Computational and experimental study of beam-plasma instabilities relevant to fast-ignition inertial confinement fusion

M. King[1], D.C. Speirs[1], R. Bingham[1,3], S.L. McConville[1], R. Bryson[1], K.M. Gillespie[1],
A.D.R. Phelps[1], A.W. Cross[1], C.G. Whyte[1], R.A. Cairns[2], I. Vorgul[2],
R.M.G.M. Trines[3] and K. Ronald[1]

[1] *SUPA, Department of Physics, University of Strathclyde, Glasgow, G4 0NG, UK*
[2] *School of Mathematics and Statistics, University of St Andrews, St Andrews, KY16 9SS, UK*
[3] *STFC Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX, UK*

Abstract

Beam-plasma instabilities can produce highly non-linear effects that can influence the particle dynamics of a system. Within fast-ignition inertial confinement fusion, the two-stream instability may be of particular importance. In this form of fusion, a deuterium-tritium fuel pellet is compressed using uniform laser irradiation. A secondary laser pulse is then utilised to accelerate a highly relativistic electron beam into the core of the pellet to provide the heating necessary to initiate fusion. Results from fast-ignition fusion experiments have indicated that more of the beam energy is being transferred to the ion population than would be expected from purely electron-ion collisions. It has been proposed that this anomalous heating mechanism can be explained by the two-stream instability. As the beam propagates through the compressed pellet, the two-stream instability occurs and can excite Langmuir turbulence that can resonantly decay into ion-acoustic waves. These waves are then damped by ion-ion collisions resulting in a collective heating of the ion population. To investigate this behaviour, a scaled low temperature, low density laboratory experiment is currently underway. Two dimensional particle-in-cell (PiC) simulations have been undertaken of this scaled experiment, the results of which will be benchmarked against those of the experiment. Preliminary results from the laboratory experiment will be presented along with the results from PiC simulations.

Background

The dynamics of beam-plasma instabilities can be of great importance to fast-ignition inertial confinement fusion. This method of fusion is achieved by compressing a deuterium tritium fuel pellet to very high densities through uniform laser pressure and then utilising a secondary high power laser pulse to accelerate a highly relativistic electron beam through the compressed core. As the electron beam transits through the compressed plasma, energy is transferred; heating the plasma to levels necessary for fusion. During this transit, however, a range of plasma instabilities can occur and affect the heating process. Experiments have shown that more energy can be transferred to the plasma than can be accounted for from purely electron-ion collisions [1,2]. It has been proposed that the two-stream instability may be responsible as it can parametrical decay into ion-acoustic waves which are then damped by ion-ion collisions resulting in additional energy transfer to the ions [3]. This work investigates this behaviour with numerical simulations of a scaled laboratory experiment.

Two-stream instability

The two-stream instability occurs when there is an interpenetration of two or more moving streams of charged particles, for example an electron beam flowing through an another electron beam or background plasma. This instability originates from a point source disturbance within such a streaming system [4]. 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 charged particle 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 energy associated with the electric fields feeding from the energy of the initial particle streams.

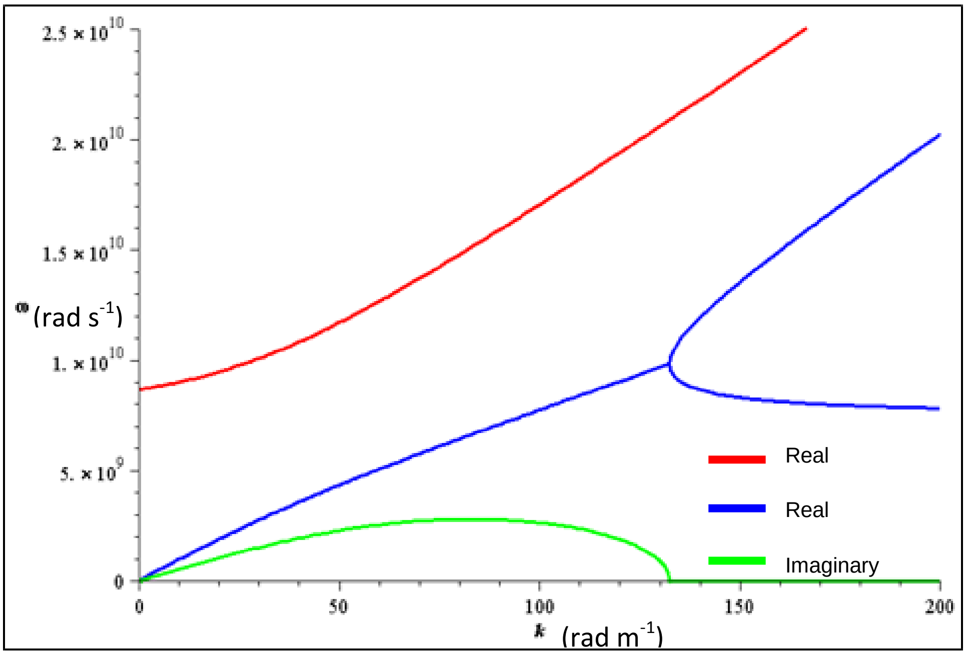

Fig 1 - Dispersion relation of the two-stream instability parameters used in the numerical simulations obtained from linear theory

However, in the nonlinear regime this instability may also parametrically decay into ion-acoustic oscillations. To observe this behaviour numerical simulations have been undertaken with laboratory experiments also underway.

Particle-in-cell simulations

Numerical simulations have been undertaken in a two-dimensional particle-in-cell code XOOPIC [5] at densities much lower than that of the fast-ignition case. These are intended to reproduce and expand upon published one-dimensional numerical simulations [6]. The simulations consist of the injection of a rectilinear electron beam at 100kV, 20A into a uniform cylindrical plasma column of fully ionised hydrogen at a density of approximately $9 \times 10^{16} m^{-3}$.

