LA-UR-04-4690

E.L.Vold

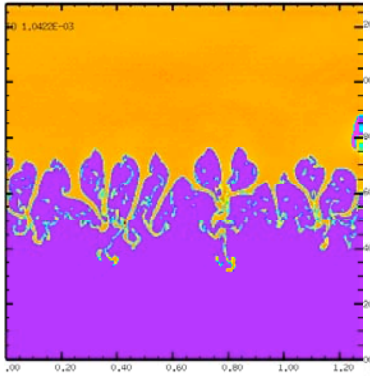
Rayleigh-Taylor and Richtmyer-Meshkov Aspects of Interface Deceleration Mixing

Erik L. Vold

w/ acknowledgement to A.J. Scannapieco, T.T. Clark, C.W. Cranfill

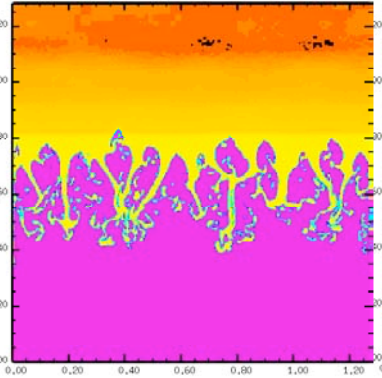
Presentation to the IWPCTM9
Cambridge, UK, July 19-23, 2004

Rayleigh instabity from Hydrostatic equilibrium



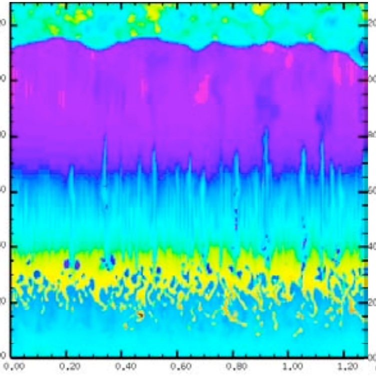
Rayleigh instabity, t= 50 (early non-linear time)

'Gentle' deceleration Instabity- 'early time'



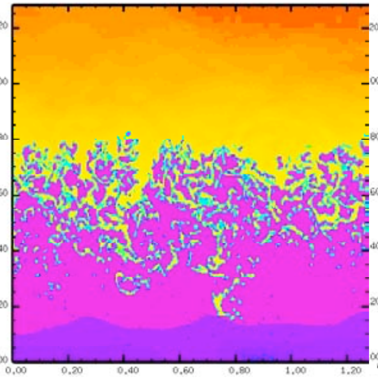
Deceleration ('shockless') Vin = -0.01, t= 70 (mid time)

"Typical' convergent deceleration instabity



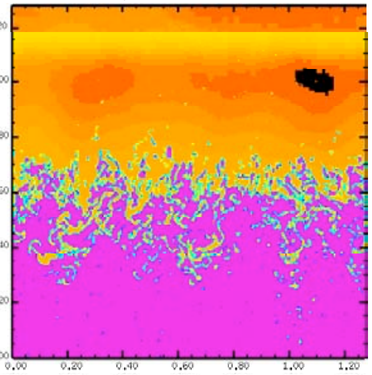
Strong Deceleration (Ct0) case:vin = -1.

'Gentle' deceleration Instabity- 'late time'



Deceleration ('shockless') Vin = -0.01, t = 110 (late time)

'weak shock' deceleration Instabity- 'late time'



Ein/e1 1.2, t = 250 (late time)

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IDM (Interface Deceleration Mixing): Epilog

- This is a collection of view graphs (LA-UR-04-4690) as presented at the IWPCTM9, Cambridge, UK, July19-23, 2004, intended to promote discussion.
- An informal report has summarized aspects of this work: E.L. Vold, "Interface Deceleration Mixing in Stagnating Pressure Flow", LA-UR-03-9023, December, 2003.
- A more formal write-up is planned.
- Technical issues which have been discussed since this work was presented are summarized briefly here.
  - A mix layer grows from the deceleration of a heavier fluid against a lighter fluid at their interface following the flow stagnation against a rigid boundary or convergent axis. The self-consistent pressure fields and time dependent deceleration produce a mix layer which is fundamentally different from the mix layer and the growth rate characterized in constant acceleration Rayleigh-Taylor mixing. The time dependence of mix width, total interface area between fluids, and average radius in a cylindrical system are not simply related. The atomically mixed fraction is also not simply related to these mix parameters. Some preliminary issues important to model this mix layer are summarized.

Erik Vold,
Los Alamos, Dec.2004

E.L.Vold

Rayleigh-Taylor and Richtmyer-Meshkov Aspects of Interface Deceleration Mixing

Abstract

LA-UR-04-0244

Presentation to the IWPCTM9
Cambridge, UK, July 19-23, 2004

Resolved scale simulations using a 2-D (r-z) compressible multi-fluid Eulerian code with interface reconstruction are used to study the mixing layer produced in interfacial fluid deceleration. The fluid interfacial deceleration (normal to the interfacial plane) is driven by transient stagnating pressure as flow is reflected from an impenetrable boundary in planar geometry or at an axis of symmetry in cylindrical geometry. Several driver conditions are evaluated and the cylindrical convergent case is related to ICF experiments currently underway. For the cases driven with a shock at the outer boundary, R-M instability growth occurs at early times prior to any deceleration and agrees with the linear impulse model. The total R-M mixing over the duration of cylinder convergence prior to deceleration is insignificant compared to later time deceleration mixing. Results show deceleration mixing can be approximated with an initial rapid growth rate and a slower late time growth rate after the acoustic transit time when pressure gradient reversals occur in the fluids. Each growth rate is characterized by a power law in time with the exponent of the initial rapid mix growth proportional to the energy into the system, and ranging from less than 1 to over 10 in the cases studied. The exponent matches the R-T growth rate scaling (~ t^2 for constant acceleration, g) only for a small energy into the system which is too small for significant convergence in the cylindrical system. The interface deceleration mix layer differs from classic R-T mix in several respects with growth rates varying in time, including phases of de-mixing and 'mode doubling' in some regimes, smaller scales and less vortical structures. An interfacial area $A_{12}(t)$, important in diffusive atomic mixing, is seen to grow faster in time than the mix layer width. The deceleration mix layer grows after the main acceleration peak has decayed to small values, and as such, interface deceleration mix more closely resembles R-M mix than R-T mix. We conclude with preliminary efforts to represent the mix layer growth dynamics and the evolution of the atomically mixed components simultaneously in an unresolved (sub-grid scale) simulation.

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Interface Deceleration Mixing (IDM) Purpose of this study

- Use RSS (Resolved Scale Simulations**) to better understand mix and instability physics of Interface Deceleration Mixing during flow stagnation in simple geometry with variable acceleration:

$$a(t) \sim -\nabla p(t) / \rho(t)$$

-
  - and in comparison to classic R-T instability mixing ($a \sim a_o$)
- Provide foundation for next step, to develop a model for IDM in Unresolved Scales Simulations (URSS) for ICF implosion applications (and possibly in more general cases of reactive mixing).

** RSS = multi-fluid Euler equations in 2-D (cylindrical r,z or rectangular (x,y) geometry) with IC perturbations imposed in varying volume fractions along the initial interface position.

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Interface Deceleration Mixing and RT Instability in ICF

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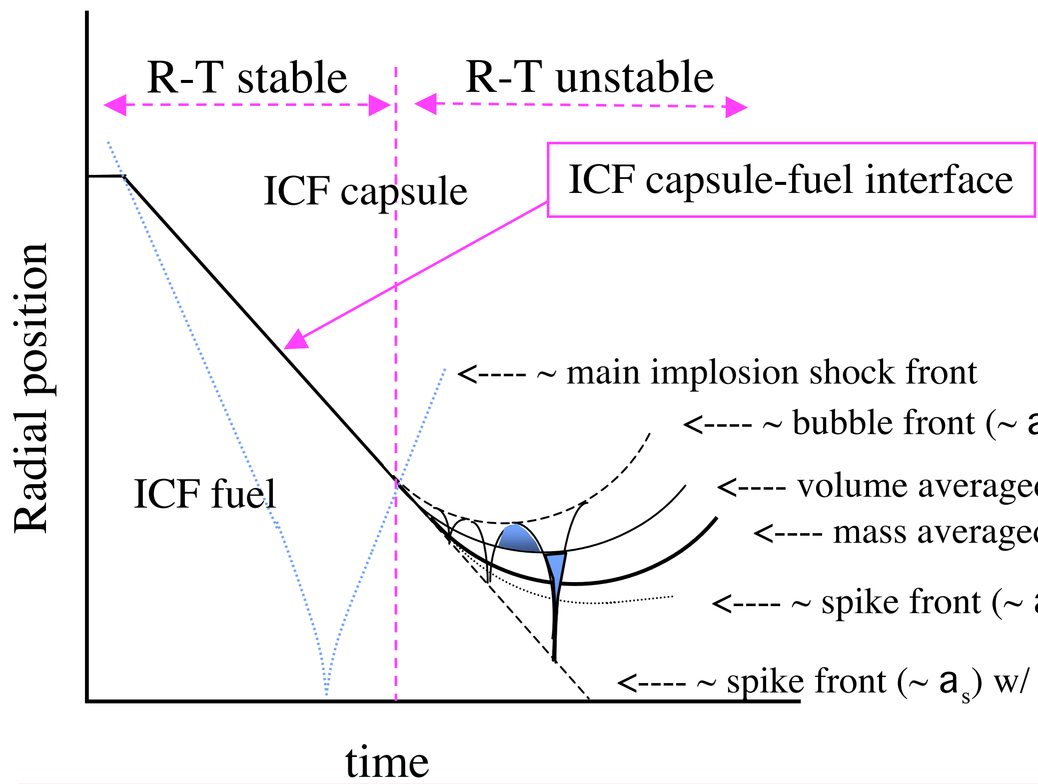

<---- ~ main implosion shock front

<---- ~ bubble front (~ a_b)

<---- volume averaged interface position (~ incompressible mix)

<---- mass averaged interface position

<---- ~ spike front (~ a_s) w/ drag > 0

<---- ~ spike front (~ a_s) w/ drag ~ 0 (free fall line)

<u>Assume Atwood number, A ~ 0.8</u>

$h_{bubble} \sim 1/2\, h_{spike}$ w/rt
volume averaged interface position

$h_{bubble} \sim h_{spike}$ w/rt
mass averaged interface position

Computations are preliminary scoping studies for detailed comparison to ICF experiments in cylindrical geometry on OMEGA (J. Fincke, S.Batha, N.Lanier,et.al.)

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R-T Experimental and Computational Results

- Constant acceleration, $a = a_o$ (R-T)
  - Experiments: Rocket rig: Youngs, et.al, LEM: Dimonte, et.al., etc
  - Experimental Results: h(t) ~ aAgt^2
    - a$_{bubble}$ ~ 0.057+/-0.008 (14%)
    - a$_{spike}$ = f(A) in range ~ 0.06 ~ 0.25 (0.5 theoretical max at A=1)
  - Computed Results: a$_{bubble}$ ~ 0.03 - 0.07
    - (most computations at low end, high end for more 'lagrangian' interface methods)
- Variable acceleration, a = a(t) -generalized R-T: $\square\square\square(t)\cdot a(t) = \square\square(t)\cdot\square p(t) < 0$
  - Experiments:
    - Smeeton and Youngs (1989, in AWE report…….) Data not compared to calculations
    - Dimonte & Schneider. (2000), examine: $h(t) \sim \square_{si} A\left[\square a^{1/2}(t)\ dt\right]^2$
  - Computations
    - Some limited to specific experiments, e.g., interface deceleration in ICF, HEDX
  - Theory
    - For $a = a_R t^g$, expect $h(t) = b a_R t^{g+2}$ $h(t) \sim \square\square\left[a(t)\right]dt\ dt$
    - Is: a a_o = b a_R ? Or generally, can coeficients from constant acceleration case apply to time dependent acceleration?
    - As: $\square\square$ and dt -> 0., one should recover the R-M limit result, h(t) ~ c t^q with q ~ 0.4

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Summary: Methods and R-T Validation

- R-T instability is: $a(t) = a_o$ compared to “R-T” instability, $\nabla p(t)\cdot\nabla\rho(t) < 0$
- Methods:
  - Resolved scale Euler equation simulations of Rayleigh instability from hydrostatic equilibrium w/ IC multi-mode perturbations, δ_o ~ Vf +/- 0.02-0.1, λ_o ~ 10 - 50 dx, k_o ~ 12 - 50 across 2-D grids of 128^2, 256^2 and 512^2.
  - Compressible multi-fluid methods set to low compressibility w/ and w/o Interface Reconstruction (IR). Each fluid has its own density, energy, pressure and volume fraction in ‘mixed cells’ which include a segment of the interface between fluids. Each fluid advected by high order monotonic Van Leer type methods.
  - Range of Atwood numbers examined from 0.96 to 0.04, base case studies at A=0.8.
- Results in hydrostatic R-T studies ($a(t) \Rightarrow a_o$):
  - R-T mix layer growth rate reflected in alpha bubble (~ 0.05-0.06) and alpha spike in good agreement with experiments across all Atwood numbers.
  - Allowing numerical diffusion (Interface Reconstruction off) has a small effect: implying numerical diffusion may not be limiting the correct alpha.
  - Vorticity and compressibility roles are important in density and energy fluctuations.
- Conclusions:
  - Code results for resolved scale wavelengths from sub-grid IC amplitudes appear to be valid.
  - Multi-fluid compressibility is a likely source of good agreement between computations and experiment.

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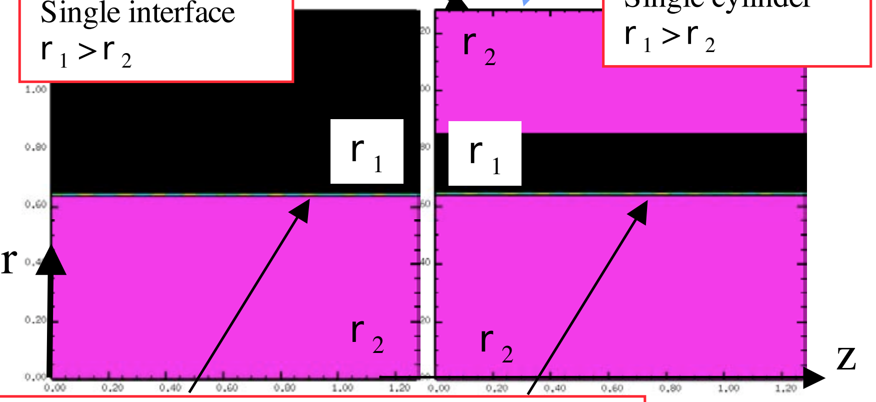
Interface deceleration - a(t) ~ - (dp(t)/dr)/r (t)

- Acceleration is a strongly varying function of time in stagnation pressure arising in convergent fluids.
- Simple cylindrical geometries examined - with resolved scale surface pertubations (~ 12 composite modes w/ wavelength ~ 20 zones, amplitude ~ Vf ~ +/- 0.1 imposed as IC) at one interface.
- Initial Conditions: flow 'driven' by one of several methods:
  - all fluid velocity fixed (towards stagnation boundary) in 'adiabatic drive'
  - internal energy set high (~10x e1) at outer radius (mild 'shock drive')
  - Constant acceleration toward stagnation boundary
- R vs. T in planar and convergent (cyl) geometries
  - Hydrostatic equilib at r = 0 and r= inf.
  - Deceleration at r= 0 (cyl) and r=inf(planar)
- Interface deceleration in several configurations.
  - simple cylinders (one to three interfaces)
  - 1 or 2 densities
  - 1 or 2 internal energies

Region = 256 x 256 zones

Geometry 1 (c21): Single interface $r_1 > r_2$

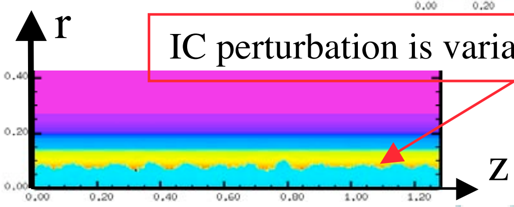
Geometry 2 (cr3): Single cylinder $r_1 > r_2$



IC perturbation is variable volume fraction at interface

This interface is located at $R_{max}/2$ in all cases.

