Investigation of the anomalous Doppler instability

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Abstract

An experiment has been constructed at Strathclyde University to investigate instabilities driven by particles accelerated along magnetic field lines.[1-3] Previously, work on cyclotron maser instabilities relevant to astrophysical radiowave generation has been studied [4-7], efforts are now directed towards modifying the system to enable research into the anomalous Doppler instability. This instability arises if an electron beam couples to an electro-magnetic mode at a negative harmonic of the cyclotron frequency. With this condition, where a particle can interact with a slow wave, it is possible for instability to occur in which the energy associated with the parallel motion of the beam goes partly into perpendicular motion of the particles and partly into the wave. Preliminary analysis will be presented to show possible experimental configurations in which the slow wave is produced either by construction of a waveguide which supports such a wave or by introducing a stationary plasma into the path of the beam. Computational simulations of electrons drifting down a magnetic field and interacting with the slow wave of a dielectric loaded waveguide are being conducted to support the theoretical analysis and to aid the design of the experimental apparatus. Initially the dispersion of the slow wave system was determined and the response of these waves to excitation by a relativistic electron beam is currently being investigated. In due course these computations shall incorporate a PiC plasma as the dielectric to allow investigation of the anomalous Doppler resonance relevant to fusion experiments.

Introduction

In a plasma which has been subject to radio frequency heating it is possible to develop a large population of electrons which drift along a bias 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 electro-magnetic wave whose energy may then be dissipated in the bulk plasma. This process is important as it is a major contribution to the heating process in a Tokamak. One wave coupling regime which may arise between rectilinear electrons and transverse slow EM waves in the plasma is the anomalous Doppler effect. [8-12] 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. This amplifies the field of the slow wave. The dynamics of this process shall be investigated in a controlled experiment and via computational simulation.

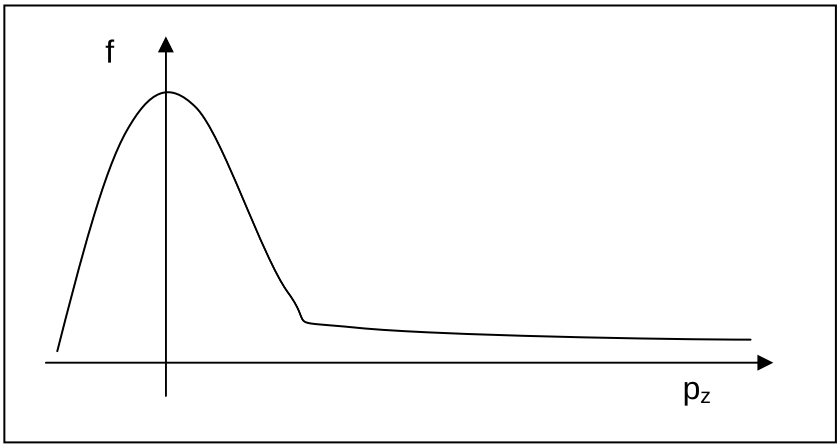

Figure 1: Electron distribution with super thermal tail

Physical Principle

The election beam initially has nearly all of its momentum along the axis of the waveguide with little transverse momentum. Electrons then experience a $v_z \times B_\perp$ 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 $v_z \times B_\perp$) exceeds the dissipation of rotational energy by the *E* field. These requirements may be satisfied by a Doppler upshifted negative cyclotron harmonic of a rectilinear electron beam drifting in a fixed magnetic field in the presence of a medium which suppresses wave phase velocity.[13] 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.

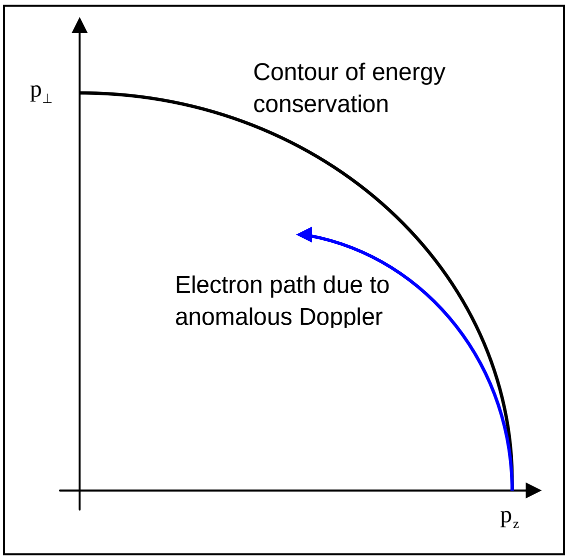

Figure 2: Relaxation of electron energy by anomalous Doppler resonance

Numerical Simulations

These preliminary simulations 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 $v_z > v_{ph}$.

