Magnetic-Field Generation and Its Effect on Ablative Rayleigh–Taylor Instability in Diffusive Ablation Fronts

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During the acceleration phase in direct-drive inertial confinement fusion (ICF), the Rayleigh–Taylor (RT) instability[1–3] grows at the ablation front, degrading the integrity of the imploding shell. During the development of the RT instability, magnetic (B) fields are generated due to the misalignment of gradients of density and pressure, known as the baroclinic or Biermann battery effect.[4] In the linear regime, the B field is coupled to the hydrodynamics mainly through the Righi–Leduc term. In essence, this term deflects the heat-flux lines, which in turn has a direct effect on the dynamics of these two instabilities (Fig. 1).

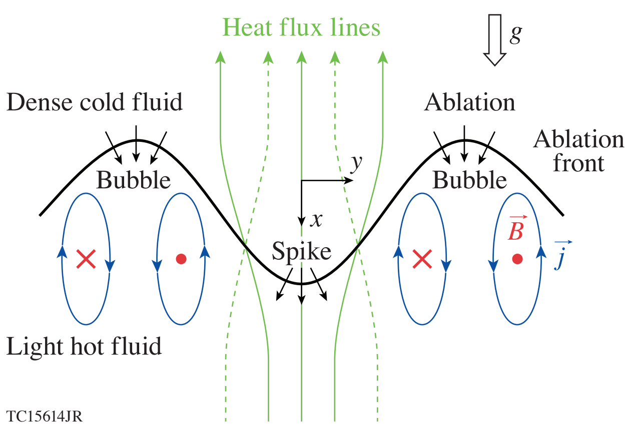

Figure 1
Sketch of the effect of the self-generated B fields on the RT instability. The magnetic field is generated by the Biermann battery effect and is perpendicular to the hydrodynamic motion. If the Righi–Leduc term causes the heat-flux lines to diverge from the spikes, then ablation is reduced and enhances the ablative RT instability (solid green lines with current $\vec{j}$ and B-field sense as depicted). If the heat-flux lines converge, ablation increases, which contributes to stabilizing the RT instability (dotted lines and current $\vec{j}$ and B-field sense opposite to the one depicted).

In this summary, the effects of self-generated magnetic fields on the ablative RT instability are investigated in the linear regime. The main governing parameters are the Froude number (Fr), which stands for the ratio between ablative convection and acceleration of the target, and the Mach number at the ablation front (Ma), assumed to be small (isobaricity). When normalized, the Righi–Leduc term is proportional to $c_R \mathrm{Ma}^2$, with c_R being a constant of order unity.

The results for the hydrodynamics coupled to the magnetic field are compared to the uncoupled case in Fig. 2. For small wave numbers, the dispersion relation is similar to the RT instability of immiscible fluids with Atwood number equal to unity, $\gamma \sqrt{kg}$. Ablation stabilization becomes effective for larger wave numbers until the RT instability is suppressed at a certain cutoff k_c. The cutoff wavelength decreases at larger Froude numbers.

The self-generated B field significantly modifies the dispersion relation even for small Mach numbers. Its effect becomes important when ablation stabilization takes place (near the maximum of the spectrum). It is not monotonic and can either enhance or stabilize the RT instability depending on the Froude number. For Fr = 1, the self-generated B field plays a destabilizing role and

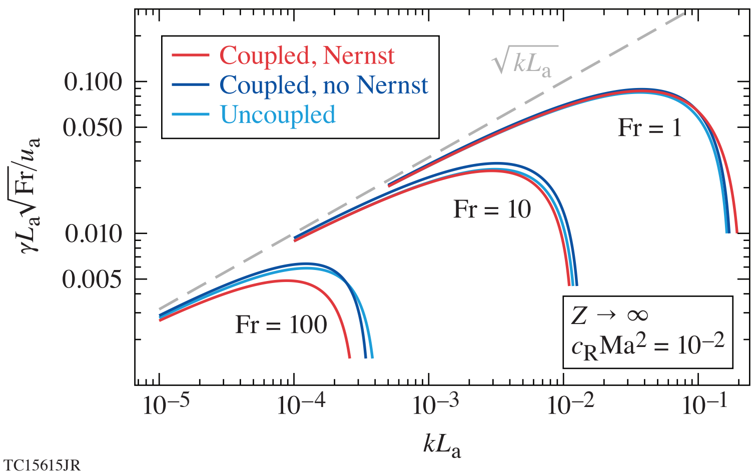

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Figure 2
Dispersion relation for different Froude numbers. Light blue curves: hydrodynamics uncoupled from induction; dark blue curves: hydrodynamics and induction coupled, $c_R Ma^2 = 10^{-2}$, without Nernst; red curves: hydrodynamics and induction coupled, $c_R Ma^2 = 10^{-2}$, with Nernst. The large atomic number $Z \to \infty$ is considered, and the magnetic Reynolds number is infinite.

