Probing Nonlinear Turbulent Dynamics with a Fully-controllable Platform for Paraxial Fluids of Light

Nuno A. Silva, Tiago D. Ferreira

INESC TEC, Centre for Applied Photonics, Rua do Campo Alegre 687, 4169-007 Porto, Portugal

Abstract. Paraxial fluids of light offer a unique platform for investigating nonlinear dynamics resulting from the interplay of wave and particle-like dynamics experienced by a laser beam as it propagates inside a nonlinear optical media. Besides, the **mathematical similarity** between these systems and two-dimensional Bose-Einstein condensates enables their use as **analog quantum simulators**, facilitating the study of a wide range of nonlinear phenomena, from quantum turbulence[1] to topological states of matter. Nonetheless, traditional experimental configurations are still limited by the finite size of the nonlinear medium, which strongly constrains the effective propagation duration and limits observations to the final output state.

Towards a fully-controllable platform

In the paraxial regime, the 2D profile of a laser beam propagating inside a nonlinear photorefractive crystal follows the Nonlinear Schrödinger Equation[3]

$$i\frac{\partial E_f}{\partial z}+\frac{1}{2}\nabla_\perp^2 E_f-\left|E_f\right|^2 E_f+i\frac{\alpha}{2}E_f=0,$$

where α is the crystal absorption and z an effective axial propagation distance. Physical emulation of 2D quantum fluid is thus possible **as long as we have full-control of the input state**. However, we **do not have access to intermediate states** and maximum **effective analogue time is limited by the crystal length** ($\propto L_z$), which bounds the range of observable dynamics.

The Digital Feedback Loop. Full control of the input state and reinjection towards unlimited propagation distances

