

Quantum vortex dynamics and reconnections in trapped Bose-Einstein Condensates

L. Galantucci¹, C. F. Barenghi¹, S. Serafini², F. Dalfovo², G. Lamporesi², G. Ferrari²

¹ *Joint Quantum Centre Durham-Newcastle and School of Mathematics and Statistics,
Newcastle University, United Kingdom*

² *INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, Italy*

Summary

Numerical investigations of the trajectory of two vortices in three-dimensional elongated trapped Bose Einstein Condensates (BECs) are performed in the zero temperature limit. In particular, we observe unperturbed precession of the vortices around the centre of the condensate, bouncing dynamics and double reconnection events. A central role is played by features peculiar to trapped BECs namely density gradients and the influence of images. The numerical results are compared to very recent experimental observations of vortex reconnections.

Vortex dynamics and reconnections play a fundamental role in quantum turbulent flows which can be loosely defined as the most general dynamical motion of tangles of thin quantized vortex lines in quantum fluids [1]. In particular, quantum vortex reconnections are, to a large extent, responsible for energy and helicity transfers between different scales [2, 3], and the change of topology induced by reconnecting events plays a central role in the balance of the total helicity of the flow [3, 4]. This last topic, i.e., whether helicity is conserved in superfluid systems exhibiting reconnection events, is of great interest due to the fact that although dissipative processes are absent in superfluids in the zero temperature limit as in ideal (Euler) fluids, reconnection events may take place, changing, hence, the topology of the flow. Additional motivation arises from the growing interest in the topology of plasmas, liquid crystals, optical and biological structures. Several recent numerical studies have examined quantum vortex reconnections in homogeneous superfluids [3, 5, 6], as, due to their discrete nature, quantum vortices are easier identified and tracked than classical vortices. Experimentally, direct visualization of the dynamics of vortex lines in an elongated BEC has been recently investigated [7] (see Fig. 1 (left)), suggesting the possibility of *double reconnections*.

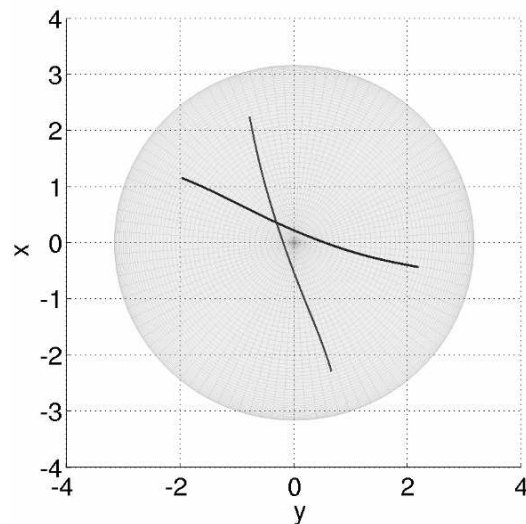
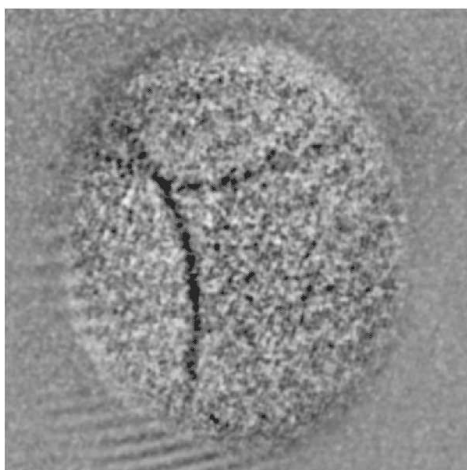


Fig. 1: (left): Experimental observation in a trapped BEC of two vortices produced via the Kibble–Zurek mechanism [8, 7]; (right): snapshot of the results achieved via the numerical simulations performed in the present study.

In this work we numerically solve the non-homogeneous Gross-Pitaevskii Equation for the condensate wavefunction inside an anisotropic harmonic trapping potential. The core of the vortices is tracked employing an algorithm based on the pseudo vorticity field [9] which allows to finely resolve the reconnection dynamics (Fig. 1 (right) shows, for instance, an instantaneous snapshot of the condensate where two vortices have been trailed). We observe different two-vortex interaction regimes depending on the orientation and curvature of the two vortices, their orbits and their initial distance: unperturbed precession around the centre of the condensate; *bounce dynamics*, where the vortices get closer before moving apart without reconnecting; double reconnection events. We reckon that the key ingredients driving the two-vortex dynamics are the anti-parallel preferred alignment of the two vortices due to energy conservation constraints, the impact of density gradients and the role of the images of the vortices with respect to the condensate's boundaries. The last two factors listed are peculiar to non-homogeneous trapped BECs, determining hence different reconnection dynamics with respect to homogeneous BECs [10].

References

- [1] C. F. Barenghi, L. Skrbek, and K. P. Sreenivasan. Introduction to quantum turbulence. *Proc. Natl. Acad. Sci. USA*, 111(1):4647–4652, 2014.
- [2] C. F. Barenghi, R. J. Donnelly, and Vinen W. F. *Quantized vortex dynamics and superfluid turbulence*. Springer Science & Business Media, 2001.
- [3] M. W. Scheeler, D. Kleckner, D. Proment, G. L. Kindlmann, and W. T. M. Irvine. Helicity conservation by flow across scales in reconnecting vortex links and knots. *Proceedings of the National Academy of Sciences*, 111:15350, 2014.
- [4] C. E. Laing, R. L. Ricca, and L. S. De Witt. Conservation of writhe helicity under anti-parallel reconnection. *Scientific reports*, 5, 2015.
- [5] D. Kleckner, L. H. Kauffman, and W. T. M. Irvine. How superfluid vortex knots untie. *arXiv preprint arXiv:1507.07579*, 2015.
- [6] S. Zuccher and R. L Ricca. Helicity conservation under quantum reconnection of vortex rings. *Physical Review E*, 92(6):061001, 2015.
- [7] S. Serafini, M. Barbiero, M. Debortoli, S. Donadello, F. Larcher, F. Dalfovo, G. Lamporesi, and G. Ferrari. Dynamics and interaction of vortex lines in an elongated bose-einstein condensate. *Physical Review letters*, 115(17):170402, 2015.
- [8] G. Lamporesi, S. Donadello, S. Serafini, F. Dalfovo, and G. Ferrari. Spontaneous creation of kibble-zurek solitons in a bose-einstein condensate. *Nature Physics*, 9(10):656–660, 2013.
- [9] C. Rorai, J. Skipper, R. M. Kerr, and K. R. Sreenivasan. Approach and separation of quantum vortices with balanced cores. *arXiv preprint arXiv:1410.1259*, 2014.
- [10] S. Zuccher, M. Caliari, A. W. Baggaley, and C. F. Barenghi. Quantum vortex reconnections. *Phys. Fluids*, 24:125108, 2012.