Turbulent transition in a high Reynolds number, Rayleigh-Taylor unstable plasma flow

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Summary

- **The transition to turbulence in a high Reynolds number, Rayleigh-Taylor unstable plasma flow is studied.**

- **1D numerical simulations (HYADES) are used to determine the plasma flow parameters (P,ρ,T, Z) from which the kinematic viscosity is then determined.**

- **The Reynolds number is determined using the experimentally measured perturbation amplitude and growth rate together with the plasma kinematic viscosity determined from the 1D numerical simulations.**

- **It is observed that the Reynolds number is sufficiently greater than the mixing transition threshold of Dimotakis (i.e. $Re \gg 2 \times 10^4$) for much of the experiment, yet the flow has not transitioned to turbulence.**

- **An extension of the Dimotakis mixing transition to non-stationary flows of short time-duration is presented.**

Outline

- Experimental setup and results of Omega laser experiment

- Results from 1D HYADES simulation of the experiment

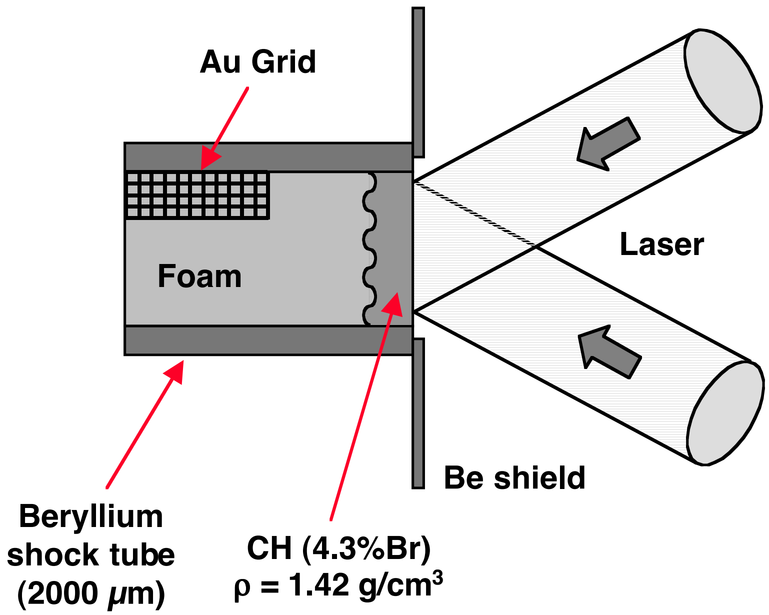
  Basic plasma flow parameters (P,ρ,T, Z)
  Derived flow parameters (ν, D)
  Estimation of the Reynolds number

- Extension of Dimotakis mixing transition to non-stationary flows of short time-duration

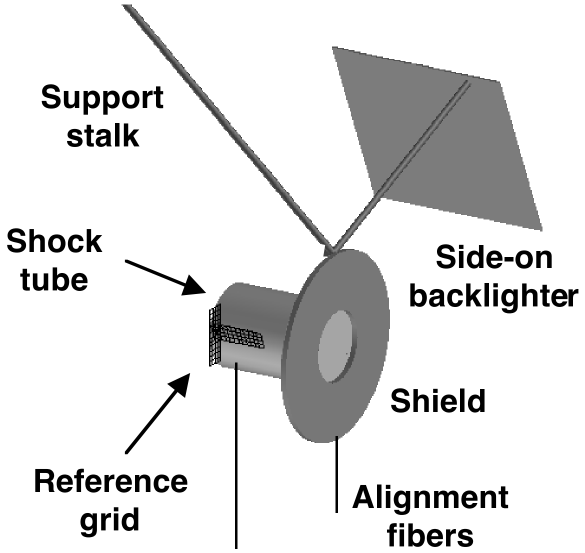
- Conclusions

The experiments are conducted on the Omega laser in a very small Beryllium shock tube

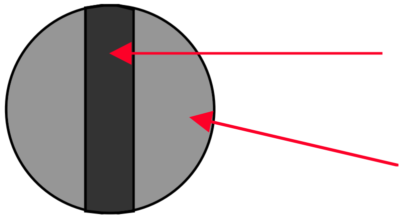
Schematic of target



3D CAD rendering of target



Face-on view of target

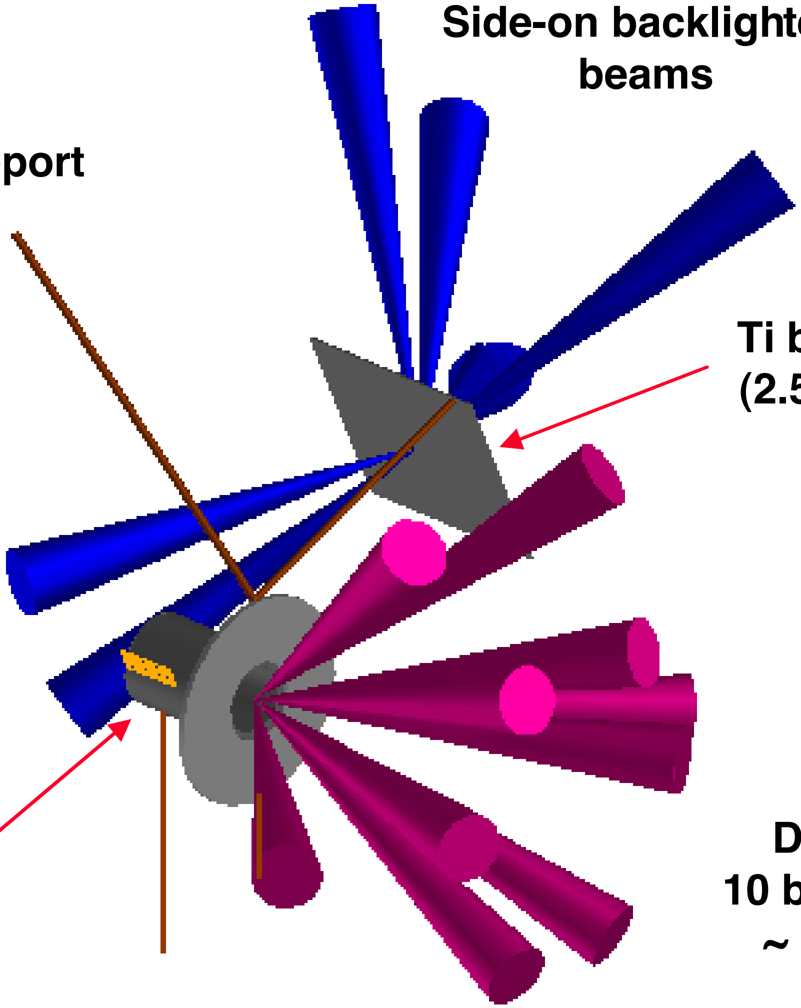


1.42 g/cm^3 CH (4.3%Br) tracer

1.41 g/cm^3 polyimide

The target has a radiographic tracer strip which is density matched to the surrounding material

Multiple beams of the Omega laser are used to both drive the strong shock and diagnose the interaction



Side-on backlighter beams

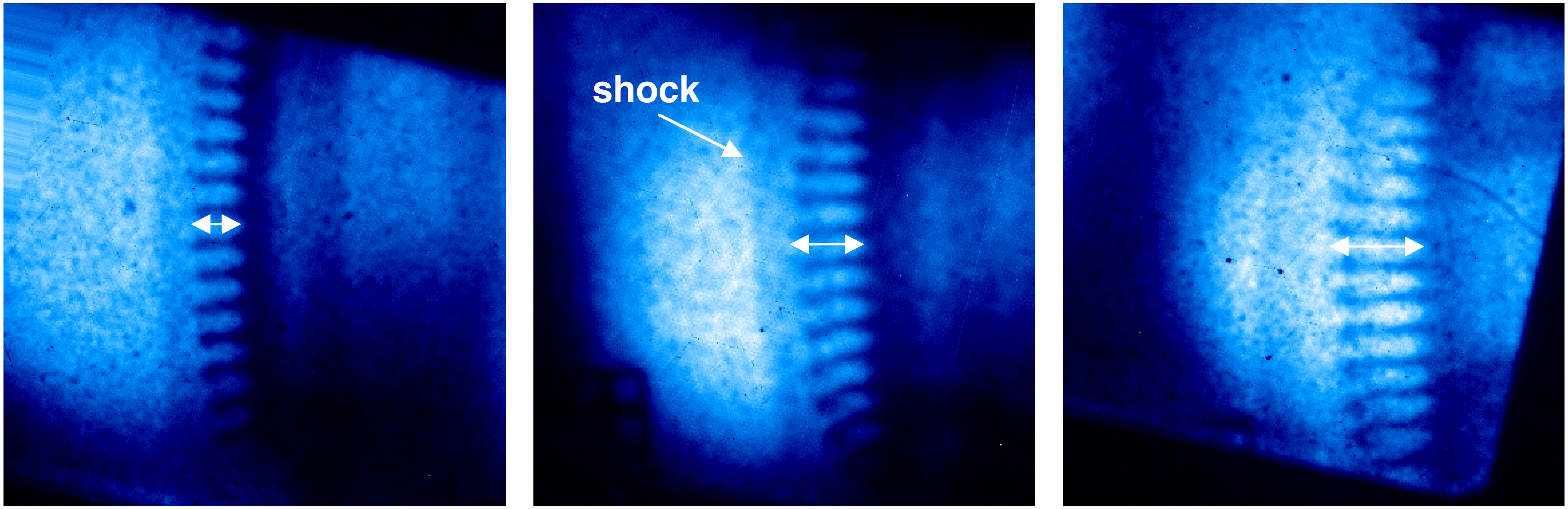
Target support stalk

Ti backlighter foil (2.5 mm^2 x 12 μm)