R_{min}=>1.e3 To approximate slab geometry



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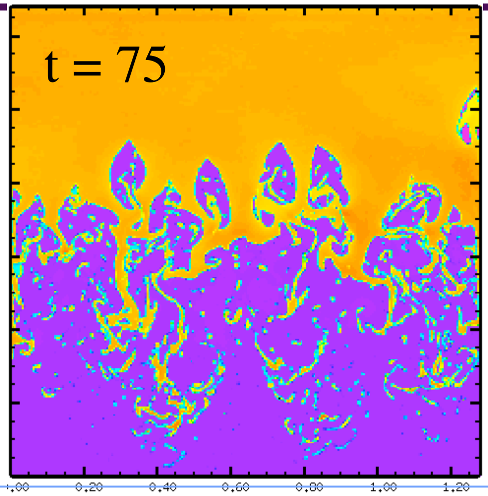
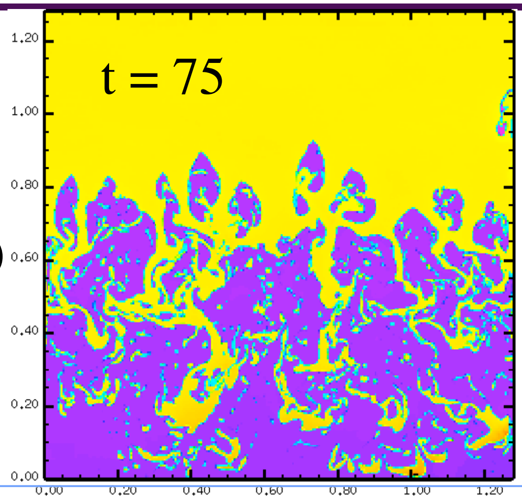
Rayleigh-Taylor vs. Deceleration instability in stagnation flow (cylindrical geometry)

Rayleigh (planar)

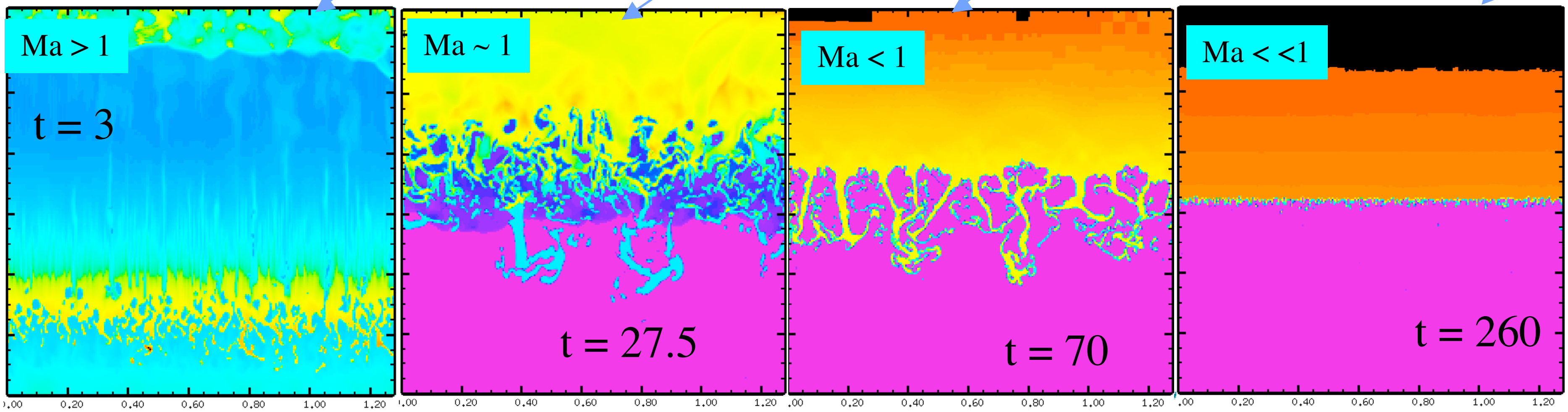


Rayleigh (cylindrical)



IDM from IC: uniform $\mathbf{v}(t=0) = v_r$ towards stagnating boundary, w/ Ma = $\mathbf{v}_\mathbf{r}(t=0)/Cs$

Interface deceleration instability ($u_r(t_0) < 0$, all in cylindrical geometry)



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Radial profiles of pressure
in various acceleration/decelerations

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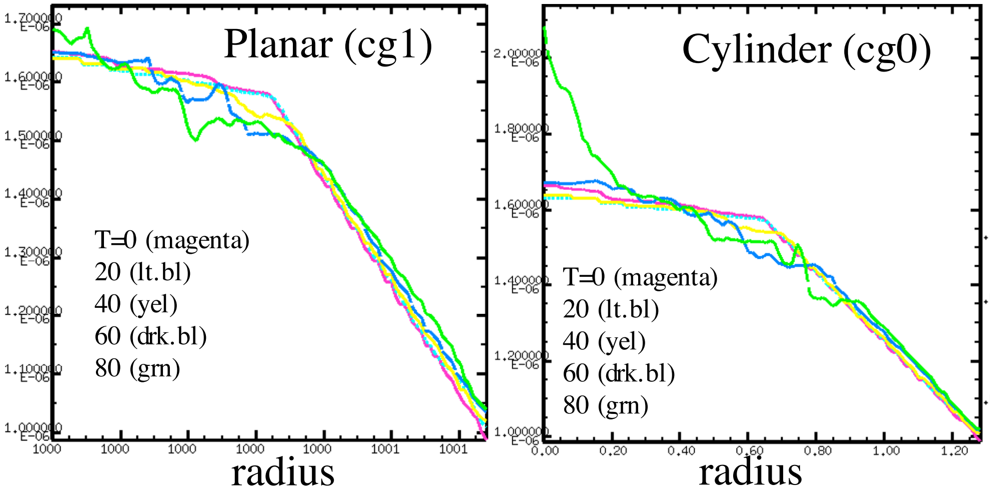
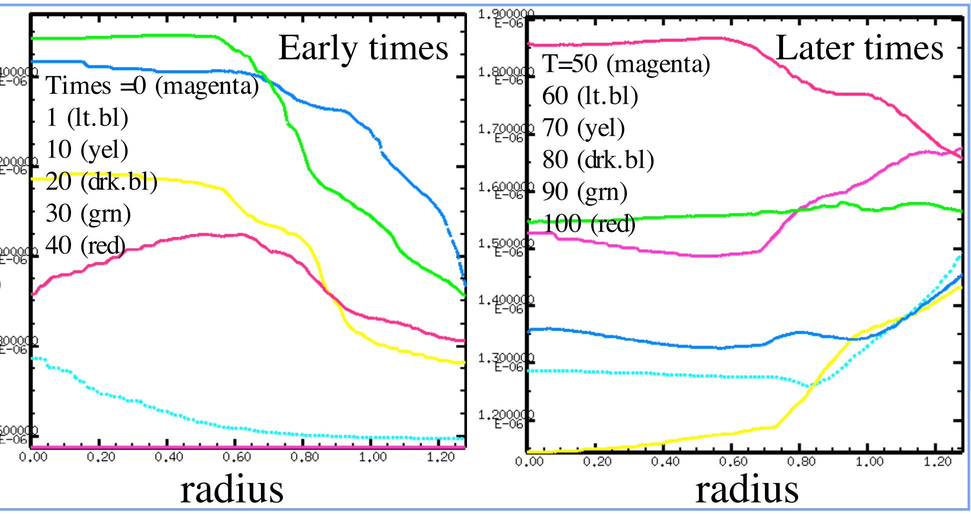
Rayleigh -
Hydrostatic
equilibrium

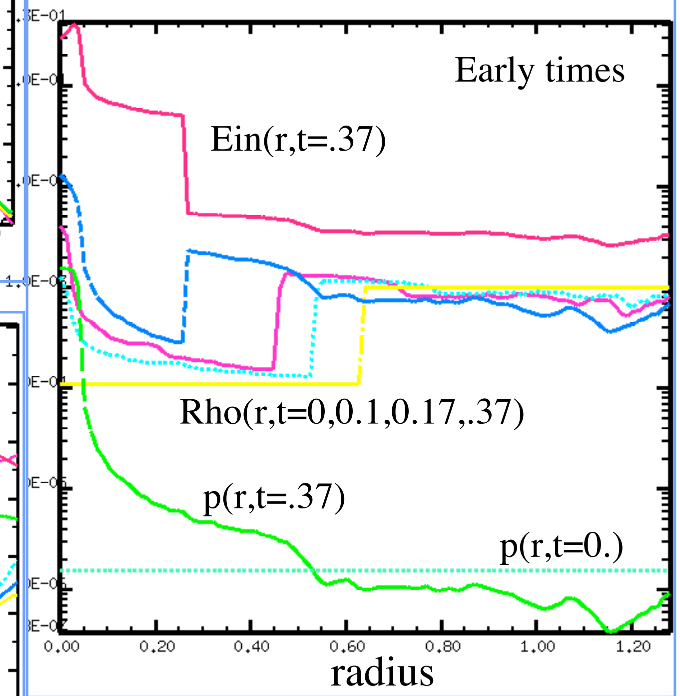


Gentle
deceleration
(negligible
convergence)

Vin = -0.01
Z slice = 0.41



Deceleration
(w/ cylindrical
convergence)



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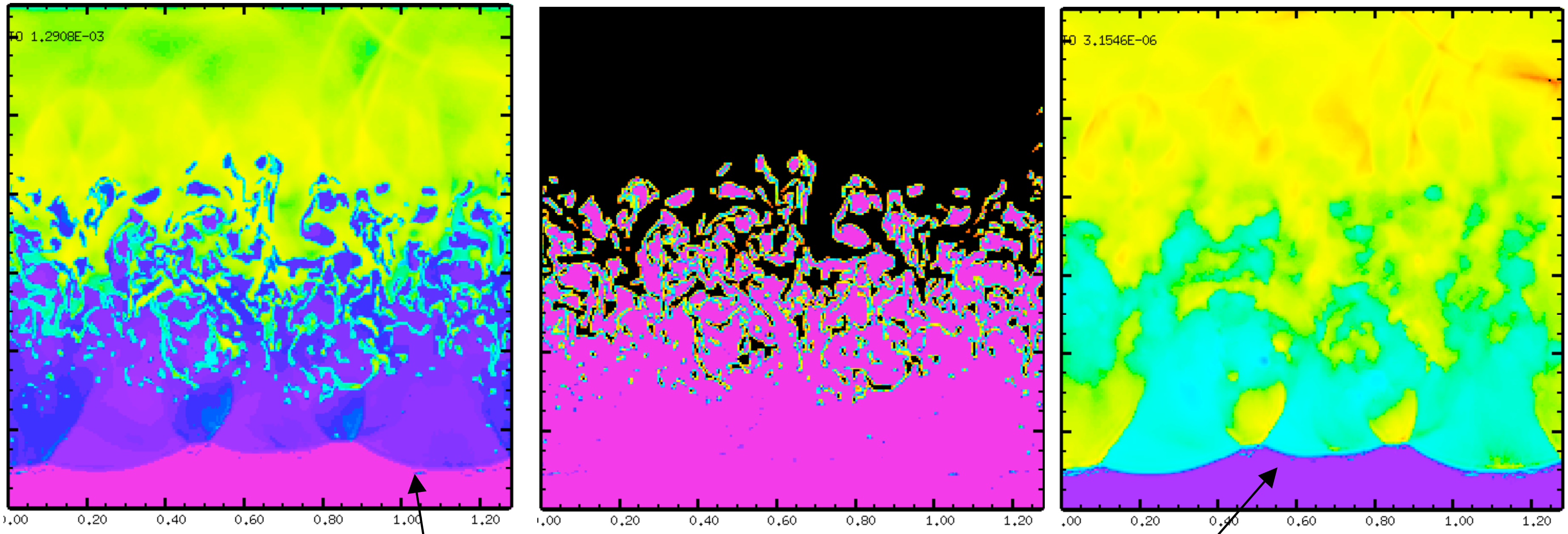
Density, Volume fraction, and pressure: Interface Decel. Cylindrical geom. Late time w/ Re-shock



Density vf.1 Pressure

NOTE: Pressure wave front after reflecting from cylinder center and then from outer BC.

