Numerical simulations and the development of experimental apparatus for the study of beam plasma instabilities

M. King[1], S.L. McConville[1], D.C. Speirs[1], R. Bingham[1,3], 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

The instabilities excited by the transit of an electron beam through a plasma is of practical interest in both astrophysical and applied plasma physics. Examples include the auroral electron flux through the polar magnetosphere and in fast-ignition inertial confinement fusion. In one method of this form of fusion, a deuterium-tritium fuel pellet is heated and compressed by uniformly distributed laser radiation, producing a high density plasma. A secondary laser pulse is then used to generate an electron beam that propagates into the compressed plasma. During the transit, the two-stream instability can occur. It has been proposed that this instability can resonantly decay into ion acoustic waves that heat the plasma when damped by ion collisions. Numerical simulations have been undertaken in a two-dimensional particle-in-cell code. These simulations are conducted at a lower temperature and lower density regime. Specifically, a 50kV, 24A electron beam is injected into a waveguide bounded cylindrical column of plasma at a density of $1.8\times10^{16}\mathrm{m}^{-3}$. These parameters represent a laboratory experiment which is being constructed to provide an experimental benchmark for the numerical predictions. This will provide an enhanced confidence in the use of PiC and other numerical methods to predict the dynamics of fusion relevant conditions.

Introduction

Beam-plasma instabilities are expected to play an important role in the heating mechanism of fast-ignition inertial confinement fusion. In this fusion method, a high power ignition laser is used to generate an energetic electron beam that interacts with a dense, compressed plasma. The main purpose of this interaction is to rapidly heat the ions within the plasma. However, in laser-plasma interaction experiments, measured laser energy transfer was found to be much higher than that expected for purely collisional heating [1-2]. To account for this anomalous heating, it has been proposed [3] that as the electron beam propagates into the highly compressed plasma, the two-stream instability can occur, producing very large electrostatic fields. These electrostatic fields can parametrically decay into longitudinal ion acoustic waves which are subsequently damped by ion-ion collisions which heat the ions. To verify this behaviour, a two-dimensional numerical model has been created to design a future low-pressure, controlled laboratory experiment.

Theory

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. This instability originates from a point source disturbance within a two-beam plasma [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 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 energy associated with the electric fields feeding from the energy of the initial particle streams.

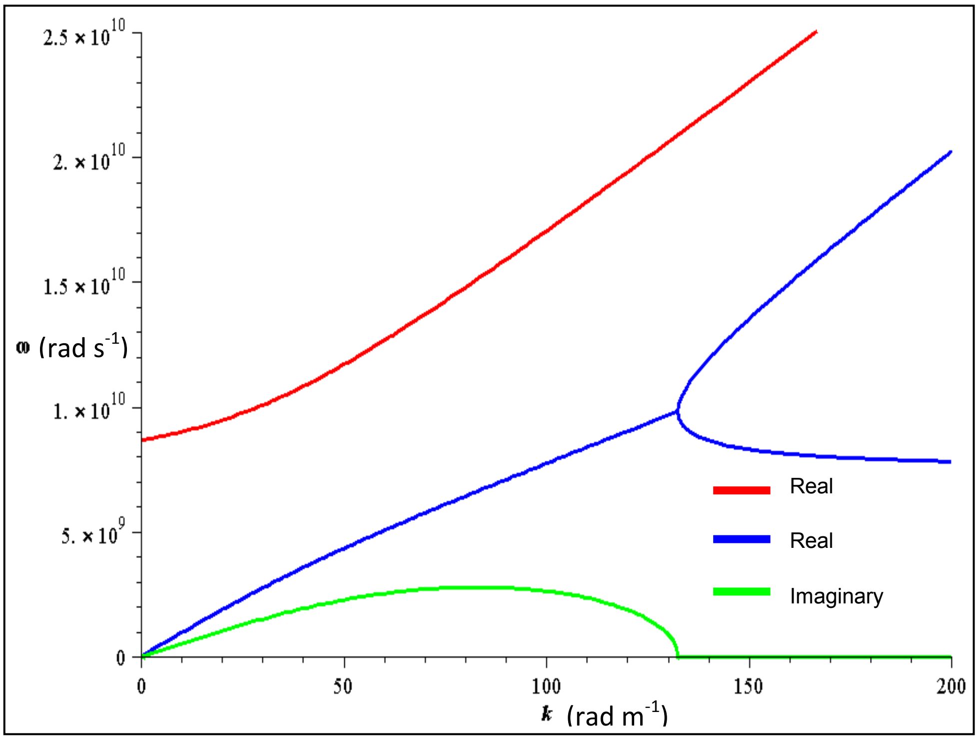

Fig 1 - Dispersion relation of the two-stream instability obtained from linear theory

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

Numerical Simulations

Numerical simulations have been undertaken in a two-dimensional particle-in-cell code at densities much lower than that of the fast-ignition case. These are intended to reproduce and expand upon published one-dimensional numerical simulations [5]. The simulations consist of the injection of a rectilinear electron beam into a uniform cylindrical plasma column of fully ionised hydrogen at a density of approximately $1.8\text{x}10^{16}\text{m}^{-3}$.

