Compressing turbulence with plasma viscosity

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Plasma is compressed in the laboratory, by lasers and magnetic fields, for a variety of important purposes, including fusion, X-ray production, and materials research. Simulations have indicated that laser driven plasma compressions, such as those at the NIF or the OMEGA facility, may be turbulent to varying degrees [7, 8]. Detailed spectroscopic measurements in gas-puff Z-pinch compressions have shown that, at stagnation, the plasma energy is dominated by non-radial hydrodynamic motion [5, 6]. Since the Reynolds numbers are high at this time, it is likely that this substantial hydrodynamic motion is turbulent; in fact, so much energy is in the turbulence compared to the thermal energy that it starts supersonic [4]. In a similar manner, astrophysical molecular clouds are dominated by turbulence, with the turbulence being supersonic. The turbulence in these clouds is compressed by the cloud self-gravity, or by external pressure. The properties of this compressing turbulence are then crucial for important astrophysical questions, such as the star formation rate. When turbulence is present, but not dominant, in a compression, it may still have important effects, for example by inducing mixing of non-fuel and fuel components in ignition experiments.

Despite the presence and impact of turbulence in a variety of important plasma compression settings, the properties of plasma turbulence under compression are not well understood. Recent work has examined the impact of the plasma viscosity on the three-dimensional, isotropic compression of homogeneous turbulence [1, 2]. Among the results are a new "sudden viscous dissipation" mechanism and an understanding of the sensitivity of compressing turbulence to ionization in the plasma. The former opens the possibility for a new fast-ignition or X-ray burst scheme [1], while the latter has implications for the sensitivity of hot-spot turbulence to mix [2]. See Figs. 1 and 2 and the figure descriptions below.

Insights into the behavior of compressing plasma turbulence have led to results in the context of astrophysics as well. We have derived a lower bound on the growth of turbulence in gravitationally compressing molecular clouds [3]. When turbulence such as that in molecular clouds is compressed, the turbulent energy will grow if the system has no dissipation. However, the turbulence will cause some level of dissipation, even with extremely small viscosity, because it rapidly transfers energy down to the smallest scales, where viscosity acts. By deriving an upper bound on the amount of this dissipation for this compressing supersonic molecular cloud turbulence, we can give a lower bound on the growth of turbulence with the compression. We show that this lower bound suggests that existing molecular cloud turbulence models may be too dissipative.

A better understanding of the properties of turbulence allows for an accounting of its impact on experimental measurements. It can be difficult to separate the impact of thermal Doppler broadening of spectra from broadening caused by hydrodynamic motion such as turbulence. However, the two forms of energy can have some non-equivalent implications for radiation emission; in particular, if the quantity of turbulence is substantial (near sonic or transonic), the density distribution will be highly nonuniform. Since the radiation emission is non-linear in the density, a conservative (of number of particles) rearrangement of the density will still impact the total radiation. The analysis of gas-puff Z-pinches at the Weizmann Institute that showed substantial hydrodynamic motion assumed a homogeneous plasma. With collaborators at Weizmann, we conduct a more faithful analysis by re-analyzing the data using a turbulent density PDF model to take into account the non-uniform density distribution implied by the presence of large quantities of turbulence. This new analysis is shown to *improve* the consistency of the experimental observations, while at the same time implying a substantial (approximately factor of 2) reduction in the stagnation density [4]. See also Fig. 3 and the figure description below.

