Observations of cyclotron instabilities in electron beams having a horseshoe velocity distribution

D.C. Speirs[*], K. Ronald[*], A.D.R. Phelps[*], A.W. Cross[*], R. Bingham[*,+], C.W. Robertson[*], C.G. Whyte[*], S.L. M^c^Conville[*], I. Vorgul[#], R.A. Cairns[#] and B.J. Kellett[+]

[*]*SUPA Department of Physics , University of Strathclyde, G4 0NG, Scotland, UK*

[#]*School of Mathematics and Statistics, University of St. Andrews, KY16 9SS, Scotland, UK*

[+]*Space Physics Division, CCLRC, Rutherford Appleton Laboratory, OX11 0QX, England, UK*

Introduction

Satellite observations within the Earth's magnetosphere have shown that horseshoe distribution functions in electron velocity space arise when particles are accelerated into the regions of increasing magnetic field of the Earth's dipole. These distributions have been shown to be unstable to a cyclotron resonance maser instability and are thought to be the cause for the production in the auroral regions of kilometre band radiation [1]. The radiation produced appears to be polarised in the X-mode [2]. A laboratory experiment was devised in which an electron beam with an initial velocity spread was magnetically compressed by means of a set of solenoids to investigate this phenomenon. The results showed the formation of the desired horseshoe distribution with measurements of the radiation frequency, power and efficiency obtained as a function of variation in the magnetic compression.

Experimental Apparatus

A system of solenoids was created to encompass the electron beam as it traversed through the system to provide a region of increasing magnetic field. The solenoids were constructed using copper tubing wound around non-magnetic formers. Each winding was core cooled by water at 20Bar allowing the solenoids to be run at an electrical power of up to 120kW. Independent control of the current in each solenoid permitted fine control of the magnetic compression [3]. 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 pitch angle. The electrons were subject to compression as they passed into solenoid 2 and reached a maximum magnetic field in the centre of solenoid 3, 0.48T. Figure 1 below shows the experimental setup of the coils. The solenoids determined the size of the evacuated anode can/beam tunnel and interaction region, 16cm and 8 cm in diameter respectively, illustrated in Figure 2.

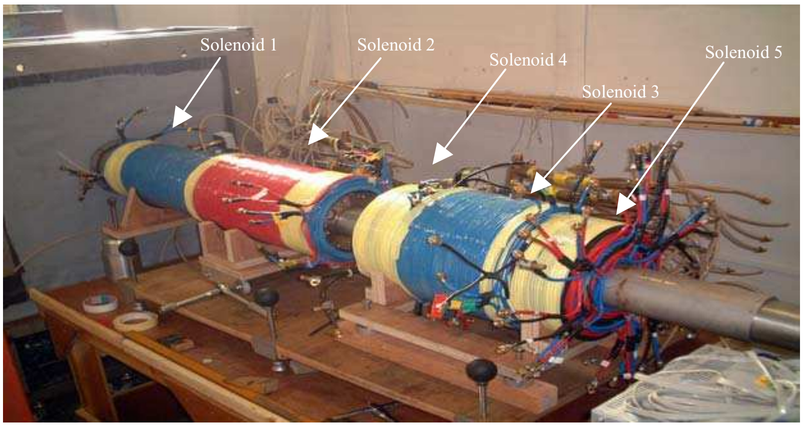

Figure 1: View of the solenoid configuration

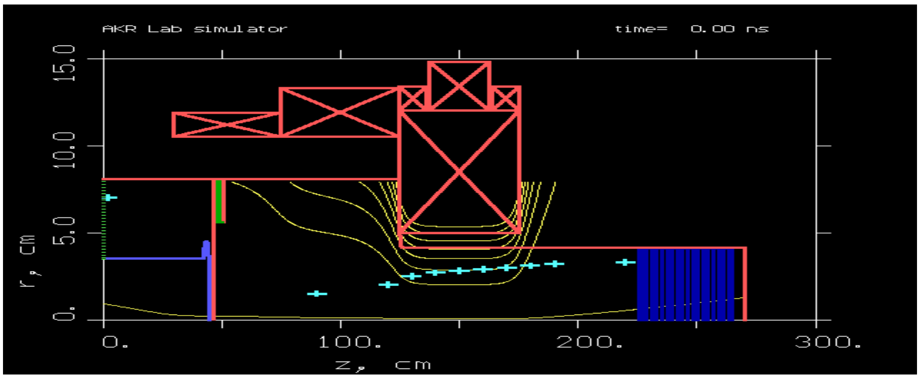

Figure 2: KARAT simulation of the experimental apparatus

A velvet coated vacuum spark electron gun was used to inject a high voltage, short duration, electron beam and was driven by 85kV, 100ns pulses from a Blumlein power supply. 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 which 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 created 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 compression ratio of 34 gave an average power of 20kW, with a peak of 60kW, and efficiency of radiation emission of 1%.