Ct1-cyl,nog,vin=-0.1 time = 30

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Interface Deceleration Mix

Shock driven

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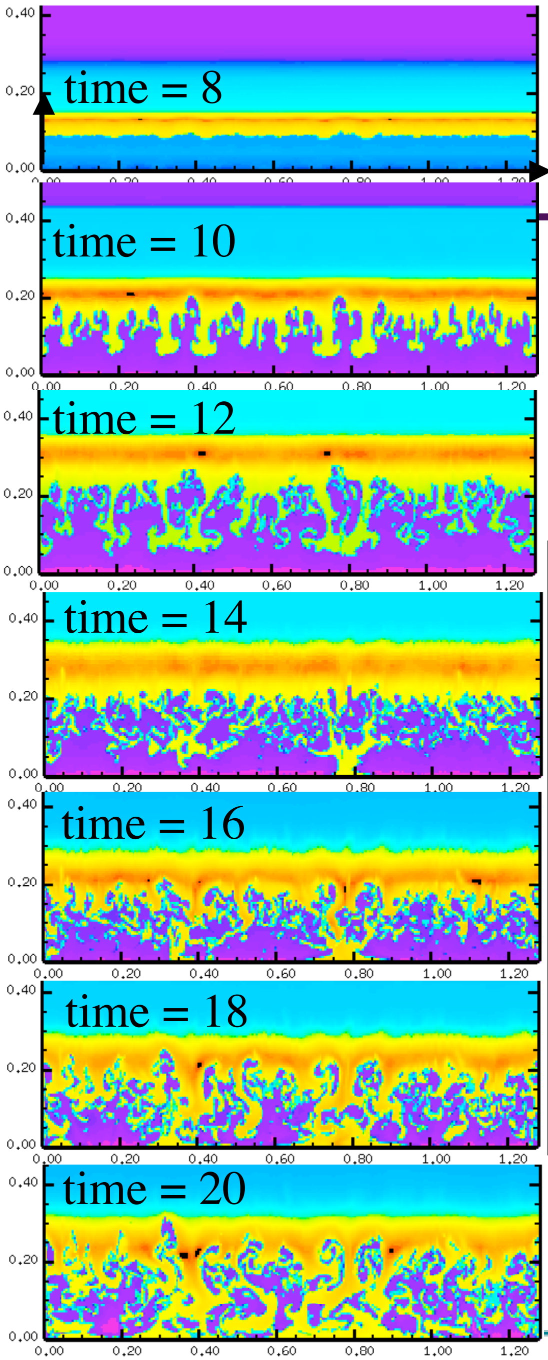
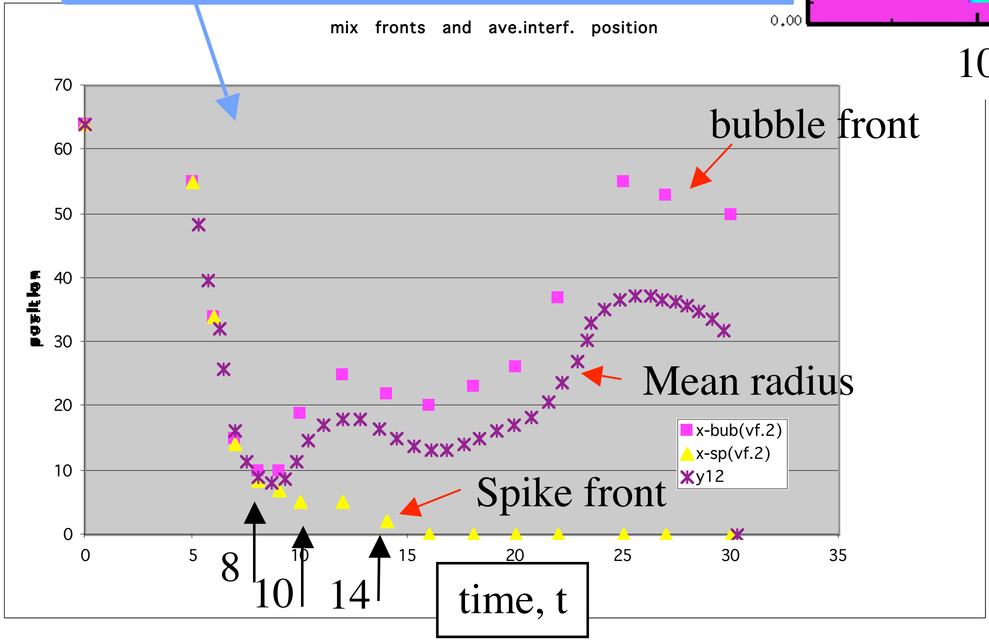
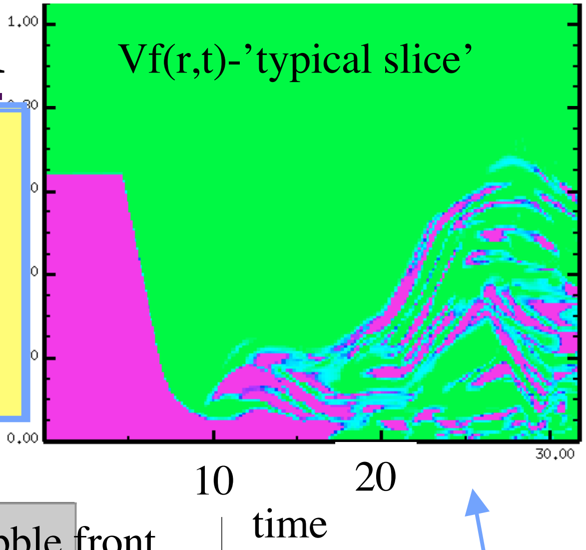


Bubble and spike front positions identified from density or volume fraction contours at varying times. Mean radius computed from interface reconstruction algorithm.





Vf(r,t)-
volume fraction
in radius vs. time
at a 'typical' slice
(fixed 'z')

(c21 case: Ein/e1=10)

Ref.for C21-t21-o21-to2* cx cases on 031003

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‘Working figure plots’ - for early time R-M instability growth rate determination

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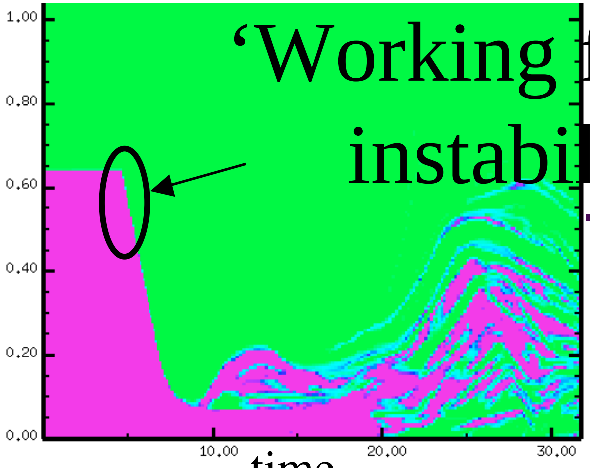
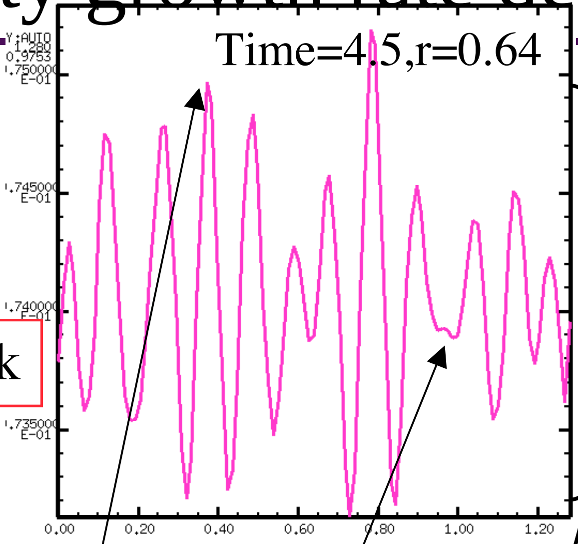
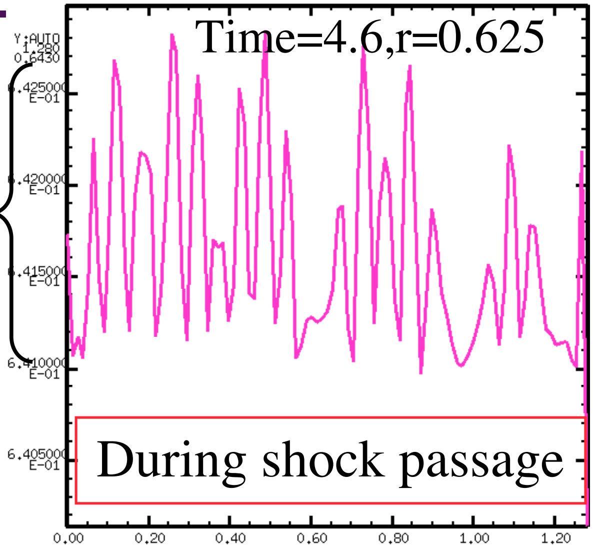


time

Vf(z) Before shock



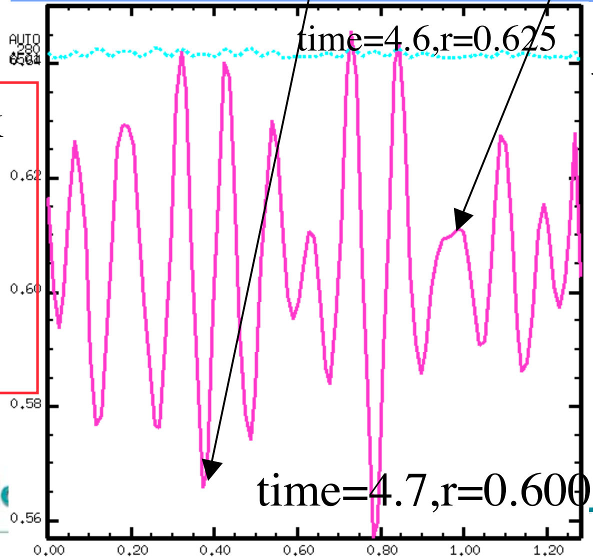


During shock passage

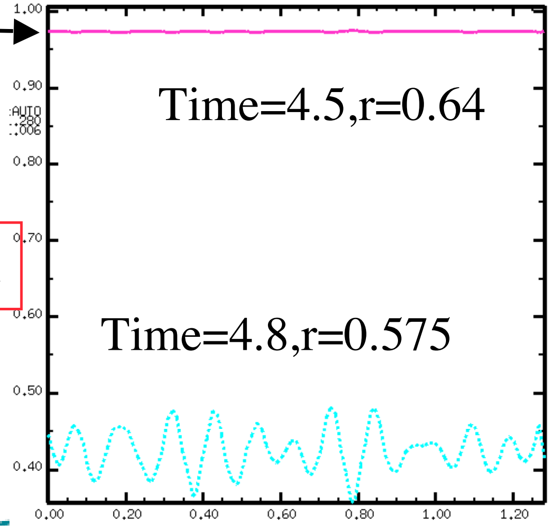
Mix widths estimated from sub-grid Vf(z) profile growing from IC perturbations.

Comparison shows inversion after shock

Vf(z) After Shock
Plots Rescaled
For increased mix
width
(~ sub-grid Vf)



After shock



No dump
Between 4.6,4.7

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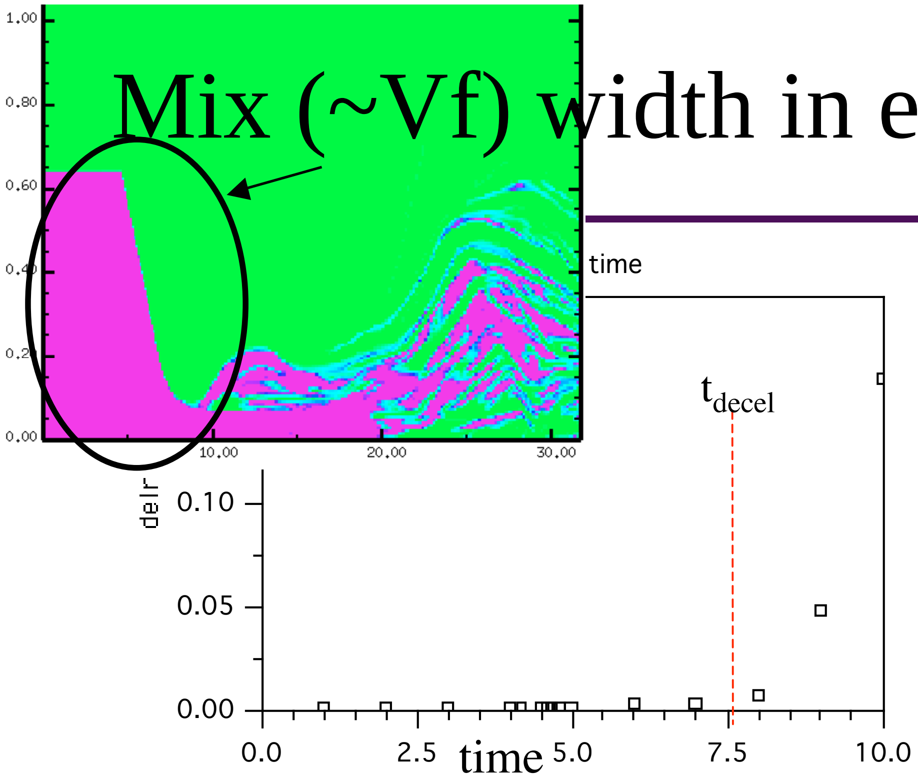
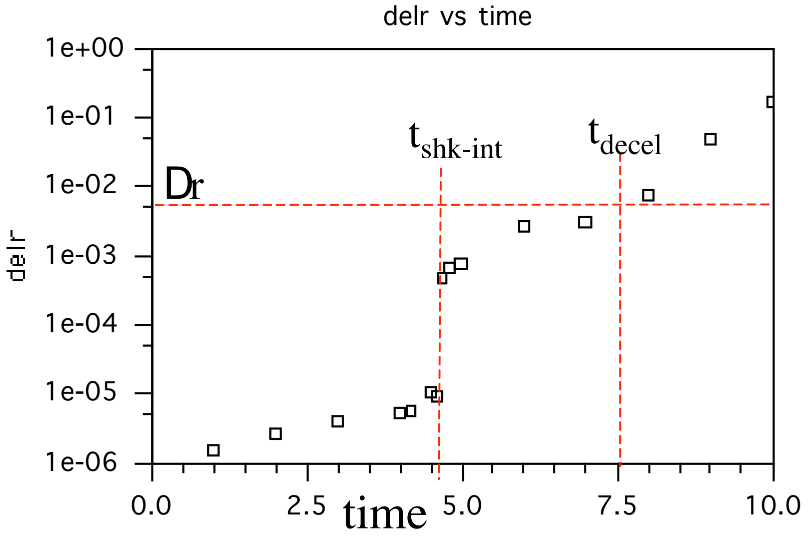
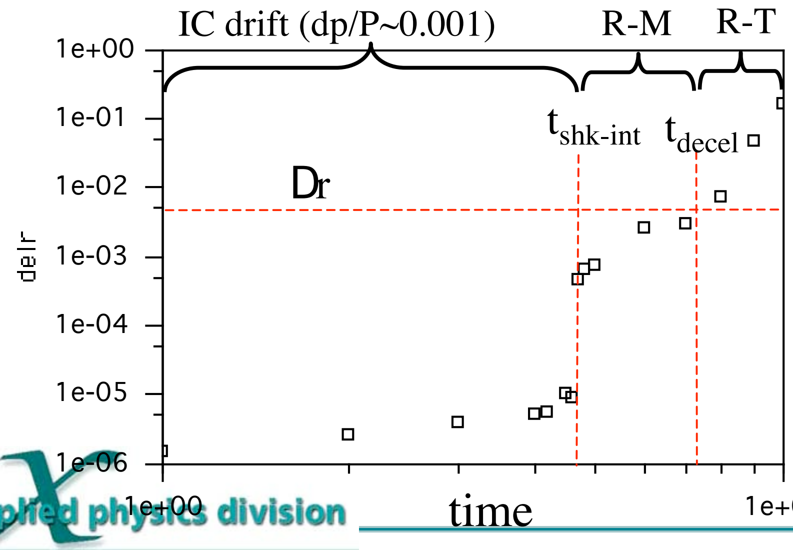
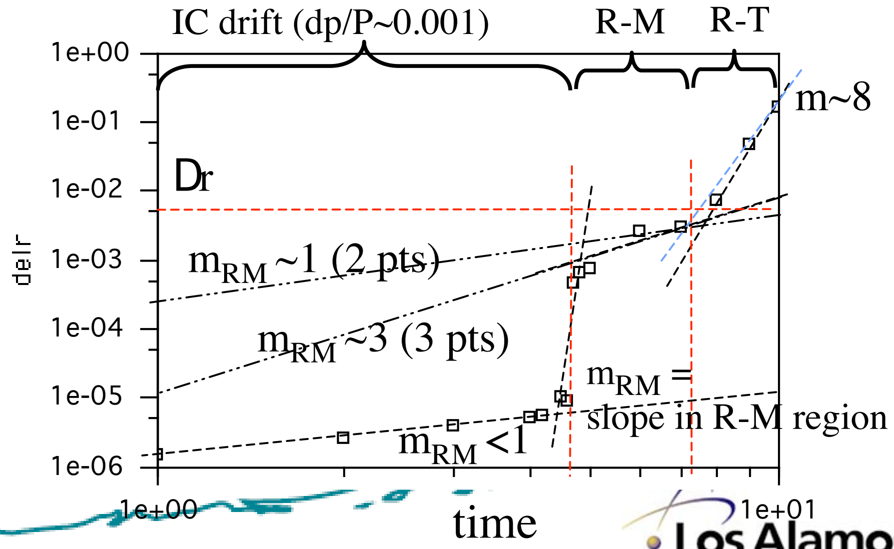
Mix (~Vf) width in early time RM evolution









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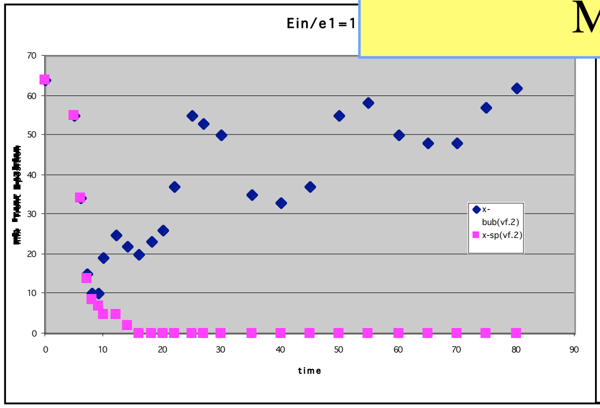
Interface deceleration (Cylindrical)
Mix fronts & mix layer widths vs. time
varying shock input energy, Ein/e1**

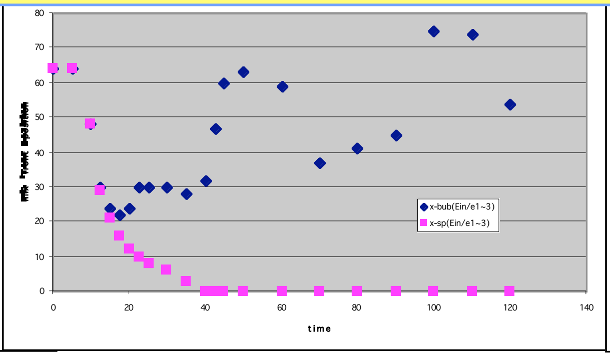
Ein/e1=10.

