Toward Engineering Superfluid Dynamics: On-Demand Stable Vortex Rings in BECs

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Understanding vortex dynamics in three-dimensional superfluid systems emerges as a key challenge. While vortex generation and evolution are well studied in two dimensions, the three-dimensional case remains only partially explored. Our work [1] aims to numerically investigate three-dimensional vortex ring dynamics and to develop experimentally reproducible methods for generating, manipulating and characterising vortex rings in harmonically trapped cylindrical Bose–Einstein condensates.

We exploit moving repulsive laser-sheet barriers that locally constrict the superflow to achieve controlled vortex ring nucleation and propagation in the condensate. We then investigate the rings dynamics and assess how it is affected by the barrier parameters. Given the symmetry of the system, we propose and validate the use of cylindrical coordinates to simulate the condensate dynamics: this framework effectively reduces the three-dimensional problem to a two-dimensional problem, leading to significant advantages in computational time while preserving an accurate physical description.

We carry out an energetic analysis throughout the vortex ring generation process and during its propagation in the system to gain insight into the microscopic physics underlying the nucleation mechanism. We also present a preliminary analysis of vortex ring nucleation and dynamics when employing attractive laser-sheet barriers. Moreover, by exploiting additional optical local potentials that break the cylindrical symmetry, we trigger destabilisation of previously formed vortex rings.

[1] G. Iori, K. Xhani, W.J. Kwon, D.E. Galli, L. Galantucci, Phys. Rev. Research 8, L022043 (2026)