Beryllium shock tube

Drive beams
10 beams @ 500J
~ 600 μm spot

The evolution of a 2D single-mode perturbation (λ=50μm, a_0=2.5μm) is observed with x-ray radiography



t = 8 ns

t = 12 ns

t = 14 ns

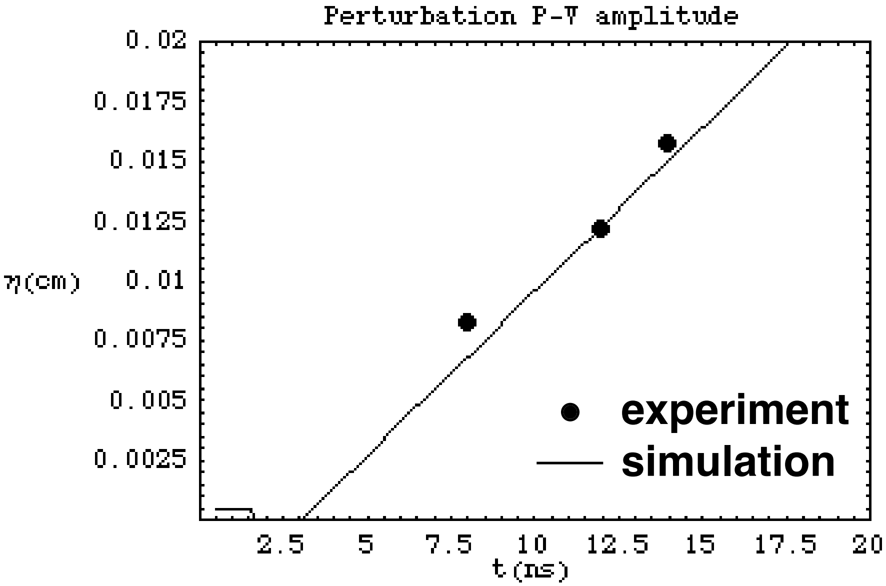
$a_{P\text{-}V}$ = 83 μm

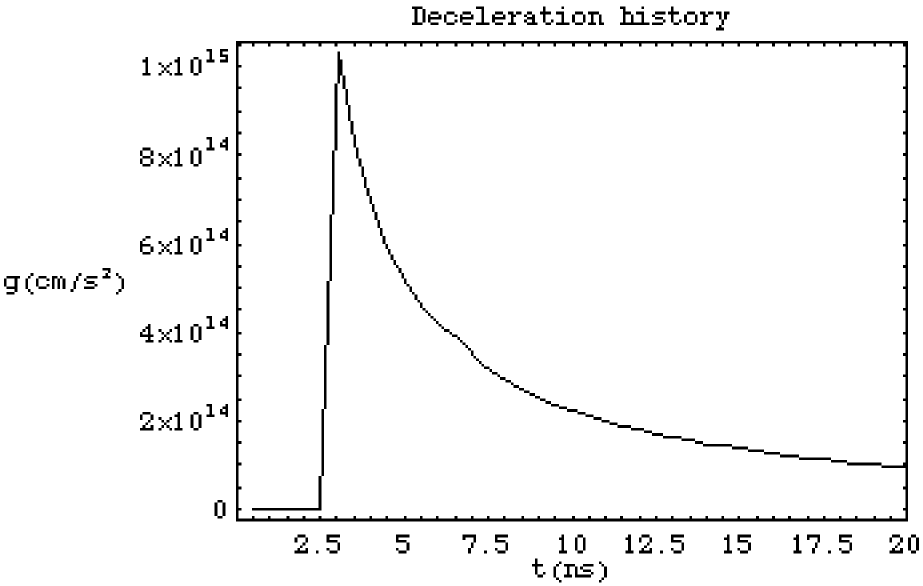
$a_{P\text{-}V}$ = 121 μm

$a_{P\text{-}V}$ = 157 μm

Radiographic images obtained with 4.7keV Ti He-α x-rays imaged onto a gated x-ray framing camera

Results from 1D numerical simulation of the experiment





The effect of decompression of the interface has been taken into account

Outline

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- Results from 1D HYADES simulation of the experiment
  - Basic plasma flow parameters (P,ρ,T, Z)
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  - Estimation of the Reynolds number

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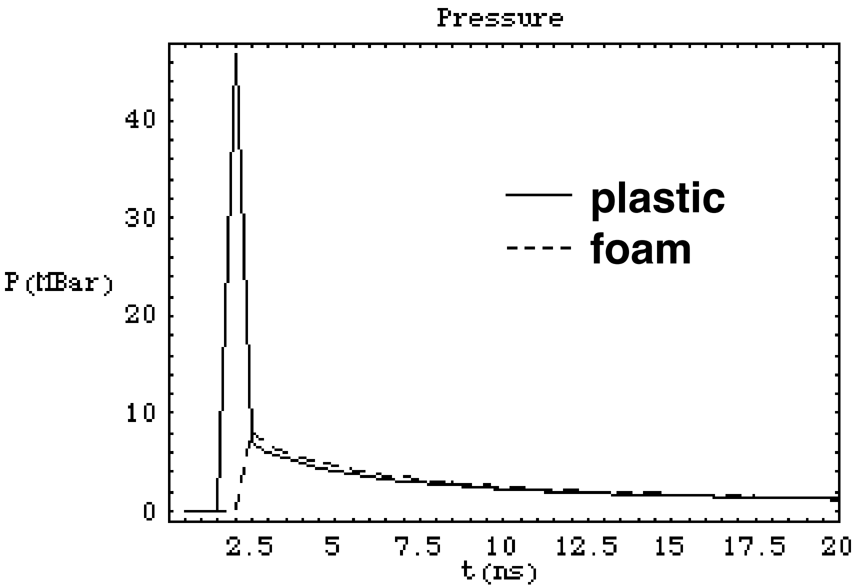
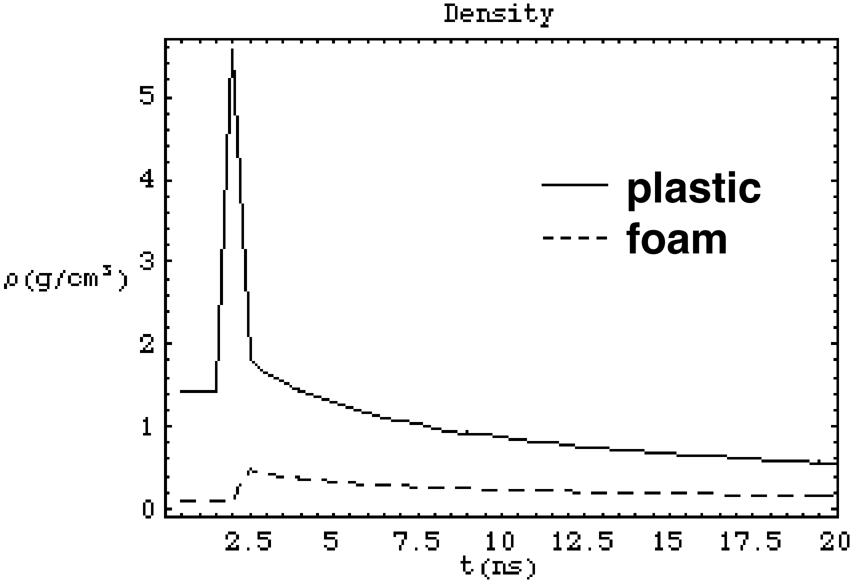
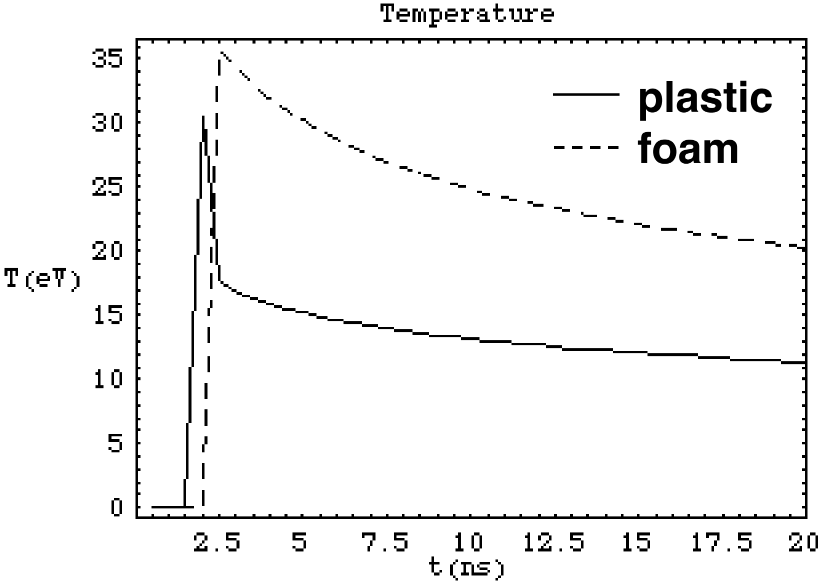
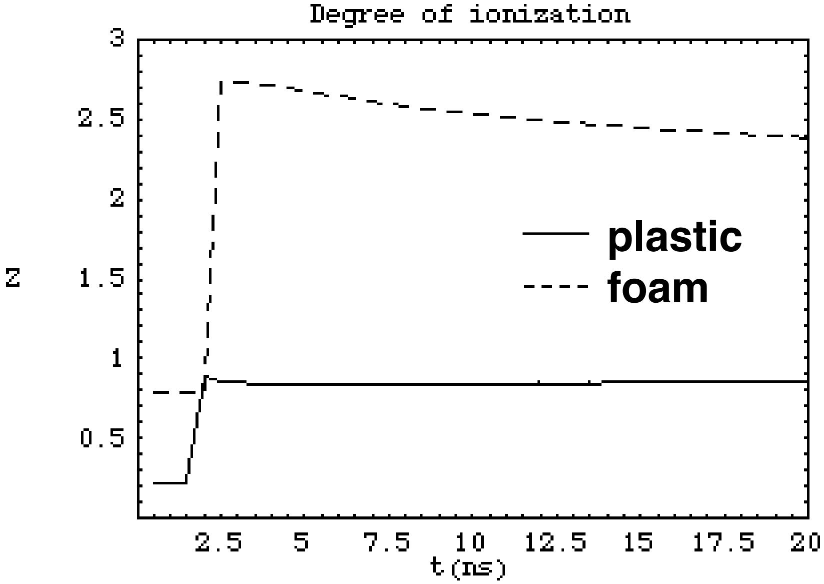
- Conclusions