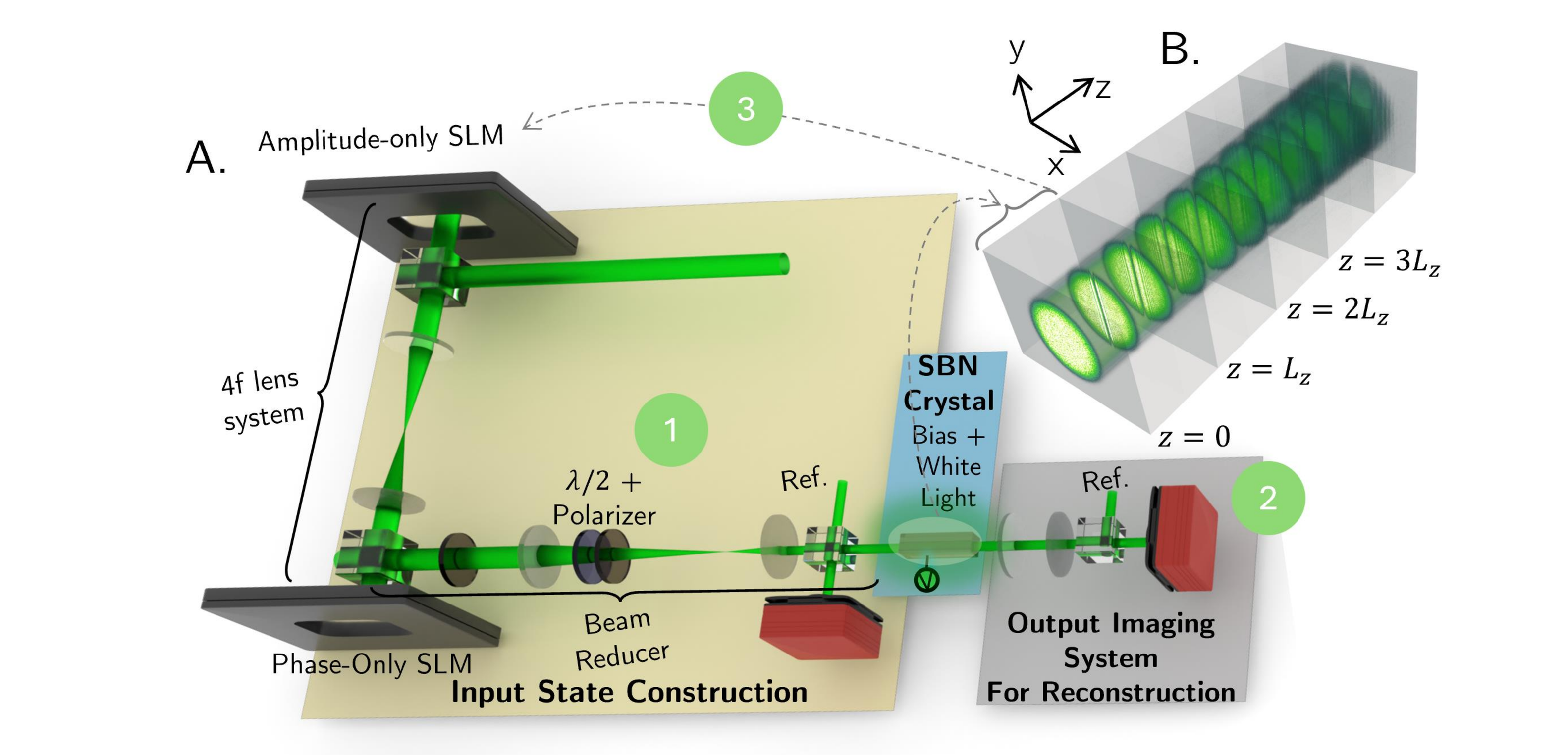


Figure 1. Illustration of the feedback loop

A - Simplified experimental setup [4]. B - Three-dimensional representation of the state evolution.

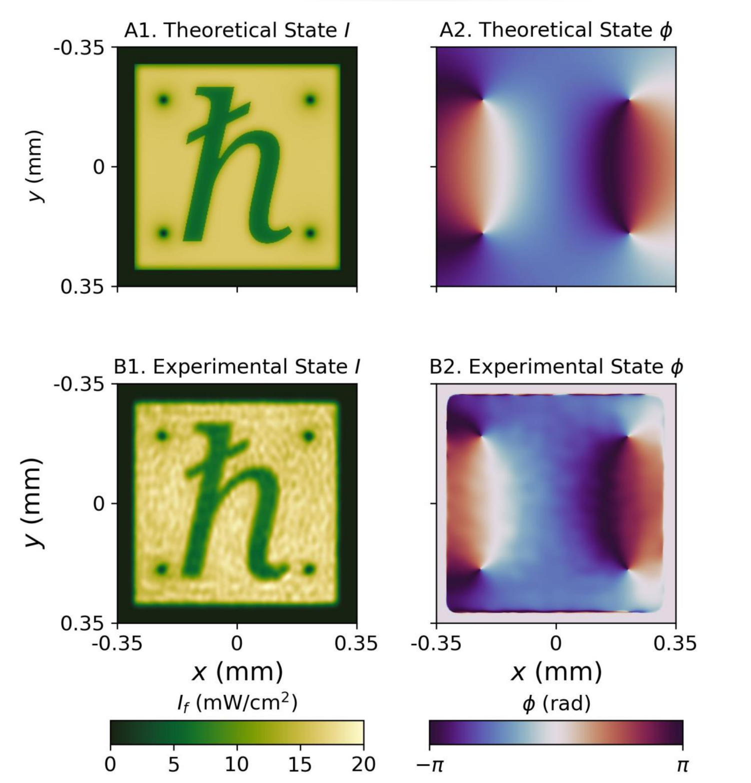


Figure 2. Generation of arbitrary states

To access the quality of the created states we use the overlap integral

$$\gamma=\frac{1}{\sqrt{P_{in}P_{in,exp}}}\int E_{in}^{*}E_{in,exp}\,dxdy,$$

defining a fidelity metric as $\mathcal{F}=|\gamma|^2$. Here the experimental state has $\mathcal{F}\approx 0.98$.