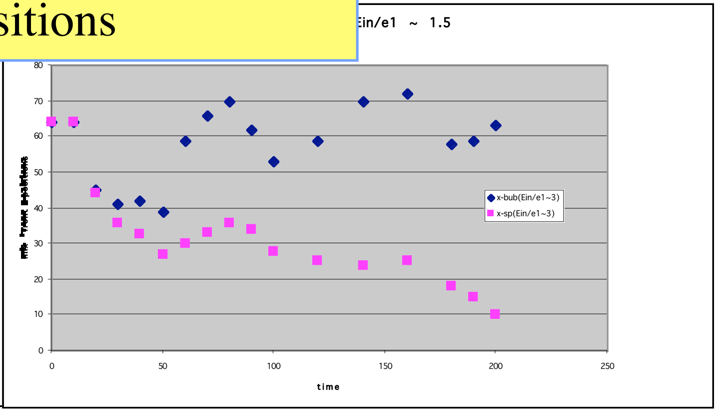
Ein/e1=3.

Ein/e1=1.5

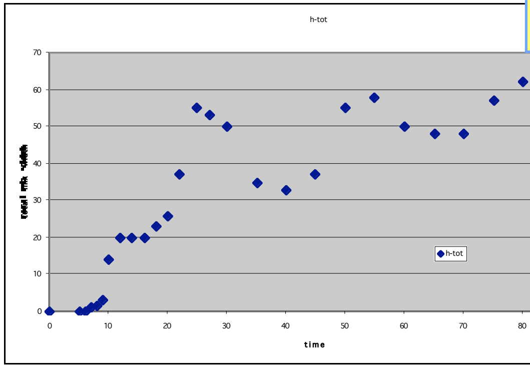
Mix front (bubble and spike) positions

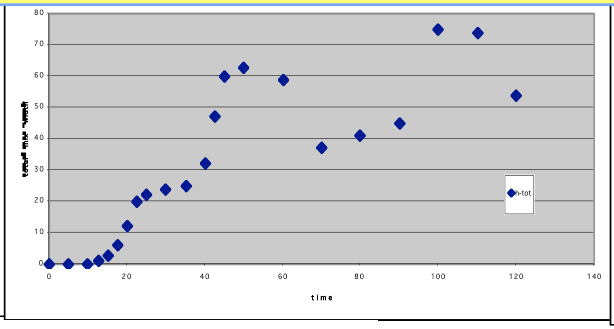


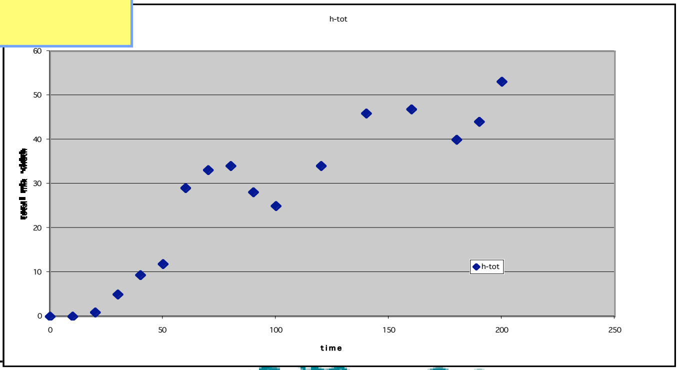




Mix layer widths







** Ein/e1=
Input drive energy
Per IC internal energy.

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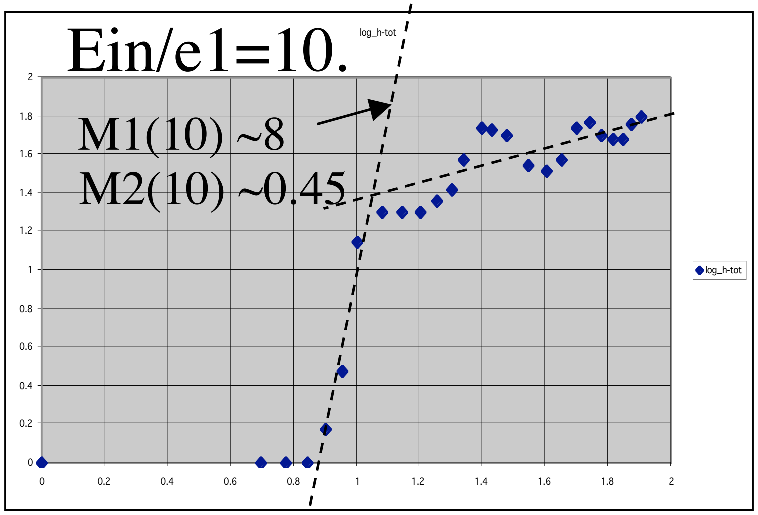
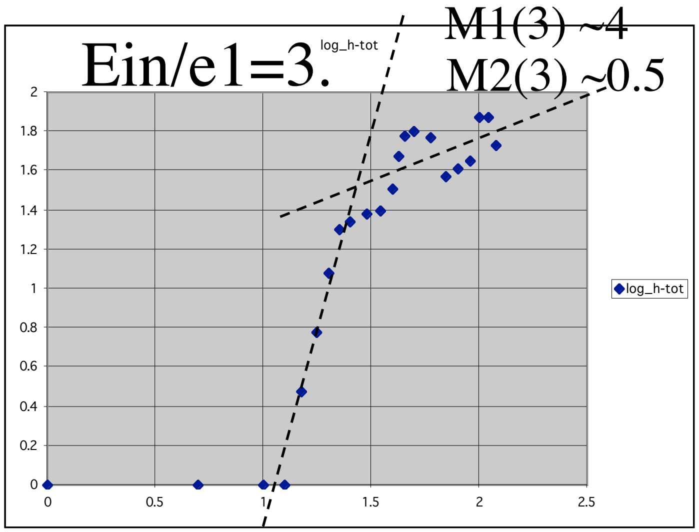
Interface deceleration (Cylindrical)
Log(mix width) vs. log(t) varying Ein/e1**



Ein/e1=10.

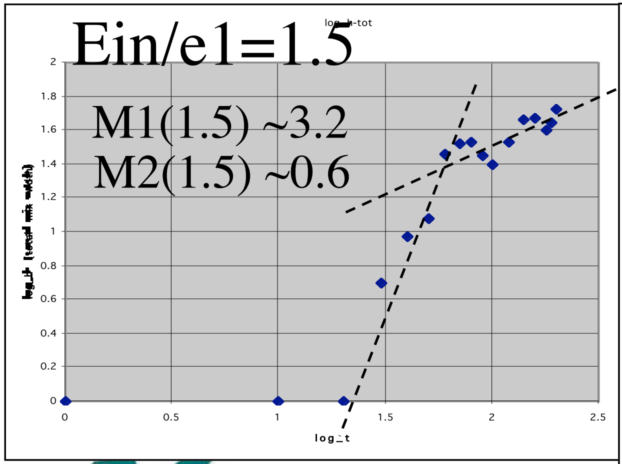
M1(10) ~8
M2(10) ~0.45



Ein/e1=3.

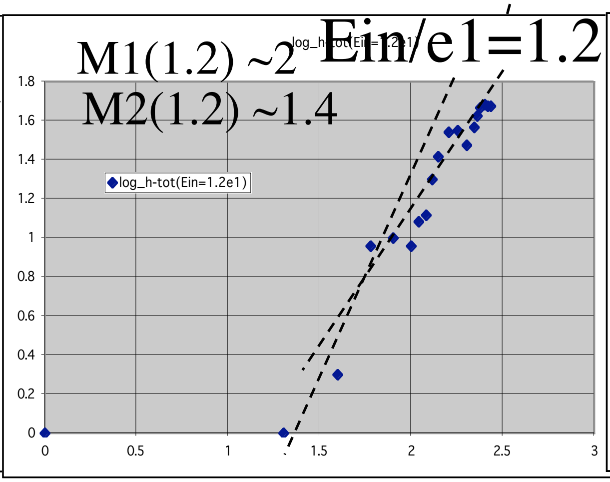
M1(3) ~4
M2(3) ~0.5

** Ein/e1=
Input drive
energy
Per IC
internal
energy.



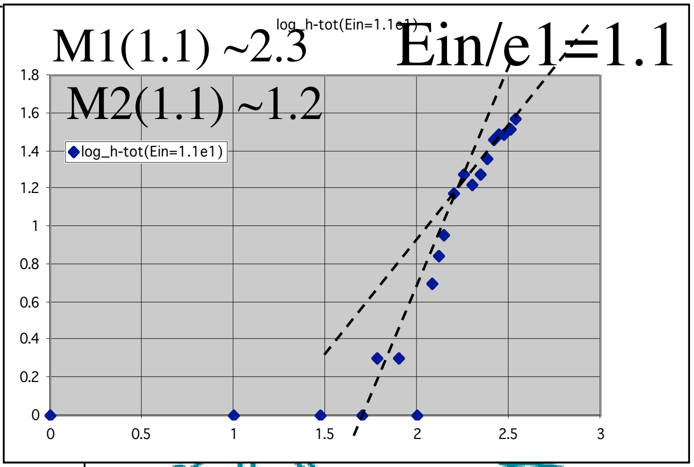
Ein/e1=1.5

M1(1.5) ~3.2
M2(1.5) ~0.6



Ein/e1=1.2

M1(1.2) ~2
M2(1.2) ~1.4



Ein/e1=1.1

M1(1.1) ~2.3
M2(1.1) ~1.2

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M1 = initial slope (growth rate)
M2 = late time slope (growth rate)

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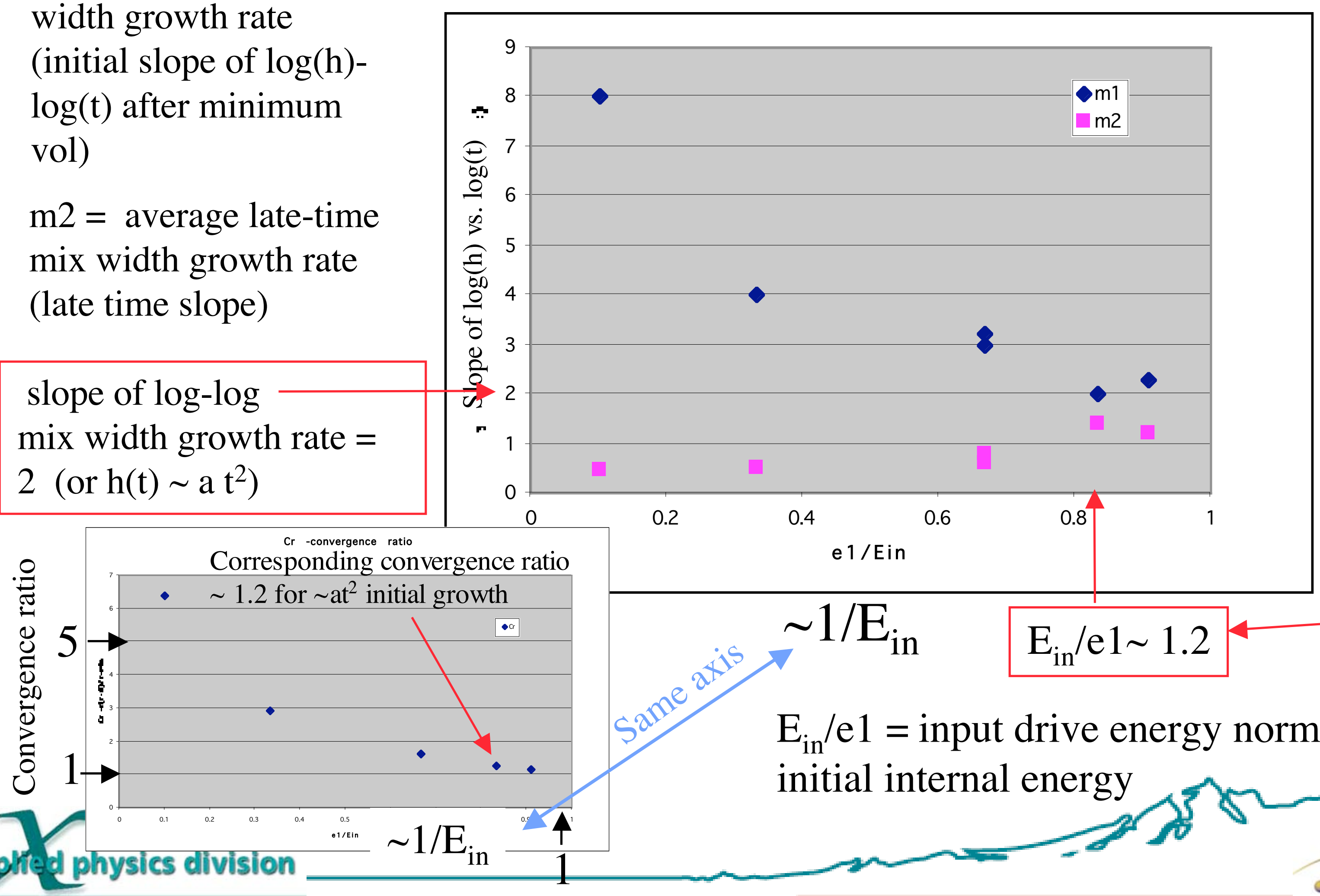
Cylindrical Interface Deceleration
Mix width growth rates vs. E_{in}**

** E_{in} = input drive energy

m1 = early-time mix width growth rate (initial slope of log(h)-log(t) after minimum vol)

m2 = average late-time mix width growth rate (late time slope)

slope of log-log mix width growth rate = 2 (or $h(t) \sim a\,t^2$)



Corresponding convergence ratio ~ 1.2 for ~at^2 initial growth

$\sim 1/E_{in}$

$E_{in}/e1 \sim 1.2$

Mix width exponential growth rate, m, decreases with decreasing energy into the system, with an apparent minimum of m ~ 2, for a small input energy.

