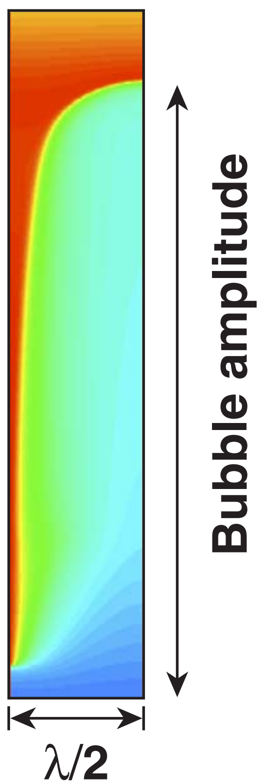
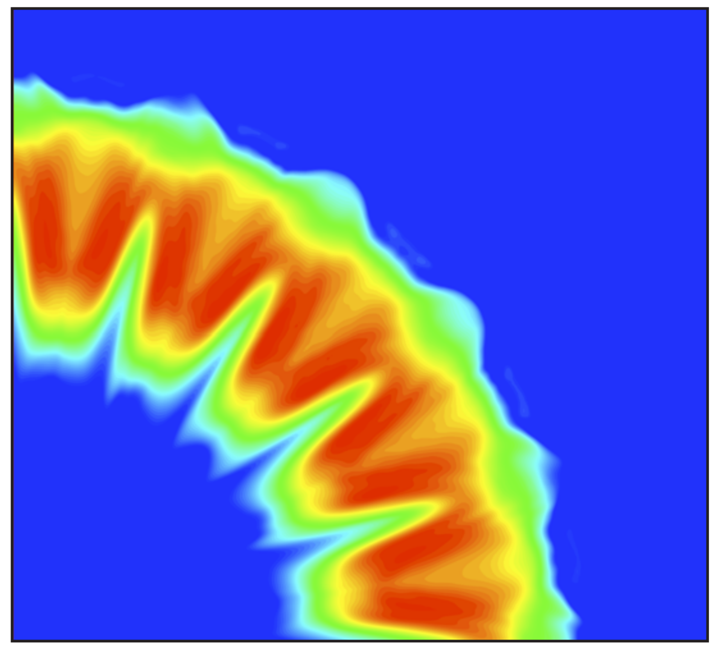
Asymptotic Bubble Evolution in the Bell–Plesset and Rayleigh–Taylor Instabilities

RT bubble



Cylindrical BP bubbles



C. Zhou, R. Betti, and J. Sanz
University of Rochester
Laboratory for Laser Energetics

46th Annual Meeting of the
American Physical Society
Division of Plasma Physics
Savannah, GA
15–19 November 2004

Summary

The asymptotic bubble evolution for the ablative-RT and BP instabilities is studied using Layzer-like models and simulations

- In the ablative Rayleigh–Taylor instability, the asymptotic bubble velocity is higher than the classical value.
- The bubble velocity in the incompressible Bell–Plesset instability exhibits a bifurcated solution
  - The bubble "expands" and "accelerates" when the initial amplitude is below a critical value.
  - The bubble "compresses" and "freezes" when the initial amplitude is above a critical value.

The nonlinear theory of Sanz *et al*. predicts that the asymptotic bubble velocity is classical

- A fully developed bubble is cold; ablation is negligible in the bubble. The bubble motion is governed by the balance between the drag and the buoyancy forces.
- The theory* predicts that the asymptotic bubble penetration velocity (i.e., the velocity relative to the overdense material) is classical