Experimental Results and Quantum-like Turbulence

Case 1. Snake Instability and vortex-pair formation, Dispersive Shoch-Waves [4]

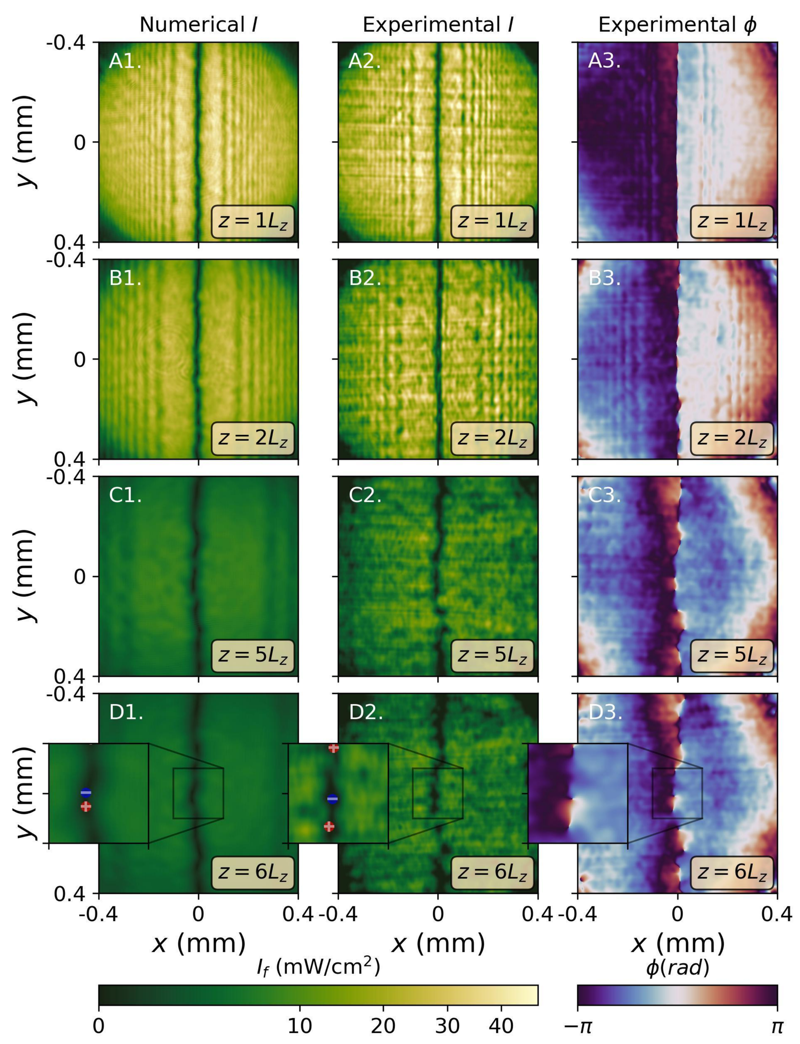
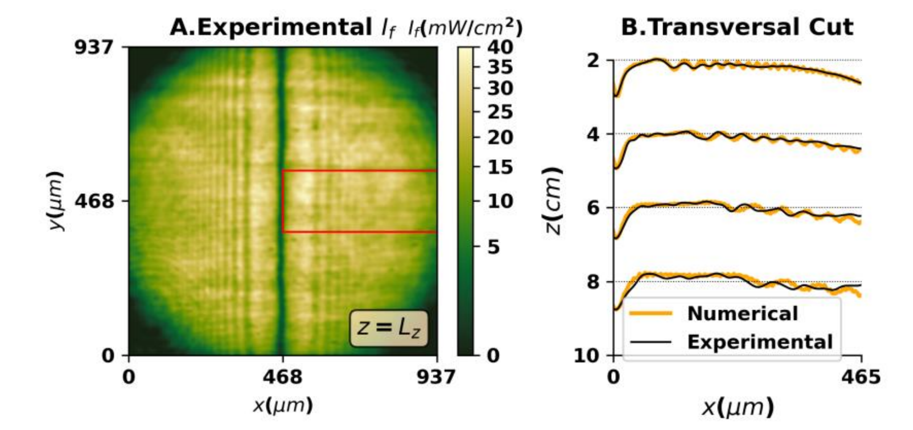


Figure 3 - Experimental results showing the decay of a dark soliton for 6 passes through the crystal. Initially, the formation of shock waves is observed, followed by their expansion. The dark soliton then undergoes the characteristic snake instability, eventually decaying into vortex pairs.

