Critical currents across the UFG-BCS Crossover in ring fermionic superfluids

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Understanding superfluid transport in ring geometries is central to a wide range of systems, from superconducting circuits and quantum technologies to neutron star interiors. In these contexts, persistent currents provide a direct probe of macroscopic phase coherence, and identifying the mechanisms that limit their stability-namely, the critical currents-is of fundamental importance [1]. Ultracold atomic gases offer a highly controllable platform to investigate superfluid transport, particularly in toroidal traps where persistent currents emerge with quantized circulation set by the winding number. Here, using the time-dependent superfluid local density approximation (TDSLDA) [2], we demonstrate that even in the absence of external impurities [3], two distinct critical winding-number (current) thresholds arise. The first corresponds to pair breaking, leading to a mixed superfluid–normal state, while the second marks the complete suppression of superfluid order, leaving only a normal fluid. The latter represents the analogue of the depairing current in superconductors and connects to the physics of gapless superfluids relevant for neutron star matter. We further show how these two critical currents depend on interaction strength across the crossover from the strongly interacting unitary Fermi gas (UFG) to the weak-coupling BCS regime, with the BCS limit exhibiting the lowest critical values. The intermediate mixed phase is dynamically unstable and evolves into an array of quantized vortices, whose number depends on both the interaction regime and the initially imprinted winding number. These results provide a unified picture of current-induced instabilities in fermionic superfluids and clarify the microscopic origin of critical currents across interaction regimes.

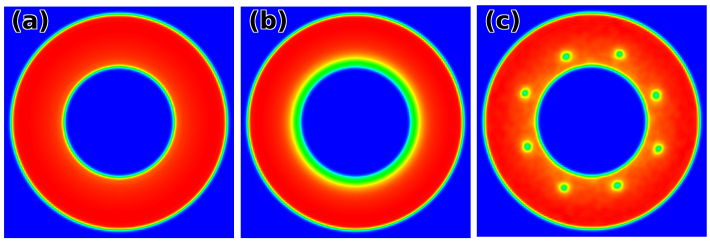

Figure 1: Order parameter amplitude in the strongly interacting unitary Fermi gas limit. (a) Static, homogeneous order parameter amplitude for winding number (persistent current) below the pair-breaking critical current, showing a stable uniform superfluid state. (b) Static order parameter amplitude once the winding number exceeds the pair-breaking critical current, showing the onset of spatial inhomogeneity. (c) Time evolution of the order parameter amplitude for the same parameters as in (b), showing the system relaxing from the unstable mixed superfluid–normal configuration into an array of quantized vortices.

[1] K. Xhani, A. Barresi, M. Tylutki, G. Wlazłowski, and P. Magierski, Phys. Rev. Res. **7**, 013225 (2025).
[2] G. Wlazłowski, P. Magierski, M. M. Forbes, and A. Bulgac, arXiv:2602.08982 (2026)
[3] B. Tüzemen, A. Barresi, G. Wlazłowski, P. Magierski, and K. Xhani, Phys. Rev. Res. **8**, 023204 (2026).