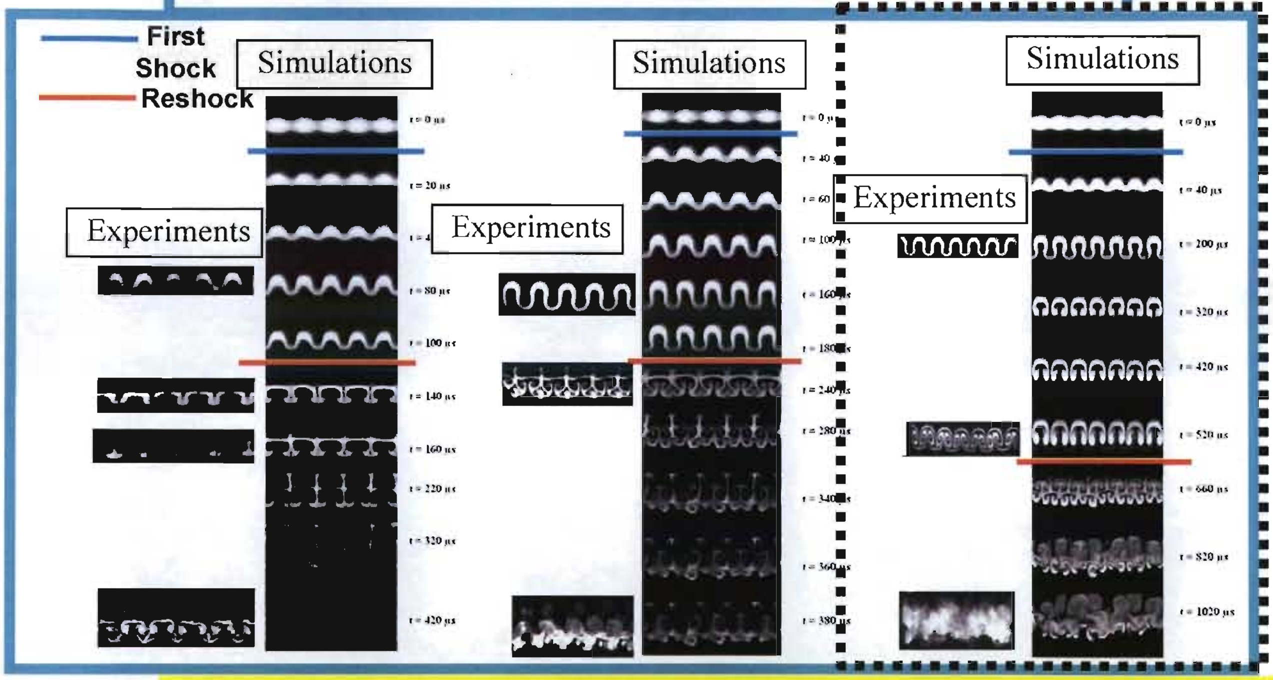
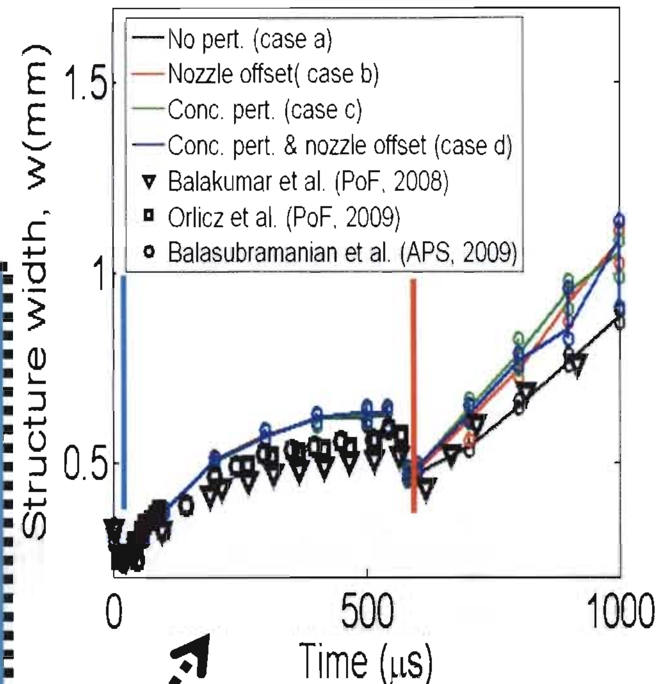
ILES of Shocked SF_6 GC vs. Expts.

