Collisional effects on ultrarelativistic beam-plasma instabilities

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Relativistic beam-plasma instabilities are ubiquitous in plasma physics. In astrophysics, relativistic beam-plasma instabilities dissipate into heat or radiation the kinetic energy of relativistic outflows from various powerful sources (e.g., pulsar wind nebulae, neutron star mergers, active galactic nuclei) [1].

Their nonlinear evolution[2] can spawn relativistic collisionless shock waves, thought to generate the most energetic particles and radiations in the universe, including the electromagnetic counterpart of gravitational waves.

In relativistic laser experiments, they affect the generation and/or propagation of fast electrons in plasmas [3], thus impacting all the processes subsequently triggered by those electrons (e.g., plasma heating and ion acceleration).

The E-305 multi-experiment project, currently ongoing at the SLAC/FACET-II accelerator [4] will aim to probe the development of beam-plasma instabilities [2] under extreme conditions, involving an ultrarelativistic (10 GeV), high-density (~$10^{19\text{-}20}$ cm^{-3}) electron beam propagating through a millimeter-scale solid-density medium. Our work here aims at providing theoretical models and particle-in-cell (PIC) simulations to support this project, which will in return help benchmarking the codes used.

Our 2D simulations of the beam propagation (modelling the aluminum target as a solid-density plasma) show the impact of the instabilities on the beam's phase space, and reveal how the plasma collisionality, along with the beam's peak density, affects the hierarchy between the competing instability classes.

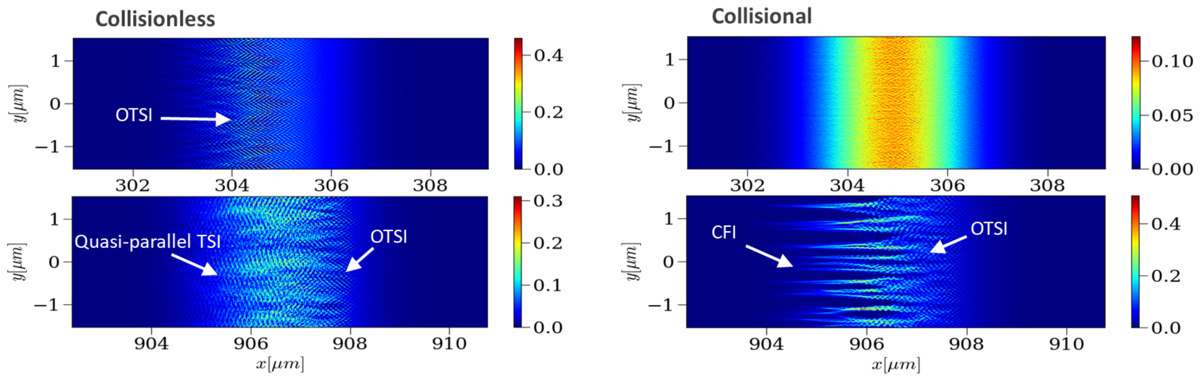

Figure 1: Beam density after 300µm and 900µm, in the collisionless and collisional case. The CFI only prevails in the rear of the beam in the collisional case.

Specifically, Coulomb collisions between the plasma electrons and ions are found to hamper the oblique two-stream instability (OTSI), usually dominant in the regime considered [5,6], and instead to favor the current filamentation instability (CFI), which prevails at ≥ 10^{20} cm^{-3} beam densities (Figure 7) in the rear of the beam. At the front of the beam, or for lower beam densities, the plasma collisionality remains low and the OTSI isn't suppressed enough for the CFI to emerge. The hierarchy between unstable modes can be observed through the evolution of electromagnetic field energies, as the OTSI is mostly electrostatic and the CFI is mostly magnetic (*Figure 2*).