Figure 4 – Dispersive shock-waves are also created, travelling close to the speed of sound with an excellent match between numerical and experimental results.



Case 2. Vortex Lattices [4]

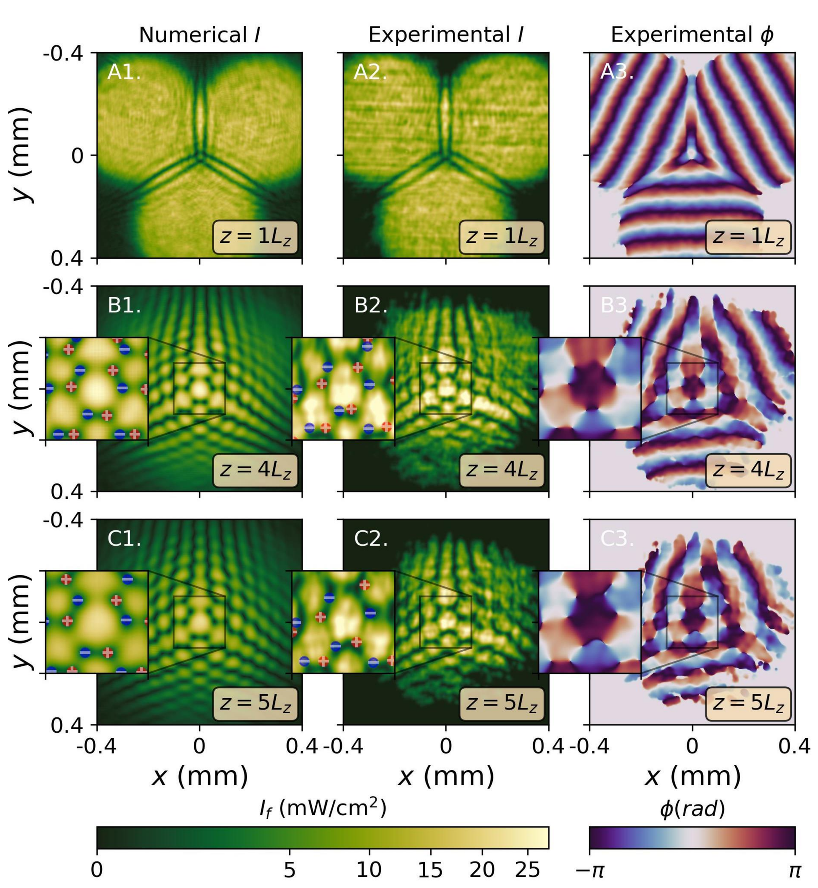
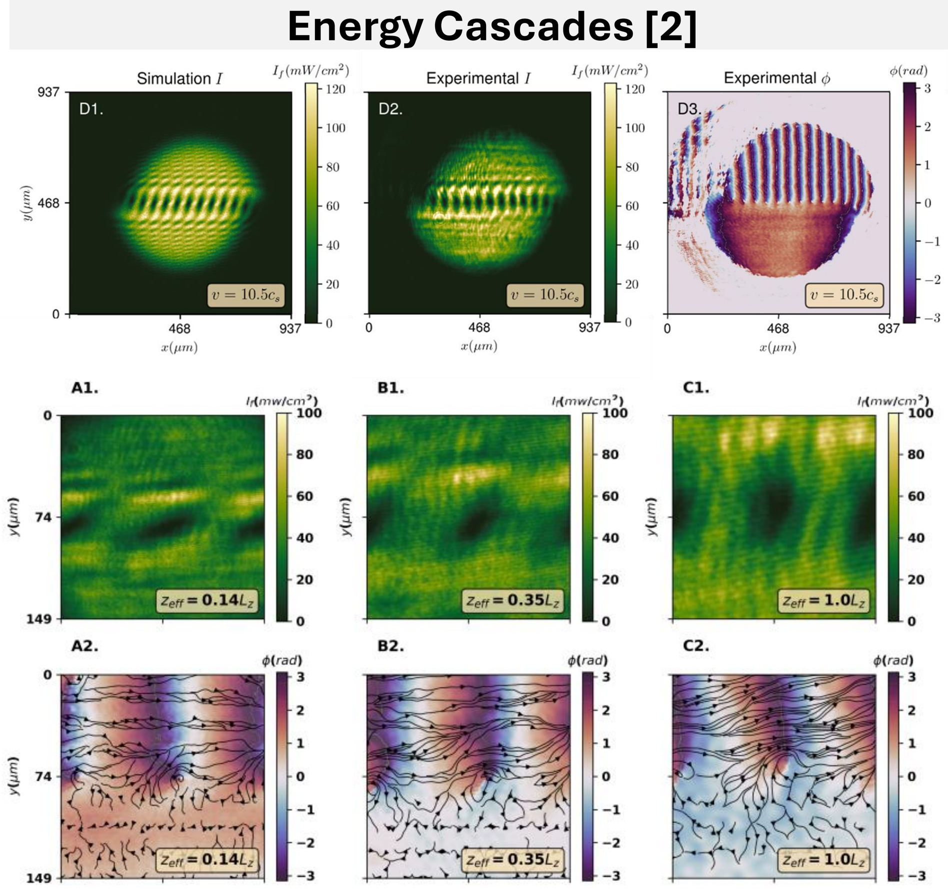


