Investigation of beam-plasma instabilities utilising numerical and experimental methods

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Non-thermal electron distributions within a plasma can result in a range of instabilities that can significantly influence the dynamics of the system. For the present paper, it is the effect of the well known two-stream instability in fast-ignition inertial confinement fusion that is of primary interest. This method of fusion utilises a high power laser pulse to compress a deuterium-tritium fuel pellet to extremely high density and then uses a second laser pulse to accelerate an electron beam into the compressed pellet. It is this electron beam that heats and ignites the fuel pellet [1]. As the electron beam interacts with the deuterium-tritium plasma, the two-stream instability can occur. It has been proposed that Langmuir turbulence stimulated by the two-stream instability may decay into ion-acoustic waves that may facilitate improved ion heating [2]. To investigate this proposed behaviour, a low-temperature, low-density laboratory experiment is planned with numerical simulations currently underway to provide the necessary parameters of the system. Results shall be reported from these numerical simulations, showing the growth rate of the instability with realistic experimental parameters and comparing this with predictions from analytical theory.

1. Introduction

Previous work at the University of Strathclyde has focused on the investigation of auroral kilometric radiation, which is generated by a cyclotron resonance maser instability [3-6]. This instability involves the transverse bunching of electrons orbiting in an imposed magnetic field which in turn results in the donation of energy to a growing wave within the system. An experiment has been constructed to investigate instabilities driven by particles accelerated along magnetic field lines [7-11]. Following on from this experiment, modifications can be made to the apparatus to study other types of instability [12]. Of primary interest is the two-stream instability, of particular relevance to fast-ignition inertial confinement fusion.

The two stream instability occurs when two or more charged particle streams flow through one another, resulting in a growing longitudinal wave [13]. This is of importance to fast-ignition inertial confinement fusion where a high power laser pulse is used to accelerate electrons into a compressed deuterium-tritium fuel pellet. As the electrons stream through the fuel pellet, collisions between the particles heat the fuel to induce fusion. However, to improve the efficiency of the process the two-stream instability may be coupled to an ion-acoustic wave that may also heat the fuel [14].

The investigation of the dynamics of this process shall be conducted initially by computational simulations followed by controlled laboratory experiments.

2. Physical principles

The two-stream instability occurs when there is an interpenetration of two beams, for example an electron beam flowing through an ion beam or another electron beam. The cause of this instability can be thought of as originating from a point source disturbance within a two-beam plasma. If a density fluctuation arises from this disturbance in one stream of particles, then the electric field will initiate a plasma oscillation at that location. However, these fields can modulate the electron densities of the second stream and the drift of these density modulations through each other can result in energy exchange. This leads to growth of the associated electric field energy feeding from the energy of the initial particle streams.

From linear theory, the dispersion relation for this mechanism for an electron beam interacting with a cold background plasma is shown in figure 1.

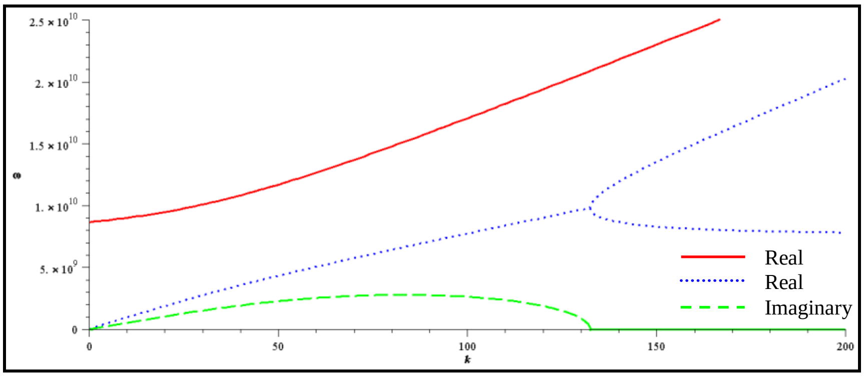

Figure 1. Dispersion relation for two-stream instability of a beam-plasma interaction

3. Numerical Simulations

In order to observe the non-linear regime of the two stream instability a simulation has been run using XOOPIC, a 2-dimensional finite-difference particle-in-cell (PiC) code. This simulation involves injecting an electron beam into a waveguide of circular cross-section filled with a warm plasma. To confine the plasma, a profiled magnetic field is used to construct a magnetic bottle.

