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Progress towards numerical and experimental simulations of fusion relevant beam instabilities

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Abstract. In certain plasmas, non-thermal electron distributions can produce instabilities. These instabilities may be useful or potentially disruptive. Therefore the study of these instabilities is of importance in a variety of fields including fusion science and astrophysics. Following on from previous work conducted at the University of Strathclyde on the cyclotron resonance maser instability that was relevant to astrophysical radiowave generation, further instabilities are being investigated. Particular instabilities of interest are the anomalous Doppler instability which can occur in magnetic confinement fusion plasmas and the two-stream instability that is of importance in fast-ignition inertial confinement fusion. To this end, computational simulations have been undertaken to investigate the behaviour of both the anomalous Doppler and two-stream instabilities with the goal of designing an experiment to observe these behaviours in a laboratory.

1. Introduction

Previous work at the University of Strathclyde has focused on the investigation of auroral kilometric radiation, which utilises the cyclotron resonance maser instability[1-4]. 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[5-9]. Following on from this experiment, modifications to the system can be made to study other types of instability. Of primary interest are the anomalous Doppler instability and the two-stream instability, both of relevance to fusion science.

The anomalous Doppler instability can occur in magnetic confinement fusion plasmas. When a plasma has been subject to radio frequency heating, such as in a Tokamak, it is possible to develop a large population of electrons which propagate along an applied magnetic field with a high kinetic energy. These non-thermal electrons can surrender their excess energy by collisions with other particles in the plasma, or by coupling to an electromagnetic wave whose energy may then be dissipated in the bulk plasma. One wave coupling regime which may arise between streams of electrons and transverse slow EM waves in the plasma is the anomalous Doppler effect[10-14]. Here electrons interact with the field components of the wave resulting in an increase of gyrational energy but with a greater loss of translational energy, amplifying the field of the slow wave.

The two-stream instability occurs when two or more charged particle streams flow through one another, resulting in a growing longitudinal wave[15]. 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[16].

The investigation of the dynamics of both these processes shall be conducted initially by computational simulations followed by controlled laboratory experiments.

2. Physical Principles

2.1. Anomalous Doppler

The electron beam initially has nearly all of its momentum along the axis of the waveguide with little transverse momentum. Electrons then experience a force due to a wave travelling in phase synchronism. This force results in acceleration of the electrons in the radial direction where they do work on the wave's E field. Providing the beam drift velocity exceeds the wave velocity, the pumping of the translational to rotational energy (by the $v_z \times B_\perp$ force) exceeds the dissipation of rotational energy by the E field. These requirements may be satisfied by a Doppler upshifted negative cyclotron harmonic of an electron beam drifting in a fixed magnetic field in the presence of a medium which decreases the wave phase velocity, as illustrated in figure 1. This is known as the anomalous Doppler resonance, where electrons are retarded along the axis of propagation, with energy conserved by the growth of the rotational and wave energy, figure 2. Energy extraction in this way can be efficient as no bunching is required before beam energy is extracted.

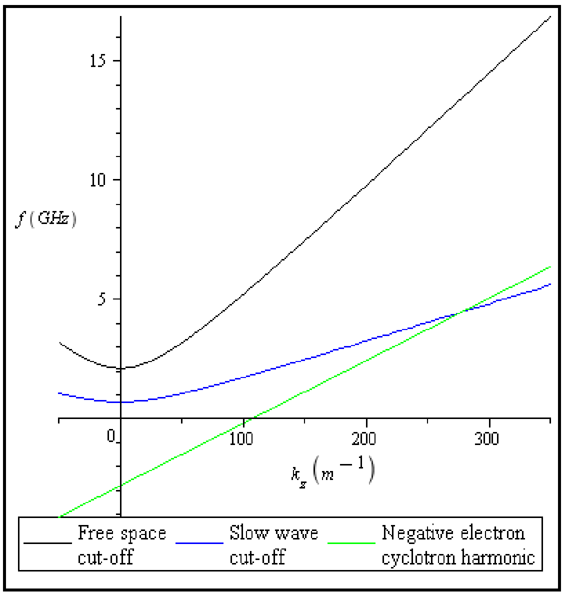

Figure 1. Dispersion showing negative beam harmonic intercepting with a wave in a dielectric loaded waveguide and an unloaded waveguide cutoff