$$V_{bubble} = \sqrt{g/3k} \approx 0.1\, \lambda\gamma_{classical}$$

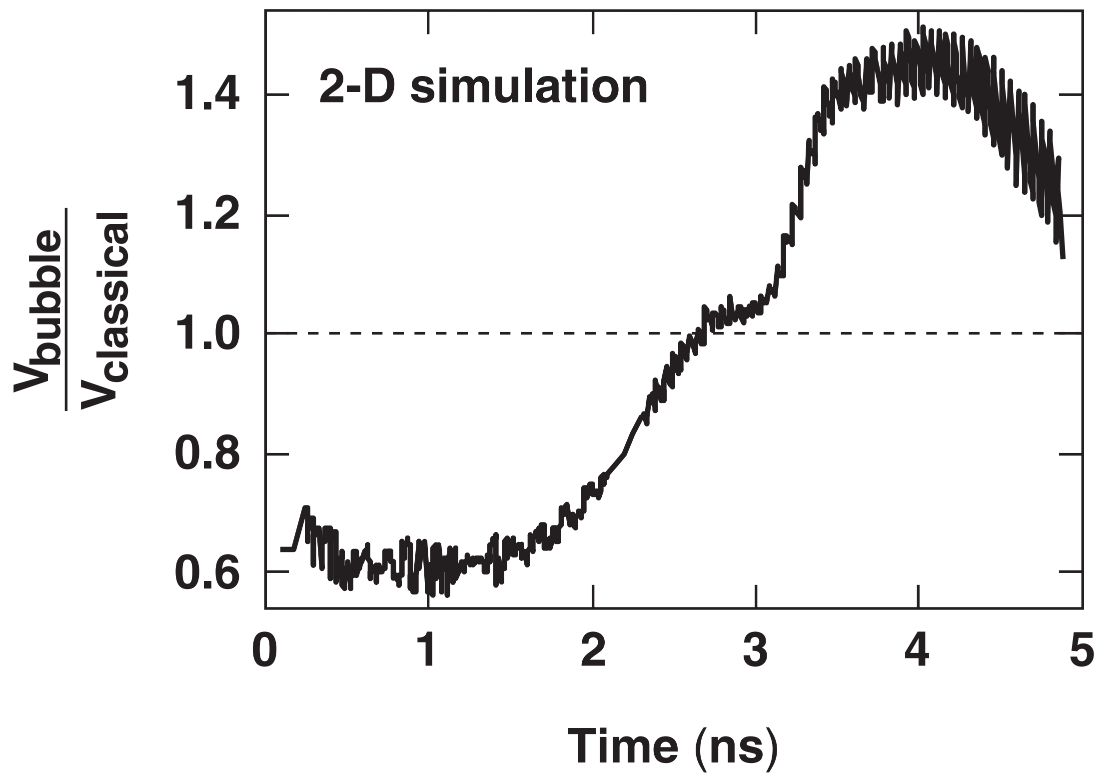
- Heuristic formula** underestimates the bubble penetration velocity at short wavelengths, where $\gamma_{classical} >> \gamma_{ablative}$

$$V_{bubble}^{heuristic} \approx 0.1\, \lambda\gamma_{ablative} + V_a$$

*J. Sanz, *et al*., Phys. Rev. Lett., 89, 195002 (2002).
**Single-mode application of S. W. Haan, Phys. Rev. A, Gen. Phys. 39, 5812 (1989).

