Electron-Positron Plasma Turbulence Driven by Pressure Gradients

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Recent high-β helium plasma discharges in the Large Plasma Device [1] have shown strong signatures of parallel (compressional) magnetic fluctuations $B_\parallel$ in the regions of strong normalized density and temperature gradients. An accompanying gyrokinetic [2] simulation study of the experimental β scan was able to largely reproduce the observed fluctuation amplitudes [3], where differences are thought to arise from the local flux-tube limit. The turbulence regime was identified to as Gradient-driven Drift Coupling (GDC), a drift-wave-like instability which relies on both the $E \times B$ and $\nabla B_\parallel$ drifts [4]. One implication of this study is that the equilibrium force balance in a magnetic slab, $\nabla B_0 \propto \beta \nabla p_0$, does not disable the instability mechanism [5], where B_0 is the equilibrium magnetic field, $p_0 = n_0 T_0$ is the pressure corresponding to equilibrium density n_0 and temperature T_0, and β is the normalized electron pressure. In the following, a simple slab geometry with $\partial B_0 / \partial x = 0$ is therefore chosen for convenience.

The focus is now shifted to electron-positron plasmas, although from a theory perspective all results are directly applicable to other pair plasmas, as well. Such plasmas have increasingly become the focus of experimental efforts. Magnetic confinement schemes include the APEX device [6, 7], where a dipole magnetic field is used to confine particles generated by an external electron-positron source, at very small β values. A distinct approach, yielding β far in excess of unity, is to use strong lasers to produce pairs, which then traverse a short region at nearly the speed of light before detection [8].

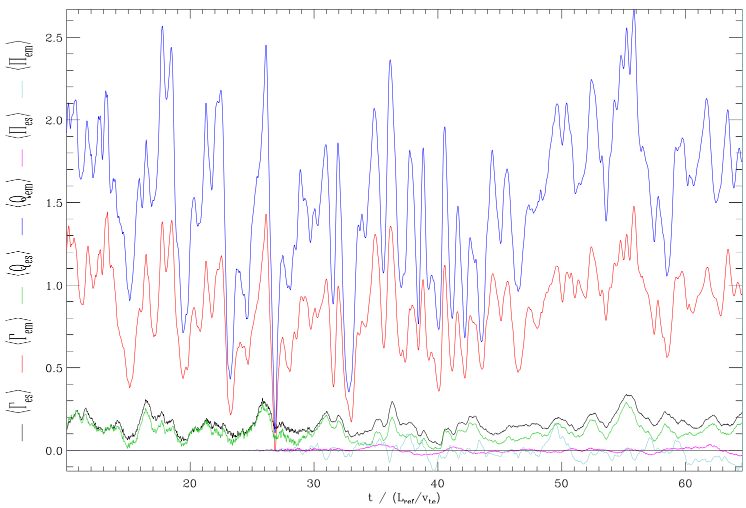

Figure 1: *Time traces of positron fluxes Γ (particle), Q (heat), and Π (momentum), split into electrostatic components induced by Φ and electromagnetic components due to both $B_\parallel$ and, at much smaller contributions, $B_\perp$. A quasi-stationary state is achieved early on in the simulation.*

Another area where electron-positron plasmas play an important role is found in astrophysics, where Gamma Ray Bursts may have a pair production region susceptible to such mechanisms as the two-stream and Weibel instabilities [9].

Such scenarios are all candidates for the GDC mechanism. In the absence of $B_\parallel$ fluctuations, pair plasmas in homogeneous magnetic fields have been found to be stable to density or temperature gradients [10], unless density and temperature gradients point in opposite directions [5]. When $B_\parallel$ is included, however, and presuming that the aforementioned force balance argument is inapplicable due to either an unbalanced background field or curvature in the system, the GDC is found to grow linearly at a rate, normalized to units of thermal velocity to L_z, of

$$\gamma = \frac{\sqrt{2}(\omega_n + \omega_T)}{\sqrt{(2+1/\beta)(2+\lambda_{\mathrm{D}}^2)}} , \tag{1}$$

where $\omega_n = -(L_z/n_0)\mathrm{d}n_0/\mathrm{d}x$ and $\omega_T = -(L_z/T_0)\mathrm{d}T_0/\mathrm{d}x$ are the gradients of the background density n_0 and temperature T_0 normalized to a macroscopic length scale L_z, and the Debye length measured in gyroradii is denoted by λ_{D}. This assumes that the electron and positron species have equal background densities and temperatures, a reasonable choice given the pair production process. Direct simulations with the gyrokinetic code GENE [11] confirm the analytical result. In addition, finite-k_z versions of the GDC are found when driving gradients are sufficiently strong, although a large k_z, in a similar way to background magnetic shear, is acting as a stabilizing force.

