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3D PiC Code Simulations of a scaled laboratory experiment investigating AKR

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Introduction

The phenomenon of Auroral Kilometric Radiation (AKR) occurs naturally within a region of plasma depletion, the auroral density cavity, in the polar zones of the Earth's magnetosphere at high altitudes (~1.5 - 3 Earth radii). Several satellite missions, over many decades, have observed emissions from this region and with the development of technology more complex, detailed observations were undertaken [1]. Data collected from satellites have revealed the peak power emitted in AKR is ~10^9W this corresponds to an estimated efficiency of around 1% of the auroral electron precipitation energy. The radiation frequency has been revealed to extend down to the local cyclotron frequency with peak emission around 300kHz and polarised in the X mode. Electrons are accelerated into the polar regions of the Earth's magnetic dipole, and radiation emissions occur when the precipitating electrons are subject to the increasing magnetic field and experience magnetic compression as they descend in altitude towards the atmosphere [2-3]. Through the conservation of the magnetic moment, μ, this results in a horseshoe-shaped velocity distribution in the auroral electron flux. It has been speculated that the transverse momentum in the electron distribution can give rise to a cyclotron maser instability [2-5]. Computer simulations were conducted with the KARAT 3D Particle in Cell (PiC) code to investigate results from a scaled laboratory experiment built to reproduce the mechanisms of AKR generation. These simulations extended the understanding developed in previous 2D PiC code models. Simulations have investigated the mode content of the output radiation, impact of injecting a seed RF signal into the apparatus and the impact of the Doppler term in the interaction dispersion. These will allow the simulation of the spatial growth rate of the instability to compare with theoretical predictions.

Experimental apparatus

The scaled laboratory apparatus was based around a system of electromagnets, illustrated in Figure 1. The electromagnets were constructed from a series of six coils. Each coil consisted of an even number of layers wound to cancel any azimuthal components of the flux density. *Figure 1(i)* shows the experimental system of solenoids, whilst the apparatus is illustrated schematically in *Figure 1(ii)*, here the electron beam being injected from the cathode is seen passing through the solenoids and being magnetically compressed. The solenoids were core cooled by water at 20bar. A velvet coated cathode electrode energised by a Blumlein power supply, was used to inject a high voltage (75-85keV), short duration (100ns), electron beam into the increasing magnetic field. The electrons need an initial spread in pitch angle in order to produce a horseshoe distribution in the electron velocity distirubtion; this was achieved by placing the electron injector into the low, fringing, magnetic field of the electromagnets. This ensured an initial spread in electron velocity and high magnetic mirror ratio [6].

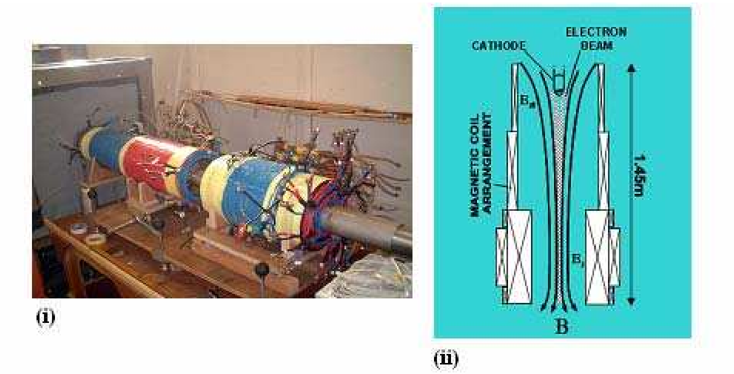

Figure 1: (i) Experimental and solenoid assembly (ii) Schematic of experimental apparatus.

The high voltage pulses from the power supply cause electrons from the cathode to be emitted through field emission from the velvet fibre tips. The field emission leads to the formation of a plasma cloud which provides for space charge limited electron emission. As the magnetospheric emissions are polarised and propagate in the X-mode the electrons were brought to cyclotron resonance in a waveguide, which was co-axial with the solenoids, with near cut-off TE modes. These modes have both the propagation and polarisation vectors normal to the waveguide axis and thus the static magnetic field.

<u>Numerical Simulations</u>

The work presented used the 3D version of the Particle in Cell code (PiC) KARAT. The simulations were undertaken to confirm and extend predictions from previous 2D PiC code simulations as 3D models can account for azimuthal structure. Two interaction regimes of microwave generation were studied, a regime at 4.42GHz where the mode expected is the $TE_{0,1}$, a relatively low order mode. The other regime was at 11.7GHz, the mode expected here was the $TE_{0,3,}$ however the system was over-moded and more representative of the magnetosphere. The corresponding magnetic plateaux were 0.18T and 0.48T respectively. *Figure 2* illustrates the bounded interaction regime of the 3D simulations, the electron beam was injected with a predefined distribution as the accelerator was not modelled due to memory constraints.