$E_{in}/e1$ = input drive energy normalized to initial internal energy

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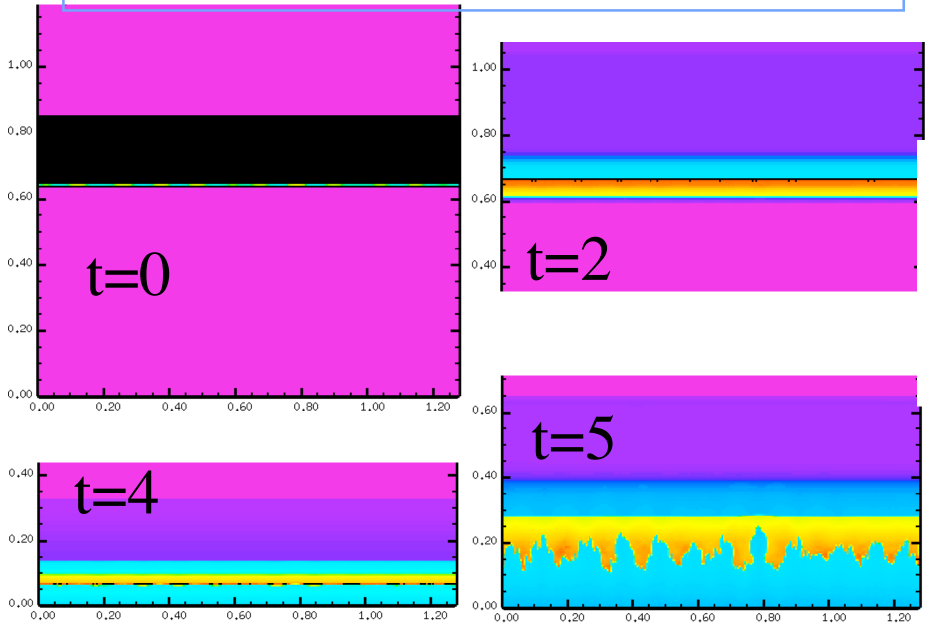
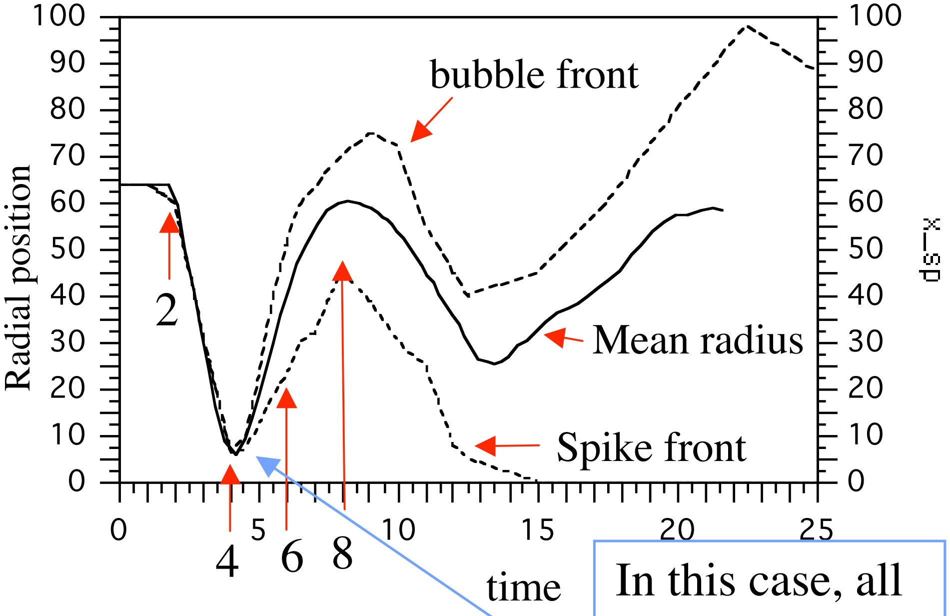
Interface Deceleration

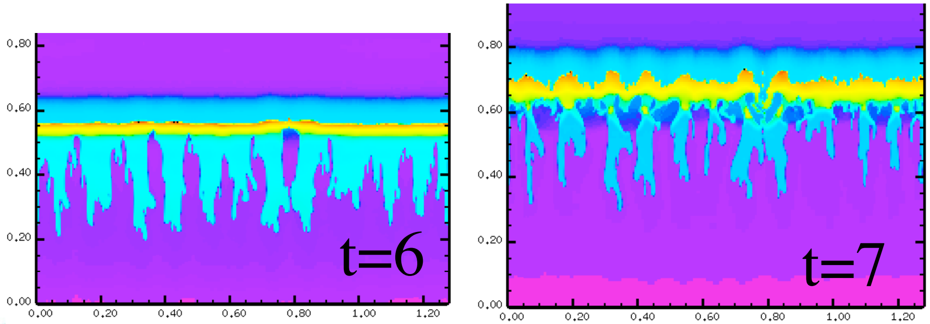
Single cylinder w/ inner surface perturbations

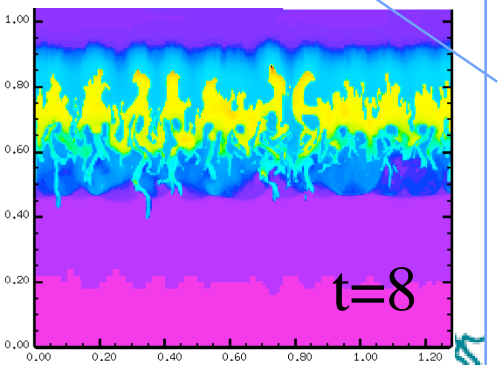
Densities at times thru initial mix regime.



Radii of fronts and mean interface







In this case, all heavy fluid ‘turns around’ with stagnating flow, creating long ‘expansion fingers’ (less vorticity?)

Case: cr3

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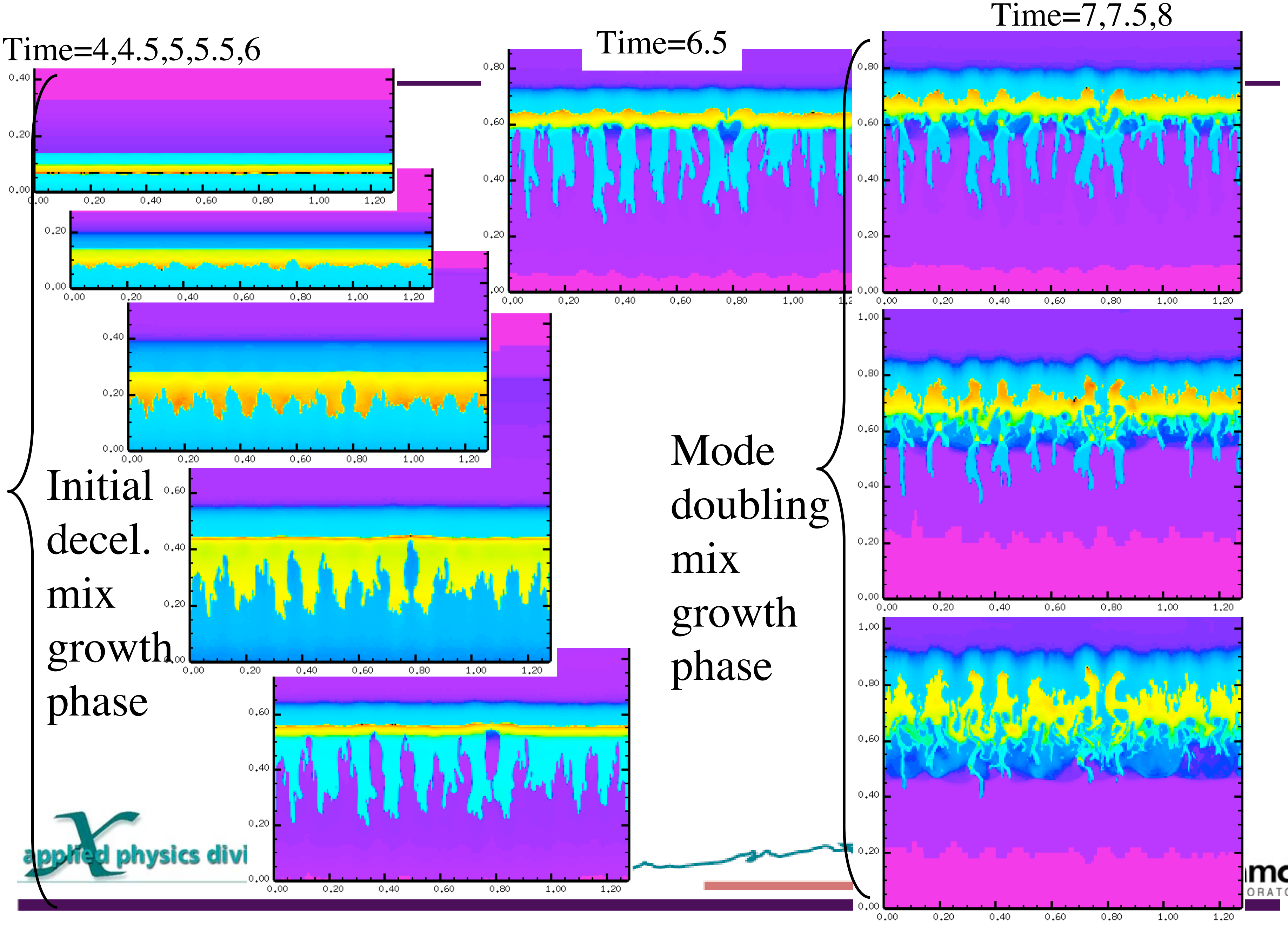
Interface Deceleration - cr3 -



Time=4,4.5,5,5.5,6

Time=6.5

Time=7,7.5,8

Initial
decel.
mix
growth
phase

Mode
doubling
mix
growth
phase

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Interface Deceleration Mixing (IDM) Parameters

- Resolved Scale Simulations indicate three mix parameters to consider:
  - Interface average position, $r_{12}(t)$
    - Easiest to compare to experiment
    - Direct measure of twice integrated $ac_{12}(t)$
  - RSS mix width, $h_{tot}(t) = r_{bubble} - r_{spike}$
    - Conventional mix parameter in R-T studies
  - RSS interface area, $A_{12}(t)$
    - Physical basis for diffusive mixing at fixed density and temperatures.
- Numerical issues to be addressed:
  - Interface area, $A_{12}(t)$ is physically most significant for diffusive atomic mixing, but depends on smallest scale-lengths, so it may be grid sensitive, $A_{12}(t) \sim L_{min} \sim dx$
  - Mix width, $h_{tot}(t)$, is related to entire region where momentum components are coupled, so it depends upon longest scale lengths, so it is relatively insensitive to grid resolution.

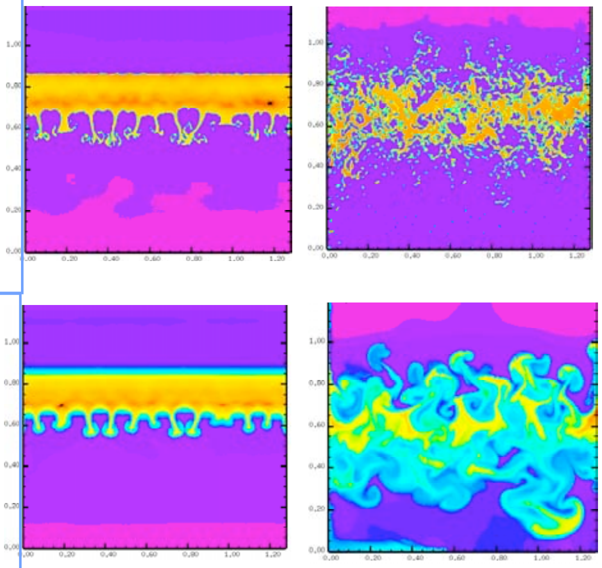
Mixing - with and without Interface Reconstruction

Early time

Late time

With Interface reconstruction: Less numerical diffusion but A_{12} is more grid sensitive at late times.

Without Interface reconstruction: More numerical diffusion but A_{12} is less (?) grid sensitive



Numerical mix - diffusive mix

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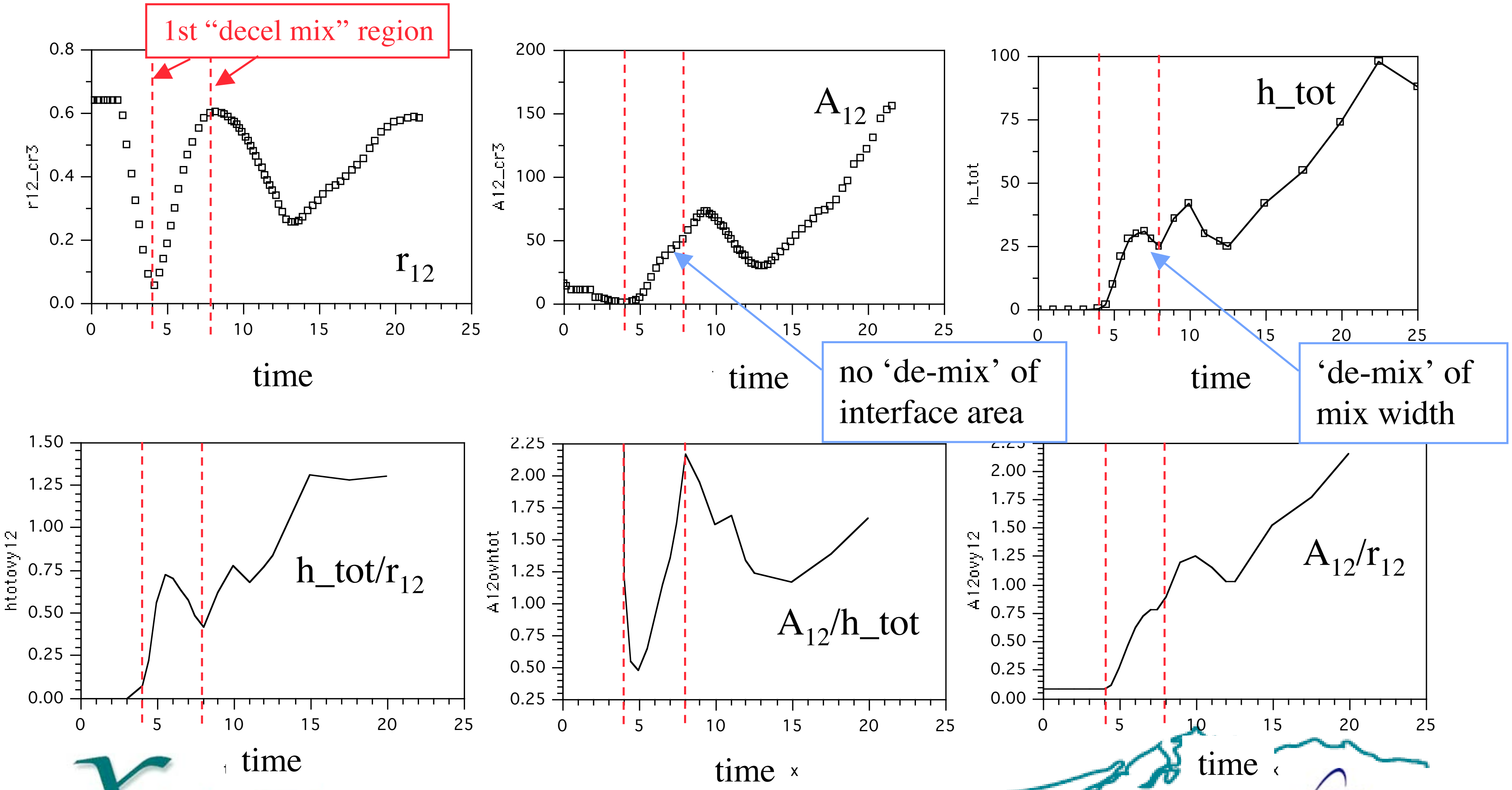
Interface Deceleration Mixing:

average radius, mix width and mix interface area evolve differently in time

r12 = average interface radius, A12 = total interface area, h_tot = mix layer width