Gowardhan, Balasubramanian, Grinstein, Prestridge, AIAA Paper 2011





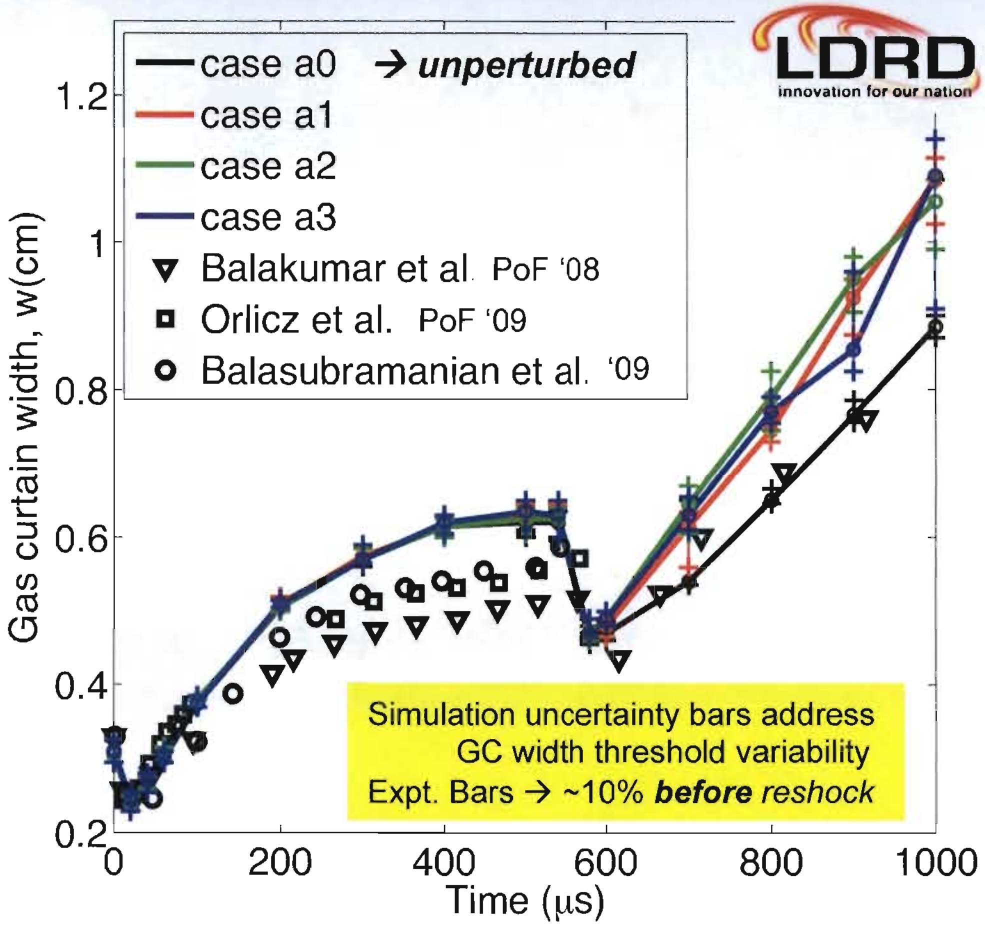


Robust agreement with lab. flow patterns and growth rates before reshock but sensitive to ICs after reshock !

over-predicted early growth reflects lower effective Atwood number in expts.

GC Width: Simulations *vs.* Expts.