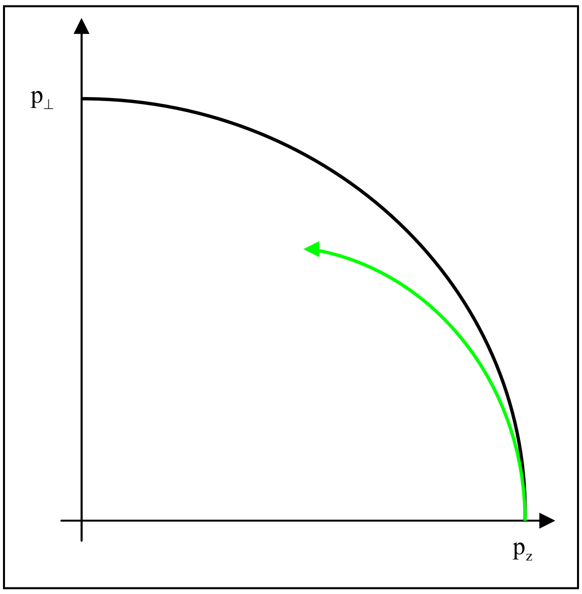

Figure 2. Relaxation of electron energy by anomalous Doppler resonance

2.2. Two-stream

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 energy associated with the electric fields feeding from the energy of the initial particle streams. Using a linear theory, the dispersion relation for this mechanism for two co-propagating beams is shown in figure 3.

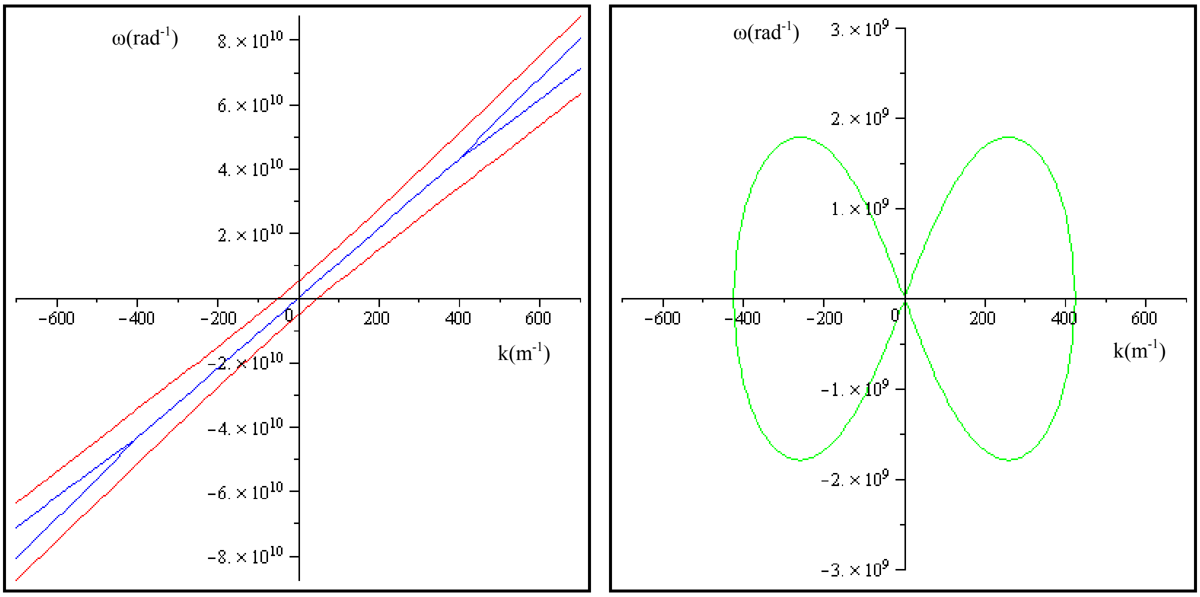

Figure 3. Dispersion relation of the two-stream instability for two co-propagating beams showing (a) the real components (spatial wave-vector) (b) the imaginary components (temporal growth rate)

3. Numerical simulations

3.1. Anomalous Doppler instability simulations

These preliminary simulations (figure 4) make use of a slow wave structure formed of a dielectric loaded waveguide with a small central aperture that allows the passage of an electron beam in place of a full plasma calculation. This configuration allows the negative cyclotron harmonic of an electron beam to interact with the TE_{11} mode in the waveguide, producing a condition where the anomalous Doppler resonance can occur providing $v_z>v_{ph}$. In this simulation, the electron beam with energy 100kV is drifting in a B-field of 0.12T in anomalous Doppler resonance with the TE_{11} mode at 4.6GHz.

Simulations are being conducted with the 3D FDTD Particle-in-Cell code MAGIC. Electrons are confined by a magnetic field to pass through the centre of a waveguide lined with dielectric. In the region of the dielectric the electron beam is in phase synchronism with the TE_{11} mode (as in figure 1). Energy is transferred from the beam to the wave in the interaction region where the magnetic field is uniform and then where the magnetic field decreases the beam is dumped on the waveguide sidewall.

