Lagrangian dynamics in electromagnetically driven turbulence

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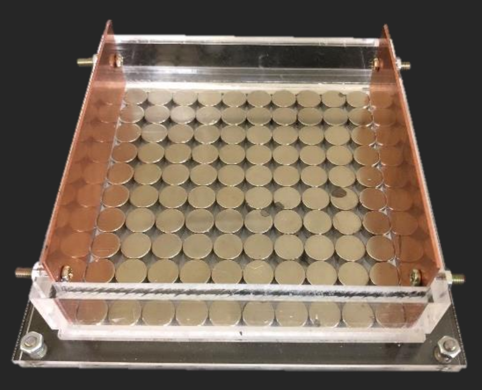
What is turbulence

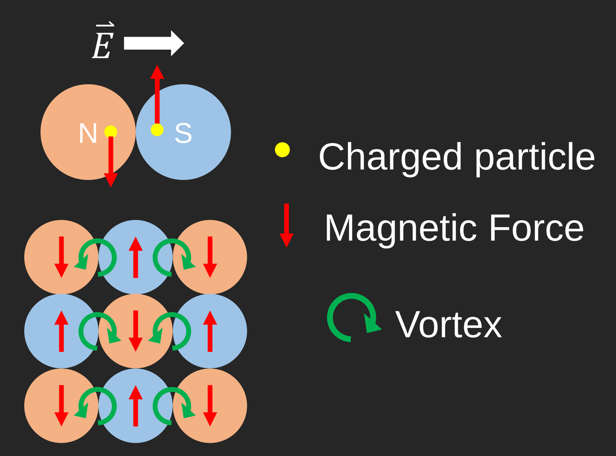
Turbulence ubiquitously occurs in our daily life, such as water, smoke and atmosphere, which contains multiscale vortices. Particles in turbulence exhibit chaotic motion.

Goal

Analyze the transition process from the single-scale state to turbulent state, through the Eulerian and Lagrangian points of view.

Setup

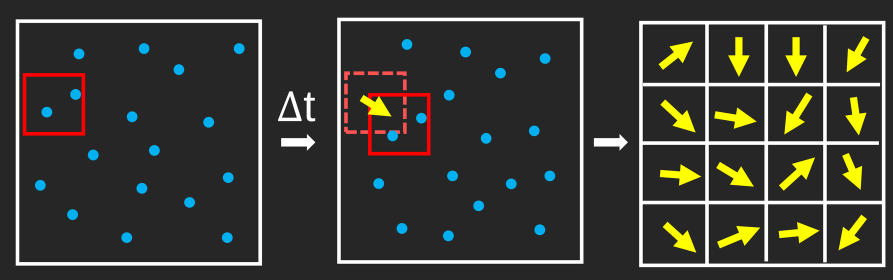




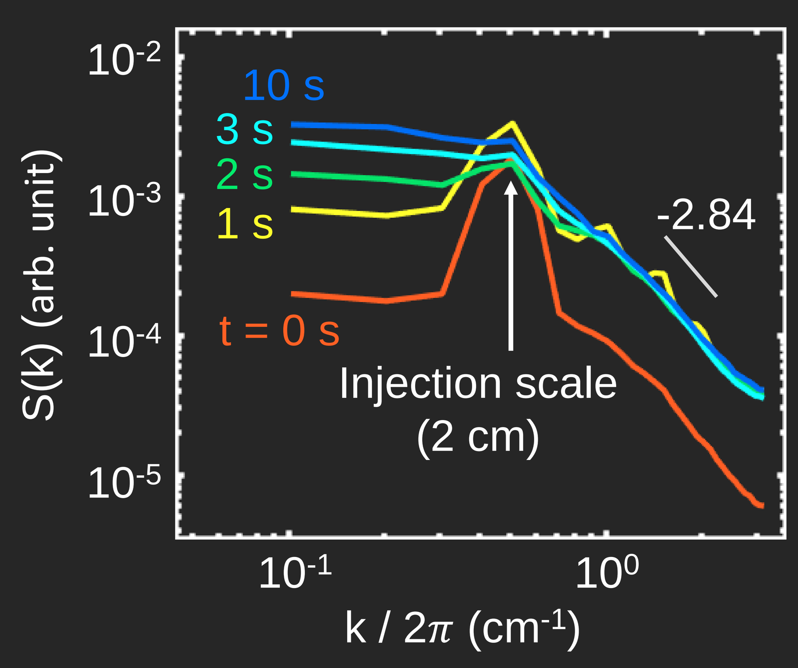
$CuSO_4$ is dissociated in water and driven by electromagnetic field through two electrodes and alternating arranging magnet array. Charged particles in the solution exhibit rotation motion due to the Lorentz force.