TC6732

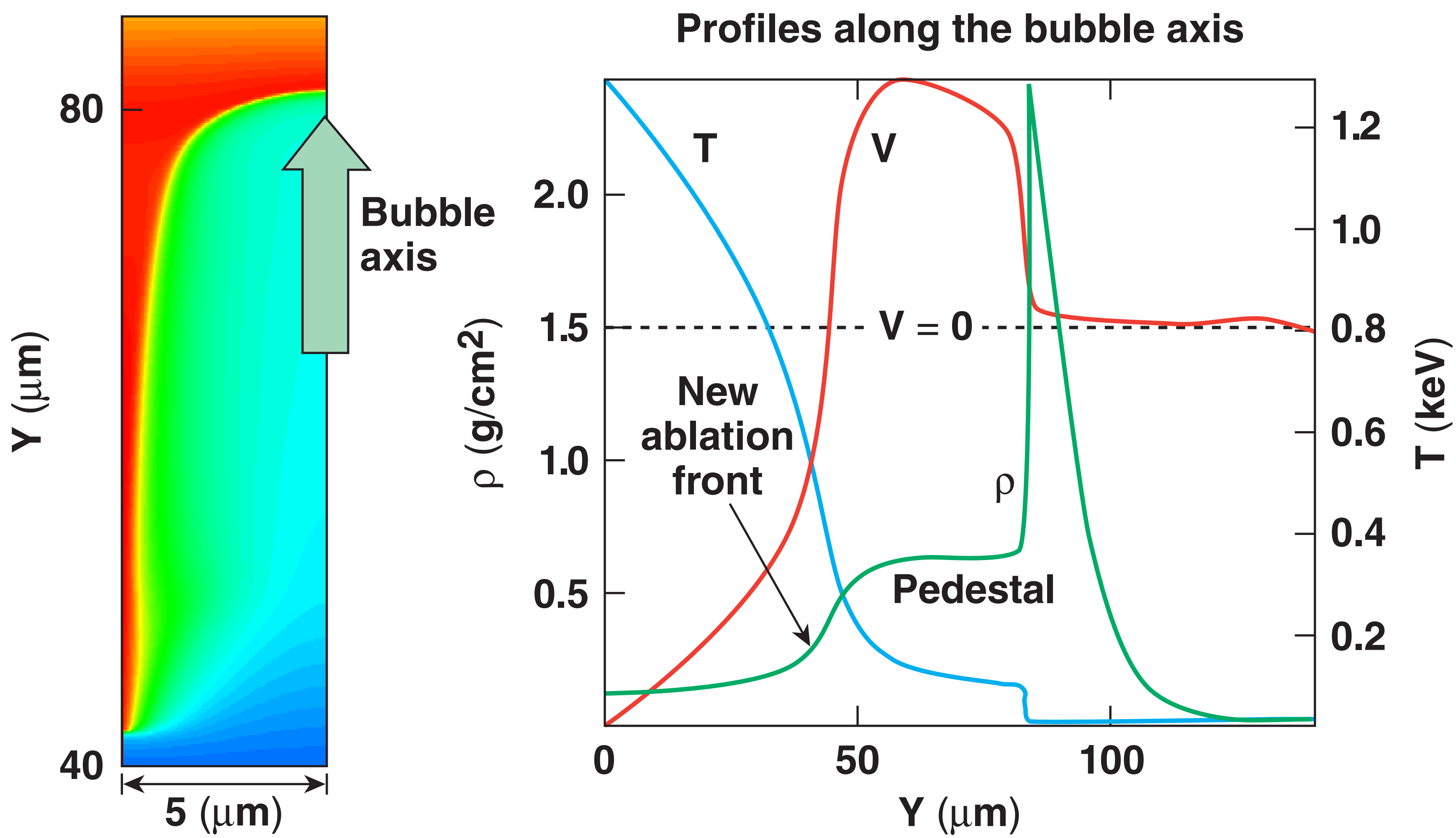
The bubble velocity relative to the overdense target material (i.e., the penetration velocity) is greater than classical



