Investigation of auroral kilometric radiation emission processes by numerical and scaled laboratory simulations

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Introduction

In the auroral region of the Earth's magnetic dipole, horseshoe distribution functions in electron velocity space have been observed by satellites when particles are subject to magnetic compression as they descend into the increasing magnetic field within the auroral density cavity as a result of conservation of the magnetic moment. This distribution, which has been shown to be unstable to a cyclotron resonance maser type of instability, is thought to be responsible for the production of auroral kilometric radiation (AKR) in these regions [1]. The radiation produced has been measured by satellites to be polarised in the X-mode [2]. To study this phenomenon, a laboratory experiment was devised in which an electron beam with an initial velocity spread was magnetically compressed by means of a set of electromagnets. The results showed the formation of the desired horseshoe distribution. Measurements of the laboratory experiments radiation frequency, power and efficiency were investigated as a function of the magnetic compression.

Experimental Apparatus

To provide the region of increasing magnetic field a system of solenoids was created to encompass the electron beam as it traversed through the system. The solenoids were constructed using (OFHC) copper tubing wound around non-magnetic formers. Each winding was core cooled by water at 20Bar, allowing the solenoids to be driven by an electrical power of up to 120kW. Being able to control each of the solenoids independently permitted fine control of the magnetic compression profile. The electron injector was placed in the low, fringing, magnetic field generated by solenoid 1 which ensured that the electrons had an initial spread in their pitch angles. The electrons were subject to compression as they passed into solenoid 2 and reached a maximum magnetic field in the centre of solenoid 3, 0.18T. Figure 1 below shows the experimental setup of the coils within the laboratory.

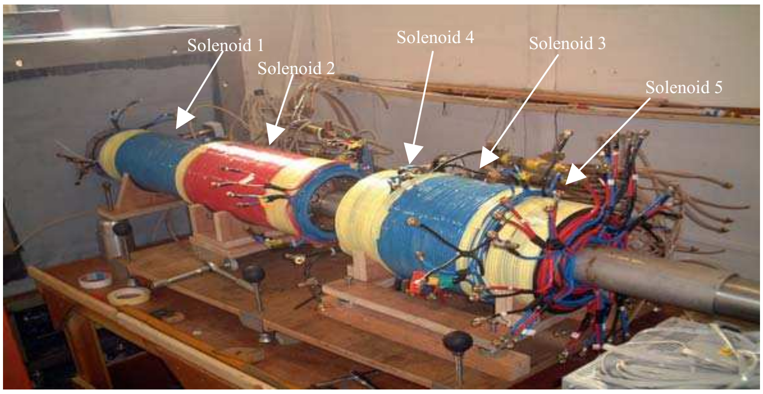

Figure 1: View of the solenoid configuration

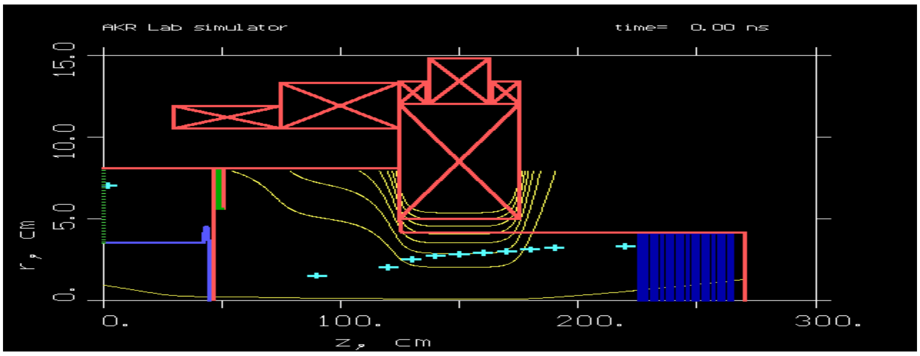

Figure 2: KARAT simulation of the experimental apparatus

The magnet solenoids determined the size of the evacuated anode can/beam tunnel and interaction space 16cm and 8 cm in diameter respectively, illustrated in Figure 2, [3]. A vacuum spark electron gun was used to inject the high voltage, short duration electron beam and was driven by a Blumlein power supply delivering 75kV, 100ns pulses. Pulses from the power supply energised the cathode and electrons were emitted due to field emission from the velvet fibres leading to the formation of a plasma cloud. The electrons were brought to cyclotron resonance in the 8cm diameter tube with near cut-off TE modes as these share similar polarisation and propagation properties with the X-mode observed in the magnetosphere.