Gowardhan, Balasubramanian, Grinstein, Prestridge, AIAA Paper 2011



GC width is defined as shockwise distance over which $\chi(x) > \chi_h$ based on a selected threshold $\chi_h \sim 0.95$, where $\chi(x) = 4\xi(x)(1-\xi(x))$, and

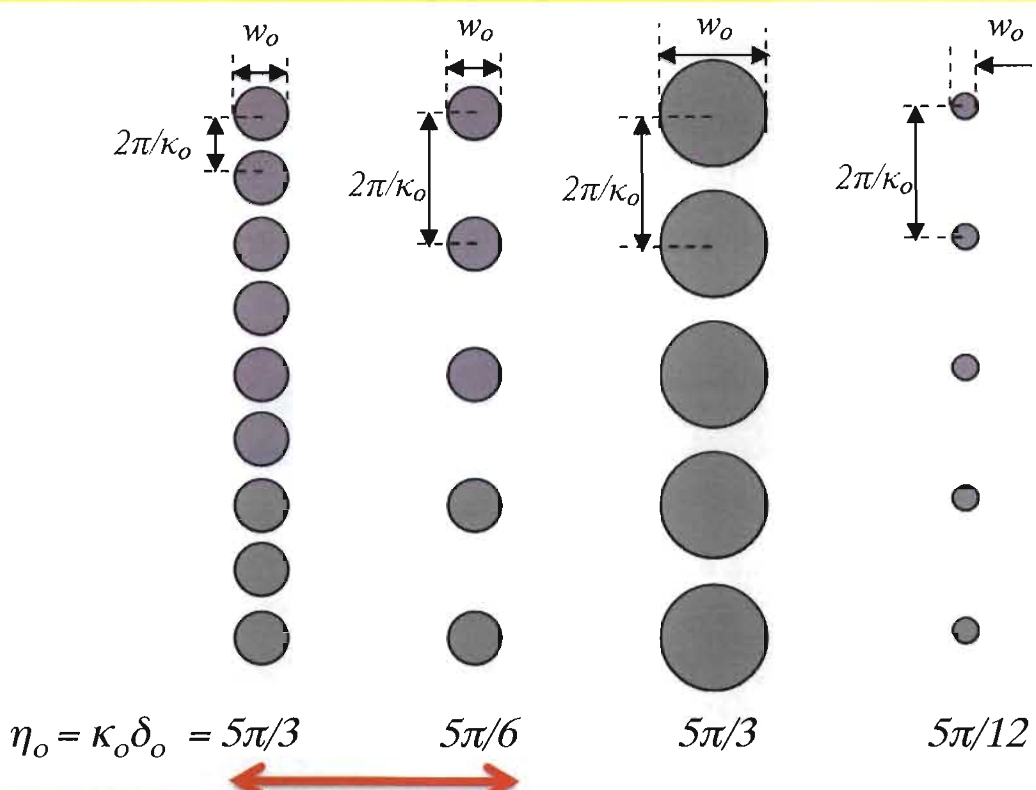
$$\xi(x) = \frac{1}{L_y}\int_0^{Ly}\left(\frac{\rho_{SF6}(x,y,z=2)}{\rho(x,y,z=2)}\right)dy$$

- Simulated growth qualitatively consistent with P-23 experiments
- **Before reshock**, GC widths for all simulations are in close agreement;
  discrepancies with expts. mainly attributed to different SF_6 (air, and acetone) mixtures in initial GCs
- **After reshock**, GC width growth rates are consistent but,
  "perturbed" ≠ "non-perturbed"
  → very sensitive to ICs ***and** consequent interface conditions* at reshock time

Characterizing Reshock effects
difficult for Expts. <u>and</u> LES !