1st “decel mix” region

no ‘de-mix’ of interface area

‘de-mix’ of mix width

Cr3 case

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Interface Deceleration

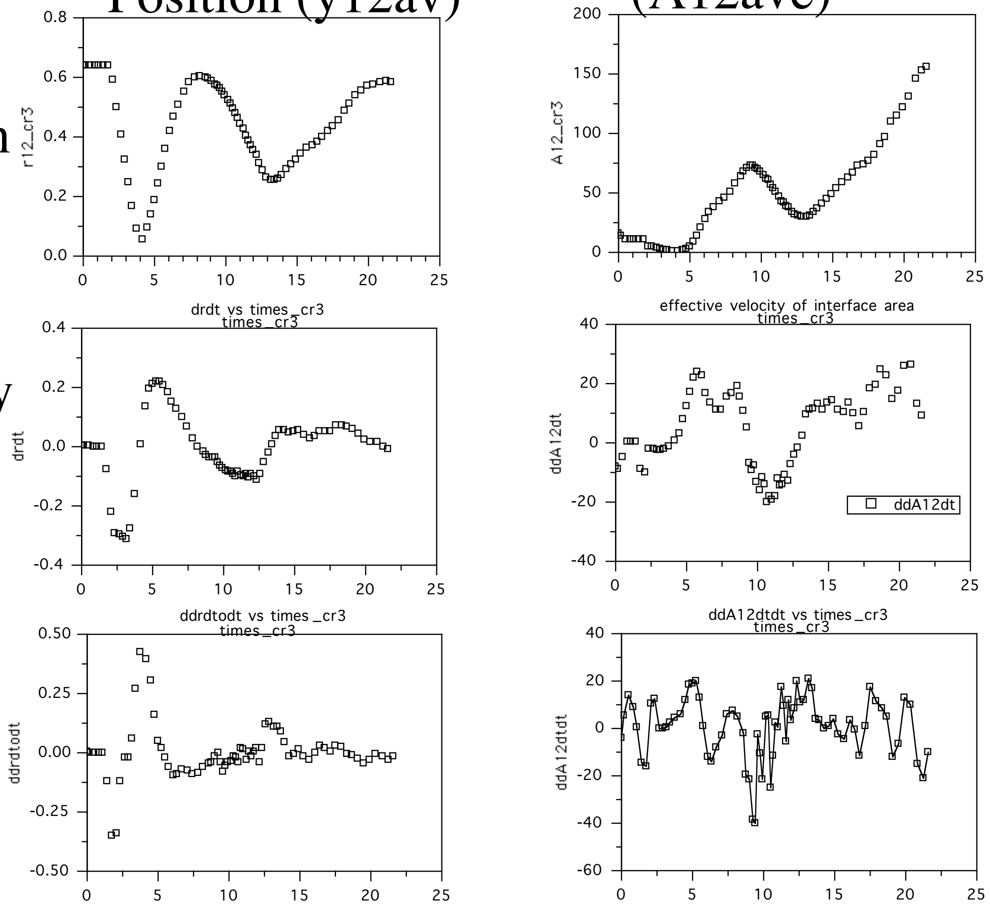
Interface Position (y12av)

Interface area (A12ave)

position

velocity

Accel.

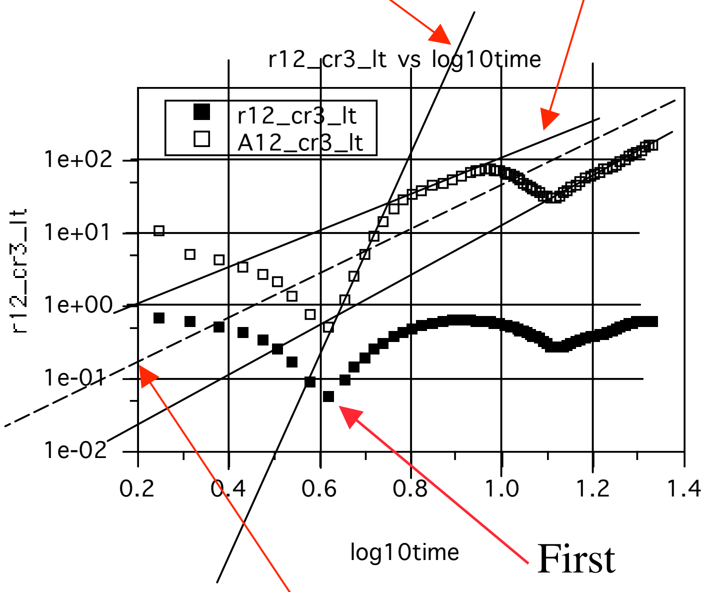


Time->

Time->

$m_1 \sim 14$

$m_2 \sim 2.5$



First Bounce (Min.Vol)

$m_{av} \sim 3$

Interface Decel - cr3

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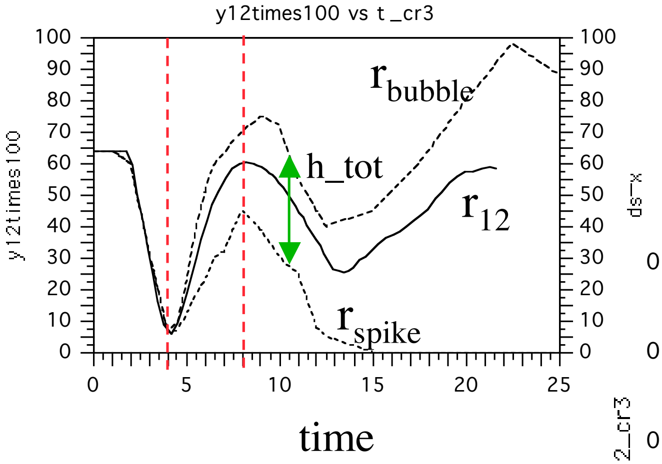
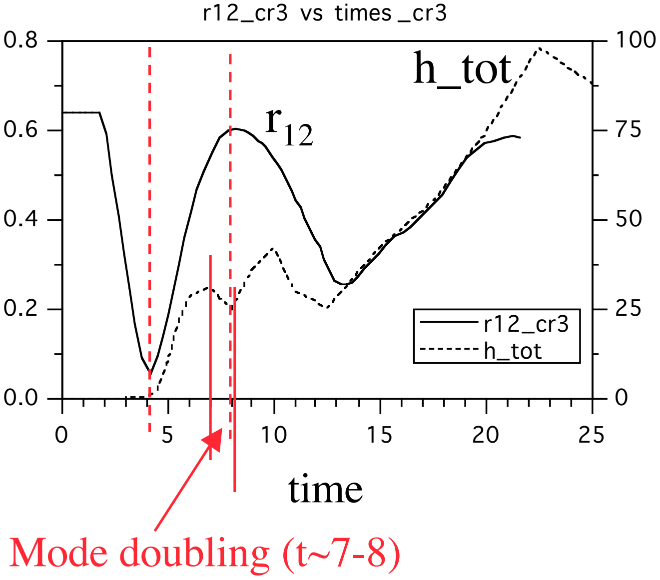
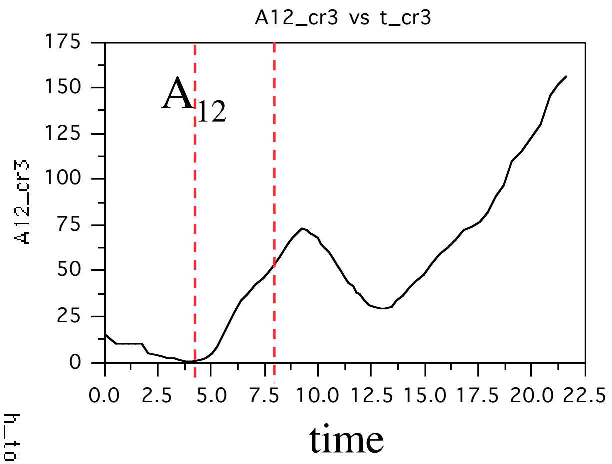
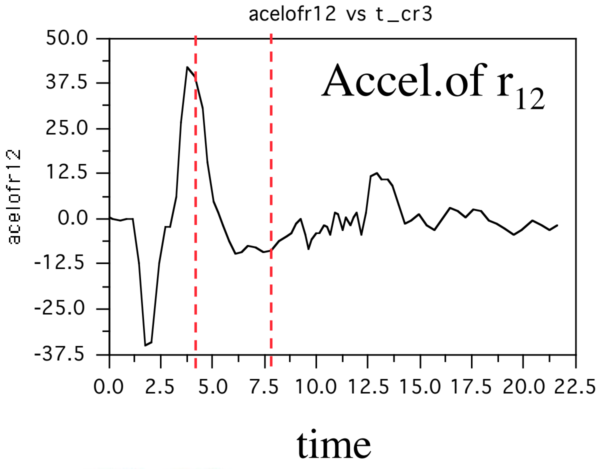
Interface Deceleration Mixing

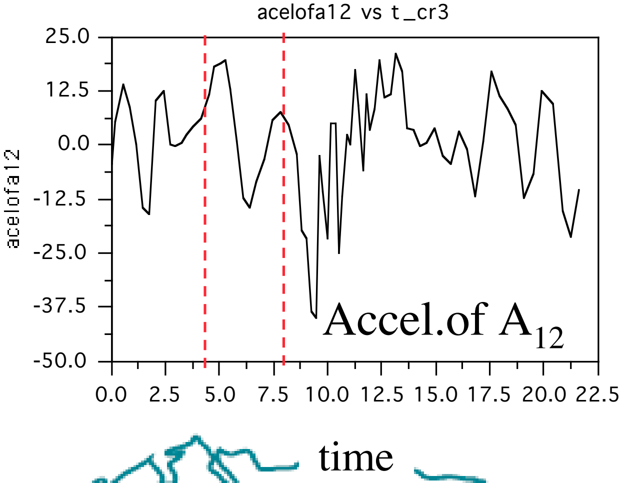
r12 = average interface radius, A12 = total interface area, h_tot = mix layer width











Cr3 case

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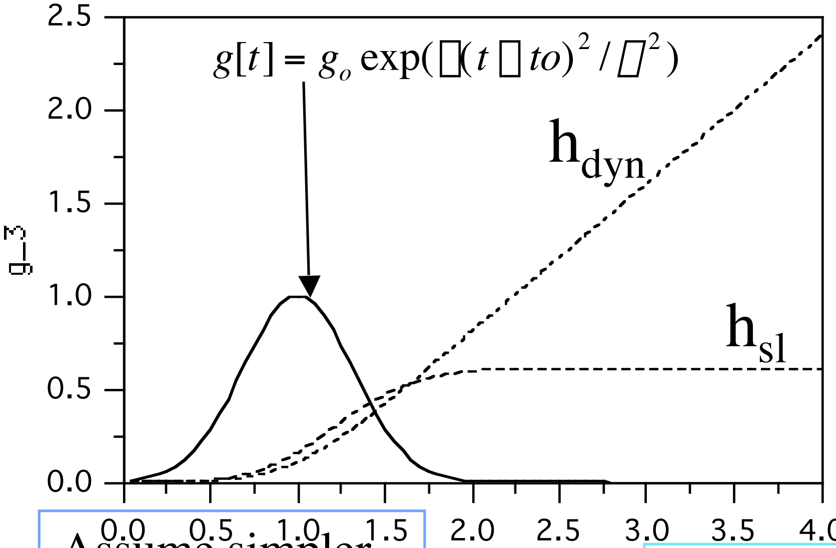
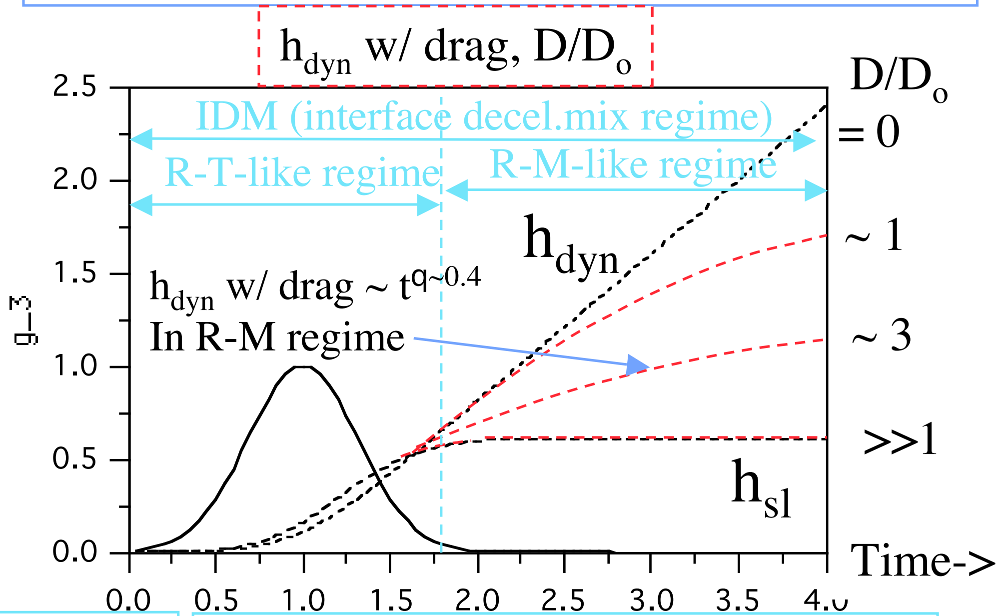
Mix widths for g(t)- dynamic (h_{dyn}) vs. scaling (h_{sl})

Scaling length argument 'invokes self-similarity in the bubble terminal velocity' (e.g., Dimonte & Schneider, 2000).

$h_{dyn} = \int\int g[t]\,dt'\,dt \qquad h_{sl} = 0.5\left[\int g^{1/2}[t]\,dt\right]^2$





Time->

Assume simpler case, g[t]~ g$_o$ t $^{\gamma}$: t

$h_{dyn} = \int\int g[t]\,dt'\,dt \approx \frac{g_o t^{\gamma+2}}{(\gamma+1)(\gamma+2)}$

$h_{sl} = 0.5\left[\int g^{1/2}[t]\,dt\right]^2 \approx \frac{g_o t^{\gamma+2}}{2(\gamma/2+1)^2}$

Dynamic mix width can include v-dependent drag in integration - seen in R-M experiments to result in h ~ t$^{q\sim0.4}$

Scaling length mix width integral has ambiguous v-dependent drag in integration - may require matching R-T and R-M like phases of mixing with two different empirical coefficients (Youngs, et.al.)