Time dependent values of the basic flow parameters (pressure, density, temperature, and degree of ionization)

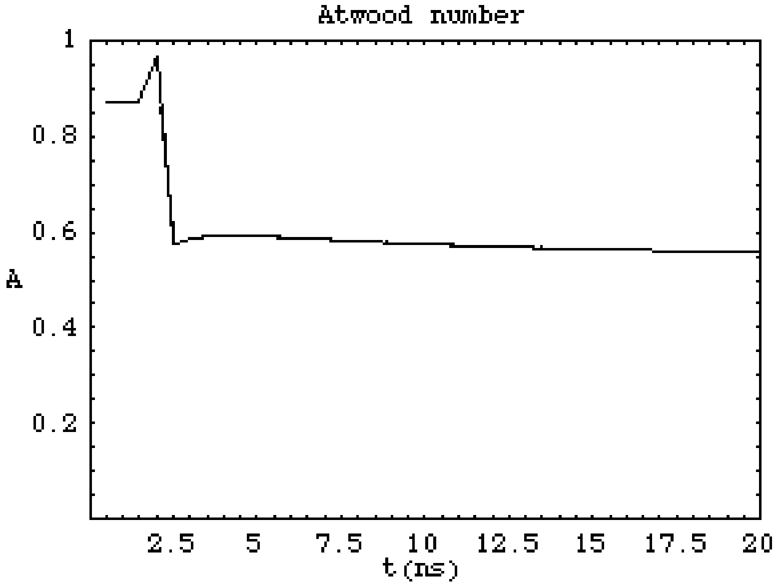


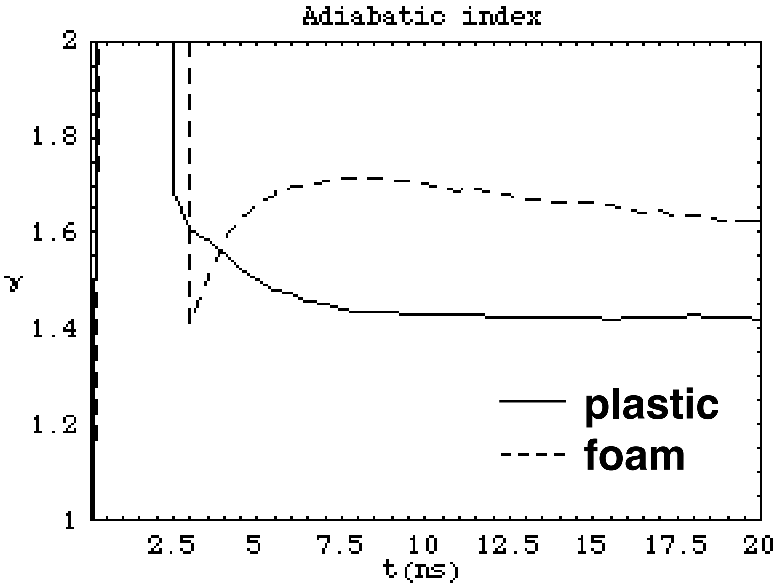


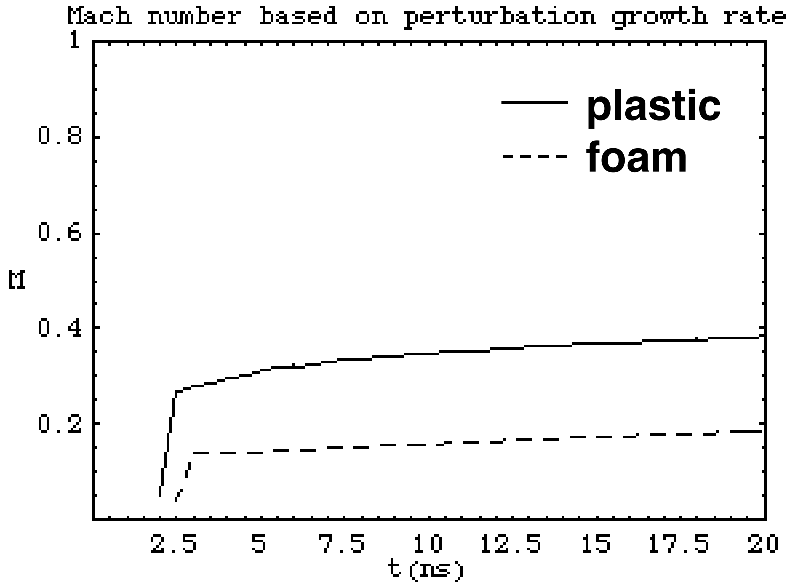




Time dependent values of related flow quantities (Atwood number, adiabatic index, and Mach number)