Data Reduction in Shocked GC (before reshock)

- IC parameterization & additional GC cases
  - Data reduction to compare results associated with different ICs
  - Bipolar RM behavior also for the shocked GC ?



lab. expts. available only for these two cases

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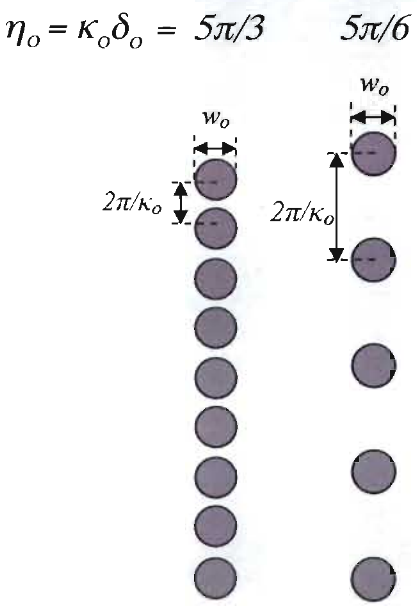
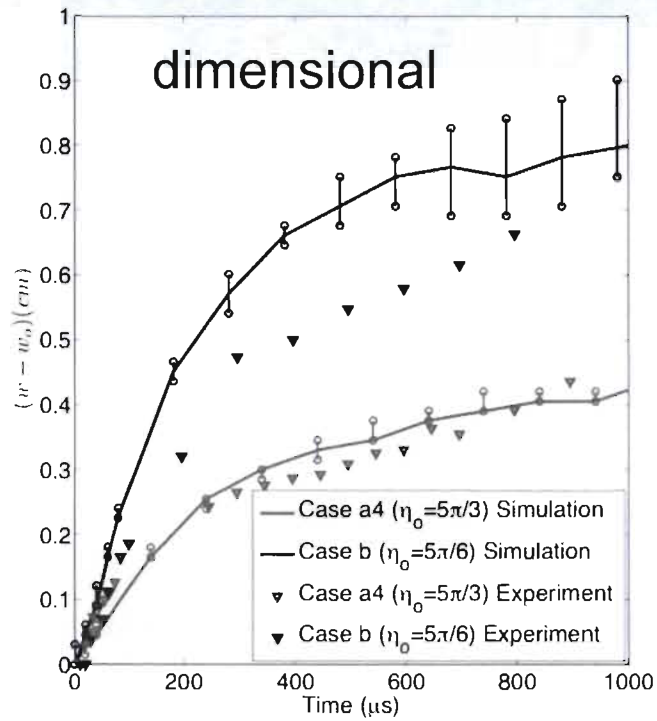
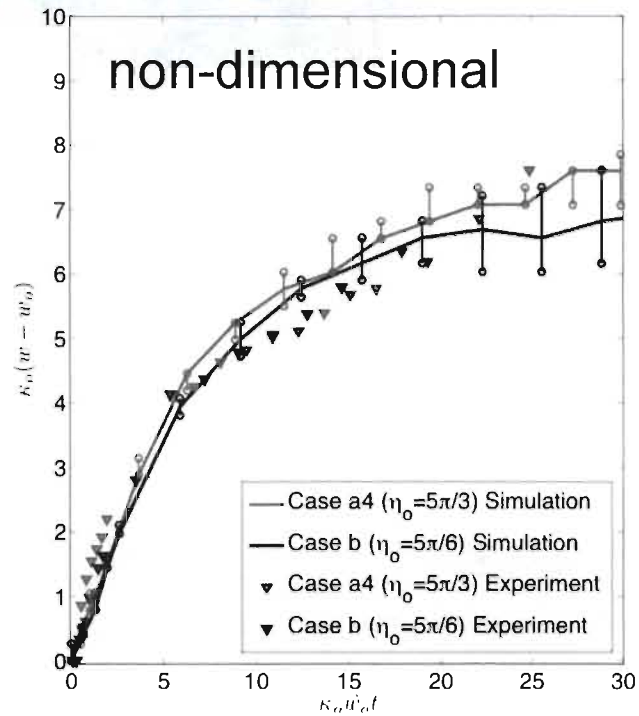
RM Behavior in Shocked GCs (simulations & expts., no reshock)