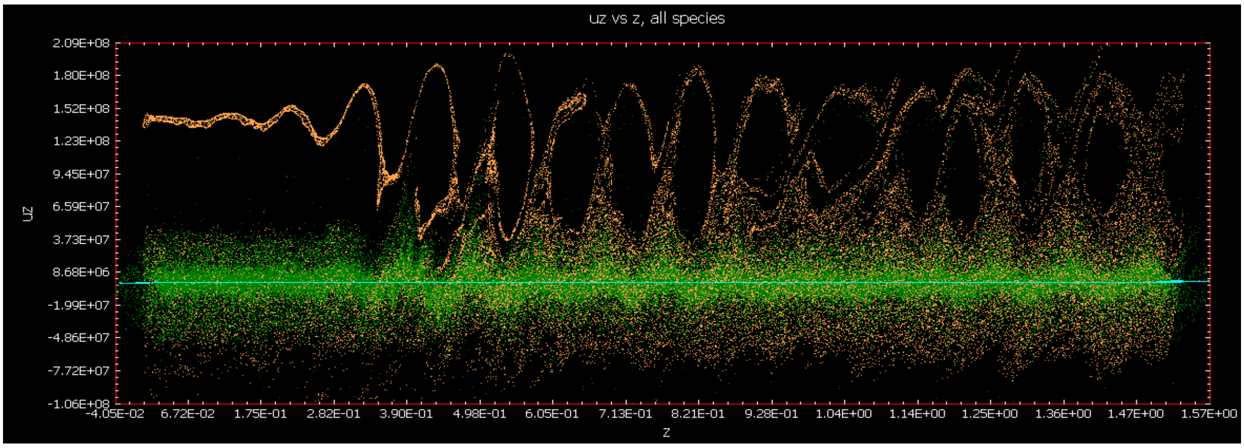

Figure 2. Axial-momentum against position of all particles in the simulation (orange = beam electrons, green = plasma electrons, blue = ions) after 100ns

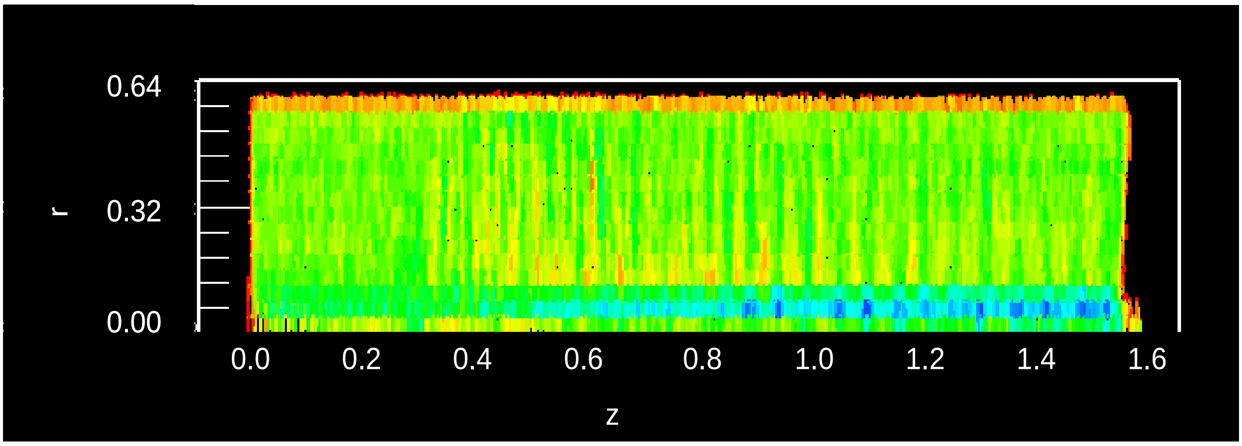

Figure 3. Ion density after 100ns

From figure 2, after 100ns the beam electrons can be seen to become trapped in phase-space vortices, a characteristic feature of the two-stream instability. As a result of this trapping, the ions become longitudinally bunched as seen in figure 3. This behaviour is suggestive of ion acoustic motion which could be a mechanism for ion heating

4. Summary

A PiC code has been used to simulate the behaviour of an electron beam injected into a magnetically confined plasma. Initial results indicate that the two-stream instability is produced, generating ion bunching that may indicate the decay of Langmuir turbulence into ion acoustic waves as expected. Further simulations are required in order to verify the presence of ion acoustic waves.

To confirm these results further, a controlled, low temperature, low density laboratory experiment is also being designed. This experimental setup will be an adaptation of existing apparatus previously used to investigate auroral kilometric radiation.

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