enlarges the region of unstable modes. This effect is greatly amplified by the Nernst term, notably close to the cutoff. For Fr = 10, however, the stabilizing character of the B field switches when the Nernst term is considered, shortening the range of unstable modes *k*. This transition in the stabilizing character is completed in the case Fr = 100, where the self-generated B field shortens the range of unstable modes in cases both with and without Nernst. In the former case, this effect is especially pronounced since the cutoff is reduced by almost 40%.

An interesting feature observed is that, when the Nernst term is considered, the stabilizing character of the B field is maintained for a given Froude number. Therefore, a Fr threshold exists that depends exclusively on *Z* for which the stabilizing character of the B field switches. This is shown in Fig. 3, where the difference in growth ratio is shown for the most-unstable mode for every Froude number. The dependence of threshold Fr on *Z* is rather weak since we obtained Fr = 6, 5, and 3.4 for *Z* = 1, 4, and ∞, respectively. Although this figure is shown for Ma ~ 10^{-1}, the same threshold Fr is obtained when varying the Mach number.

The effect of magnetic diffusivity is shown in Table I, where the computed coefficient measures the similarity of the growth rate to the pure hydrodynamic case (close to 0) or to the perfectly conductive case (close to 1). It can be seen that for Fr = 1 the

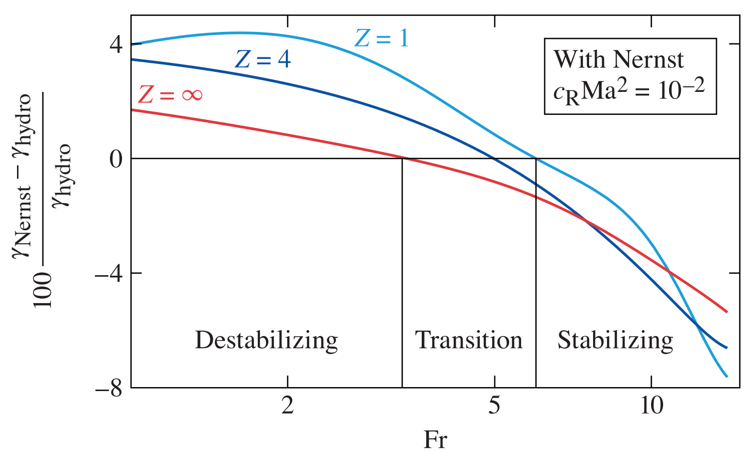

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Figure 3
Difference in growth rate (computed as a percentage) between the uncoupled (γ_{hydro}) and coupled with Nernst (γ_{Nernst}) cases. For every Froude number, the most-unstable mode, maximum γ_{hydro} is chosen.

system is very sensitive to the magnetic Reynolds number. Ablation fronts in ICF tend to be very diffusive, and Re_m is usually low. Therefore, the effect of the B field on perturbations whose wavelengths are comparable to the ablation front length scale is suppressed by resistivity. Contrary to this behavior, long-wavelength perturbations are insensitive to Re_m, as can be seen for the case Fr = 10. At this Froude number, unstable perturbations penetrate deep into the hot conductive plasma, and the effect of the B field (which, for these perturbations is stabilizing) is unaltered by diffusion.

Table I: Coefficient $\gamma - \gamma|_{\text{hydro}} / \gamma|_{\text{Nerst}} - \gamma_{\text{hydro}}|$. Case considered: $Z \rightarrow \infty$ and Ma = 0.1.

	$Re_m = 10^{-2}$	$Re_m = 10^{-1}$	$Re_m = 1$	$Re_m = 10$
Fr = 1, $k = 10^{-1}$	0.076	0.28	0.62	0.97
Fr = 10, $k = 5 \times 10^{-3}$	1.16	1.19	1.18	1.13

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