Gowardhan, Balasubramanian, Grinstein, Prestridge, AIAA Paper 2011



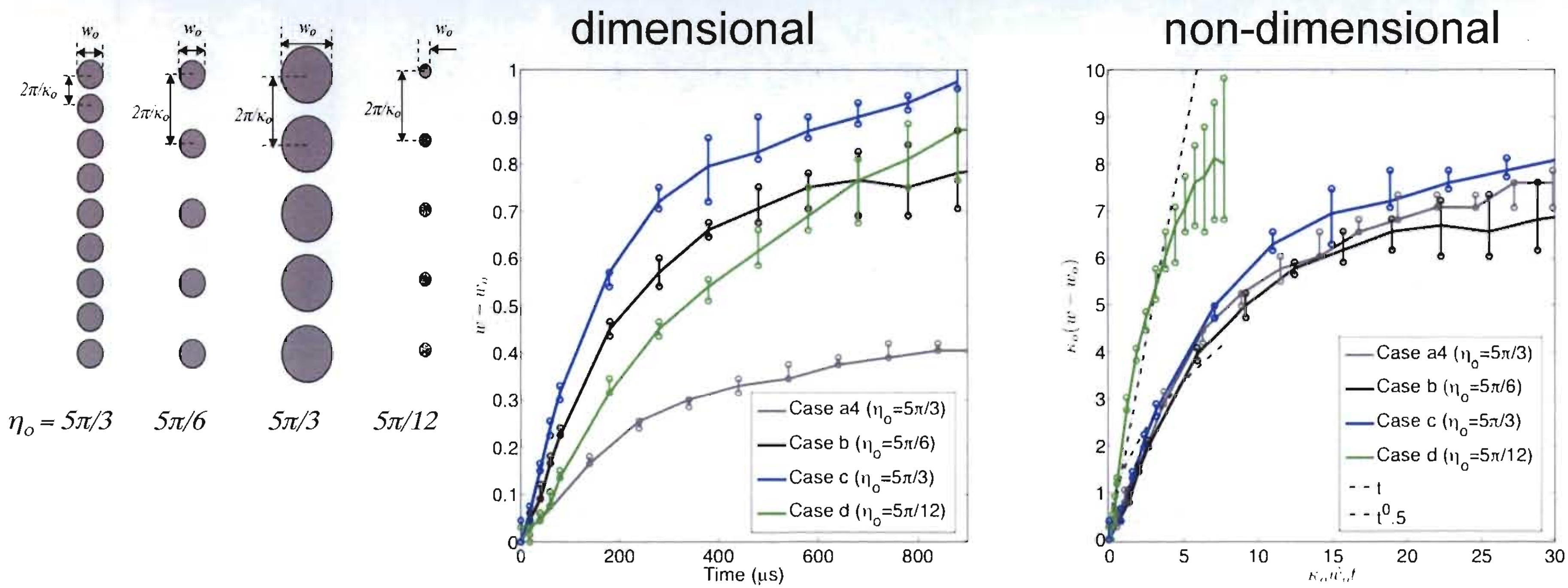




- **Non-dimensionalized results compare well for both GC cases**
- GC widths scaled with κ_o; time scaled with ***actual*** initial width growth rates (*first proposed by Jacobs et al. 1996*)
  → curves collapse well in a "non-linear" (~$t^{1/2}$) group

Bipolar RM Behavior in Shocked GCs (simulations, no reshock)

