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Mitigation of Interfacial Instabilities in Magnetized Plasmas

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Interfacial instabilities play a crucial role in various plasma phenomena ranging from astrophysical environments to laboratory experiments. In particular, the Richtmyer-Meshkov instability (RMI), which occurs when a shock wave interacts with a corrugated contact discontinuity, significantly influences turbulent mixing in supernova explosions, inhomogeneous interstellar media, and fuel implosion processes in inertial confinement fusion (ICF) and magnetized liner inertial fusion (MagLIF). In astrophysical contexts, RMI-driven turbulence is considered a key factor in amplifying interstellar magnetic fields and generating interstellar turbulence.

Magnetic field application is a well-known mechanism to suppress RMI growth. When the ratio of linear growth velocity to the Alfvén speed (Alfvén Mach number) is less than unity, magnetic tension effectively mitigates instability growth ([1,2]). However, if the magnetic field direction is parallel to the interface and perpendicular to the surface wavevector, the Lorentz force has limited influence, making suppression challenging in fully three-dimensional geometries. While vorticity deposited at the interface immediately after shock passage drives RMI growth, residual vorticity in the bulk fluid acts to reduce interface perturbation growth, particularly under conditions of sufficiently strong shocks or high compression ratios.

Moreover, the smoothness of the density gradient at the interface, i.e., the transition layer thickness, has a significant impact on instability growth. If the scale length of the density gradient exceeds the wavelength of the interface modulation, the RMI growth is strongly suppressed. This suppression condition can be interpreted as the shock transit time through the transition layer exceeding the sound crossing time of the modulation wavelength, a universal feature observed across a wide range of shock-interface interactions ([3]).

In this study, we systematically investigate the suppression of RMI in laser-driven magnetized plasmas, focusing on the effects of magnetic field application, density gradient scale length, and equation of state (EOS) dependence, primarily through high-resolution MHD simulations. We confirm that magnetic tension near the interface and local magnetic field amplification due to fluid motion suppress instability growth. Increasing the density gradient scale length complements magnetic suppression, further reducing growth rates. Additionally, EOS dependence reveals that larger compression ratios tend to suppress the instability growth.

These findings suggest that RMI mitigation can be achieved not only by applying magnetic fields but also through controlling density gradient structures and appropriate EOS settings. This has significant implications for improving fuel compression uniformity and energy coupling efficiency in ICF and MagLIF. Furthermore, the results contribute to better understanding of the growth of mixing layers behind supernova shocks and enhance the modeling accuracy of material and magnetic field transport and turbulent mixing in astrophysical plasma environments.

Based on these simulation results, magnetic field amplification near the interface has been observed experimentally in laser-driven magnetized plasma, and the potential for RMI suppression is currently under discussion ([4]). Future work includes experimental campaigns to further examine the influence of magnetic fields, density gradient scale lengths, and EOS, as well as extensions to kinetic and multi-fluid models and comparisons with high-power laser experiments to deepen the understanding of interfacial instability mitigation and its applications to space plasma physics.

References

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