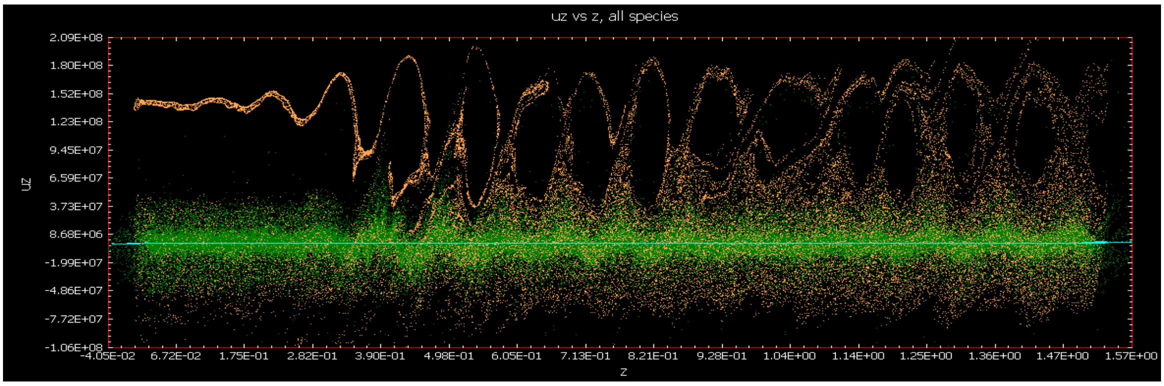

Fig 2 - Z-momentum against z of all particles in the simulation after 100ns (orange=beam electrons, green=plasma electrons, blue=plasma ions)

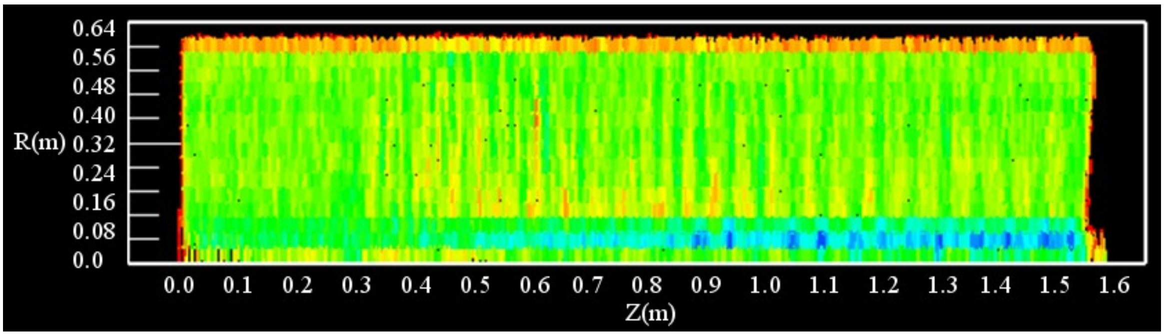

Fig 3 - Z-R plot of ion density after 100ns

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.

Scaled laboratory experiment

The laboratory experiment to observe the two-stream instability behaviour shall be built upon the apparatus used in the previous experimental investigations into auroral kilometric radiation [6-8]. 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 are being 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.

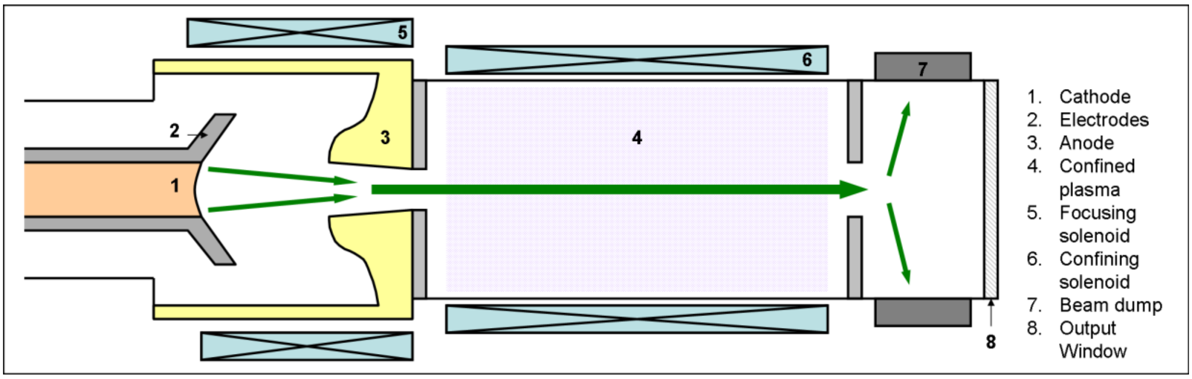

Fig 4 - Proposed experimental design

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.

References

[1] R. Kodama et al., Nature (London) 412, 798 (2001)
[2] R. Kodama et al., Nature (London) 418, 933 (2002)
[3] J.T. Mendonça et al, Phys Rev Lett, 94, 245002 (2005)
[4] Stix T.H., Waves in Plasmas, Springer (1992)
[5] N.J. Sircombe et al, Plasma Phys. Control. Fusion, 50, 065005 (2008)
[6] Speirs D.C. et al, Plasma Phys. And Control. Fusion 50, 074011 (2008)
[7] Ronald K., et al, Plasma Sources Science and Tech. 17, 035011 (2008)
[8] McConville S.L. et al, Plasma Phys. and Control. Fusion 50, 074010 (2008)