Diagnosing plasma turbulence down to the micrometer scale

Turbulence appears in the late evolution of many fluid systems. This remains true even when considering plasma flows, where nonlocal phenomena affect the fluid dynamics. Its most iconic example might be turbulence in astrophysics, which organizes density and velocity perturbations inside the filaments and ultimately affects star formation rates. As classically depicted by Kolmogorov theory, turbulence is a phenomenon that locally transports energy from its injection scale (large spatial scale) to its dissipation scale (small spatial scale), thus forming an energy cascade. However, this theoretical approach may be inadequate in the more complex framework of high energy density (HED) and plasma physics, as nonlocal transport and collective phenomena also play a role. The numerical approach is also limited since turbulent scales extend spatially over several orders of magnitude, and both the injection and the dissipation are needed to correctly described the turbulence cascade. The only remaining approach is the experimental measure of a portion of the turbulent spectrum to constrain theories. The main difficulty, in the laboratory, is to measure the smallest spatial scale. Indeed, the best measure has been limited to scales larger than 100 μm in HED [1]. With the achievement of high-resolution X-ray radiography (HRXR), we managed to measure the turbulent spectrum of HED plasma down to the micrometer, thus revealing unforeseen features.

The first step is to produce a turbulent plasma and diagnose its spatial fluctuations with micrometer-scale spatial resolution. To that end, we work on the hutch EH5 of the X-ray free electron laser (XFEL), SACLA **BL3**. At this station, a high-power laser was employed with a hybrid phase plate to deliver ~20 J in ~4.3 ns onto a focal spot of ~240 μm on a solid multilayer target (~10^{13} W·cm^{-2}) (Fig. 1). Its first layer, a plastic ablator, is ablated, launching a shock wave, which sets into motion the second target layer, a brominated plastic pusher where a sinusoidal modulation is preimposed. The pusher then expands into a plastic foam and decelerates. This leads to the development of Rayleigh–Taylor instability (RTI) [2], which ultimately results in the formation of turbulence. To diagnose the evolving system, HRXR was performed. The quasi-monochromatic, collimated XFEL beam (Gaussian envelope centered on 7 keV, with a 30 eV full width at half-maximum) of SACLA was employed as a probe beam. An effective snapshot (~8 fs) of the system can be obtained with no geometrical constraints on the resolution. In this configuration, the spatial resolution of X-ray radiographs is only limited by the intrinsic resolution of the detector and its distance to the observed system (phase contrast imaging (PCI)). By employing a lithium fluorine crystal (LiF) as a detector (~0.5 μm resolution) placed 10 cm away from the target, ~1.5-μm-resolution (PCI) radiographs were obtained [3]. The radiograph contrast is ensured by the bromine in the pusher, which absorbs more X-rays than a simple plastic of the foam.

Our experimental configuration allows us to diagnose the dynamics of the system from the early stage of its evolution up to its late stage (80 ns after laser shot). From the sequence of snapshots obtained, the global dynamic can be reconstructed (see Fig. 2). At the interface between the expanding pusher and the foam, RTI grows from its linear phase to its nonlinear phase before its transition to turbulence after 50 to 60 ns. The growth of RTI already provides a wealth of information that can be used to constrain numerical simulations. For instance, the resolved images of the RTI spike extremity, a novelty in HED physics, differ from simulations and yield information on the plasma viscosity.

What interests us here is the late time phase (after 50 ns), where only isotropic fluctuations of the pusher concentration occur (no RTI). We analyzed this phase like a turbulent field of concentration. In other words, we performed the 2D spatial Fourier transform of the region of interest in the radiographs. Since the resulting power spectra were isotropic, we took the average over the angle to obtain 1D radial spectra. Figure 3 shows the spectra we obtained at different times. In this figure, the reference corresponds to

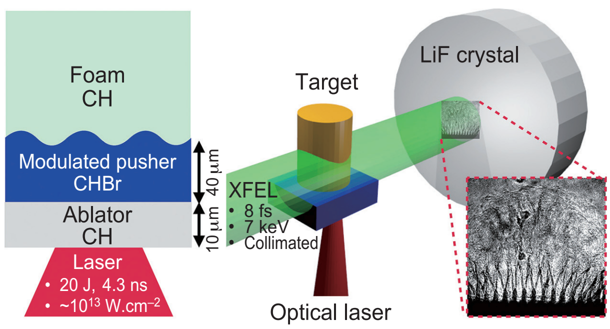

Fig. 1. Target design and experimental setup. A collimated XFEL beam is used in conjunction with a LiF crystal to perform high-resolution radiography.