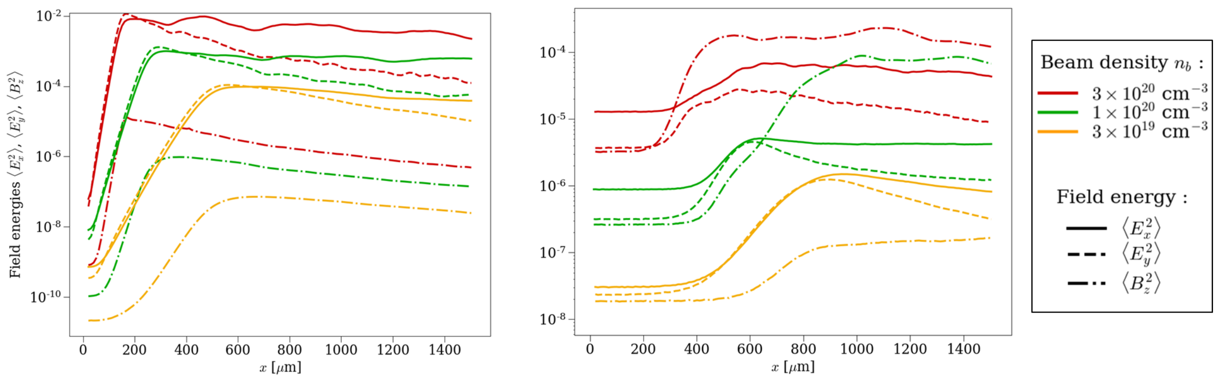

Figure 2: Evolution of the electromagnetic field energies, relative to the beam propagation distance, and its peak density. In the collisionless case (left), E_x and E_y grow to higher energies in all considered cases, while the B_z magnetic field is more energetic in the collisional case (right) for high beam densities.

In a low temperature ($T_p \lesssim 10eV$) solid-density plasma, the simulated electron collision frequency no longer follows the classical (Spitzer) scaling, giving $\nu_{ei} \propto T^{-3/2}$, but rather evolves as $\nu_{ei} \propto T^{-1/2}$ due to saturation of the mean free path [7,8].

As low-density electron beams propagate, they only weakly heat the plasma, and its collisionality is instead set by its initially chosen plasma temperature, with the OTSI being dominant at low plasma temperature and the CFI emerging when starting with a 10eV background plasma. In higher-beam-density cases, the plasma temperature evolves with time as the plasma is resistively heated, and the CFI rules the interaction in the rear of the beam.

Those findings are interpreted by solving numerically the 2D collisional dispersion relation of the beam-plasma instability, in which the nonrelativistic Vlasov-Fokker-Planck equation, using the Landau collisional operator, is used to treat the plasma electrons [9] and allows us to obtain an exact expression of the susceptibility of the plasma in the Spitzer regime.

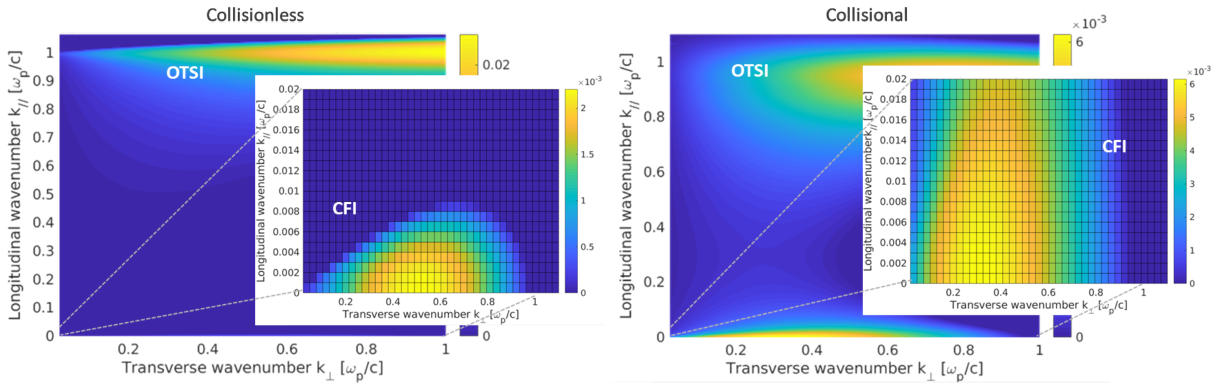

Figure 3: map of the instability growth rate relative to its wavenumber. Beyond quenching OTSI and favoring CFI, collisions enlarge the unstable domain along $k_{||}$, while decreasing the dominant $k_\perp$ of both the OTSI and CFI.

The theoretical growth rate of the OTSI and CFI (*Figure 3*) is consistent with the PIC results, as linear theory predicts that collisions tend to dampen the OTSI and exacerbate the CFI, while reducing the range of their transverse wavenumbers. Notably, our study predicts an optimal plasma temperature for the growth of OTSI in the collisional case. On the other hand, collisions particularly increase the CFI growth rate for a low plasma temperature and a low beam Lorentz factor.

Using FACET-II parameters, the kinetic theory also shows a dominance of the CFI for plasma temperatures below 50eV for a 10^{20}cm^{-3} beam density, which is consistent with our simulation results yielding a final plasma temperature of ~5eV in that case.

References

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