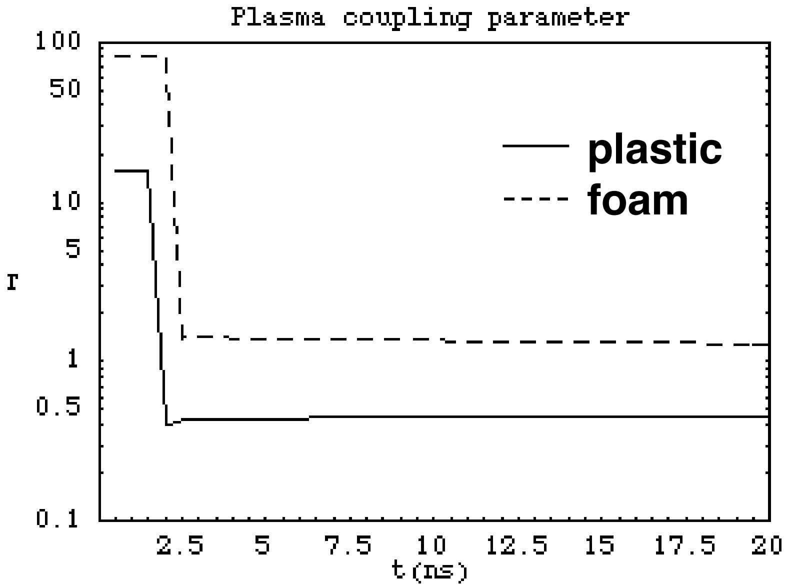


$$A^* = \frac{\rho_1^* - \rho_2^*}{\rho_1^* + \rho_2^*}$$

$$\gamma = \partial \ln(P) / \partial \ln(\rho)$$

$$M = \frac{\dot{h}_{bubble-spike}}{\sqrt{\gamma P / \rho}}$$

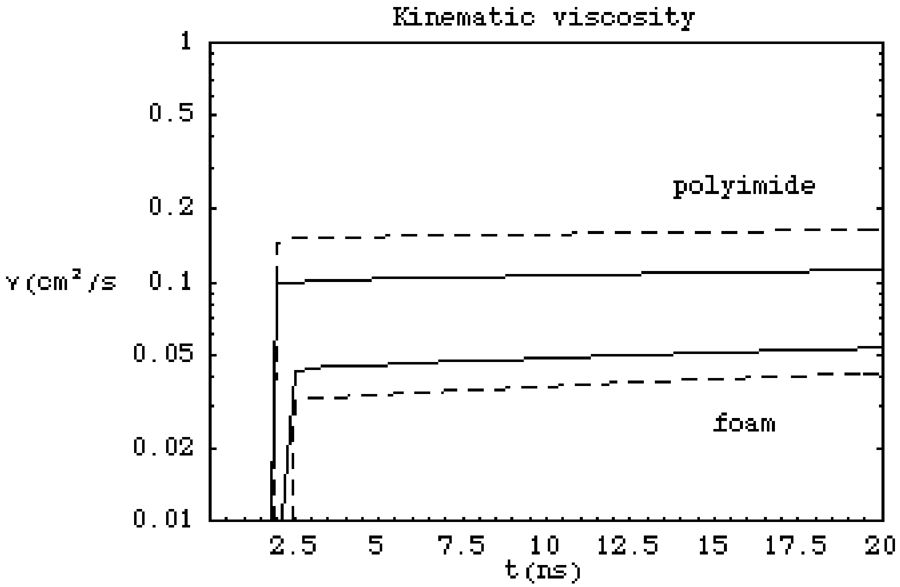
Time dependent values of the plasma coupling parameter, Γ



$$\Gamma = \frac{Z^2 e^2}{k_B T \lambda_i} \quad , \quad \lambda_i = \left(\frac{3}{4\pi N_i}\right)^{1/3}$$

The plasma coupling parameter is in the "uncomfortable" range, i.e neither weakly coupled (Γ<<1) where kinetic theory applies nor strongly coupled (Γ>>1) where molecular dynamics simulations can provide rigorous transport properties

Time dependent values of the kinematic viscosity, ν

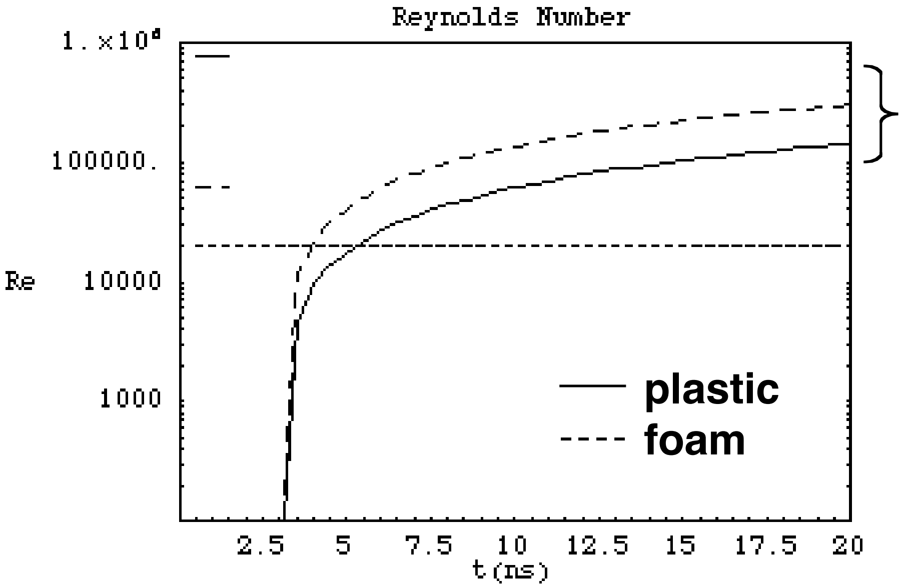


- - - - - - S.I. Braginskii, in *Reviews of Plasma Physics*, New York, Consultants Bureau (1965).

——— J.G. Clerouin, M.H. Cherfi, and G. Zerah, *EuroPhys. Lett.* **42**, 37 (1998).

- The kinematic viscosity is relatively constant throughout the experiment
- The value differs by more than a factor of 2 across the interface
- The Braginskii and Clerouin models show significant differences

Time dependent values of the Reynolds number

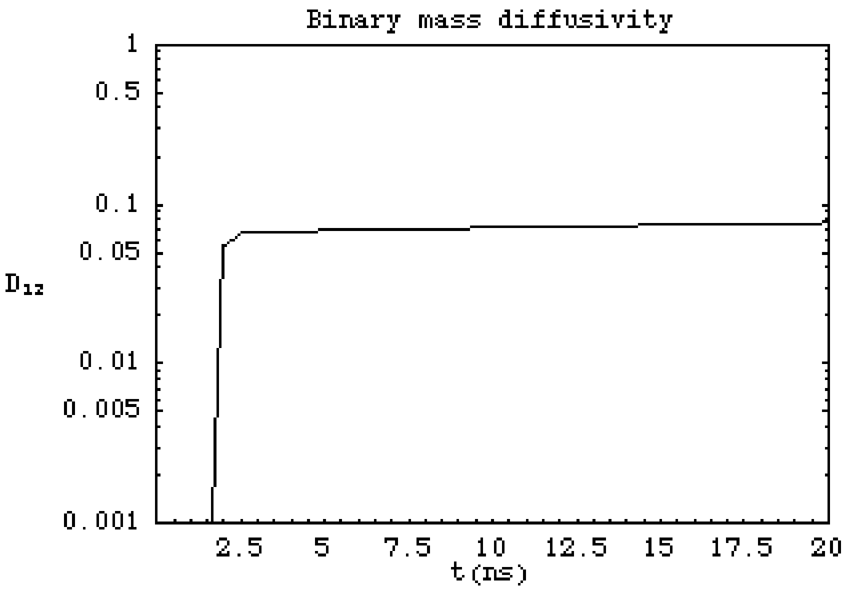


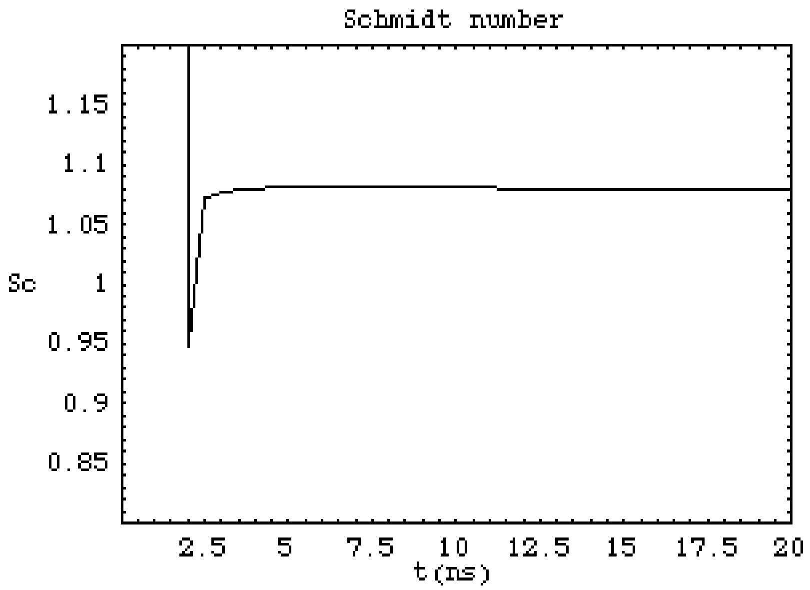
Different values due to differences in kinematic viscosity on either side of the interface

The Reynolds number exceeds the mixing transition threshold of Dimotakis* ($Re_{crit} = 2 \times 10^4$) on both sides of the interface for t > 5ns.

