Pipe flow and ultra-long fiber laser

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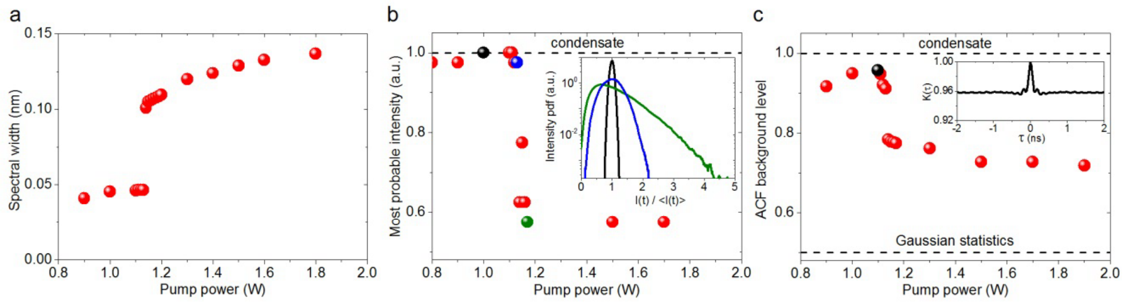
Studying transition to turbulence from a linearly stable laminar state is conceptually and technically challenging (because of its probabilistic nature) and immensely important (enough to say that all pipe and channel flows are of that type [1-2]. The main challenge is to describe: i) universal features of the transition, which requires going beyond fluid mechanics, ii) the classes of perturbations able to destroy the laminar state, and iii) the turbulence that appears after the transition. Here we identify arguably the simplest system where such questions can be addressed experimentally and by direct modeling. The system is a long fiber laser which we are able to operate in both laminar and turbulent regimes.

Nature does not allow us to increase the size of a system without eventually loosing coherence. For example, even though a coherent laminar flow through a pipe is always linearly stable, increasing the pipe diameter or the flow rate eventually makes the flow turbulent, vastly increasing drag1. In fibers with normal dispersion, a coherent monochromatic wave or spectrally narrow packet are stable with respect to the modulation instability [3,4]. As we show, increasing the cavity length or the power of a fiber laser, we similarly pass from a coherent laminar state to a turbulent one. Having a laminar-turbulent transition in an optical system allows us to ascend the higher level of generality and to address the most fundamental questions of non-equilibrium studies, those of universality: Is the transition to turbulence from a linearly stable coherent state always of probabilistic nature? Is the transition due to an increase of temporal or spatial complexity?

Going from general to specific, one needs to identify the building blocks of turbulence onset as a way to understand and control turbulence. For a linearly stable system, it is a formidable task [4,5], since we lack the guide of a linear instability analysis, which shows what destroys the laminar state and helps to identify the patterns that appear instead [6,7]. One asks the following questions: What are the most dangerous perturbations that one needs to control to keep the system in a coherent laminar state? In a state of turbulence, what are the structures in the phase space that keep our system from returning to a simple (laminar) attractor?

Contrary to the popular perception of laser as a boringly coherent system, operational regimes in many fibre lasers correspond to very irregular light dynamics. Fiber laser normally generates so many modes (up to 106), so that fluctuations in their amplitudes and phases result in stochastic radiation, which calls for a description in terms of wave turbulence. It is important that we are able to observe not only turbulent, but also a laminar (highly coherent) state in the same fiber laser by changing system parameters. The figure shows the transition. By combining experiments and numerical modeling, we show that the laminar phase is an analogue of a one-dimensional coherent condensate. We find that dark and grey solitons play a crucial part in the laminar-turbulent transition and show how soliton clustering destroys the condensate. We find that, properly interpreted, the turbulence onset is through a spatial rather than temporal loss of coherence. We show that the transition is of probabilistic nature and find that the probability of the condensate lifetimes decays exponentially as for radioactive decay.



Laminar-turbulent transition in the fibre-laser experiment. a) The optical spectrum width (proportional to the number of excited modes) versus power. b) The most probable intensity versus power and the full intensity probability density functions before and after the transition (inset). The colour code attributes curves at the inset to points at the main graph. c) The background level of the intensity autocorrelation function (ACF) $K(\tau) =< I(t)I(T+\tau) >$ measured at large τ. Inset shows typical ACF before the transition. For a coherent state, $K(\tau) \to 1$. For a completely stochastic radiation having Gaussian statistics, $K(\tau) \to 1/2$.

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