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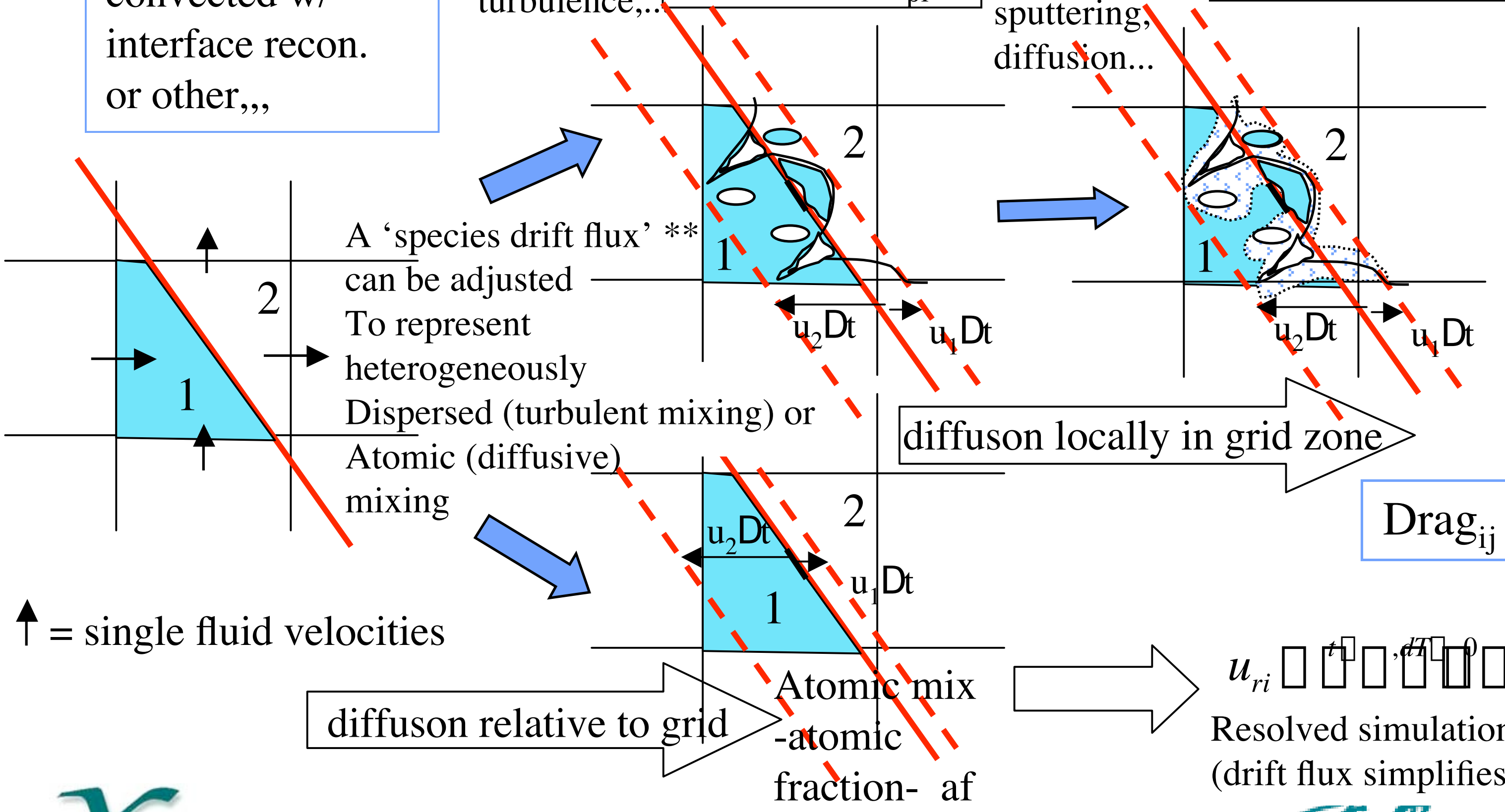
Distributions of materials in mixing

Volume fractions for each material, i, as: $Vf_i = Vf_{ci} + Vf_{pi} + Vf_{ai}$



Unmixed
-continuum
fraction- Vf_{ci}-
convected w/
interface recon.
or other,,,

Drift flux
Advection
Represents:
Instability,
turbulence,..

Dispersed mix
-particle
fraction- Vf_{pi}

Atomic flux
Local Diffusion
Represents:
Evaporation,
sputtering,
diffusion...

Atomic mix
-atomic
fraction- Vf_{ai}

atomically
mixed
evolution
af(**x**,t)=>

$R \sim n_{ai} n_{aj} <\square v>$

A ‘species drift flux’ **
can be adjusted
To represent
heterogeneously
Dispersed (turbulent mixing) or
Atomic (diffusive)
mixing

diffuson locally in grid zone

$Drag_{ij} \sim D_p n_{pi} + D_a n_{ai}$

= single fluid velocities

diffuson relative to grid

Atomic mix
-atomic
fraction- af

$$u_{ri}\ \square\square\square\square\square\square\ \square\ \frac{\square_{ij}\square p^{*}}{\square_R v_{th}}$$

$t\square\ ,dT\square\ 0$

Resolved simulation:
(drift flux simplifies to diffusion)

** drift flux model based on:
Scannapieco and Cheng, Phys.Lett.A 299 (2002) 49-64

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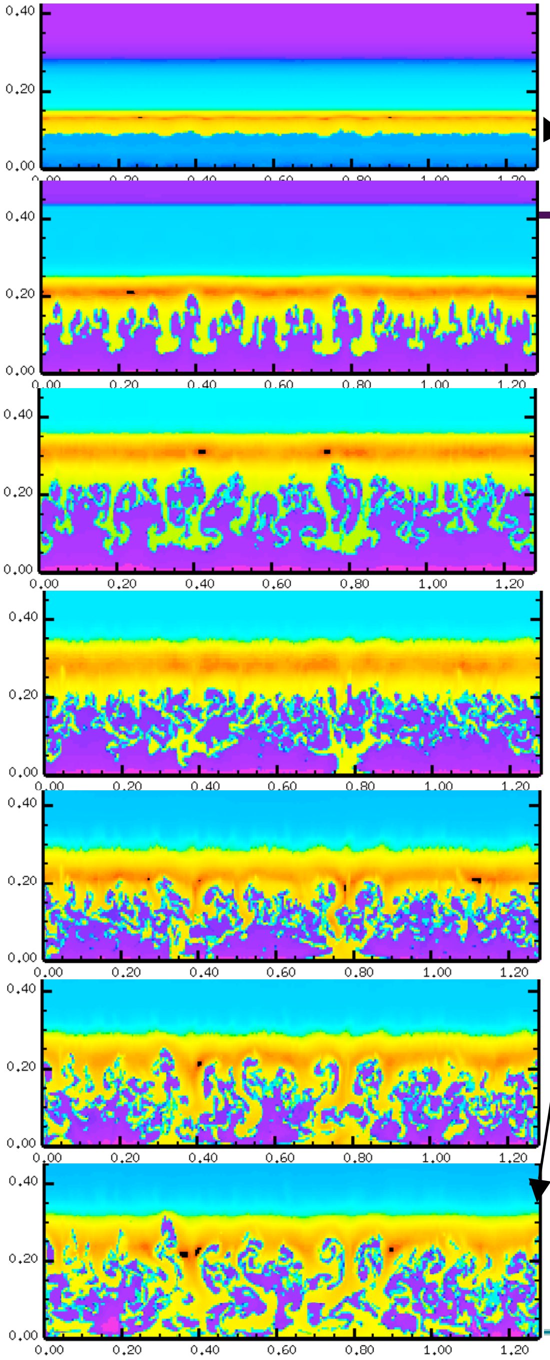
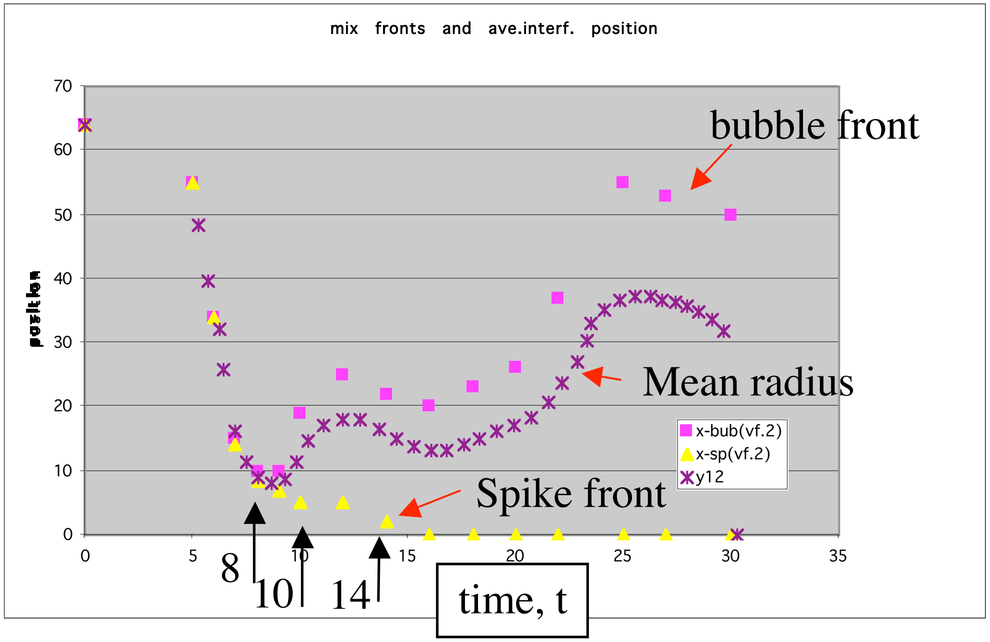
Reference Case for RSS/URSS Comparison (Ein/e1=10)

Case:c21

density contours (z,r) at times = 8,10,12,14,16,18,20





Ref.for C21-t21-o21-to2* cx cases on 031003

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Volume fractions and density (t,r) at select axial slices (z)

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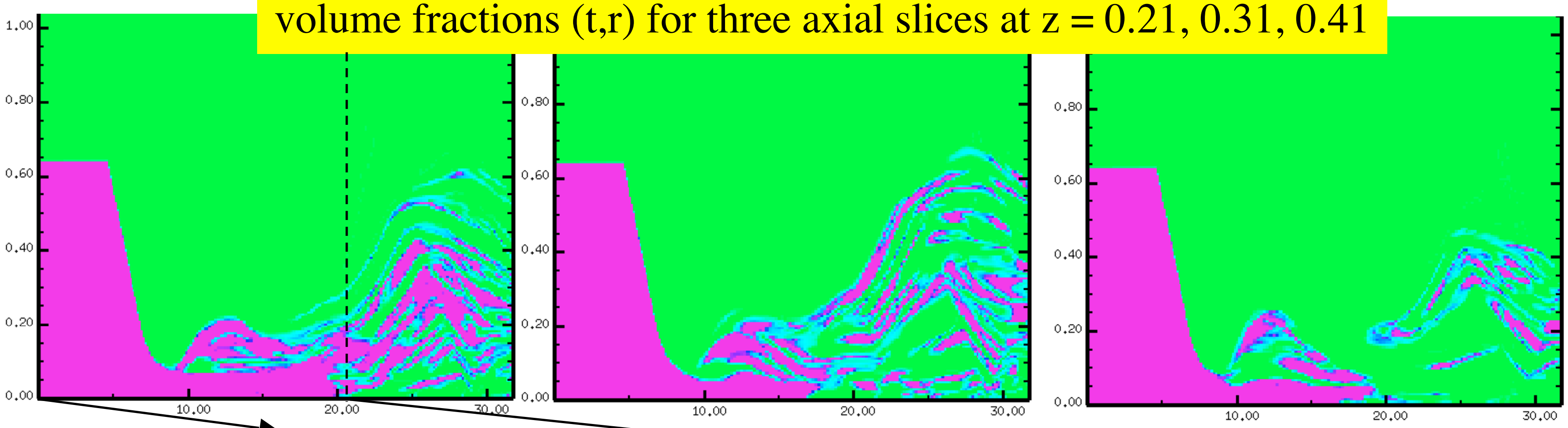
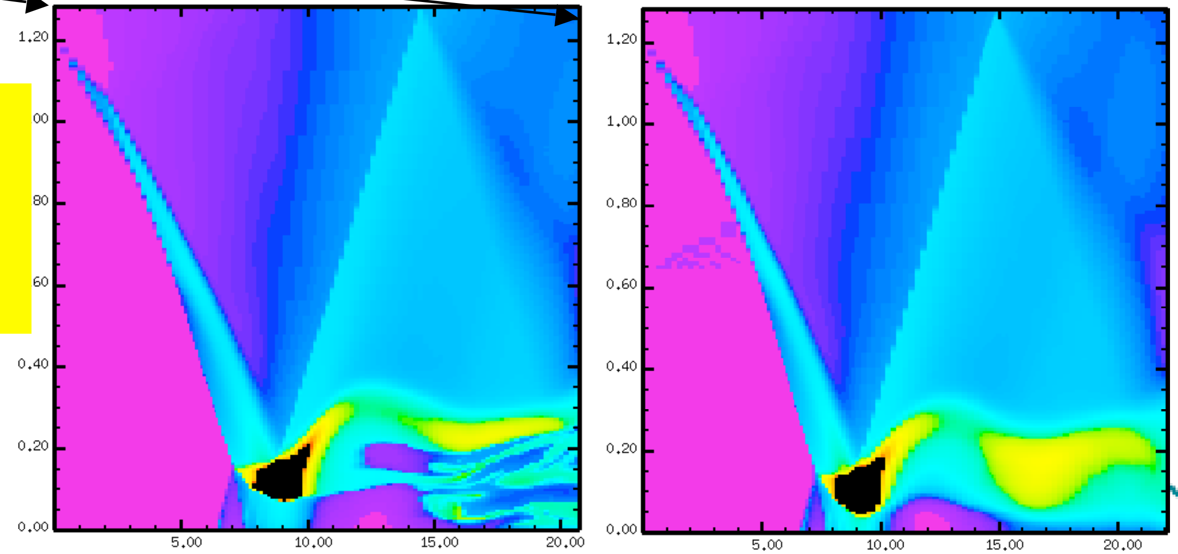
volume fractions (t,r) for three axial slices at z = 0.21, 0.31, 0.41



density in RSS w/ diffusion, (d=5e-6) At z=0.22



density in URSS w/ diffusion (d=5e-6) and ‘drift flux’ enhanced mixing (a=0.1) at any z

Rho(t,r) for t21(z=0.22) and ps5 (z= any)

case: c21

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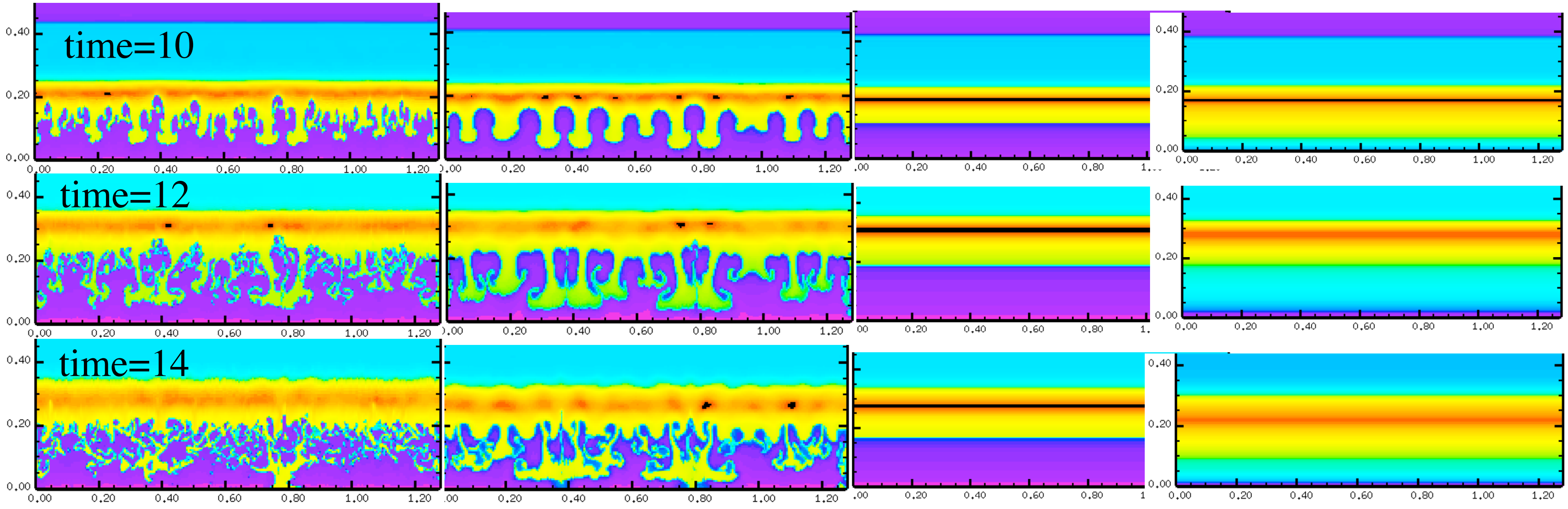
Mix in RSS and URSS shocked cases