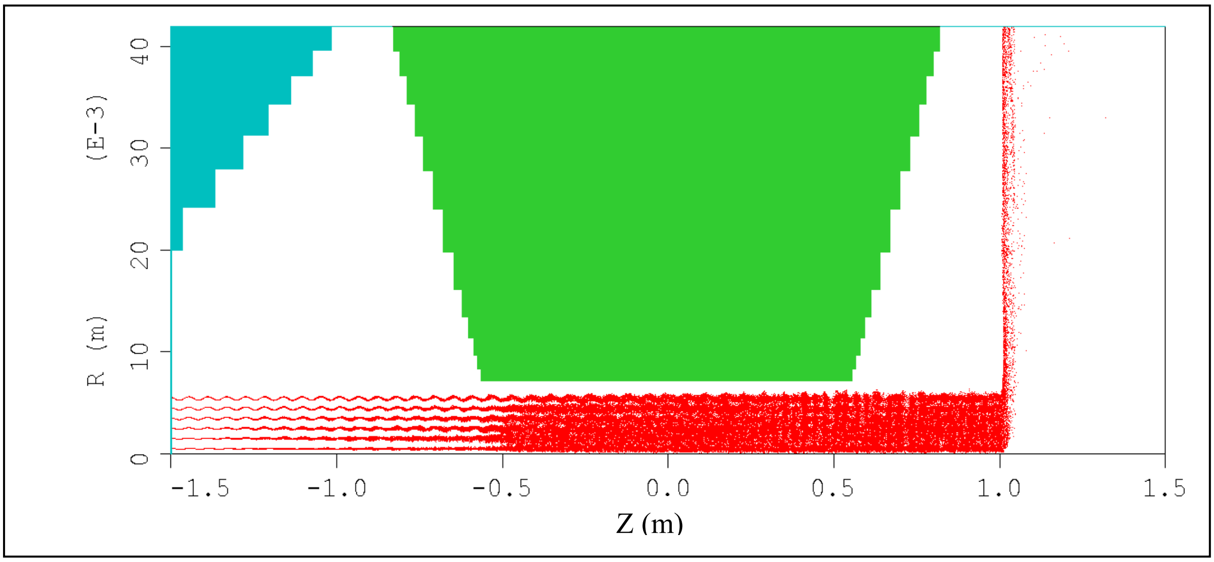

Figure 4. Geometrical illustration of MAGIC simulation showing electrons drifting through a dielectric-lined waveguide

3.2. Two-stream instability simulations

To compare with linear theory, the 2D FDTD Particle-in-Cell code OOPIC Pro was used to create a simple simulation of two co-propagating electron beams at differing velocities. This simplified simulation was undertaken to analyse the features of the two-stream instability without the complication of a background plasma. The beams are of identical radii with one propagating at a velocity of 0.4c and the other at 0.32c. Neither beam has any initial thermal velocity. The beams are contained in a waveguide of circular cross section with a radius of 32mm and are allowed to propagate over a distance of 1.02m. Both beams have the same current of 12A. In order to keep the beams superimposed on each other, a confining magnetic field of 0.1T has been used. From linear theory both the spatial growth length and temporal growth length match the observed behaviour. Further simulations in which one of the beams is replaced with a background plasma are being undertaken. This demonstrates that the presence of a confining B-field does not inhibit the two-stream instability making an experiment to observe this instability easier to design. Therefore it is possible to utilise a Penning trap type of plasma column[17].

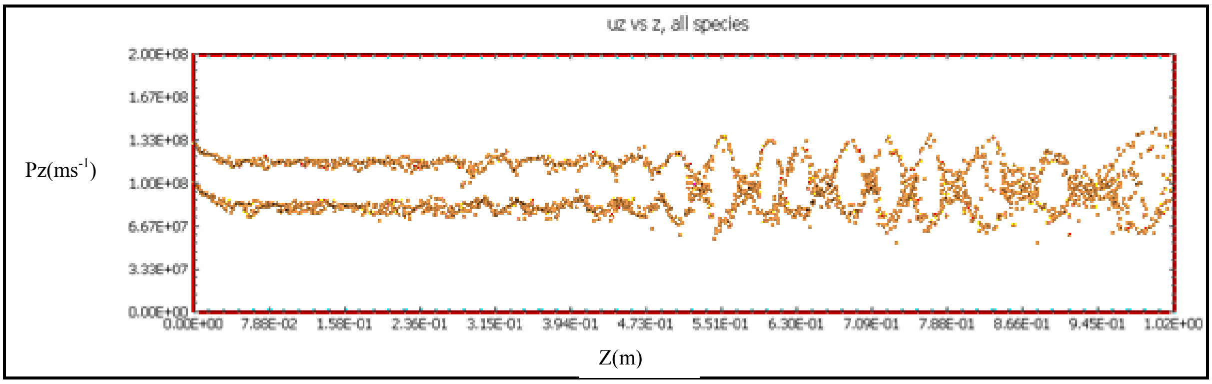

Figure 5. z-momentum of two co-propagating electron beams at 0.4c and 0.32c

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4. Summary

Initial calculations for the anomalous Doppler resonance have revealed a rich spectrum of behaviour, including the observation of a radiation signal at the correct frequency for the anomalous Doppler resonance.

The data gathered from the simplified 2D simulation of the two-steam instability for two co-propagating beams will allow for greater understanding of future simulations of the beam-plasma type two-stream instability.

Following from the results of these and ongoing simulations, an experimental setup to investigate both types of instability is being developed.

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