PIV

Particle Image Velocimetry (PIV) method compares the position of tracers in two pictures and extracts the velocity from displacement within time interval Δt.

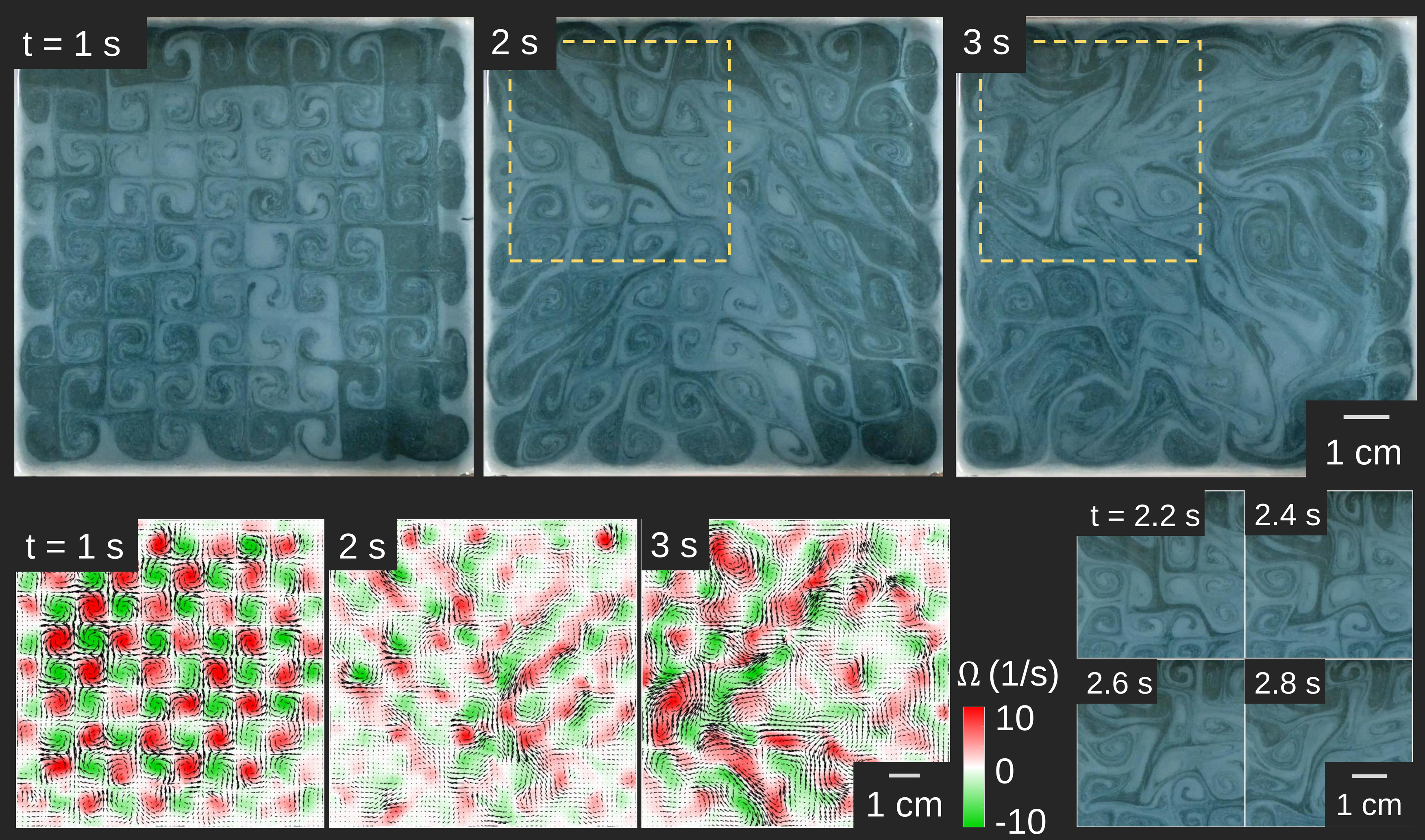


Energy spectrum



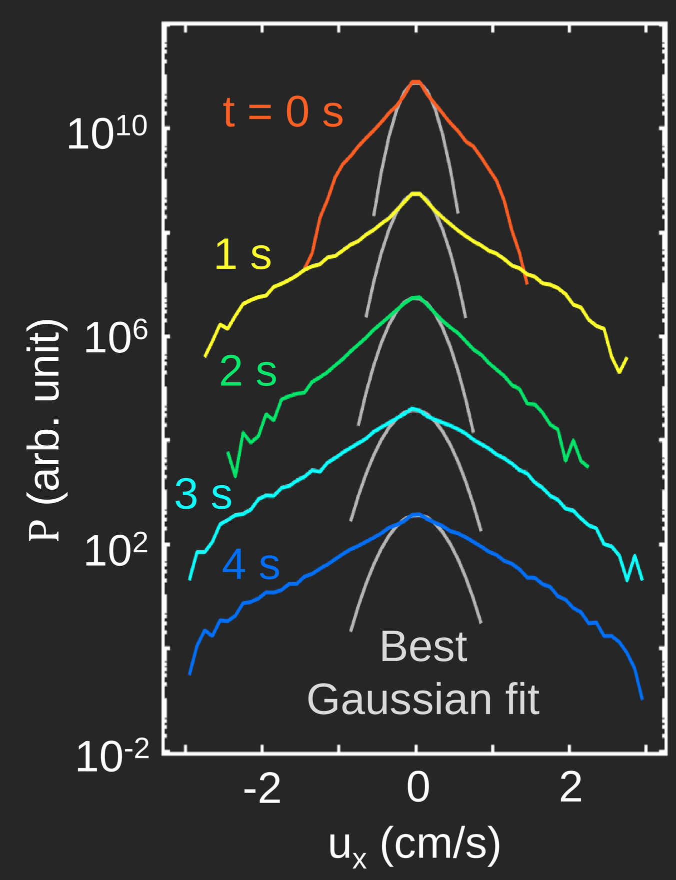
At t = 0 s, the spatial spectrum shows the peak at 2 cm, indicating the injection scale of the system. With increasing time, the spectra transit to power-law decay. It means the vortices are generated over a wide range of scales in the turbulent state.