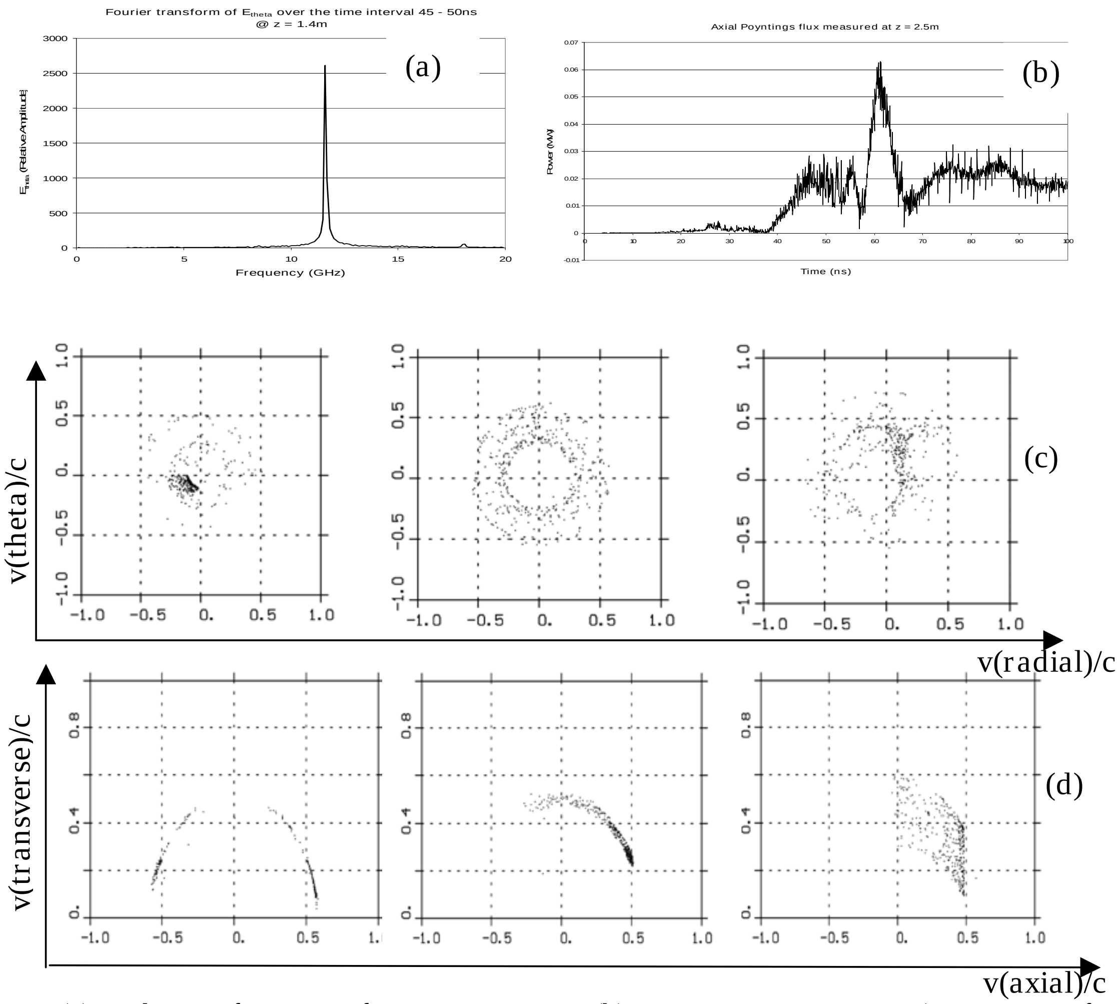

Figure 3: (a) Prediction of operating frequency, 11.7GHz, (b) Microwave output power (mirror ratio of 34), (c) Illustration of phase space bunching of electron orbits, (d) Evolution of the electron distribution function

Experimental Results

Following the numerical and theoretical analysis [4], 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 [5]. As the mirror ratio was decreased from 32 to 10, by increasing the flux density on the cathode, the current of the electron beam increased from 6A to 47A, 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 electron beam. By Fourier transform of the AC output waveform, the operating frequency of the experiment was measured to be 11.7GHz, confirmed by cutoff filters. Mode scan measurements of the radiation launched from the output antenna demonstrated mode competition the output antenna pattern switching with time, producing two time-separated peaks of power, figure 4b. Integration of the normalised antenna pattern produced output powers of 9.4kW and 7.1kW for the first and second peak respectively, for a magnetic mirror ratio of 32. For a mirror ratio of 19, output powers of 30kW and 20.5kW were obtained for the first and second peak respectively. A maximum efficiency of emission of 0.95% was obtained at a mirror ratio of 16.

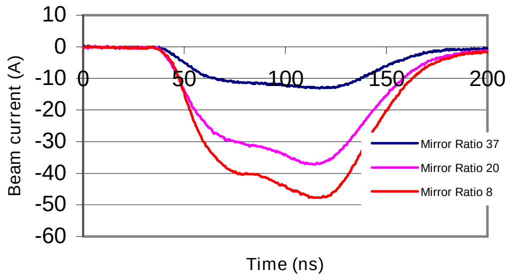

Figure 4a: magnetic mirroring data

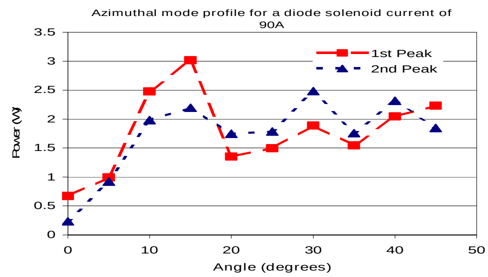

Figure 4b: antenna pattern results for compression of 19

Summary

A laboratory experiment was constructed using solenoids to produce a progressively increasing magnetic field profile, through which an electron beam was transported to create a horseshoe distribution function in velocity space. Radiation energy was extracted from the beam by the postulated AKR mechanism. Production of the horseshoe electron distribution function, at a magnetic field corresponding to a cyclotron frequency of 11.7GHz, was demonstrated by the beam transport measurements. Numerical simulations showed maximum power output of 20kW and efficiency of 1.3%. Integration of the experimental mode scan yielded power values ranging from 7.1kW-30kW with a maximum efficiency of 0.95% in good agreement with the auroral observations and a series of lower frequency laboratory simulations [6].

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