***P.E. Dimotakis, *JFM* 409, 69 (2000)**

The binary mass diffusivity at the interface and the Schmidt number have been calculated as well

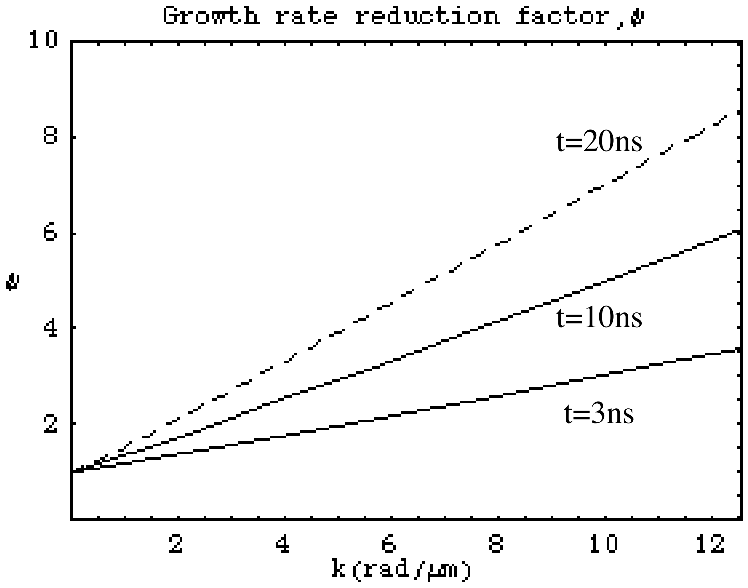


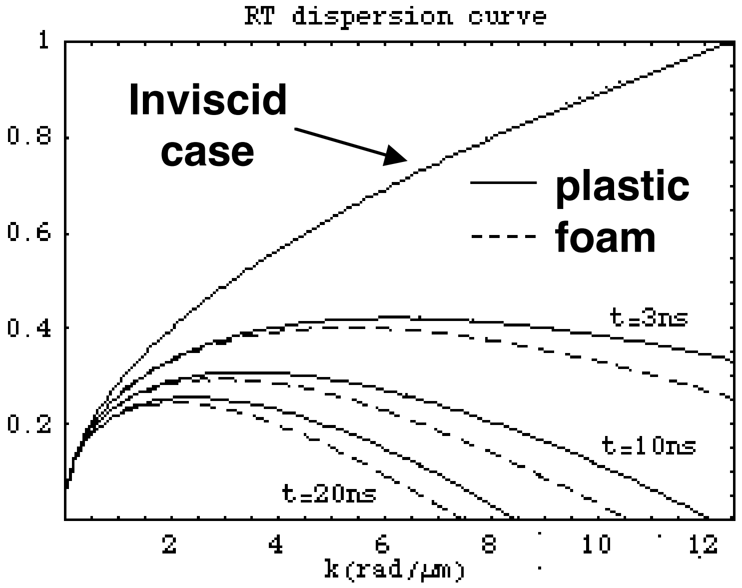


Binary mass diffusivity calculation follow the method outlined in :

C. Paquette et al., *Astrophys. J. Suppl. Ser.* 61, 177 (1986).

From the kinematic viscosity ν and mass diffusivity *D*, the Rayleigh-Taylor growth rate dispersion curve can be calculated





The Rayleigh-Taylor dispersion curve is :

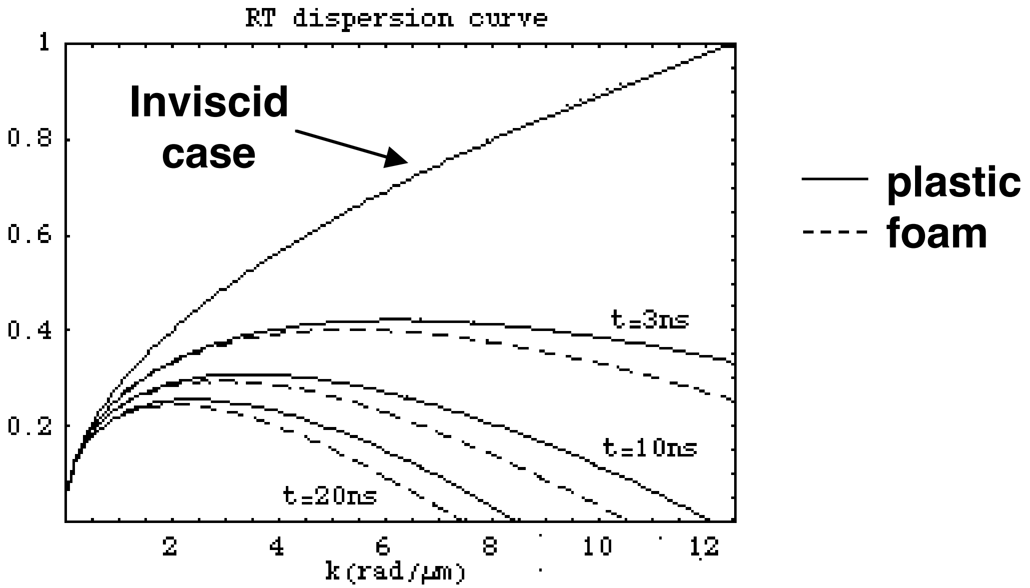
$$\eta_{\nu,D} = \sqrt{\frac{A\,k\,g}{\psi(k,t)} + \nu^2\,k^4} - (\nu + D)\,k^2$$

where Ψ (k,t) is the growth rate reduction factor due to a finite density gradient and is found as the solution of the following eigenvalue equation :

$$\frac{d}{dz}\left(\rho\,\frac{dw}{dz}\right) = w\,k^2\left(\rho - \frac{\psi}{A\,k}\,\frac{d\rho}{dz}\right)$$

From Duff, Harlow, and Hirt, “*Effects of diffusion on interface instability between gases*”, Phys. Fluids **5**(4), 417 (1962).

A sufficient range of Rayleigh-Taylor unstable scales exists to populate a turbulent spectrum



- The initially imposed perturbation has wavelength λ = 50 *μ*m, or k = 0.126 rad / *μ*m.
- At t = 20 ns, perturbations with k > 8 rad/*μ*m (λ < 1.3 *μ*m) are completely stablized.
- At t = 20 ns, the peak growth rate occurs at k = 2.5 rad/*μ*m (λ = 2.5 *μ*m)
- A sufficient range of scales exists, subject to RT instability which can populate a turbulent spectrum

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  Plasma flow parameters (P,ρ,T, Z)
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  Estimation of the Reynolds number

- Extension of Dimotakis mixing transition to non-stationary flows of short time-duration

- Conclusions

Dimotakis has identified a critical Reynolds number at which a rather abrupt transition to a well mixed state occurs

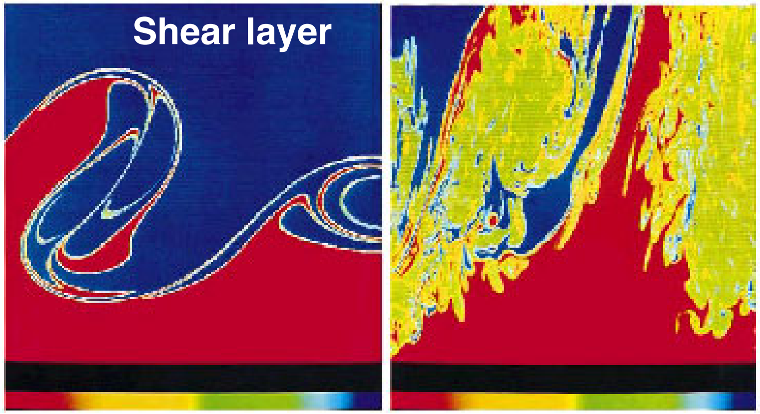


FIGURE 2. Laser-induced fluorescence streak images of the scalar field in a liquid-phase shear layer, for $Re \simeq 1.75 \times 10^3$ (*a*) and $Re \simeq 2.3 \times 10^4$ (*b*). From KD86, figures 7*b* and 9, respectively.

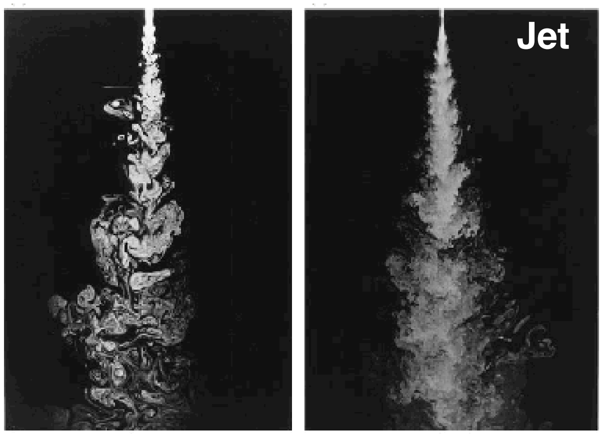


FIGURE 5. Jet-fluid concentration in the plane of symmetry of a round turbulent jet. (*a*) $Re \simeq 2.5 \times 10^3$ ($0 < z/d_s < 35$). (*b*) $Re \simeq 10^4$ ($0 < z/d_s < 200$). Data from Dimotakis *et al.* (1983, figures 5 and 9).