Transition to turbulence



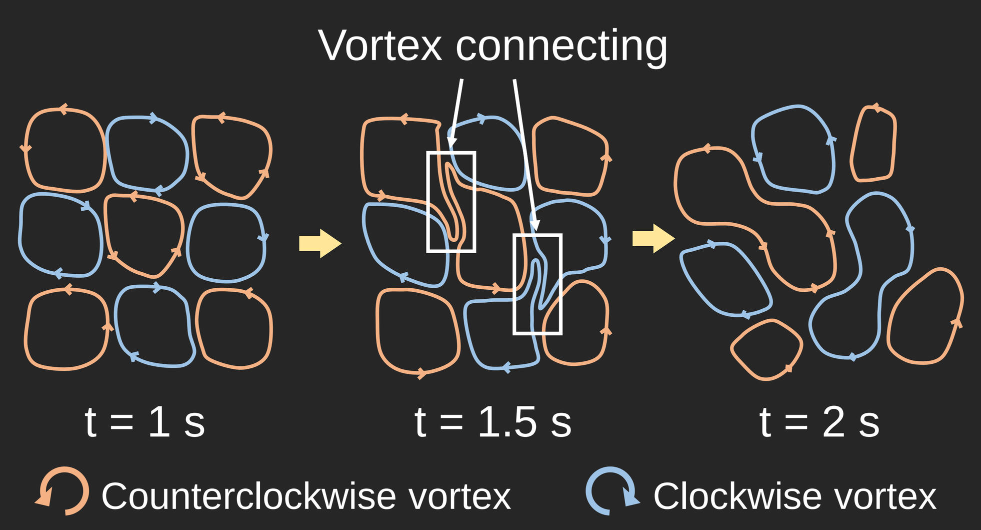
The system is turned on at t = 0 s. At t = 1 s, the system forms square lattice, in which the velocity and vorticity of vortices are similar. At t = 2 s, the vortices start to merge with decreased velocity and vorticity, which is the transition process between single-scale and turbulent states. At t = 3 s, the multiscale vortices are generated.