As described in Ref. [3], nonlinear GDC simulations can be challenging in flux-tube geometry due to the tendency of the mode to peak at the system scale, potentially resulting in unphysical, self-connecting structures along the gradient direction x, due to periodic boundary conditions. One solution is to artificially remove the $k_x = 0$ mode. Using this strategy for an electron-positron plasma with $\beta = 100$, quasi-stationary turbulence is achieved, as seen in Fig. 1. Due to the high β value, fluxes are dominated by the

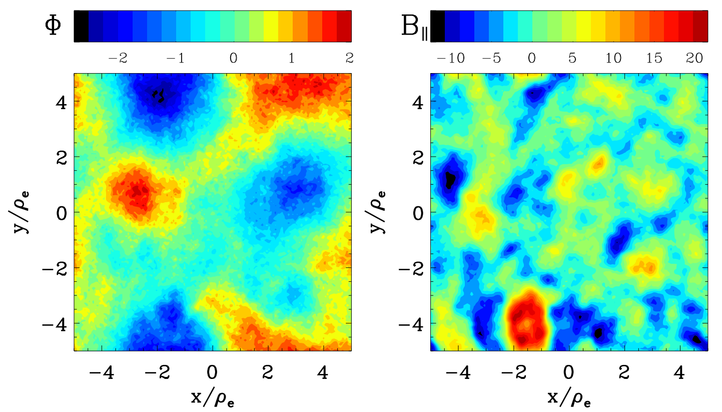

Figure 2: *Contours of the electrostatic potential* Φ *and the parallel magnetic fluctuations* $B_\parallel$ *for a pair plasma simulation with* $\beta = 100$ *where the* $k_x = 0$ *mode has been artificially suppressed.*

electromagnetic channels, which in turn are primarily caused by $B_{\|}$ fluctuations, as $A_{\|}$ is not driven linearly by the instability in this $k_z = 0$ simulation.

Examining contours of the electrostatic potential Φ and the parallel magnetic fluctuations $B_{\|}$ in Fig. 2, one observes that the turbulence is largely isotropic and exhibits a moderate scale separation between structure sizes in Φ and $B_{\|}$, a feature directly arising from the form of the field equations [4], where $k_\perp^2 \Phi \sim B_{\|}$. Note furthermore that while $\beta = 100$, only one order of magnitude separates the fluctuations in amplitude.

Interestingly, for this particular parameter case, deletion of the $k_x = 0$ mode produces a non-intuitive effect, where fluxes are increased rather than lowered relative to the case where the mode is allowed to evolve, as shown in Fig. 3. It is important to recall that the mode deletion is physically motivated, as a realistic, finite-extent system will not be able to drive infinitely large structures in an inhomogeneous coordinate. In the figure, one observes coherent structures in $B_{\|}$, which drift along y and whose shape does not change over time, thus no turbulent state is achieved after saturation. This is due to the production of a strong zonal flow in Φ, suppressing the linear eigenmode.

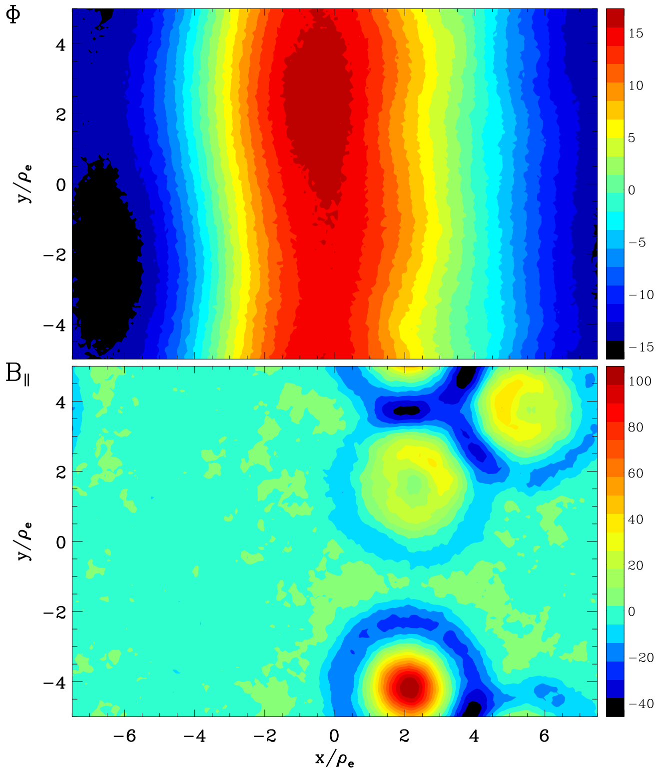

Figure 3: *Contours of the electrostatic potential* Φ *and the parallel magnetic fluctuations* $B_{\|}$ *for a pair plasma simulation with* $\beta = 100$ *where the* $k_x = 0$ *mode was allowed to evolve.*

At present, code development is ongoing to allow for simulation with $B_{\|}$ in radially global geometry, i.e., lifting the restriction on constant gradients across the simulation domain. Once completed, it will be possible to investigate both the helium plasmas in the Large Plasma Device and various scenarios of pair plasmas with much greater accuracy. Another focus will be to implement dipole geometry to predict instability and turbulence characteristics in APEX.

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