Gowardhan and Grinstein, JoT 2011, under review



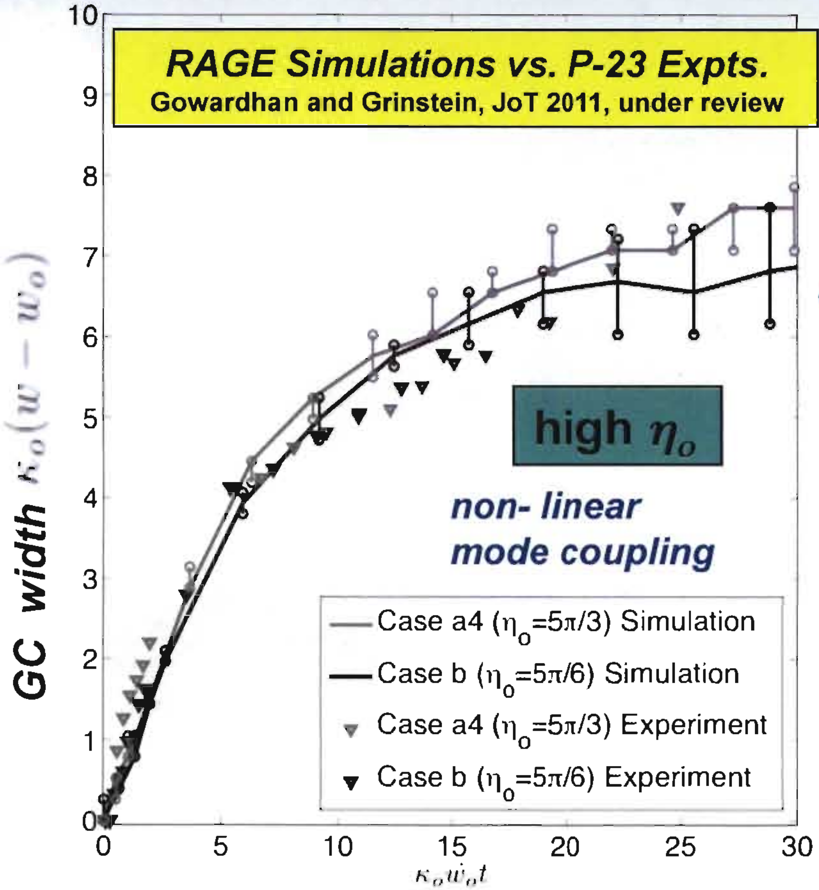
When simulated results are plotted in non-dimensional form

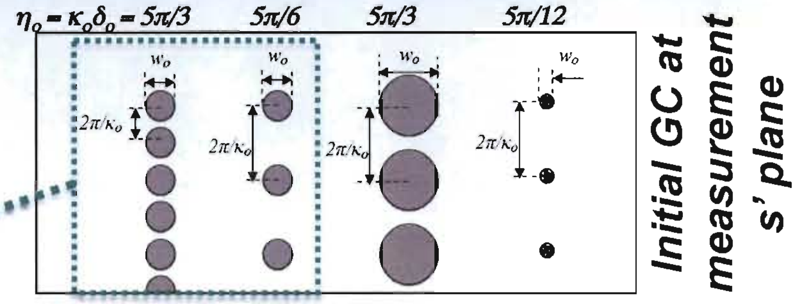
- **cases with η_o > π/2 collapse in "non linear" group,**
- **case with η_o < π/2 falls on "linear" group**

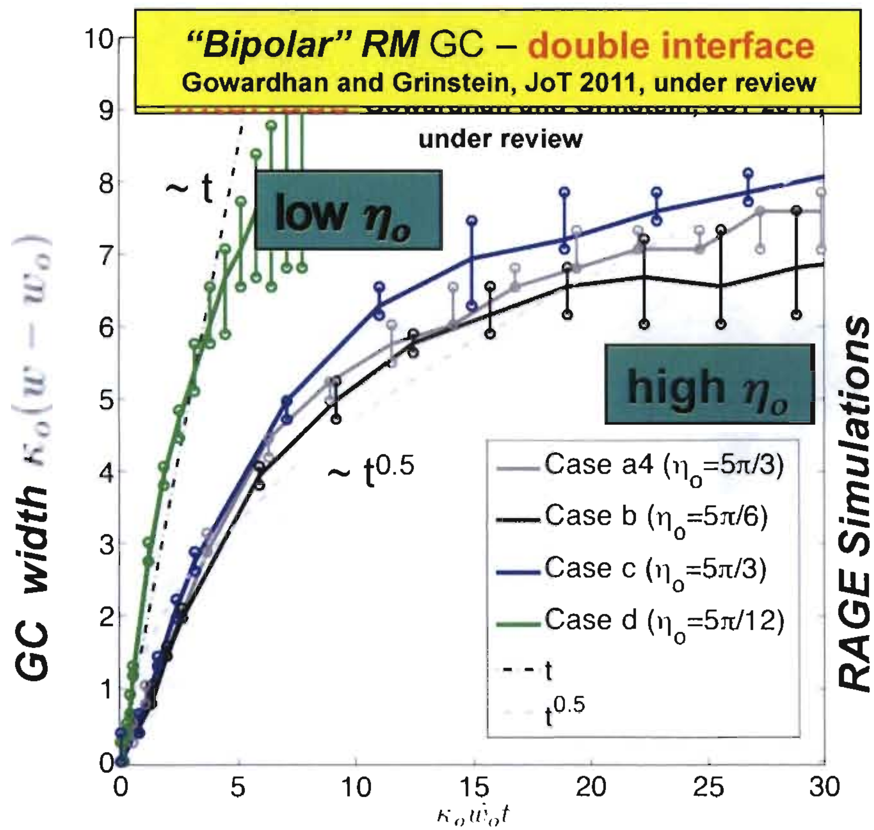
This demonstrates the bipolar RM behavior also for shocked GC

