First experimental observation of nonlinear travelling waves in turbulent pipe flow.

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1. Background
Since the pioneering experiments of Osborne Reynolds¹ in 1883 the understanding of the laminar-turbulence transition in pipe flow is regarded as one of the great challenges in fluid dynamics. Although pipe flow is considered to be linearly stable to infinitesimal perturbations at all Reynolds numbers (Re), in practice all pipe-flows eventually turn turbulent at finite Re. Here we report the first observation of periodic coherent states in turbulent pipe flow.

2. Pipe Facility
Water is pumped through a 32 m long cylindrical pipe. The pipe diameter D=4 cm and typical flow speeds range from 5 cm/s (Re=2000) to 1 m/s (Re=40000).

3. Measurement Technique
• 500 Hz high speed stereoscopic PIV (HS-SPIV)
• time resolved measurement of three velocity components throughout a cross-sectional plane (see van Doorne, 2004 for details)

4. Travelling waves at Re=2000
With the aid of the HS-PIV measurements we could identify periodic states within turbulent puffs (localized turbulent structures), shown on the right. The upper figure is the experimental measurement whereas the lower one is a numerically observed unstable travelling wave state³. Both figures show a cross-section through the pipe. The colours represent the axial velocity component with respect to the laminar profile (high speed streaks in red, low speed streaks in blue).

An azimuthal correlation of the axial velocity for the entire turbulent puff is shown below. Along the puff the flow structure changes from a 120° symmetry (streak pattern not shown) to the 6 streak (60°) flow pattern shown on the right.

5. Travelling waves at higher Re
Further periodic states were observed at larger Re. A state with a m=2 symmetry was found at Re=2500 and is shown on the top right. The corresponding traveling wave state found in the numeric simulations³,⁴ is shown underneath.

At Re=5300 at which the pipe flow is fully turbulent a hexagonal flow state has been observed (shown bottom right). A Hexagonal state has also been observed numerically⁴.

6. Conclusion
We successfully identified travelling wave states and provide evidence of their dominating influence on turbulent structures.

References
4. Wedin, H. & Kerswell, R.R. submitted to JFM