$$V_{classical} = \sqrt{\frac{g}{3\,k}\left(1 - \frac{\rho_l}{\rho_h}\right)}$$

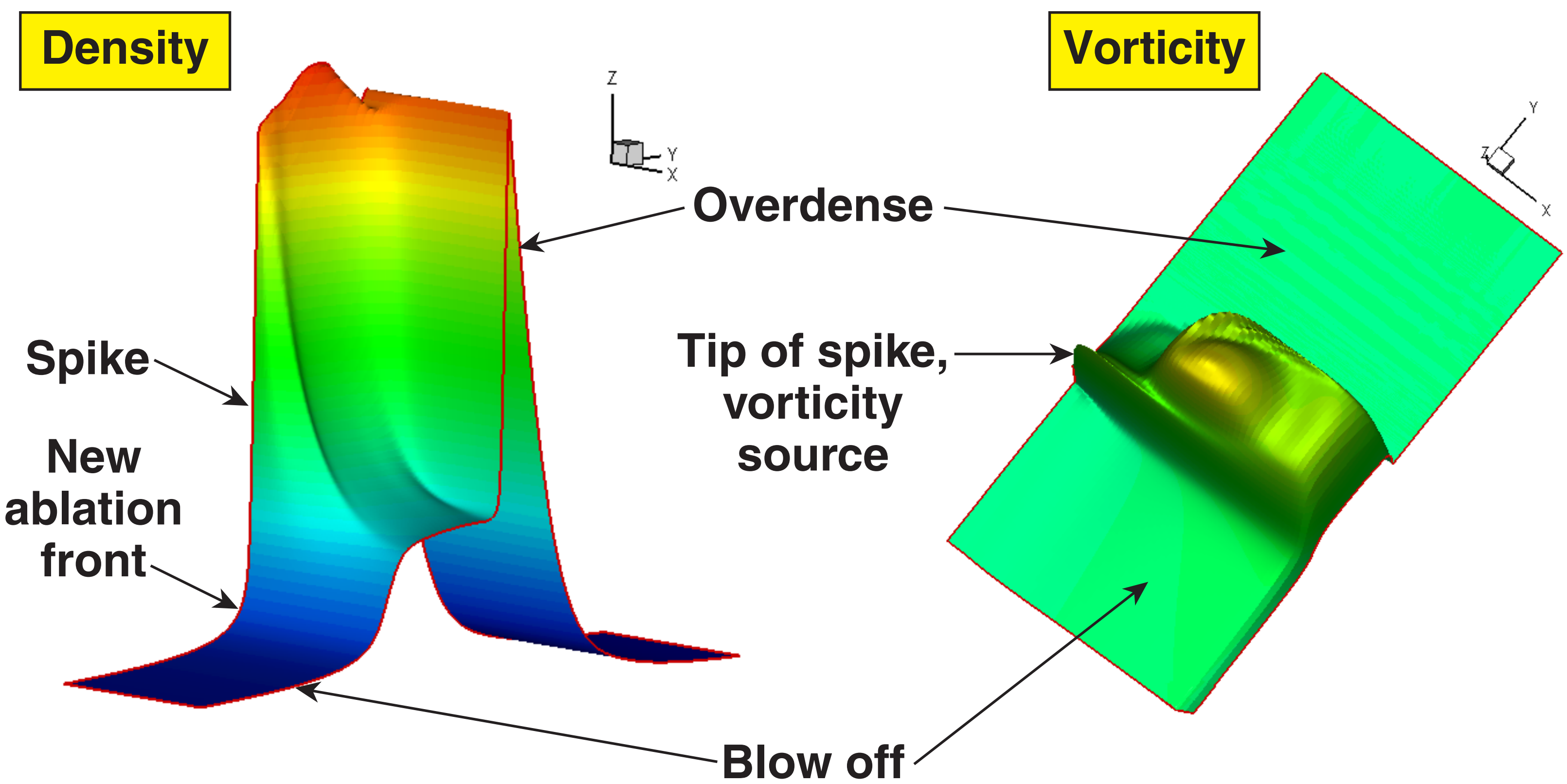
TC6733

A pedestal forms in the density profile and the bubble is classical with no ablation inside