Figure 5. Collision between three flat-top states. The interaction leads to the formation of a polygonal structure composed of multiple vortices in the center.

Case 3. Kelvin-Helmholtz instability and Energy Cascades [2]



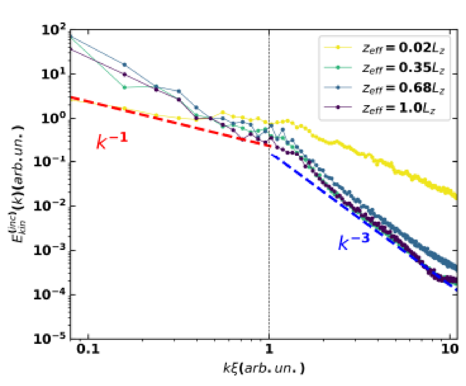
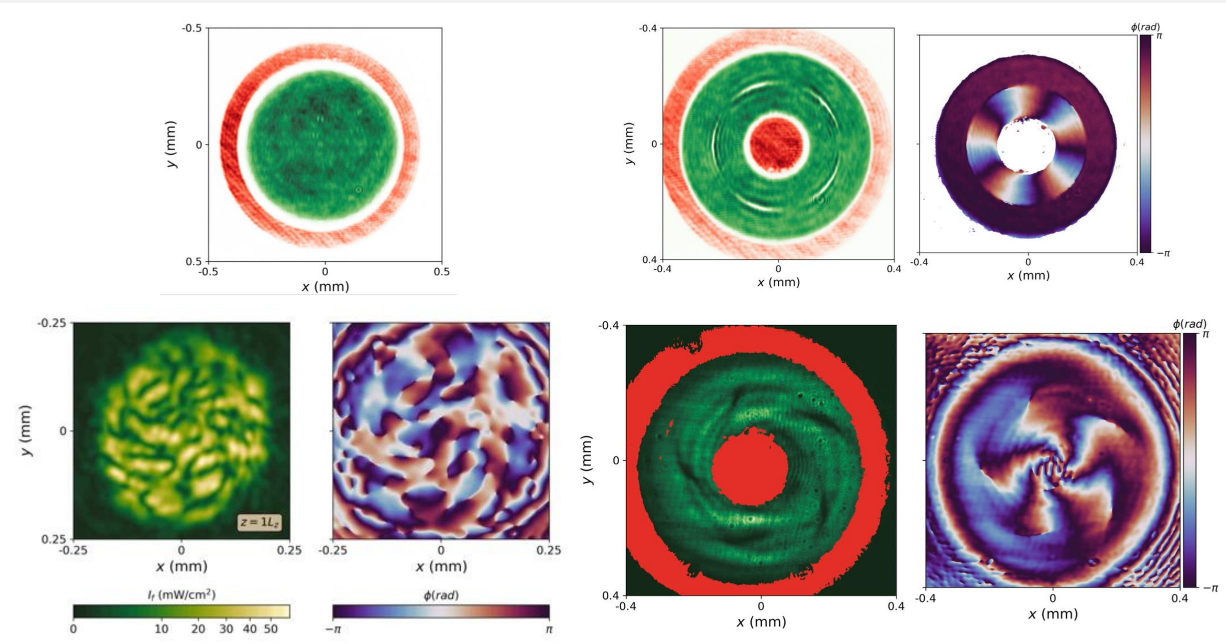


