Bubble Acceleration in the Ablative Rayleigh–Taylor Instability (RTI)

Vorticity is convected from the ablation front.

Vorticity accumulates in the bubble. The bubble accelerates.

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In the ablative RTI, the terminal bubble velocity is significantly larger than predicted by classical theory; ablation is nonlinearly destabilizing.

- The vorticity convected off the ablation front fills the rising bubble.
- The centrifugal force of the rotating flow in the vortex pushes the bubble to higher velocities.
- The terminal bubble velocity is approximately

\[
V_{\text{bubble}}^2 (\infty) \approx \sqrt{\frac{g}{3k} (1 - r_d)} + \frac{V_a^2}{r_d} \quad r_d = \frac{\rho_{\text{bubble}}}{\rho_{\text{dense}}}
\]
The single-mode ablative Rayleigh–Taylor instability is simulated for the NIF direct-drive point design using the code ART with a $210 \times 4000$ grid.

A weak vortex is used as initial perturbation.
Simulations show vorticity convection and accumulation.
A density pedestal forms inside the bubble and a new ablation front is established between the spikes.

$t = 2.8\text{ ns}$

![Graph showing temperature and density distributions with a focus on the density pedestal.](image)
The density in the bubble is the same as predicted by the linear theory* and a significant fraction of the dense target density.

\[ \rho_{\text{bubble}} \approx (0.1 \ kL_m)^{2/5} \rho_{\text{dense}} \]

\[ \rho_{\text{dense}} \approx 4 \ \text{g/cc} \]

\[ L_m \approx 0.18 \ \mu m \quad \lambda \approx 10 \ \mu m \]

\[ \rho_{\text{bubble}}^{\text{linear}} \approx 0.66 \ \text{g/cc} \]

\[ \rho_{\text{bubble}}^{\text{simulation}} \approx 0.65 \ \text{g/cc} \]

\[ L_m = \text{the minimum density-gradient scale length} \]

\[ k = \text{mode wave number} \]

A large vortex forms inside the bubble; the vortex generates a centrifugal force \( (F_c) \) pushing on the bubble tip.

\[ F_c \]

\[ \omega \text{ (ns}^{-1}) \]

\[ t = 2.8 \text{ ns} \]

\[ 40 \mu\text{m} \]

\[ 10 \mu\text{m} \]

\[ \Omega \approx \omega/2 \]

\[ R \approx \lambda/2 \]
The asymptotic bubble velocity is higher than the classical value due to the vorticity accumulated inside the bubble.

Centrifugal force and buoyancy force add up.

**Centrifugal force:**
\[ \rho_{\text{bubble}} R \Omega^2 = \rho_{\text{bubble}} \frac{R \omega^2}{4} \]

**Buoyancy force:**
\[ (\rho_{\text{dense}} - \rho_{\text{bubble}}) g \]

**Bubble-velocity enhancement**
\[ V_{\text{bubble}}^{\text{vort}} = \sqrt{\frac{g}{3k} (1 - r_d) + r_d \frac{\omega^2}{4k^2}} \]

\[ r_d = \frac{\rho_{\text{bubble}}}{\rho_{\text{dense}}} \]
After a first plateau starting when $\eta \approx 0.1\lambda$, the vorticity in the bubble increases; saturation occurs when $\omega \approx 2\,kV_a/r_d$

\[
\hat{\eta} = \frac{\eta}{0.1\lambda} = \frac{0.5(y_{\text{bubble}} - y_{\text{spike}})}{0.1\lambda}
\]

\[
\hat{\omega} = \frac{\omega}{kV_a/r_d}
\]
The bubble accelerates to final velocities well above the classical value and in agreement with the theory.

\[ \frac{V_{\text{bubble}}}{V_{\text{class 2-D}}_b} \]

\[
\begin{align*}
\sqrt{\frac{g}{3k}(1 - r_d)} + r_d \frac{\omega(t)^2}{4k^2} - \sqrt{\frac{g}{3k}(1 - r_d) + \frac{V_a^2}{r_d}}
\end{align*}
\]
Summary/Conclusions

In the ablative RTI, the terminal bubble velocity is significantly larger than predicted by classical theory; ablation is nonlinearly destabilizing.

- The vorticity convected off the ablation front fills the rising bubble.
- The centrifugal force of the rotating flow in the vortex pushes the bubble to higher velocities.
- The terminal bubble velocity is approximately

\[ V^{2-D}_{\text{bubble}}(\infty) \approx \sqrt{\frac{g}{3k}}(1 - r_d) + \frac{V_a^2}{r_d} \]

\[ r_d = \frac{\rho_{\text{bubble}}}{\rho_{\text{dense}}} \]

- Will the ablation-induced vorticity affect the multimode bubble-front growth \( a gt^2 \)?
The bubble velocity is defined as the penetration velocity inside the overdense target.