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Katherine E. Weimer Award Talk: Instabilities and magnetic reconnection in space plasma and the physics of laser-plasma interactions

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First-principles, kinetic simulations are invaluable for understanding nonlinear plasma physics in a diverse range of complex systems ranging from magnetic reconnection in space and astrophysics to laser plasma interactions in both long- and short-pulse regimes. Employing the state-of-the-art particle-in-cell (PIC) simulation code VPIC, with and without Coulomb collisions, to conduct three-dimensional simulations at unprecedented scales on the world's most powerful supercomputers, we address three outstanding problems. First, magnetic reconnection in electron-positron plasmas involves a complex interaction of tearing and kink modes. The diffusion region tends to elongate in the outflow direction and become unstable to secondary kinking and formation of "plasmoid-rope" structures. These secondary instabilities determine the time-dependent nature of reconnection. Second, backward stimulated Raman scattering (SRS) in a laser speckle involves two intricate electron plasma wave behaviors, wavefront bending and self-focusing, caused by trapped electron nonlinear frequency shift and amplitude-dependent damping. Self-focusing exhibits loss of angular coherence by formation of a filament necklace and leads to a reduction of electron plasma wave coherence. The latter reduces source coherence for backscattered light and increases damping, which fundamentally limits how much backscatter can occur from a laser speckle. Finally, we show how GeV ion beams can be generated via the interaction of ultra-intense short-pulse lasers with solid-density targets. This "Break-out Afterburner" mechanism promises to enable development of ultra-compact GeV ion beam sources. (Collaborators: B. J. Albright, B. Bergen, K. J. Bowers, W. Daughton, J. C. Fernandez. K. A. Flippo, B. M. Hegelich, J. Kline, T. Kwan, D. Montgomery, H. Rose, and D. Winske)