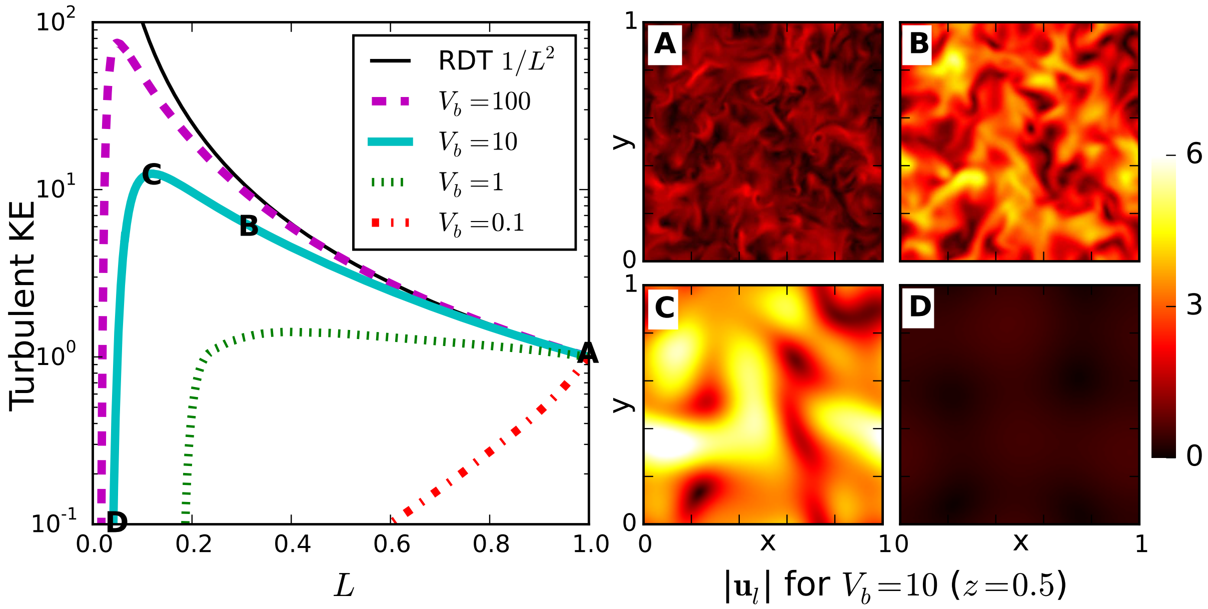

Figure 1: Turbulent kinetic energy (TKE), having been amplified by rapid compression of the plasma, is sudden dissipated into thermal energy at a late stage of the compression. See text. Figure from [1].

Figure 1 — On the left, the TKE as a function of linear compression ratio ($\bar{L}$), for 3D,

isotropic compressions of homogeneous turbulence with a plasma viscosity at four different compression velocities, V_b. The compression velocity is normalized to the initial turbulent decay time, so that, e.g. $V_b = 10$ indicates a compression that starts at a rate ten times the faster than the initial turbulent decay. When the compression is fast $V_b > 1$, the TKE amplifies initially, then suddenly dissipates later in the compression. On the right, snapshots (plane slices) of the magnitude of the flowfield at four different times (values of $\bar{L}$). In these simulations the TKE is small compared to the thermal energy, so that dissipated TKE has no appreciable impact on the temperature; the temperature rises during the compression, steadily increasing the viscosity. If the TKE is a substantial fraction of the total energy at the time of the dissipation, the temperature will rise very rapidly when the dissipation is triggered and the TKE is transfered into thermal energy. In such a case, it may be possible, by initially storing most energy in the TKE, to reduce energy losses, e.g. to radiation, during the compression.

Figure 2 — The x-axis, $\bar{L}$, is the linear compression ratio, which starts at 1 (10^0) and decreases as the compression progresses. Results are shown for compressions at two different compression velocities, U_b, and three different amounts of ionization during compression. The case $\beta = 2.5$ corresponds to no ionization, as β decreases the plasma ionizes more strongly as a function of compression. Of note is that increasing the strength of ionization with compression: can make the difference between decreasing or increasing turbulence for a given compression velocity; and can determine whether the TKE eventually dissipates or saturates.