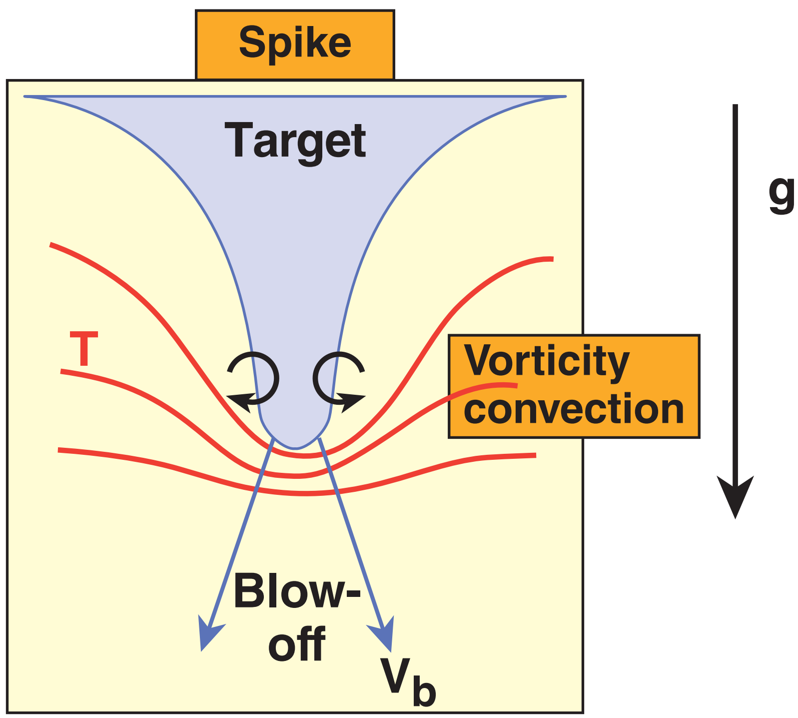
TC6734

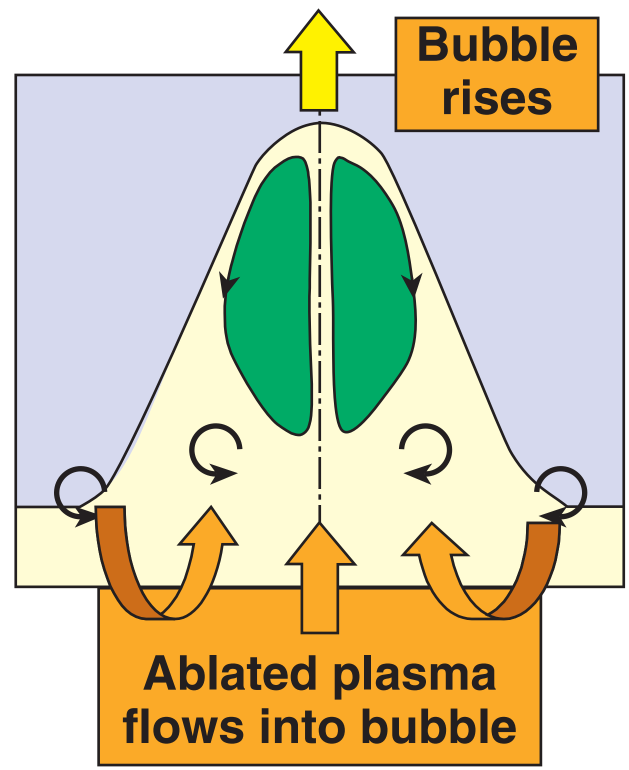
A large vortex forms inside the bubble; the vorticity convected from the tip of the spike accumulates inside the bubble



TC6735

Ablated material with finite vorticity fills the bubble; vorticity inside the bubble grows in time