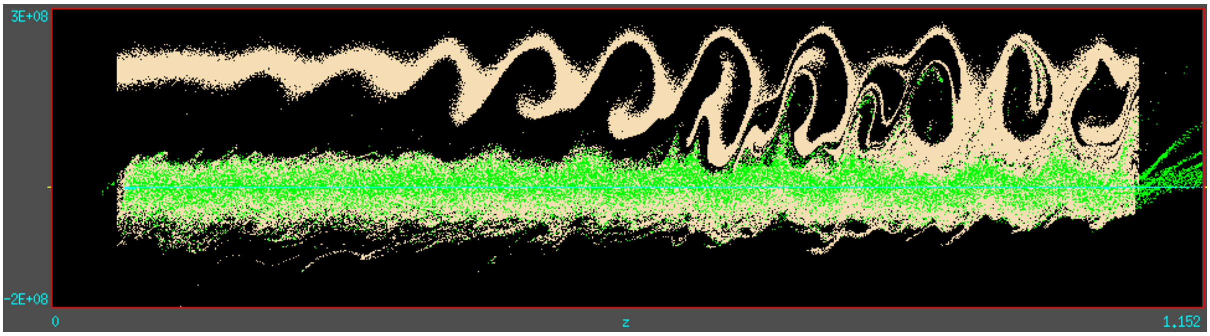

Fig 2 - Z-momentum against z of all particles in the simulation after 70ns (orange=beam electrons, green=plasma electrons, blue=plasma ions)

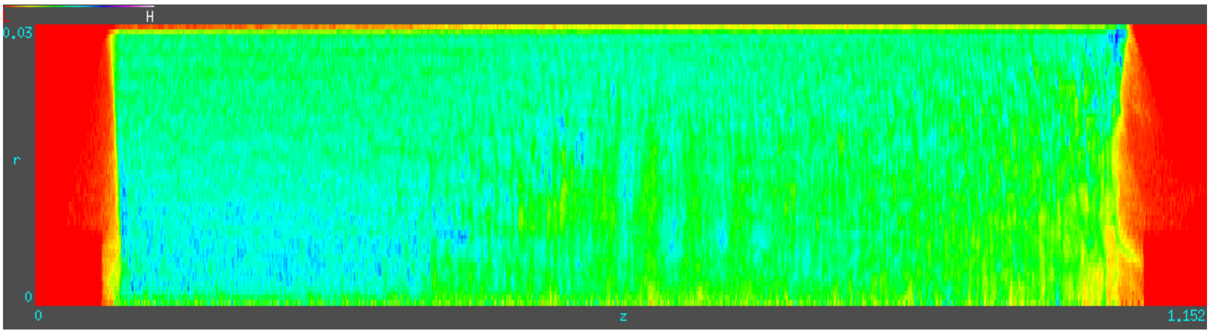

Fig 3 - Z-R plot of ion density after 70ns

From these preliminary results it can be seen that the two-stream instability occurs and the beam electrons become phase trapped in axial velocity due to strong axial electric fields. The ions appear to longitudinally bunch which is indicative of ion acoustic behaviour.

Experimental setup

The scaled laboratory experiment to observe the two-stream instability behaviour is built upon the apparatus used in the previous experimental investigations into auroral kilometric radiation [7-9]. The electron beam shall be created using a redesigned electron accelerator utilising a Pierce-type geometry. From previous experiments, a Penning trap type plasma discharge can be used to create the necessary plasma. Modifications have been made to increase the length of the plasma region. Existing water-cooled solenoids can be used to create the focusing magnetic field for the electron beam as well as the confining magnetic field for the plasma. These solenoids will allow the magnetic fields to be varied as required. This experiment will be run at a medium vacuum level. Allowing components to be replaced or adjusted easily.

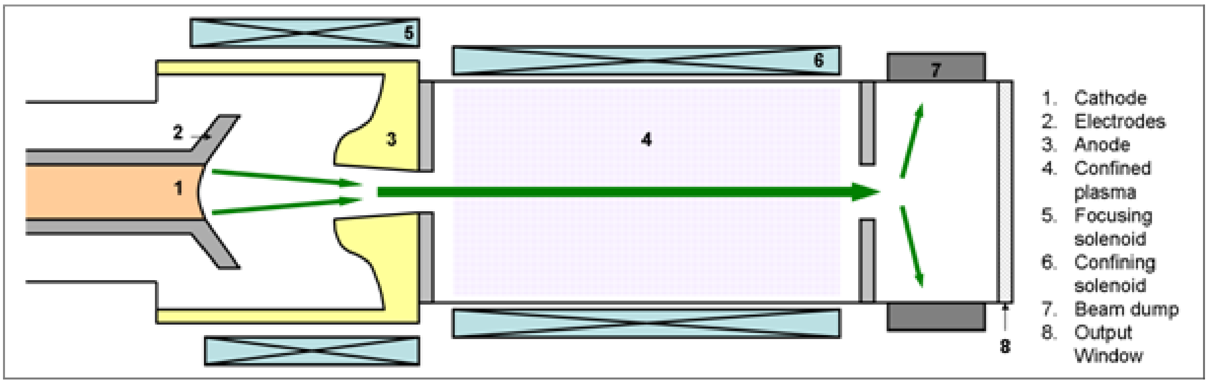

Fig 4 - Experimental design

Results from this laboratory experiment will then be used to benchmark the results seen in the numerical simulations which can then provide confidence in simulations of higher fusion relevant densities.

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