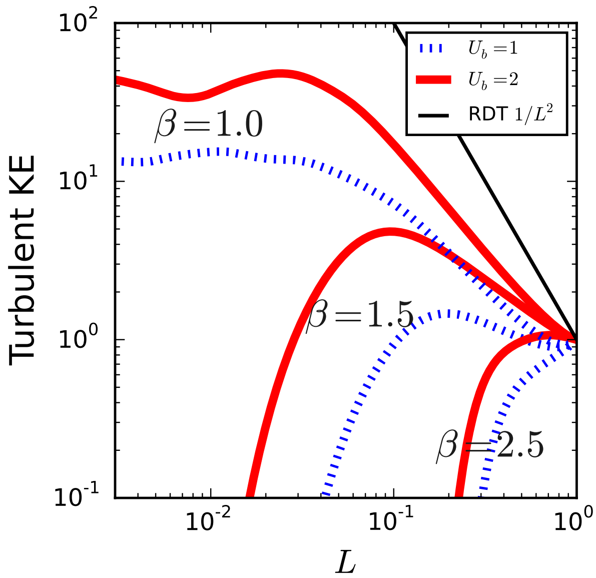

Figure 2: Similar to Fig. 1, the turbulent kinetic energy (TKE) of a homogeneous turbulence with a plasma viscosity as it undergoes 3D, isotropic compression, with different amounts of ionization during compression. See text. Figure from [2].

Figure 3 — The inferred mean density multiplicative factor, (β), for the plasma stagnation density in a gas-puff Z-pinch, when the experimental data is analyzed relaxing the assumption of plasma homogeneity. Under the assumption the hydrodynamic motion at stagnation is turbulent, the plasma density will be highly inhomogeneous, owing to the flows initially being supersonic. This inhomogeneity must be accounted for in the spectroscopic analysis previously used [5, 6]. Doing so yields new limits for

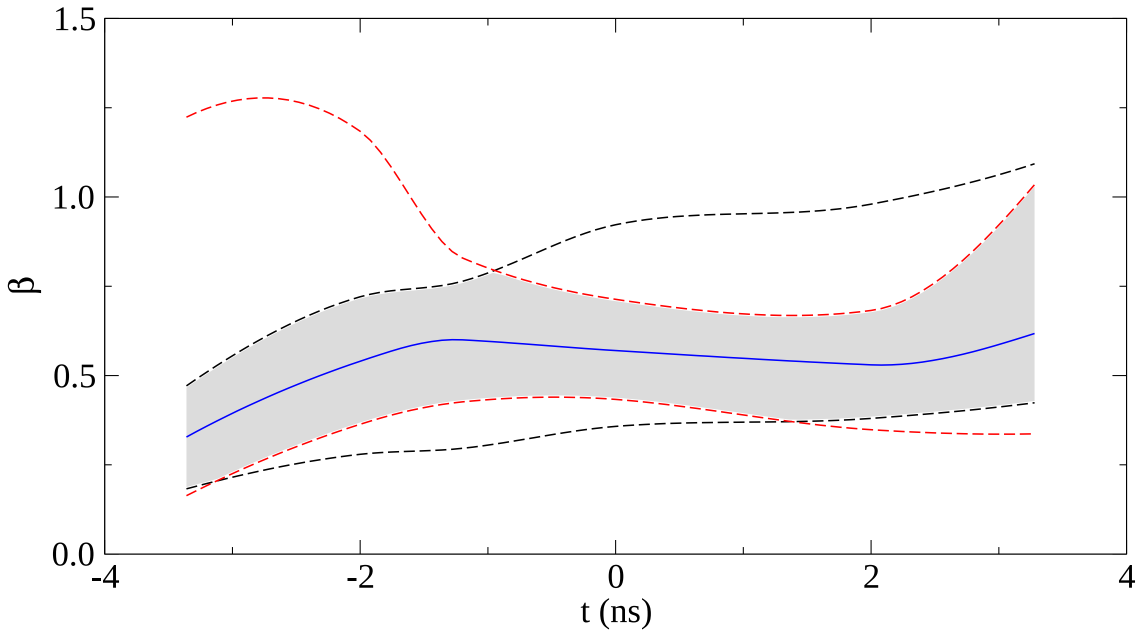

Figure 3: Calculation of measured mean density reduction factor over the homogeneous case, accounting for the density inhomogeneity that would be caused by highly turbulent stagnation plasma. See text. Figure from [4].

the density, indicated by the dashed red and dashed black curves, which together give the shaded gray region for possible value of the factor, β, that converts the old (homogeneous) mean density into the new inferred mean density. Thus $\beta < 1$ indicates a reduction of the mean stagnation plasma density when the inhomogeneity is accounted for. The blue line shows the "best fit" β value. Before, during, and immediately after stagnation ($t = 0$), the factor $\beta \sim 0.5$, implying a mean density approximately half that inferred from the homogeneous analysis.

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