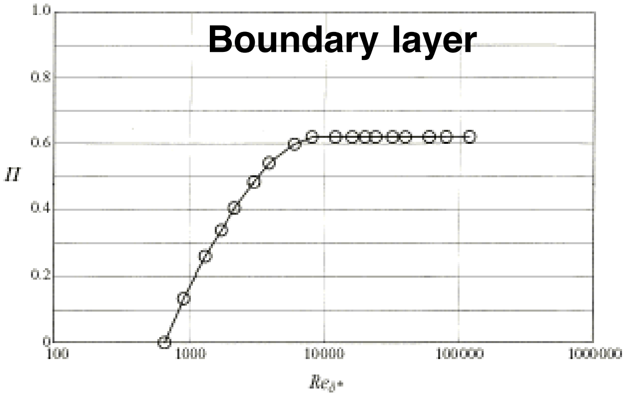


FIGURE 12. Turbulent boundary-layer Π parameter vs. Re_{δ^*}. Skin-friction-law fit data (Collins *et al.* 1978, table 4).

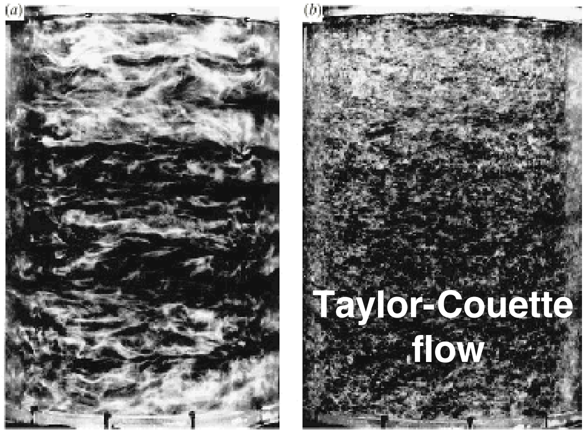
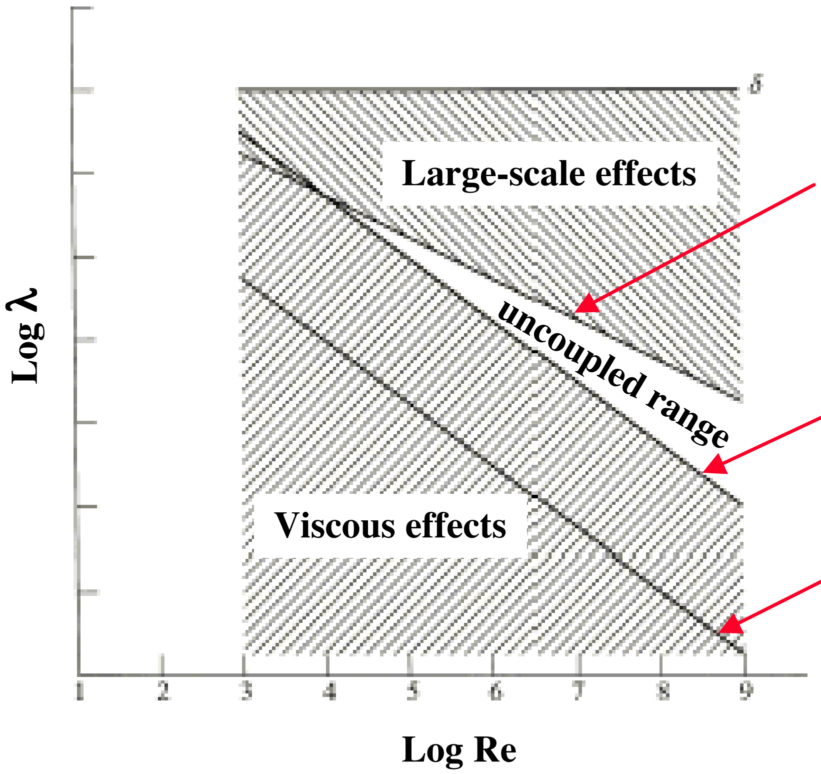


FIGURE 16. Couette–Taylor flow-visualization data at (*a*) $Re = 0.6 \times 10^4$, and (*b*) $Re = 2.4 \times 10^4$. From Lathrop *et al.* (1992*b*, figures 5*a*,*b*). Reproduced by kind permission of Professor H. Swinney.

This mixing transition at Re ≈ 2 x 10^4 is observed to occur in a very wide range of stationary flows

All figures from P.E. Dimotakis, *JFM* 409, 69 (2000)

This transition is co-incident with the appearance of a range of scales decoupled from both large-scale and viscous effects



Liepmann-Taylor scale
$\lambda_T \sim Re^{-1/2}$

$50 \times \lambda_K$

Kolmogorov scale,
$\lambda_K \sim Re^{-3/4}$

Figure 19. Reynolds number dependence of spatial scales for a turbulent jet

Figure 19 from P.E. Dimotakis, *JFM* 409, 69 (2000)

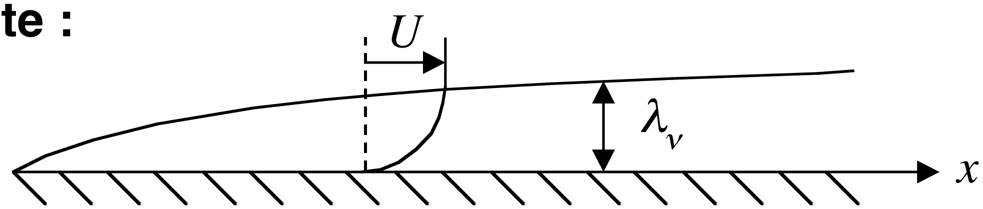
In high Re flows of short time duration, the Taylor microscale may not have sufficient time to reach its asymptotic value

The Taylor microscale (for stationary, homogeneous, isotropic flows) depends on the integral scale δ and the Reynolds number as :

$$\lambda_T \sim \delta \, \mathrm{Re}_\delta^{-1/2}$$

This dependence is analogous to the development of a laminar viscous boundary layer on a flat plate :

$$\lambda_\nu \sim x \, \mathrm{Re}_x^{-1/2}$$



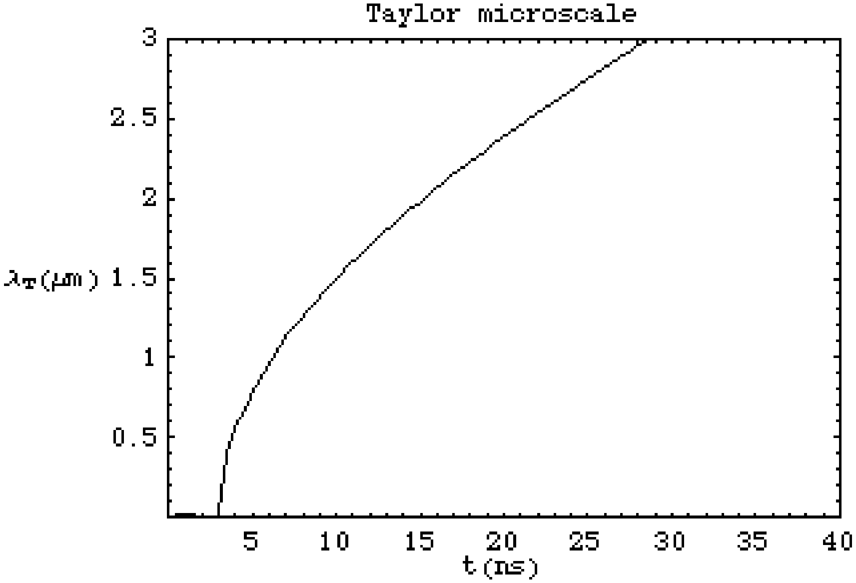
For an impulsively accelerated plate, however, the boundary layer development will initially grow as :

