Numerical simulations of the anomalous Doppler resonance using 3D Particle-in-Cell code

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Abstract

The anomalous Doppler resonance is an instability that occurs due to coupling between a negative harmonic of the electron cyclotron frequency and an electromagnetic wave, as such this regime is only achievable in slow-wave media, including plasma [1] In magnetic confinement fusion experiments the generation of fast electrons by Lower Hybrid Current Drive [2], or in extreme cases Dreicer acceleration [3], can lead to the criterion for which the anomalous Doppler resonance is fulfilled.

Simulations have been developed to study non-thermal electrons drifting at relativistic velocities (upto 0.5c) along a magnetic field (0.1-2T) with a background plasma (1x10^{10} cm^{-3}) acting as the slowwave media. The simulations will be used to inform the design of a scaled laboratory experiment at Strathclyde, the results of which will be compared with the predictions of the numerical simulations and analytical theory. Once benchmarked by the experiment simulations will be further developed to investigate regimes relevant to tokamak plasmas.

Introduction

Following on from previous work at Strathclyde on the cyclotron maser instability relevant to astrophysical radiowave generation,[4-10] numerical studies of the anomalous Doppler resonance have been undertaken with deveopment towards a laboratory experiment.

Physical Principles

Consider an election beam initially moving paralell to magnetic field, with little transverse momentum, passing through a plasma. Building from noise, electrons experience the Lorentz force due to EM radiation travelling in phase synchronism with the beam. This results in acceleration of the electrons in the radial direction where work is done on the E-field.[11-13]

Providing the beam drift velocity exceeds the wave velocity, the pumping of the translational to rotational energy exceeds he dissipation of rotational energy by the E field. These requirements may be satisfied by a Doppler upshifted negative cyclotron harmonic of the electron beam interacting with the upper hybrid mode of a plasma. See figure 1.[14]

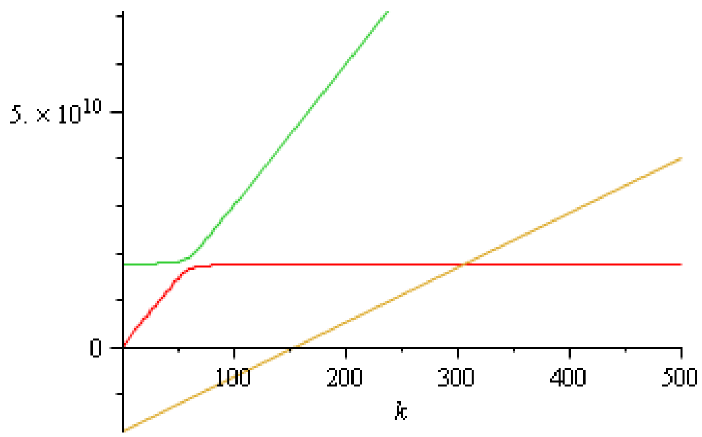

Figure 1: Dispersion diagram of the negative cycltron harmonic (yellow) crossing the Upper Hybrid mode (red)

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. See figure 2. Energy extraction in this way can be efficient as no bunching is required before beam energy is extracted.

Coupling to the upper-hybrid mode of a plasma allows the energy extracted from the superthermal tail electrons to be deposited into the bulk plasma and provide heating effects. [15]

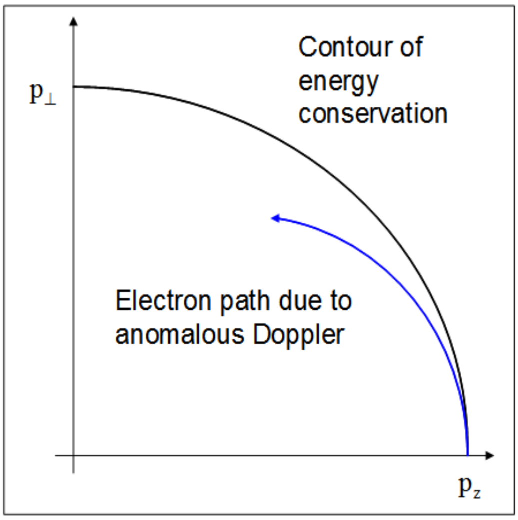

Figure 2: Contour of energy conservation showing the expected path of the superthermal electrons

Numerical Simulations

Using 3D Particle in Cell code VORPAL a neutral plasma with a superthermal tail is simulated. 10% of the electrons reside in the tail with a tapered density with increasing velocity as shown in figure 3.