Velocity histogram



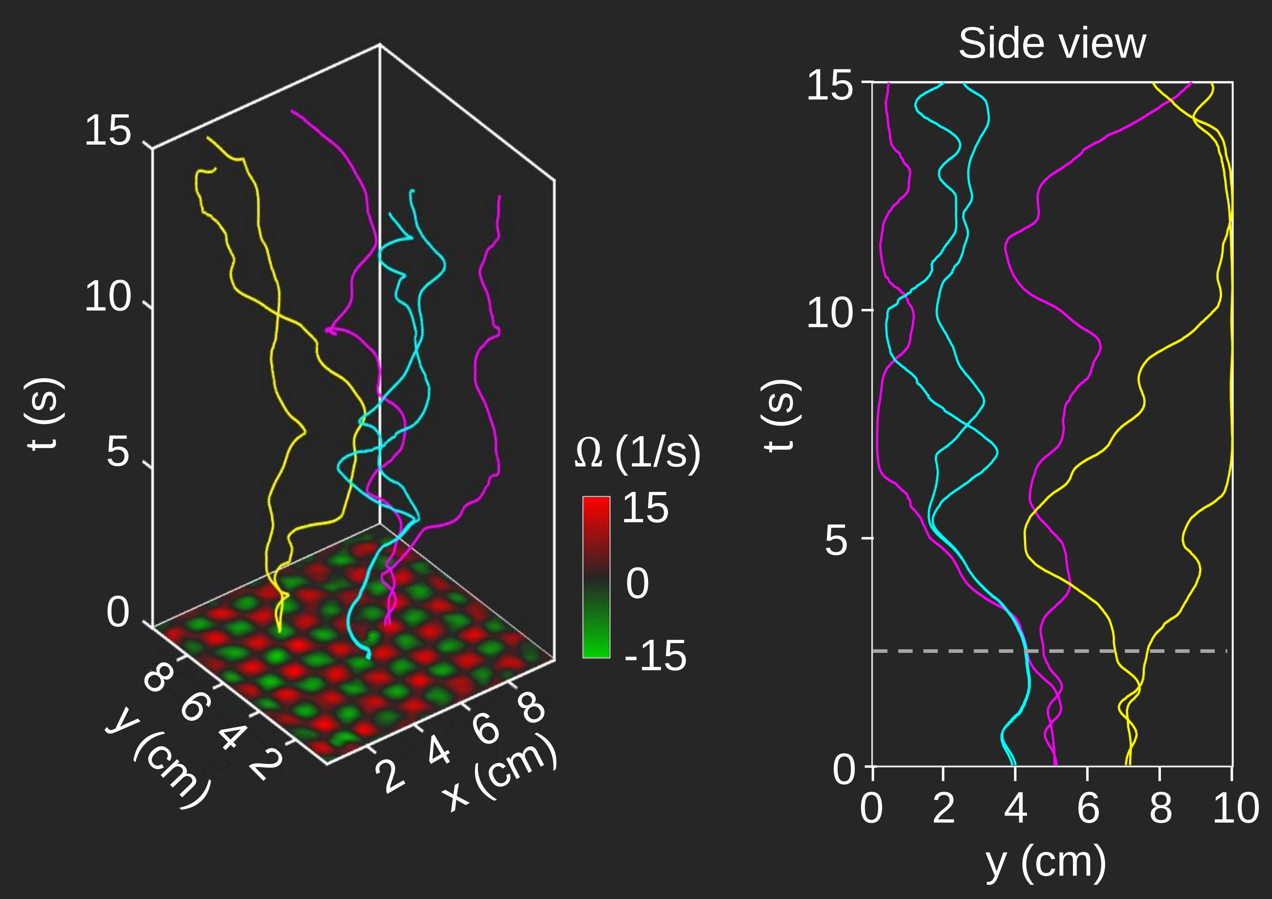
The non-Gaussian tails are formed of as time increases due to the increased velocity. However, the histogram becomes narrow at t = 2 s which is caused by the vortices merging.