Bipolar RM also demonstrated for shocked GC

GC test case ? Initial 3D GC conditions available …





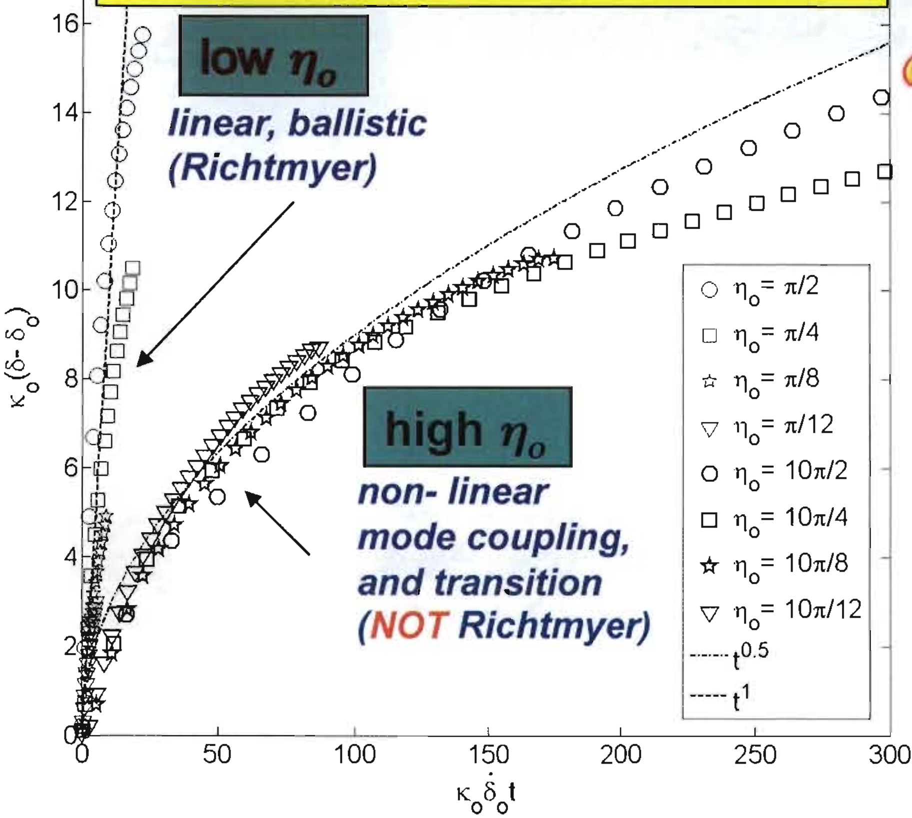


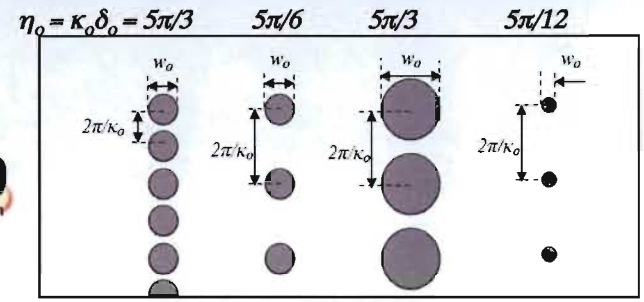
- **Modeler's Initial Condition Challenge:**
  different instabilities,
  growth trends,
  late-time characteristics
- **Instability behavior switches for η_o ~ 1**