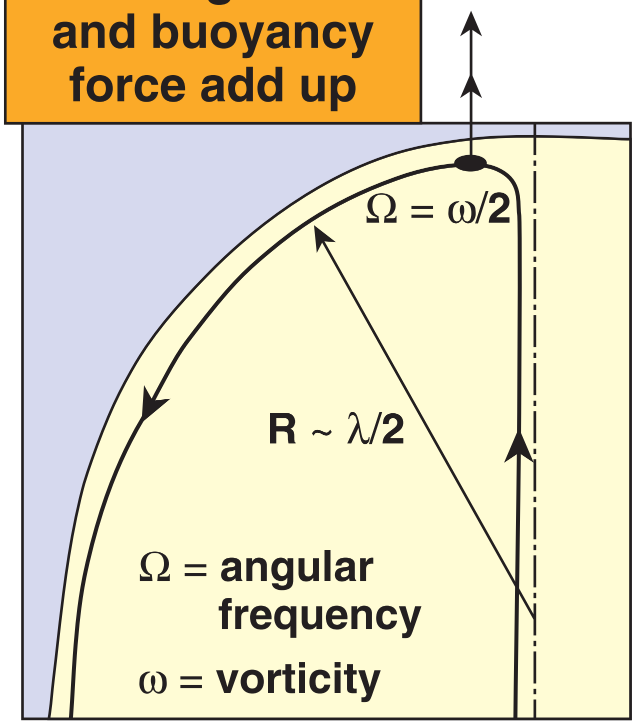


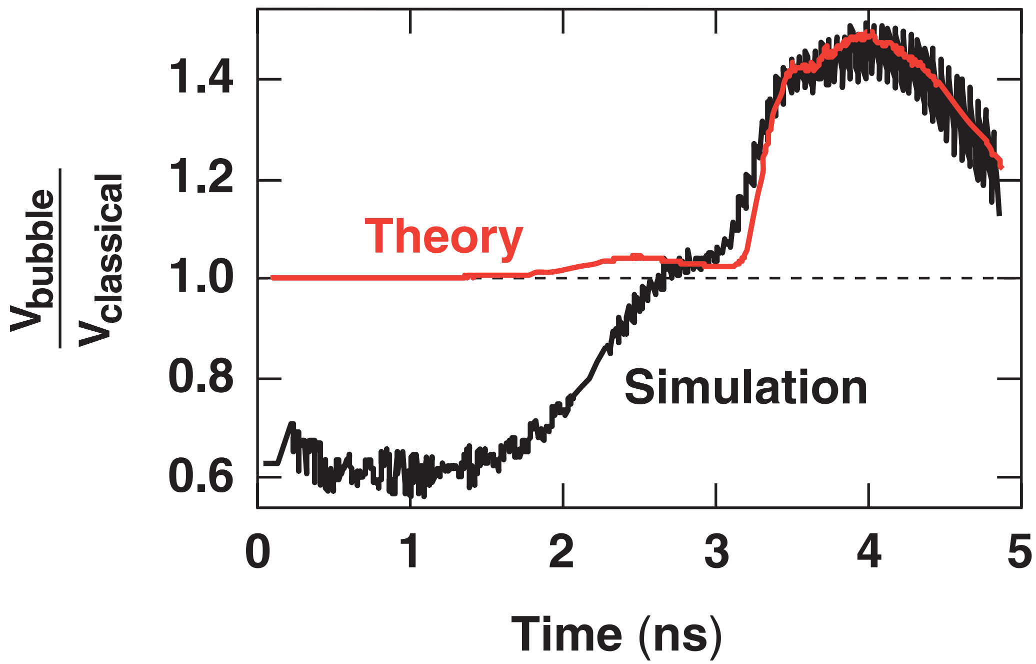


TC6736

Asymptotic bubble velocity if higher than the classical value due to the vorticity accumulated inside the bubble

Centrifugal force and buoyancy force add up





Centrifugal force $\rho_l R \Omega^2 = \rho_l \frac{R\omega^2}{4}$

Buoyancy force $(\rho_h - \rho_l)\, g$

$$V_{bubble}^{vort} = \sqrt{\frac{g}{3k}\left(1 - \frac{\rho_l}{\rho_h}\right) + \frac{\rho_l}{\rho_h}\frac{\omega^2}{4k^2}}$$

TC6737

The asymptotic bubble velocity is also calculated for the Bell–Plesset instability; a Layzer model for the BP is developed

- **Two coupled differential equations are derived for the bubble position (ξ) and bubble curvature (η).**

$$\gamma_\rho \xi^2\left[(3\ell+2)\eta+\ell^2\xi\right]+2\ell(3\eta+\ell\xi)\left(R\dot{R}-\xi\dot{\xi}\right)-2\xi\frac{d\xi\eta}{dt}=0$$