Merging process



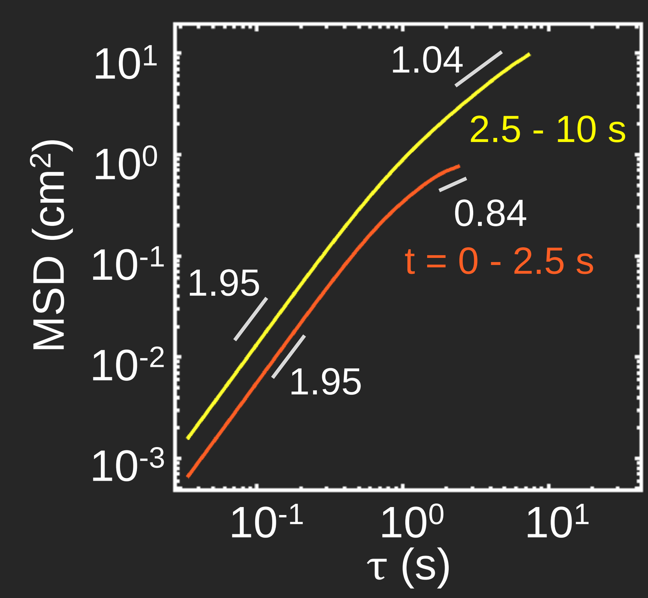
Vortices with same rotational direction merge together because the velocities between vortices are canceled out.

Particle trajectory



The particles are trapped in the same vortex at the single-scale state. When the system becomes turbulence, the particles will travel to different vortices. Gray dashed lines indicates the transition time to the turbulent state.

MSD

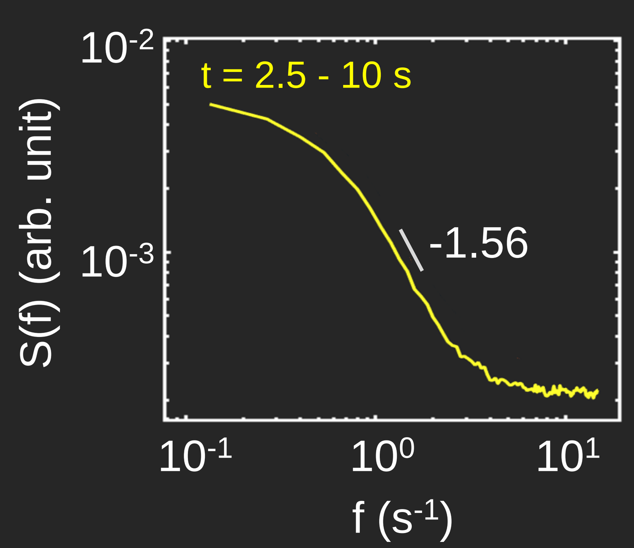


$$\text{MSD} = \langle |\vec{r}(t+\tau) - \vec{r}(t)|^2 \rangle$$

Position at time t + τ   Position at time t

MSD slope > 1 meaning that particles tend to maintain moving direction. MSD slope < 1 indicating that particles are trapped.

Lagrangian velocity spectrum



Lagrangian velocity spectra of particle trajectories follow power-law decay, which represent the turbulent like particle motion.

Conclusion

- The system becomes turbulent through the merging of vortices.
- The power spectra with power-law decay at turbulent state shows that energy diffuses from the injection scale to different scales.
- The particles are trapped before the transition and spread out in the turbulent state with power-law like behavior.

Reference

[1] H. Xia et al., Nat. Phys. **7**, 321 (2011)
[2] H. Xia et al., Nat. Commun. **4**, 3013 (2013)
[3] H. Xia et al., Phys. Rev. Lett. **101**, 194504 (2008)