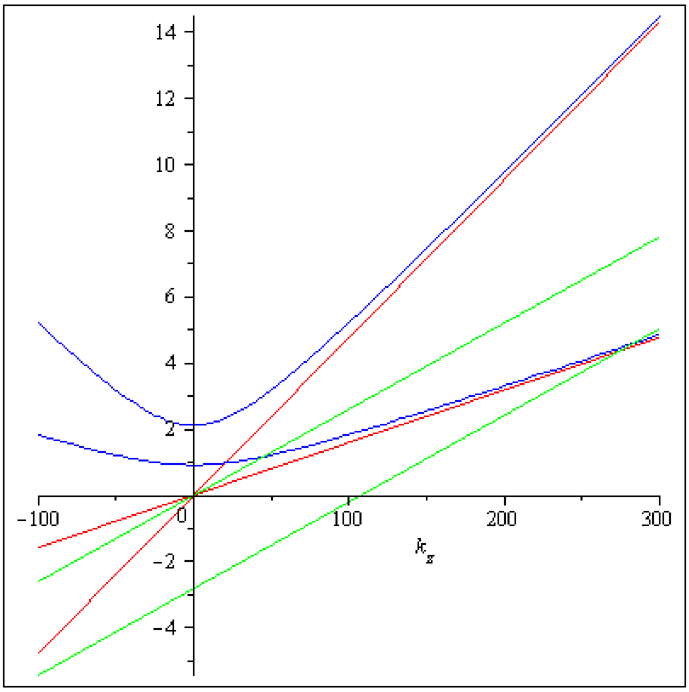

Figure 3: Dispersion showing negative beam harmonic intercepting with a wave in a dielectric loaded waveguide (solid lines) and zeroth beam harmonic and unloaded waveguide cutoff (dashed lines)

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 3). Energy is extracted from the beam into the wave before the magnetic field is turned off and the beam is dumped on the waveguide sidewall.

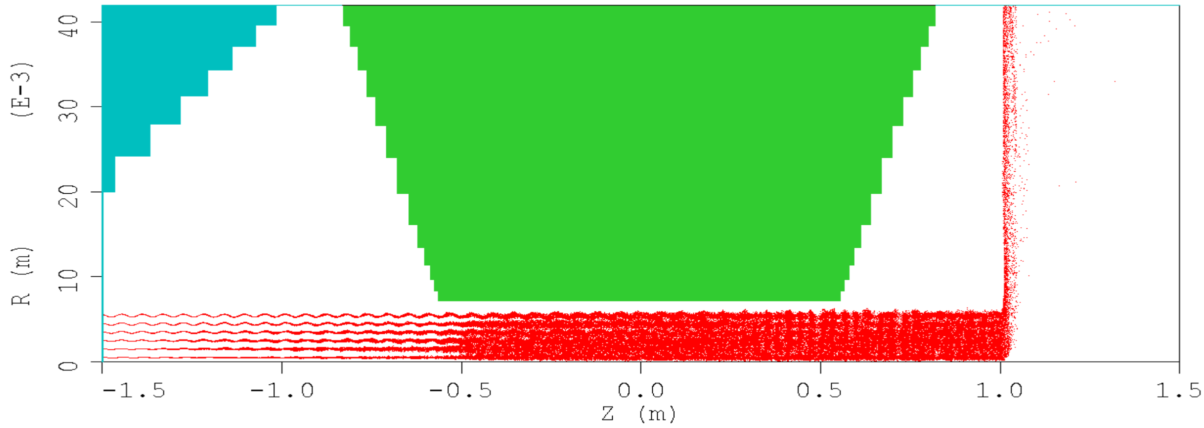

Figure 4: Geometrical illustration of MAGIC simulation showing an electron beam guided by a magnetic field passing through a dielectric lined waveguide.

Summary

Initial calculations have revealed a rich spectrum of behaviour including the observation of a radiation signal at the correct frequency for the Anomalous Doppler resonance. Results from these simulations and the schemes for experimental realisation will be discussed.

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