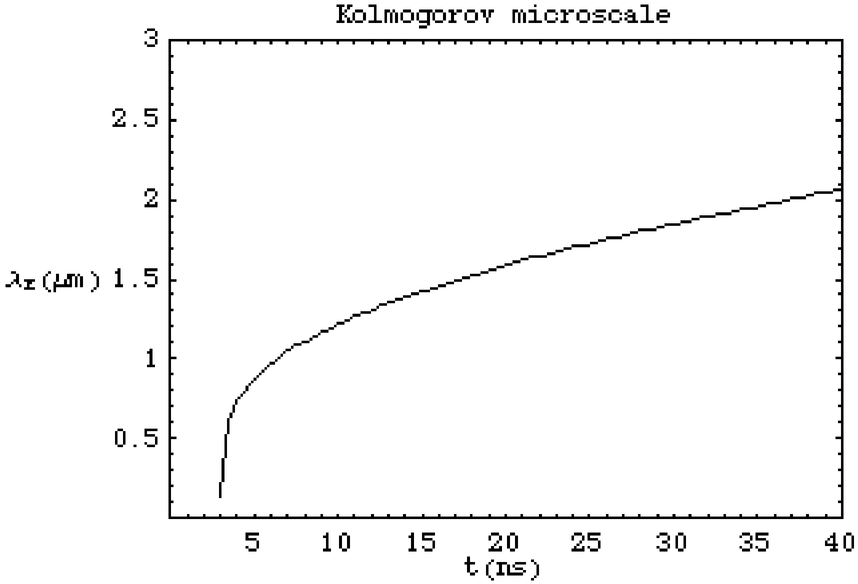
$$\lambda_\nu(t) \sim \sqrt{\nu t}$$

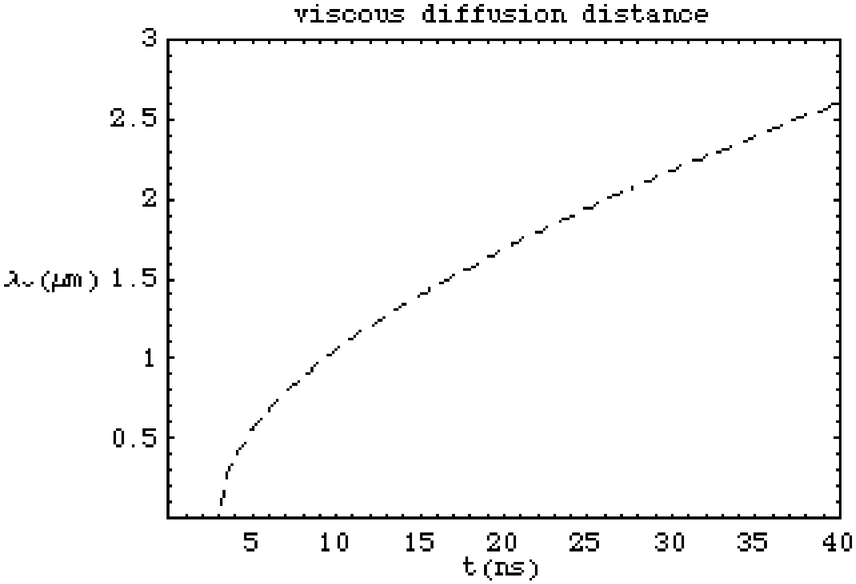
We propose a modification to the mixing transition as the time at which the smaller of the Taylor microscale and the viscous diffusion scale exceeds the dissipation scale (50 x Kolmogorov scale) :

$$Min(\sqrt{\nu t}, \lambda_T) > 50\lambda_K$$

Time dependent values of the Taylor microscale, Kolmogorov scale, and viscous diffusion scale



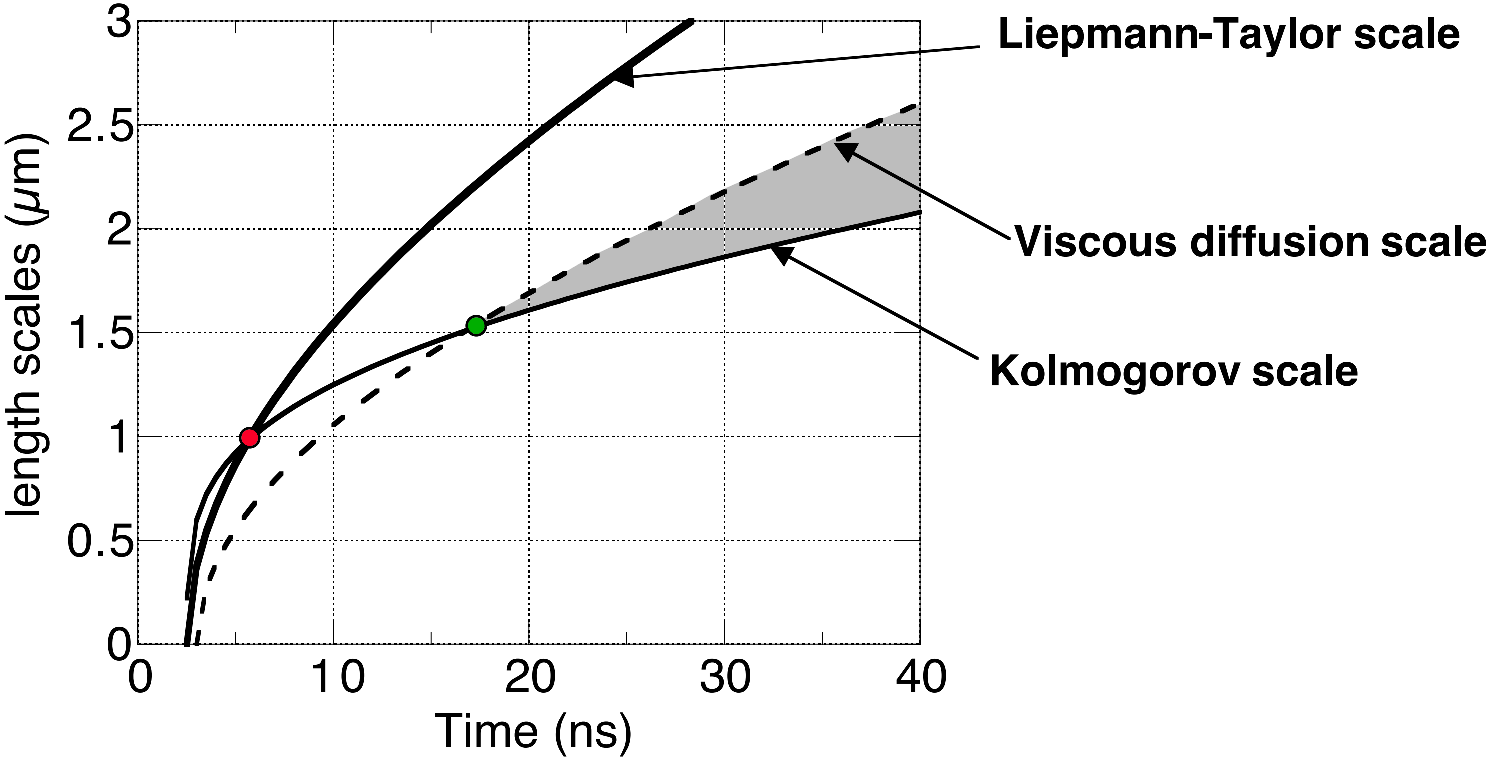




For the present experiment, the viscous diffusion scale is less than the Taylor microscale for the entire duration of the flow.

Therefore the viscous diffusion scale sets the time for a time-dependent mixing transition.

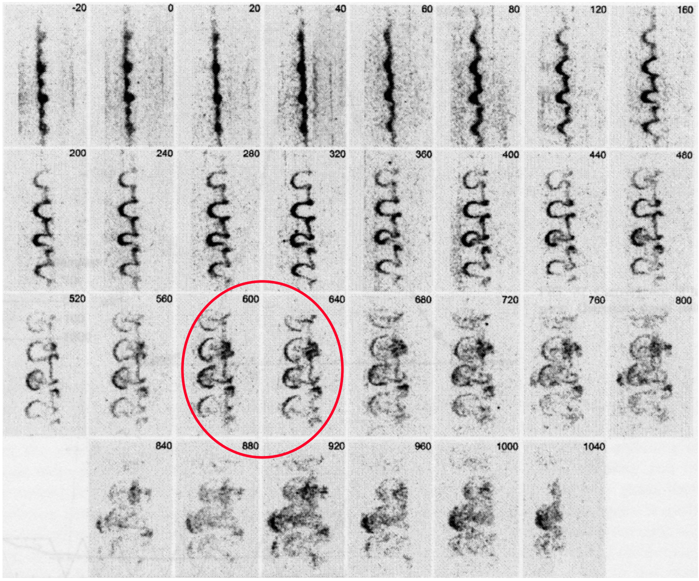
A comparison of viscous length scales shows the appearance of a decoupled range of scales for t > 17 ns

