An investigation of the mechanisms of Auroral Kilometric Radiation through comparative PiC modelling and laboratory experiments

K.M. Gillespie[1], D.C. Speirs[1], S.L. McConville[1], K. Ronald[1], A.D.R. Phelps[1], A.W. Cross[1], C.W. Robertson[1], C.G. Whyte[1], R. Bingham[1,2], B.J. Kellett[2], I. Vorgul[3], and R.A. Cairns[3]

[1] SUPA Department of Physics, University of Strathclyde, Glasgow, G4 0NG, Scotland.
[2] Space Physics Division, STFC, Rutherford Appleton Laboratory, Dicot,OX11 0QX, England.
[3] School of Mathematics & Statistics, University of St. Andrews, St. Andrews, KY16 9SS, Scotland.

Electron cyclotron radio emissions, known as Auroral Kilometric Radiation (AKR) originate in the X-mode from regions of locally depleted plasma in the terrestrial polar magnetosphere. A laboratory experiment was constructed to study the emission mechanism of AKR scaled to microwave frequencies [1-2]. 3D PiC simulations of the experiment were conducted to study resonant energy transfer with non-azimuthally symmetric modes of the bounding radiation structure. These 3D simulations show the backward-wave resonance has enhanced resilience to Doppler broadening of the beam-wave coupling [3]. This would suggest that the auroral process may generate radiation with a finite backward-wave component giving a spectral downshift, potentially avoiding the upper hybrid stop-band [4]. Simulations have shown the influence of the electron beam current and cyclotron-wave detuning on beam-wave coupling within the interaction region and the saturated rf output power. The results also demonstrate that cyclotron-wave coupling becomes weaker as the resonant wave moves away from near transverse propagation ($k_z > 0$). Experiments have confirmed these results and the potential for relatively efficient emission in the R-X mode at close to the electron cyclotron frequency. This may be particularly interesting where field aligned ducting of the radiation signal is relevant, e.g. chorus [5].

1. Auroral Kilometric Radiation (AKR)

Electrons precipitating into the Earth's magnetosphere are subject to increasing magnetic field with decreasing altitude. In the absence of collisions and given that the field increases slowly compared to the electron oscillation period, the adiabatic conservation of the magnetic moment comes into effect, and electrons having a small initial component of velocity perpendicular to the magnetic flux lines experience an increase in their rotational component of velocity as they descend towards the atmosphere. The effect of this process is that an initially primarily rectilinear electron beam assumes a horseshoe formation in electron velocity space with a significant number of electrons having high pitch angles across a region with a positive gradient in number density vs perpendicular velocity, $dn/dv_{\perp}$. Such horseshoe electron distributions have been measured in the AKR [1-3] source region within the terrestrial polar magnetosphere. Due to correlation between the electron cyclotron frequency and the observed AKR emission frequency, it has been hypothesized for some time that the auroral radio emissions are generated by an electron cyclotron-maser instability [4].

2. Experimental studies

The AKR generation process has been replicated in the laboratory using scaled experimental apparatus [6-10]. Figure 1 shows the apparatus used at Strathclyde, where the emission process was scaled to microwave frequencies by increasing the electron cyclotron frequency through a proportionally increased magnetic field. A velvet coated cathode emitter provided an 85keV, 100A pulsed electron beam through plasma flare emission. The beam was magnetically compressed by up to a factor of 30 and brought into cyclotron-wave resonance using a set of 6 DC magnet solenoids.

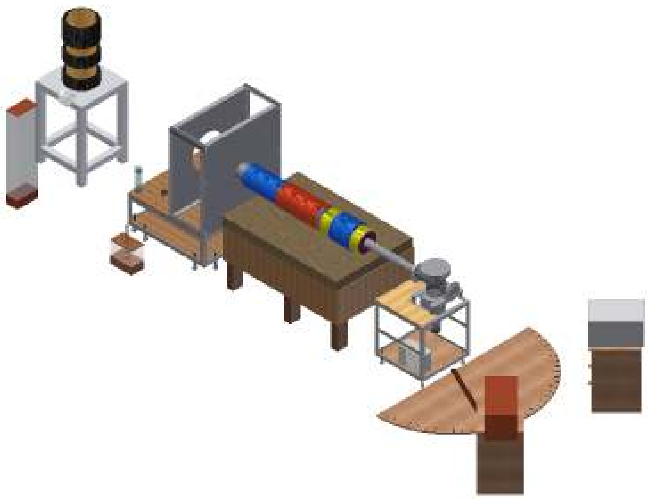
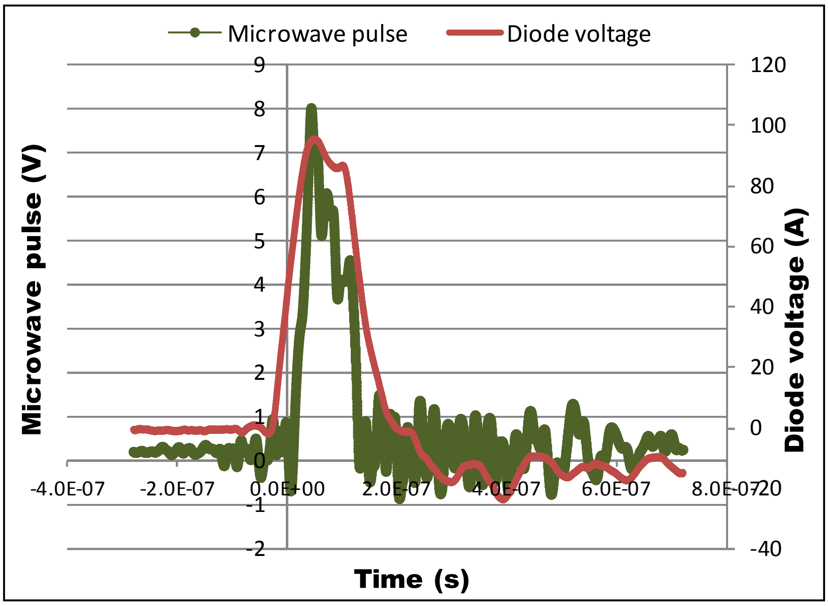