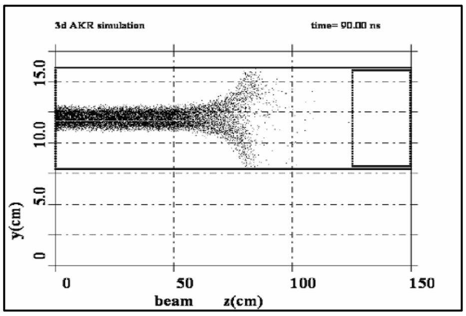

Figure (2): Electron trajectories predicted by the 3D simulation. The beam can be seen dumping into the walls.

Numerical Results

The initial simulations conducted were to expand on data produced by the earlier 2D simulations [7]. *Figure 3(i)* illustrates the modes predicted by the simulations for the 11.7GHz resonance, in this case the $TE_{0,3}$ can be seen dominating but with significant competition from alternative modes including the $TE_{2,3}$ consistent with the experiments [6,8]. The FFT for the 4.42GHz resonance is shown below in *Figure 3(ii)*, the peak frequency of emission was close to the cut-off of the waveguide for the $TE_{0,1}$ mode. There was also coupling to a second harmonic, a result predicted by the 3D simulations, which could not be anticipated by the 2D simulations [7] but is consistent with experimental measurements [6,8].

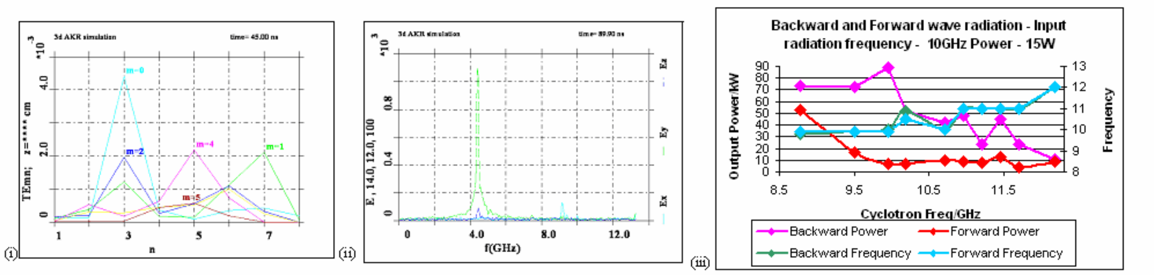

Figure (3) : KARAT results; (i) mode index showing the modes being excited by a 11.7GHz cyclotron beam. It is highly overmoded – resemblance to the magnetosphere. (ii) Spectra of the coupling with $TE_{0,1}$ mode at 4.42GHz also resonance with a second harmonic. Not predicted by 2D simulation. (iii) Doppler resonance plots produced from KARAT data.

In further work, excitation of a smaller waveguide of 2cm diameter in its fundamental $TE_{1,1}$ mode were studied as a function of the electron cyclotron frequency, input wave frequency and amplitude using the 3D version of KARAT, *Figure 3(iii)*. The objective of this study was to investigate the resilience of the resonance to the forward and backward Doppler term which appears in the dispersion relationship. It was found that moving away from cut-off, 8.79GHz, by increasing the B-field, yielded a reduction in the RF AC field. From the plots it can be seen that the backward wave has a much higher resilience to Doppler broadening compared to the forwards resonance. A peak was observed in the backward resonance at a cyclotron frequency of 10GHz. It was also established that the input wave power had no strong effect on the output spectra (although it did impact on the power). Simulations are now being undertaken to study the growth of the backward wave instability in the absence of an injected wave as the cyclotron frequency is increased above cut-off.

Conclusions and work for the future

In conducting 3D simulations a more complete interaction regime could be analysed, as modes with azimuthal indexes can be identified. The simulations demonstrated that cyclotron maser instabilities with horseshoe electron velocity distributions become weaker as they move away from transverse resonance. By analysing spectral output it was seen that the backward wave resonances are more resilient than forward wave resonances to this Doppler shift. This would suggest that the auroral process may emit with a backward wave coupling giving a spectral downshift and thus avoiding the upper hybrid stop-band [9]. As the injected wave had a minor impact on the interaction, ongoing studies (initially 2D simulations) will follow looking at self oscillation. These simulations will be used to design a modification for the experiment to allow the study of the Doppler shifted resonances and impact of injected seed signals. The results of this work shall be applied to understand the astrophysical problem both in the magnetosphere and extraterrestrial situations.

Acknowledgements

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References

[1] Delroy G.T et al, Geophys research letters 25, no 12, pp 2069-2072, (1998).
[2] Wu C.S. and Lee L.C., J. Geophys. Res., 103, 20159-20194, (1998).
[3] Bingham R. et al, Contrib. Plasma Phys. 44, 382, (2004)
[4] Twiss R.Q, Australian J. phys.11, pp564, (1958).
[5] Chu K.R, Reviews of modern physics,76, pp490-493, (2004).
[6] McConville S.L., Plasma Phys. Control. Fusion, 50 Art 074011, (2008).
[7] Speirs D.C. et al., Plasma Phys. Control. Fusion, 50 Art 074011, (2008).
[8] Ronald K. et al., Phys. of Plasmas, 15 Art. 056503, (2008).
[9] Savilov AV et al, *Phys. Plasmas* 14 Art. 113104, (2007).