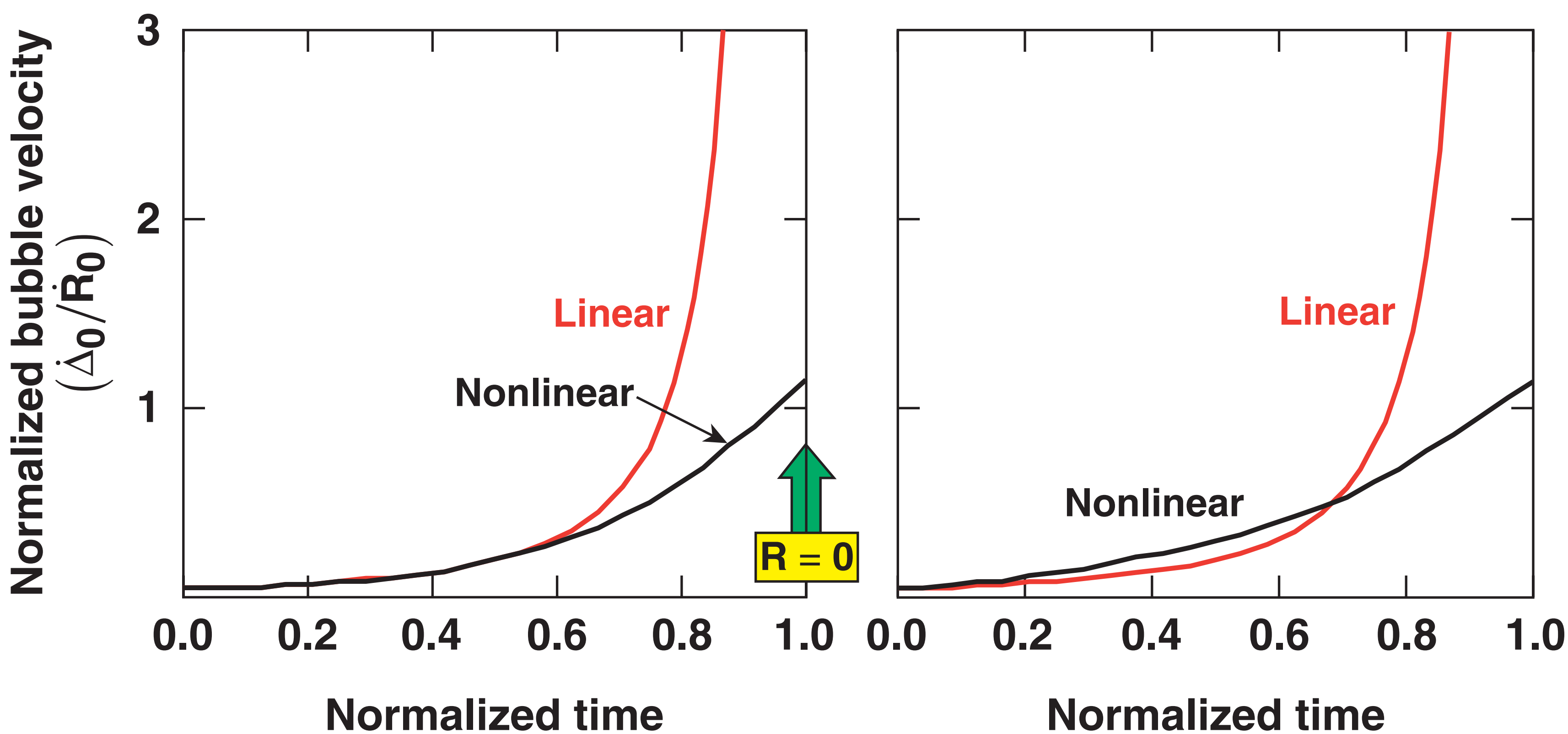
$$\ell^2\gamma_\rho^2\xi^4+4\ell^2\gamma_\rho\xi^2\left(R\dot{R}-\xi\dot{\xi}\right)-2\ell\xi^2\frac{d\gamma_\rho\xi^2}{dt}$$
$$+4\ell^2\left(R\dot{R}-\xi\dot{\xi}\right)^2-4\ell\xi^2\frac{d}{dt}\left(R\dot{R}-\xi\dot{\xi}\right)+4\eta\xi^2\ddot{\xi}=0$$

- **ℓ is the wave number**
- **R(t) is the inner radius**
- **Bubble amplitude $\Delta = \xi - R$**
- **$\gamma_\rho = \dot{\rho}/\rho$ is the compressibility; take $\gamma_\rho = 0$**

TC6738

The BP nonlinear bubble velocity may temporarily exceed its linear value but asymptotically falls below linear