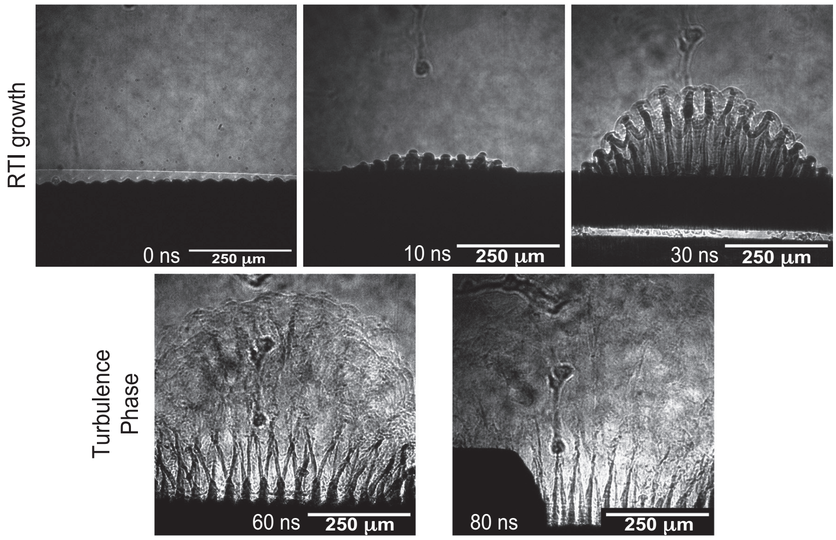

Fig. 2. X-ray radiographs recreating the evolution of the system.

a foam without an expanding pusher, and the early spectra (before 50 ns) are shown as reference as the situation was not yet isotropic. The power-law fitting of the "lower" part (spatial frequency <10 μm^{-1}) of the late time spectra shows a slope (-1.75 ± 0.25) compatible with Kolmogorov turbulence theory ($-5/3$), depicted by the black dashed line. The observed situation is thus turbulent.

However, two aspects of the spectra are not in accord with the turbulence theory. First, the bump, which appears with a spatial scale of 3.9±0.1 μm, is a feature that we cannot explain yet. It may correspond to an energy injection scale due to magnetic coupling for instance, or to the development of small-scale instability that we could not identify. Then, there is an inflection point in the power spectra at around 7 μm. This inflection of the turbulent spectra is unexpected as it appears at a spatial scale much larger than the dissipation scale (~0.5 nm). This may correspond to a transition between the inertial range of the turbulence and a sub-ionic range, as this scale corresponds to the ion inertial length. This would indicate the importance of ionic phenomena in the plasma turbulence.

New experiments are now under way to ascertain the nature of these unexpected features.

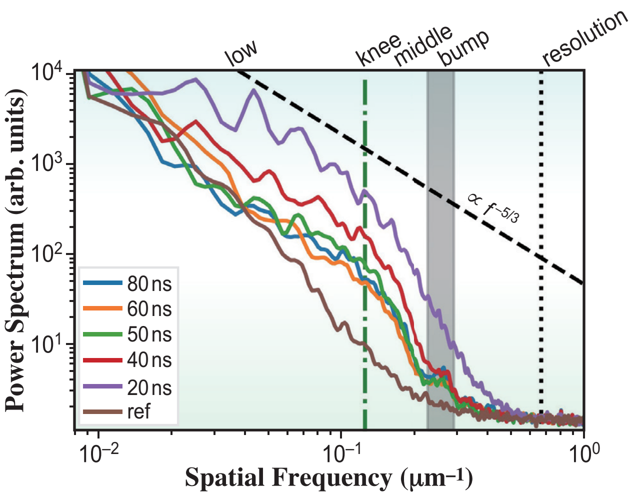

Fig. 3. Evolution of the spectra as a function of time. The late-time spectra are consistent with turbulence, but some features remain unexplained.

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