Bipolar RM behavior also demonstrated in terms of single IC parameter η_o for shocked GCs

"Bipolar" RM – single interface

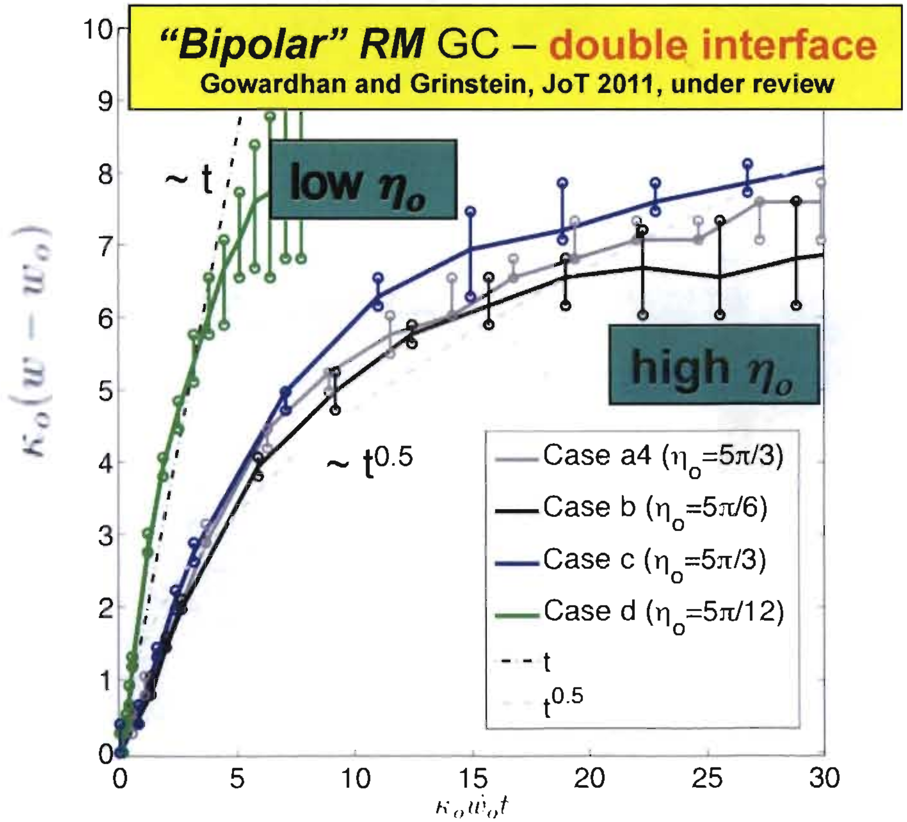
Gowardhan, Ristorcelli, Grinstein, PoF Letters 2011





"Bipolar" RM GC – double interface

Gowardhan and Grinstein, JoT 2011, under review



- **Modeler's Initial Condition Challenge:**
  different instabilities,
  growth trends,
  late-time characteristics
- **Instability behavior switches for η_o ~ 1**

ILES-*RAGE* of Shocked GC Main Conclusions

Simulated initial 3D GC (constrained by lab. data)
+ fluctuations → ICs for ILES RAGE

Effective GC width data reduction (***before reshock***) with single parameter

- **robust agreement with expts. (despite IC uncertainties)**

  (opportunities for defining RM test case)

- **bipolar behavior demonstrated for double-interface RM**

  (a possible first "generalization" might involve: η_o → η_o A Ma)

  - RM behavior switches for h_o ~ 1 (as in planar case)
    - low-h_o : linear, ballistic, GC width ~ t
    - high-h_o : non-linear, mode coupling, GC width ~ $t^{1/2}$

Outstanding Challenge for Experiments *and* LES (ILES)

(high-η_o) IC characterization (data-reduction) at reshock time