UR LLE



Normalized initial amplitude $\Delta_0/R_0 = 0.01$

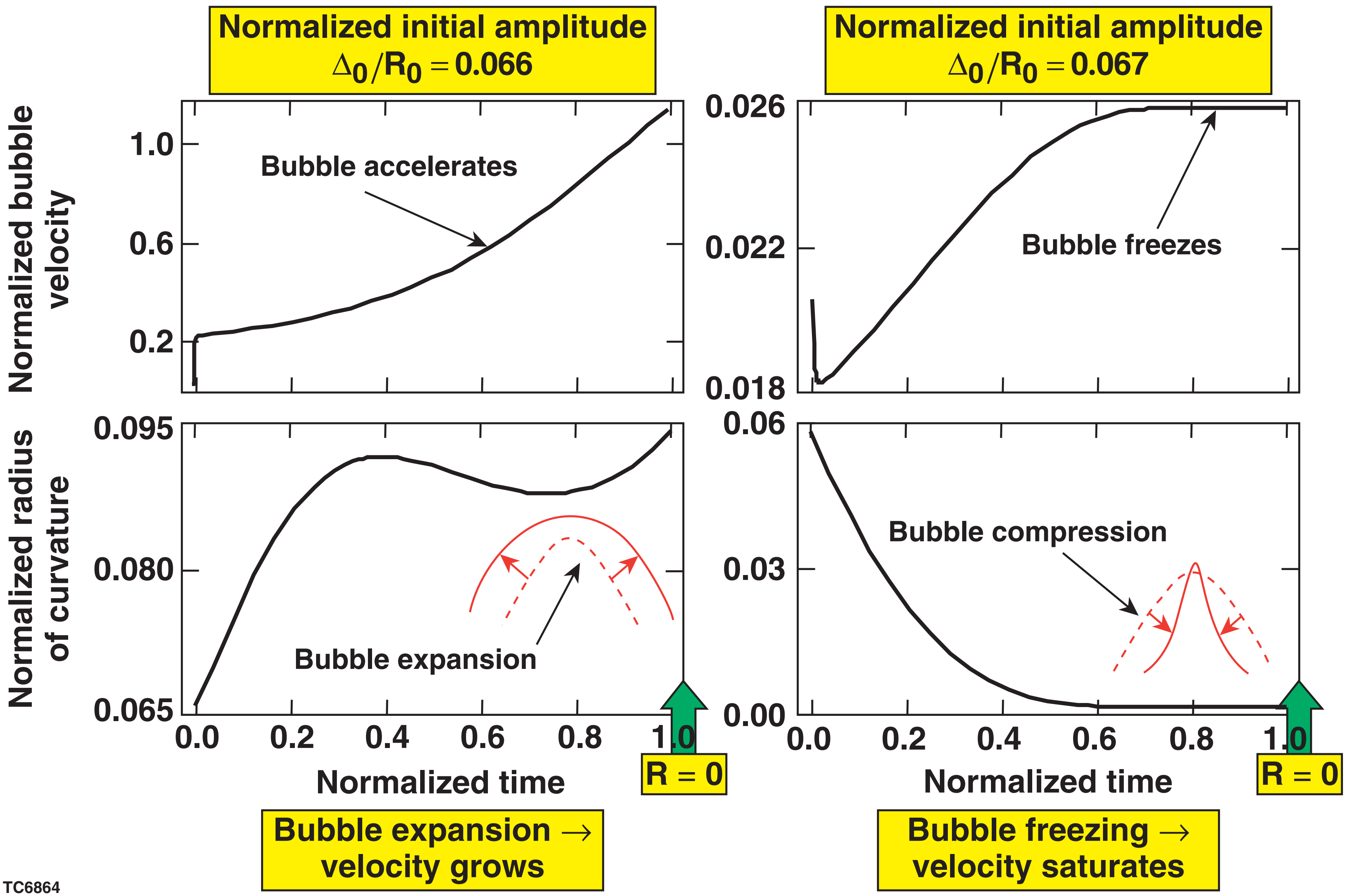
Normalized initial velocity $\dot{\Delta}_0/\dot{R}_0 = 0.05$

Normalized initial amplitude $\Delta_0/R_0 = 0.03$

Normalized initial velocity $\dot{\Delta}_0/\dot{R}_0 = 0.05$

TC6863

A bifurcated solution develops when the initial amplitude exceeds a critical value



TC6864

Criterion for bifurcation of the solution depends on initial conditions of the perturbation

Bifurcation criterion for initial sinusoidal perturbation

$$\tilde{\Delta}/R_0 = 1.32/\ell^{1.1}$$

$\Delta_0 > \tilde{\Delta}$ **Bubble freezes, velocity saturates before full convergence.**

$\Delta_0 < \tilde{\Delta}$ **Bubble expands, velocity increases until full convergence.**

Summary/Conclusions

The asymptotic bubble evolution for the ablative-RT and BP instabilities is studied using Layzer-like models and simulations

- In the ablative Rayleigh–Taylor instability, the asymptotic bubble velocity is higher than the classical value.
- The RT bubble acceleration above classical is caused by the vorticity accumulation inside the bubble.
- The bubble velocity in the incompressible Bell–Plesset instability exhibits a bifurcated solution
  - The bubble “expands” and “accelerates” when the initial amplitude is below a critical value.
  - The bubble “compresses” and “freezes” when the initial amplitude is above a critical value.