Numerical and experimental simulation of cyclotron instabilities relevant to the magnetosphere

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Experiments have been conducted to replicate major aspects of the electrodynamics of the polar magnetosphere. These experiments have been used to validate numerical simulations of plasma mediated cyclotron instabilities. The experiments and simulations have been found to be in good agreement, showing radiation efficiencies of ~ few % of electron kinetic energy, with wave emission preferentially into the X mode at the cyclotron frequency. These results support the proposal that the primary driver of radio wave emission in the auroral zone of the Earth's magnetosphere is the kinetic energy associated with horseshoe, or half shell, electron distributions in the descending auroral electron flux.

1. Introduction

Cyclotron coupling between electrons and waves is thought to occur in both polar and equatorial regions of the Earth's magnetosphere. Polar emissions are associated with other magnetized planets (Saturn) and stars (UV Ceti), In the terrestrial case this radiation emission is known as Auroral Kilometric Radiation [1-4]. Approximately 3200km above the Earth's surface there exists a region of plasma depletion known as the Auroral Density Cavity. Particles descend through this region towards the ionosphere following the path of the magnetic field lines. Along their descent path the particles undergo magnetic compression. Due to conservation of the magnetic moment there is a transfer of axial to perpendicular velocity leading to a horseshoe shaped distribution function forming in velocity space.

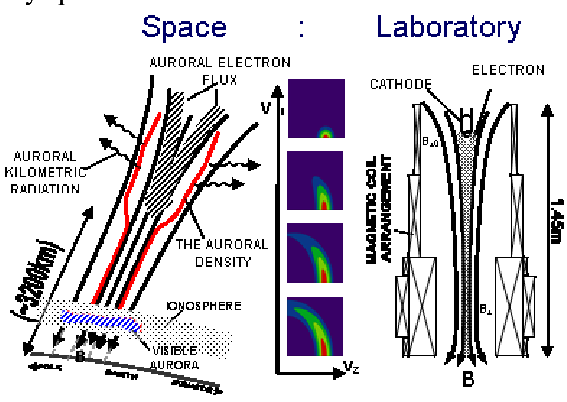

Figure 1: Comparisons in the geometry between magnetospheric and laboratory environment

Figure 1 shows a model of the evolution of this distribution alongside a schematic of the magnetospheric geometry. The horseshoe distributions have been shown to be unstable to X-mode [5] emission (as observed by satellites) by an electron cyclotron resonance maser type of instability [6-8], and are therefore proposed as the source of free energy responsible for the production of AKR in these region. To provide a controlled environment to study this naturally occurring phenomenon, a scaled laboratory apparatus experiment was constructed at Strathclyde University, Figure 1, to replicate the process.

Plasma kinetic analysis of the stability of these electron distributions have been carried out at the University of St Andrews [9,10]. These results correlate well with the experimental and numerical measurements at Strathclyde.

Experimental and numerical simulations

An experimental apparatus has been built to vestigate cyclotron emissions from an electron am moving into a waveguide with an increasing am-aligned magnetic field, scaled so that the ectron cyclotron frequency is in the microwave nds. The apparatus is shown in figure 1. onservation of angular momentum produces an ectron distribution with a high degree of velocity read, (which can be quantified by magnetic mirroring in the experiment) as expected in the natural environment.

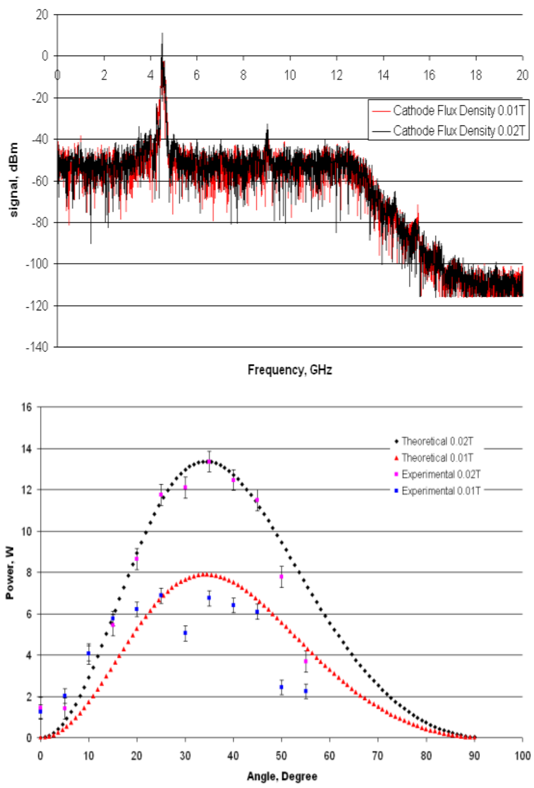

Figure 2: Operating frequency of emitted radiation, & near cut off TE_{01} mode pattern

The measurements have shown wave production efficiencies of up to a few % into near to cut-off TE modes of a cylindrical waveguide (which are similar in polarisation and propagation properties to the plasma X mode) at a frequency within a few % of the cyclotron frequency from an electron beam of 75keV energy gyrating in a magnetic field in the range 0.18-0.21T, the spectral content and TE mode excited are illustrated in Fig 2 [11]. These results correlate well with PiC simulations of the interaction waveguide excited by an electron beam whose distribution is matched to the experimental measurements [12]. The experiments, when adjusted to include a background plasma [13] clearly revealed that the wave production efficiency dropped substantially when the plasma density approached ~ 1% of critical density. This is also borne out by the numerical simulations. The numerical routines benchmarked by the experiment [11-14] have subsequently been used to simulate the cyclotron wave emissions into an unbound environment [15-17], more representative of the polar magnetosphere. These simulations have shown wave production efficiencies of up to ~1%, comparable with the magnetospheric measurements, with similar polarisation and propagation behaviour. These simulations indicated that the wave propagation is slightly off perpendicular to the bias magnetic field in the backwards wave direction. This is found to correlate well to theoretical expectations of the maximum growth direction of the instability driven by a horseshoe distribution electron beam.

3. Summary

Experimental measurements of cyclotron emission from electron beams with a horseshoe velocity distribution have been used to benchmark numerical simulation routines. Good agreement was obtained with efficiencies ~few % and preferential emission to X-like modes at the cyclotron frequency. The simulation routines are being used to simulate cyclotron emissions in an unbound environment showing similar efficiencies, polarisation and propagation to the satellite observations.

4. References

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