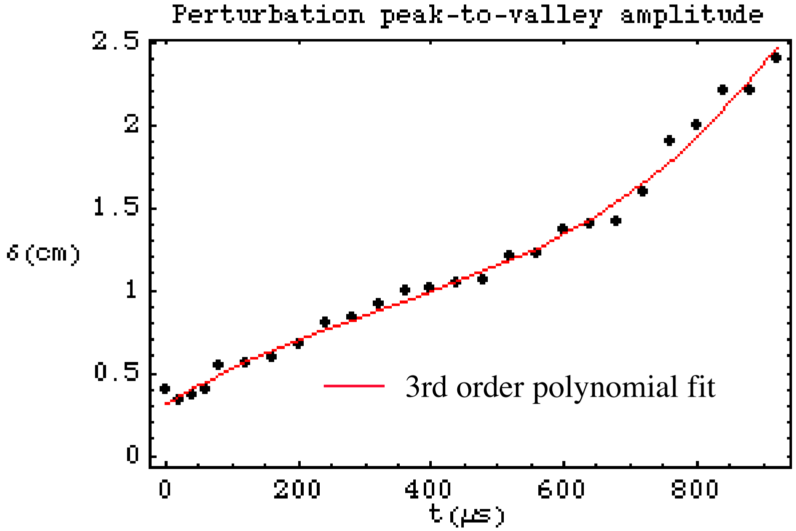


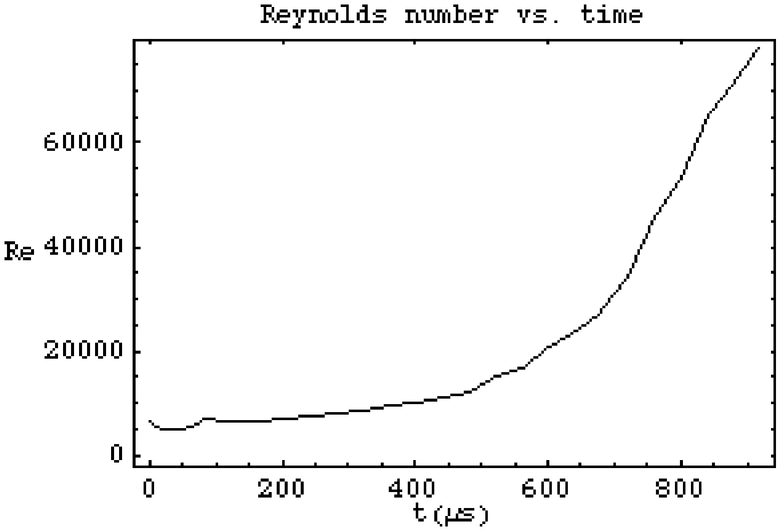
- The red dot indicates the Dimotakis criterion for transition in a stationary flow. This occurs at t ≈ 5.5 ns or Re ≈ 2 x 10^4.

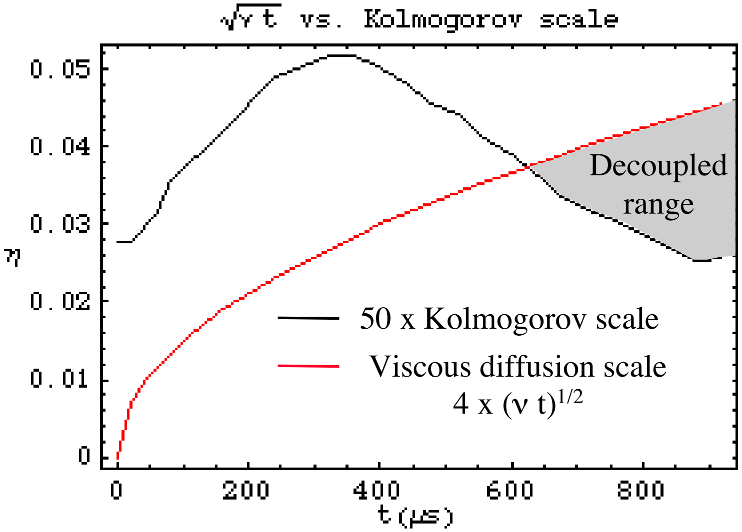
- The green dot indicates the present criterion for transition in a temporally-limited flow. This occurs at t ≈17 ns or Re ≈ 10^5.

This method has been applied to estimate the turbulent transition time in the LANL gas curtain experiment *




Perturbation peak-to-valley amplitude

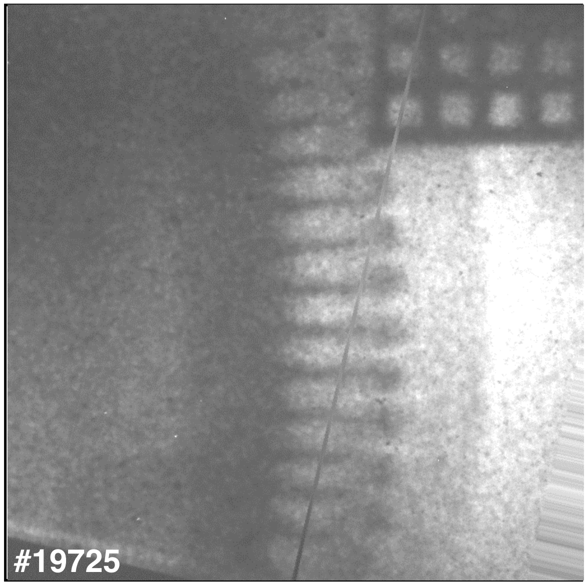

Reynolds number vs. time

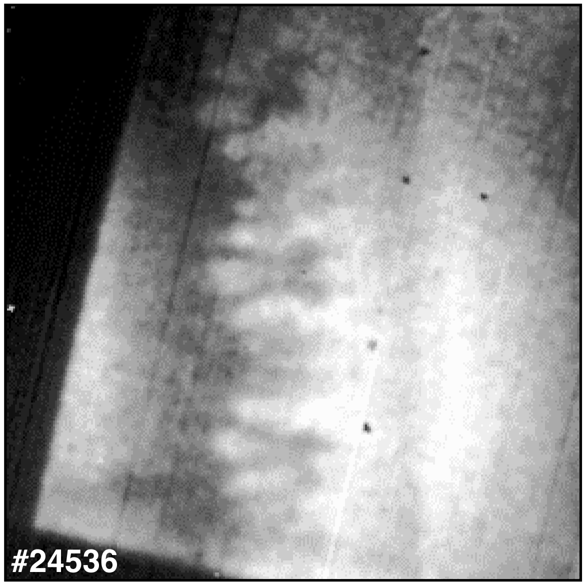

$\sqrt{\nu t}$ vs. Kolmogorov scale

* From Rightly, Vorobieff, Martin, & Benjamin, Phys. Fluids 11(1), 186 (1999)

Current and future work on Omega will focus on the role of modal content and dimensionality of the initial perturbation

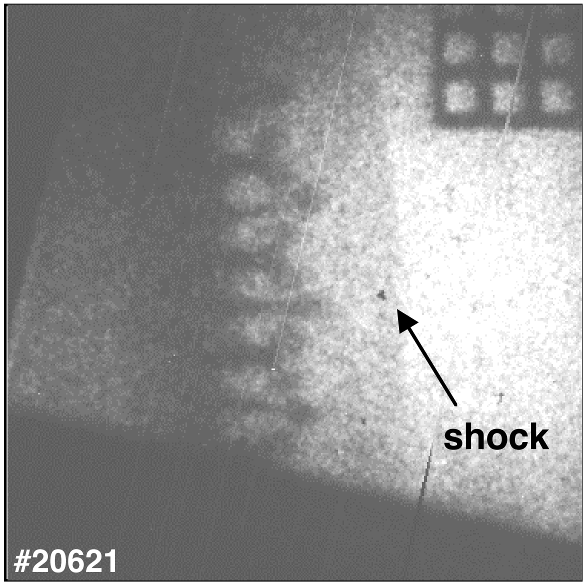
2D, single-mode
@ 13 ns

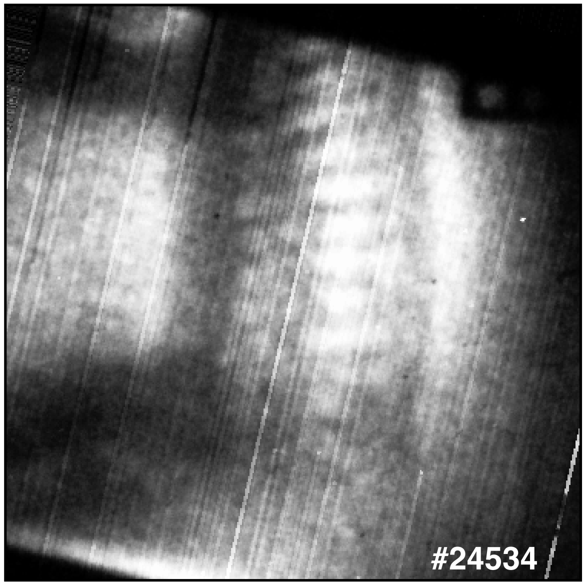




2D, 8-mode
@ 13 ns

2D, 2-mode
@ 13 ns





3D, single-mode
@ 13 ns

Conclusions

The transition to turbulence in a high Reynolds number, Rayleigh-Taylor unstable plasma flow has been studied experimentally.

The following observations are made :

- The Reynolds number exceeds the mixing transition threshold of Dimotakis (i.e. $Re \gg 2 \times 10^4$) for much of the experiment, yet no transition to turbulence is observed.
- An extension of the Dimotakis mixing transition to non-stationary flows of short time-duration is presented. This method illustrates that the temporal duration of the present flow is insufficient to allow for the appearance of a mixing transition.