RSS-resolved scale sim.
W/ IR, no molecular mix

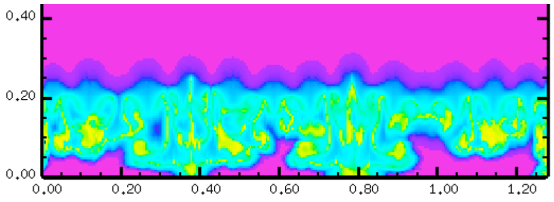
RSS-resolved scale sim.
W/IR and molecular mix

URSS-Un-resolved
scale sim.(d(IC)=0)
W/ molecular mix

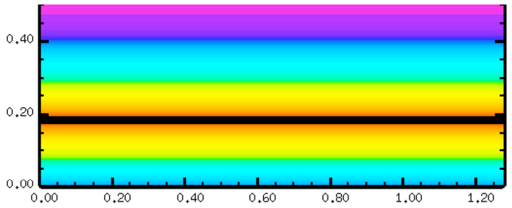
URSS-Un-resolved
scale sim.(d(IC)=0)
W/ 'drift flux' Tmix



time=14
atomic mix =>



time=14
atomic mix =>



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Note: de-mix from t=14-16
Is reproduced by the mix model

4 'c21' cases:
c21,t21,o21,to2

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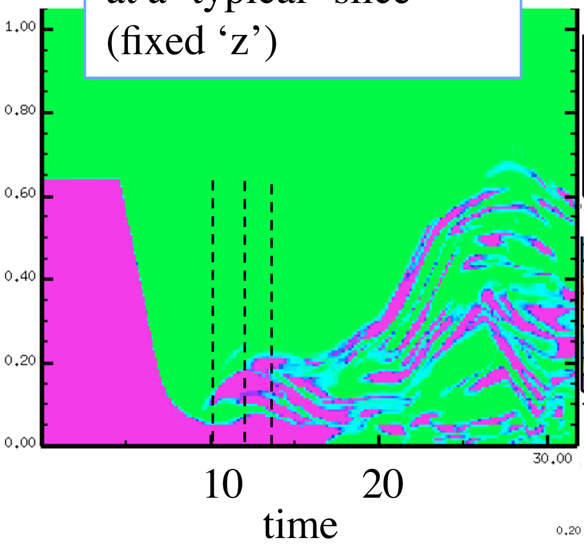
Mix in RSS and URSS shocked cases

(Resolved Scale Simulations and Un-Resolved Scale Simulations)

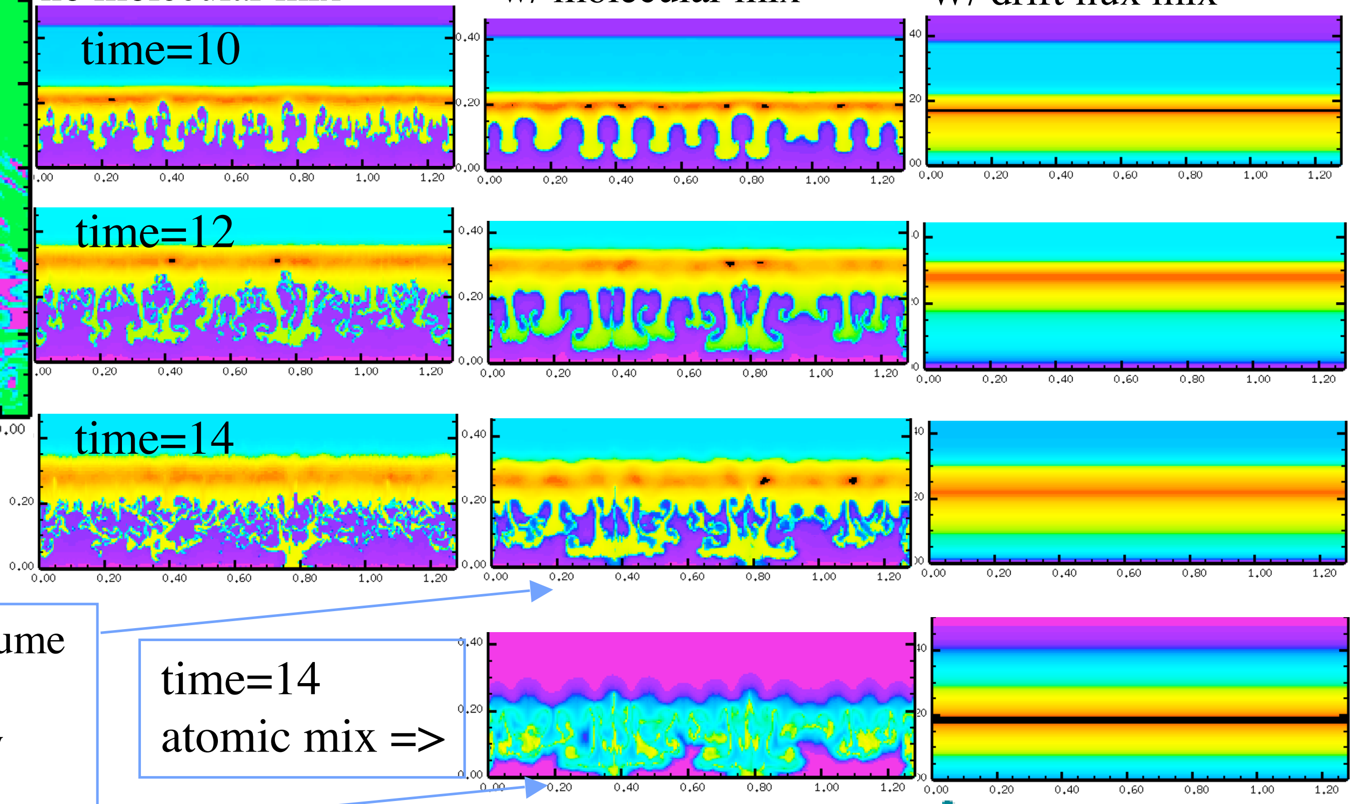


Vf(r)- volume fraction in radius vs. time at a 'typical' slice (fixed 'z')

RSS- resolved scale simulation w/ interface recon., no molecular mix

RSS- resolved scale sim. w/ interface recon and w/ molecular mix

URSS- Un-resolved scale sim. (d(IC)=0) W/ drift flux mix



time=14 atomic mix =>

Note: atomic mixed volume fraction ~ 3%, so it has minor impact on density contours

3 'c21' cases: c21,t21,to2

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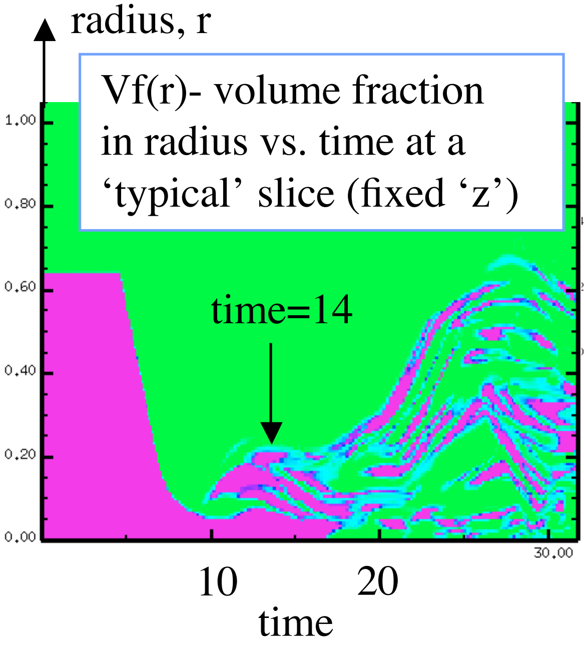
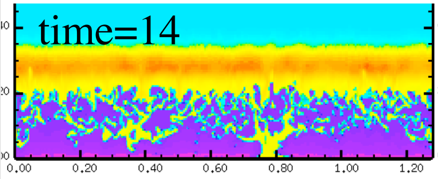
Mix in RSS and URSS shocked cases

(Resolved Scale Simulations and Un-Resolved Scale Simulations)

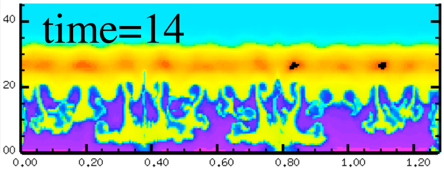


Vf(r)- volume fraction in radius vs. time at a ‘typical’ slice (fixed ‘z’)

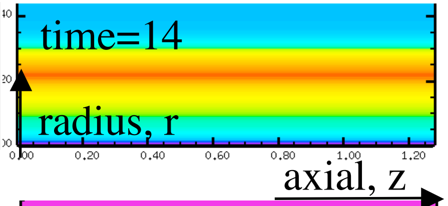
RSS- resolved scale simulation w/ interface recon., no molecular mix

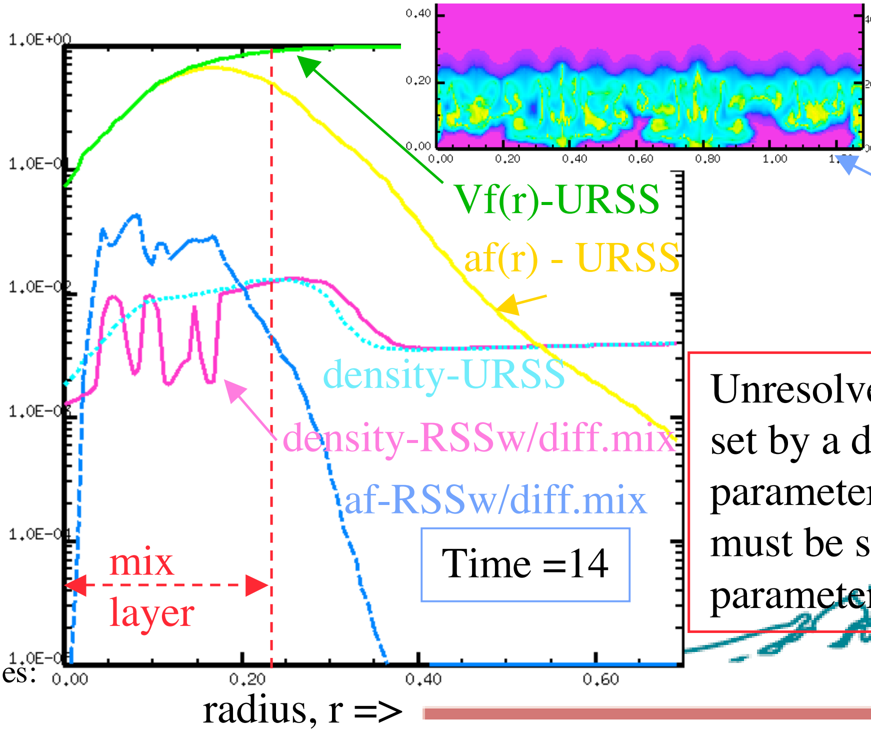


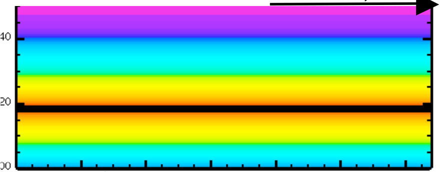
RSS- resolved scale sim. w/ interface recon and w/ diffusion mix



URSS- Un-resolved scale sim. W/ drift flux mix







time=14 atomic mix

Radial profiles of volume fraction (Vf), atomic fraction (af) , and density for cylinder material (originally at r>0.64) in RSS and URSS. (RSS profiles at random z).

Unresolved mix layer width is set by a dynamic drag parameter. Atomic fraction must be set by an independent parameter.

3 ‘c21’ cases: c21,t21,to2

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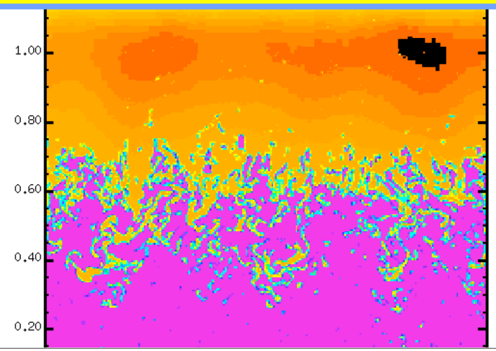
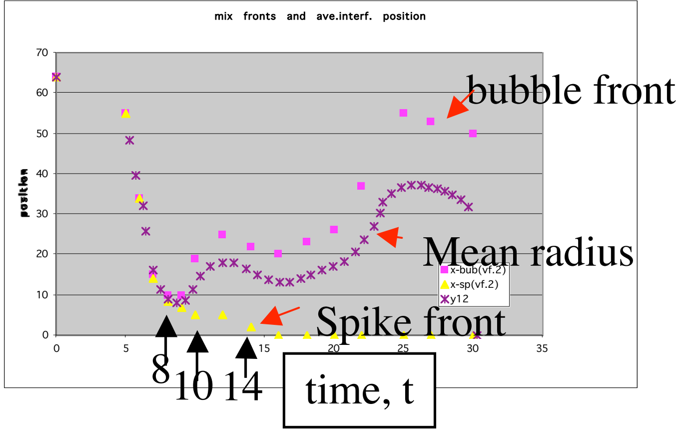
Interface Deceleration Mixing (IDM) Results

- If there is enough energy into system for significant convergence, then interface deceleration mixing departs significantly from RT constant accelaration case and mix grows more like RM, after the g[t] has decreased to near zero. RM instability from initial shock passage is relatively insignificant compared to interface deceleration mix during flow stagnation in converging or planar cases.

- Resolved Scale Simulations characterize IDM w/ the variable deceleration, a(t)) in stagnating flow:
  - Initial mix growth rate, $h(t) \sim t^{g}$, w/ g related to energy input, ranging from g ~ 2 - 14.
    - Energy input as IC uniform velocity (v_{in}) or high energy region near outer boundary
    - Initial growth as acceleration ‘ pulse’ receeds -more like R-M (Richtmyer-Meshkov) than R-T instability.
    - Scales like R-T mix ($\sim t^{g=2}$) only for very small energy input to outer boundary ($C_r < 2$) or some ‘ adiabatic’ (v_{in}) cases.
  - Interface area in mix region, A12, is not simply related to mix width, h_tot, and increases with input energy.
  - Mode doubling observed in thin cylinder case during ‘de-mix’ (h-tot decreasing but A12 still increasing).
  - Small scale structures dominate instability growth in most cases. No apparent bubble merger as in R-T mix ($a \sim a_o$).
- ICF experiment simulations are next.





- Un-resolved scale modeling can use species dynamic equations to match mix layer (w/ drag ~ f(u(t))) and requires a second ‘step’ (or 2nd scale length) to match evolution to atomic mix.

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