Figure 1: Experimental layout illustrating the power supply, solenoid arrangement and scanning microwave apparatus.

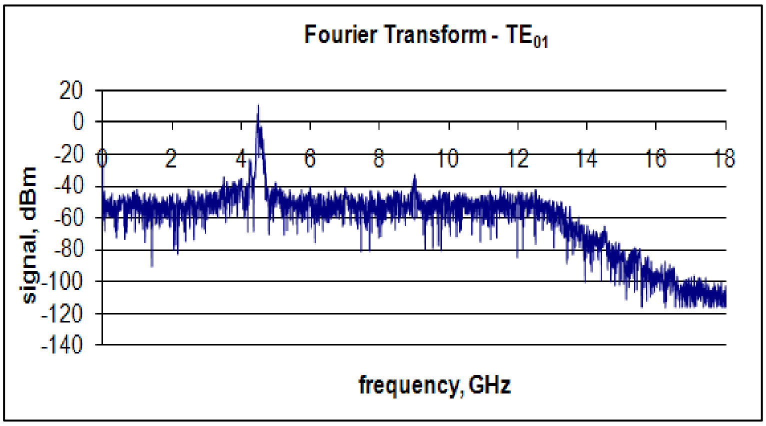
It has been shown that a full 3D PiC code model can more accurately simulate the resonant coupling between a complex electron beam and electromagnetic radiation [11]. These new simulations have proven accurate in confirming the resonant modes and mode competition occurring in the laboratory experiment. The peak rf output powers also agree well with those observed in the experiment and previous 2D simulations. Building on these earlier experiments and simulations, subsequent experimental work and numerical modelling has shown that the radiation is generated preferentially at a small angle in the opposite direction to the beam propagation, i.e. with a finite negative axial wavenumber. Analysis of the measured microwave antenna patterns has also shown that there may be an R-mode excitation along with the close to cut-off X-mode excitation.

3. Simulation and experimental results

For a resonant magnetic flux density of B=0.18T corresponding to a cyclotron frequency of 4.42GHz, microwave antenna patterns were measured for both the azimuthal and radial electric field polarisations. The measured output power was primarily associated with the azimuthally polarised E field, with an angular structure indicative of the $TE_{0,1}$ mode. At a higher magnetic flux density of B=0.192T and cyclotron frequency of 4.6 GHz, the rf output was primarily along the centre line in azimuthal polarisation, implying a $TE_{1,1}$ mode. For the experimental waveguide radius of 4.14cm and cyclotron frequency of ~4.6GHz this implies close to R-mode excitation far from cut-off of the $TE_{1,1}$ mode.



(a)



(b)

Figure 2 (a) Experimental measurements of diode voltage and diode current. (b) Fourier transform of experimentally measured microwave pulse for a cyclotron frequency of 4.42GHz.

Figure 2a contains the rectified microwave output pulse as measured by a crystal detector / pickup antenna and corresponding diode current pulse for an electron cyclotron frequency of 4.42GHz. An FFT of this microwave pulse as measured by a 12GHz digital sampling oscilloscope is presented in figure 2b. A well-defined spectral peak can be seen at ~4.42GHz, along with a second harmonic at ~9GHz. In both simulations and experiments it has been observed that as the cyclotron frequency is increased by adjusting the axial magnetic field, there is a comparably small increase in the wave emission frequency, indicating a spectral downshift and backward-wave coupling near cut-off with the $TE_{0,1}$ mode. This may have important implications for AKR generation, upward refraction / field-aligned beaming [12] and potential avoidance of absorption at the upper hybrid resonance [4].

4. Acknowledgments

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5. References

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