Numerical Results

A computer program was used to work out the magnetic field configuration produced by the solenoids and these values along with dimensions of the vacuum vessel and electrodes, figure 2, were then programmed into a second program, KARAT, a 2-D PiC code used to predict the operating frequency, Figure 3a, and the output power of the experiment, Figure 3b. Phase space plots of electron bunching, Figure 3c, and formation of the horseshoe distribution, Figure 3d were also obtained. A magnetic mirror ratio of 17 gave a power of 25kW and efficiency of radiation production of 2%, whilst a mirror ratio of 9 gave 1kW with efficiency of 0.1%, at an operating frequency of 4.45GHz. Maximum efficiency was predicted to occur at a cyclotron detuning of 1%. Numerical simulations were based on mathematical theoretical studies. [4, 5]

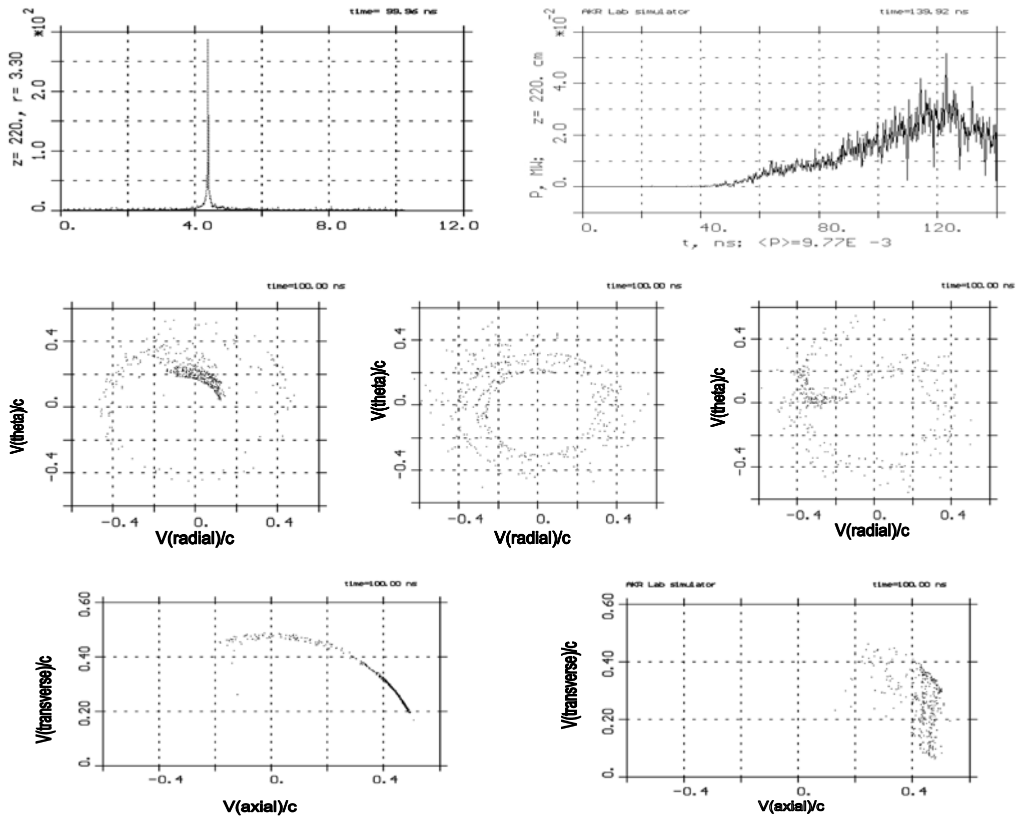

Figure 3: (a) Prediction of operating frequency, 4.45GHz, (b) Microwave output power (mirror ratio of 17), (c) Illustration of phase space bunching of electron orbits, (d) Evolution of the electron distribution function