Figure 5. Kelvin-Helmholtz instability and incompressible kinetic energy featuring a characteristic power-law k^{-3} decay associated to localized 2D quantum-like vortex turbulence[1,3].

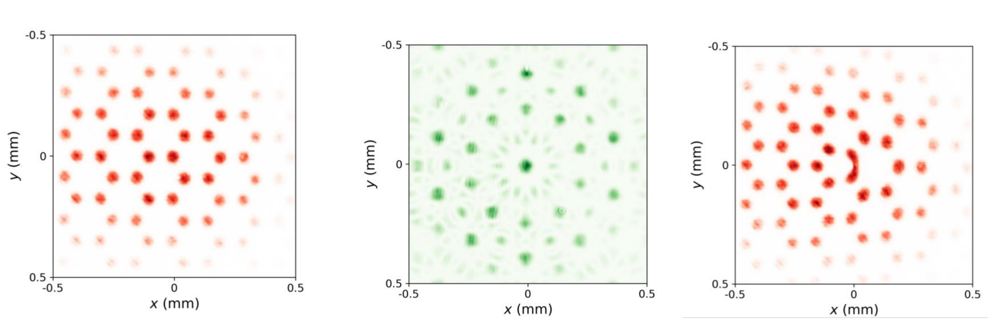
Key Takeaways and Perspectives

1. Featuring a digital feedback loop, our fully-controllable paraxial fluids of light setup is a versatile and high-throughput quantum simulation platform.
2. Enables exploration of complex phenomena in particular 2D quantum turbulence.
3. Future work includes the exploration of non-trivial topologies using optically-induced lattices, vortex dynamics in trapped systems, and topological properties of quantum fluids in Moiré Lattices.

Perspective 1. Cross-Kerr Trapping Potentials and Non-trivial Geometries



Perspective 2. Topological Quantum Fluids



References

[1] T. D. Ferreira, V. Rocha, D. Silva, A. Guerreiro, and N. A. Silva, New J. Phy 24, 113050 (2022).

[2] T. D. Ferreira, J. Garwo la, and N. A. Silva, Physical Review A 109, 043704 (2024).

[3] I. Carusotto, Proceedings of the Royal Society A 470, 20140320 (2014).

[4] Ferreira, Tiago D., Ariel Guerreiro, and Nuno A. Silva. "Digital Feedback Loop in Paraxial Fluids of Light: A Gate to New Phenomena in Analog Physical Simulations." Physical Review Letters 133.24 (2024): 243802.

Acknowledgments. This work is co-financed by Component 5 - Capitalization and Business Innovation, integrated in the Resilience Dimension of the Recovery and Resilience Plan within the scope of the Recovery and Resilience Mechanism (MRR) of the European Union (EU), framed in the Next Generation EU, for the period 2021 - 2026, within project HfPT, with reference 41, and by national funds through FCT – Fundação para a Ciência e a Tecnologia, I.P., under the support UID/50014/2023 (https://doi.org/10.54499/UID/50014/2023). Nuno A. Silva acknowledges the support of FCT under the grant 2022.08078.CEECIND/CP1740/CT0002 (https://doi.org/10.54499/2022.08078.CEECIND/CP1740/CT0002).

Our team