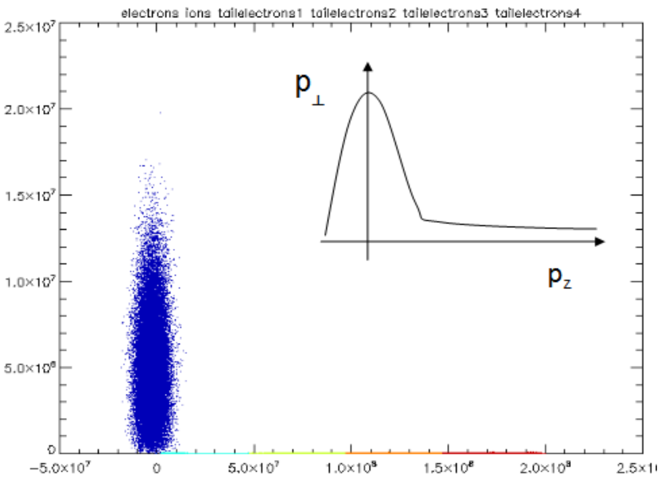

Figure 3: Simulated electron velocity distribution showing the superthermal tail

The maximum velocity in the tail is $1.4x10^{8}$ ms^{-1} with the simulation breaking the tail into discrete species to enable more detailed analysis of the interaction.

Periodic boundaries and perfectly matched layers are used to keep the particles from exiting the simulation while eliminating boundary conditions for generated EM waves.

Experiment Outline

An experiment will be carried out to test the validity of the simulations. Using a partially ionised gas to represent the background plasma and a high energy electron beam to emulate the high velocity tail electrons the anomalous Doppler instability can be observed.

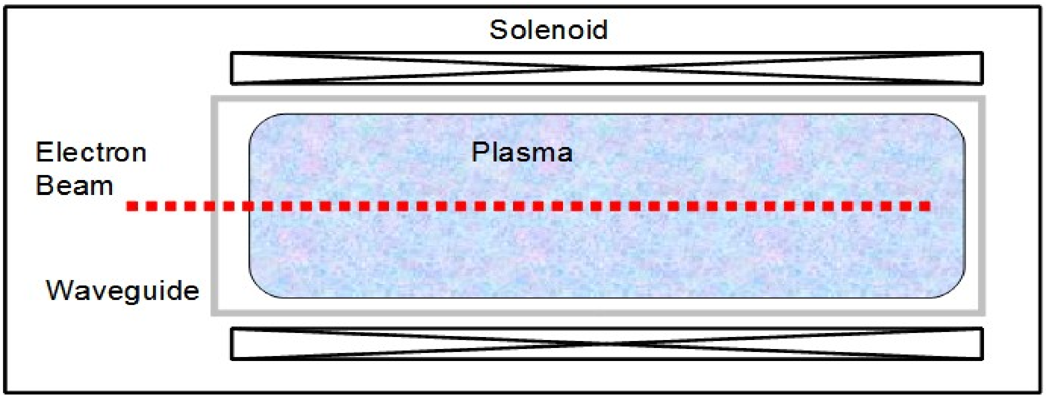

Figure 4: Outline schematic of proposed laboratory experiment

The lab environment allows a low temperature plasma with a density of approxiamately 10^{17} m^{-3} and a the use of a solenoid generating up to 0.4T. The plasma will be confined in a Penning trap which electrostatically and magnetostatically confines the electrons.

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