Experimental Results

The experimental electron beam current was measured as a function of the degree of magnetic compression, controlled by the current flowing in the magnet solenoids. As the mirror ratio was decreased from 17 to 4, by increasing the flux density on the cathode, the current of the electron beam increased from 5A to 45A, shown in Figure 4a. By taking beam transport measurements of the electron beam as the maximum magnetic field was increased, evidence of the formation of the horseshoe distribution function was seen by progressive magnetic mirroring of the electrons. By Fourier transform of the AC output waveform, the operating frequency of the experiment was obtained to be 4.45GHz as expected close to cutoff for the TE_{01} mode which was confirmed by mode scan measurements of the radiation launched from the output antenna, figure 4b. Highest efficiency was obtained at a cyclotron detuning of 2.4%. Integration of the normalised antenna pattern obtained from these mode scan measurements gave output powers of 19kW and 35kW for mirror ratios of 17 and 9 and maximum efficiencies of emission of 2% and 1% respectively. [3]

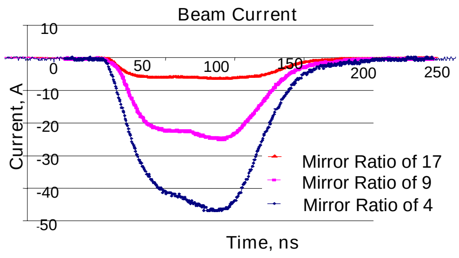

Figure 4a: magnetic mirroring data

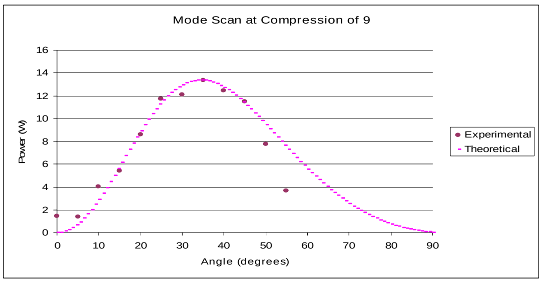

Figure 4b: antenna pattern results for TE_{01} mode

Summary

A laboratory experiment was constructed using magnet solenoids to produce a progressively increasing magnetic field profile, through which an electron beam was transported, in order to create a horseshoe distribution function in velocity space. Microwave radiation was extracted by the postulated AKR mechanism. The production of the horseshoe electron distribution function, at a maximum magnetic field corresponding to a cyclotron frequency of 4.45GHz, was shown by the beam transport measurements.

KARAT results showed instabilities at 1% cyclotron detuning, with a maximum power output of 25kW and efficiency of 2%. Microwave measurements confirmed the instability of the distribution function to cyclotron emissions, whilst frequency measurements showed the radiation frequency to be just above the relativistic cyclotron frequency. Integration of the mode scan results gave an output power value of 19kW with corresponding efficiency of up to 2% agreeing with both numerical predictions, auroral observations and high frequency laboratory measurements [6].

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References

[1] Bingham R. and Cairns R.A., Physics of Plasmas, 7 (2000) 3089.
[2] Delory G.T. et al, Geophysical Research Letters, 25 (1998) pp2069-2072.
[3] McConville S.L. et al, 2006, The 33rd Annual IoP Plasma Physics Conference, Crieff
[4] Vorgul I. et al, Physics of Plasmas, 12, 122903, (2005)
[5] Cairns R.A. et al, Physica Scripta, T116, 23
[6] Speirs D.C. et al, these proceedings