Investigating the mechanisms of Auroral Kilometric Radiation through comparative 3D PiC modelling and laboratory experiments

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The particle in cell (PiC) code KARAT has been used to investigate electron cyclotron radio emissions that are known to originate in the X-mode from regions of locally depleted plasma in the terrestrial polar magnetosphere. These emissions are commonly known as Auroral Kilometric Radiation (AKR). A laboratory experiment was constructed to study the emission mechanism of AKR scaled to microwave frequencies. 3D PiC simulations of the experiment were conducted to study resonant energy transfer with non-azimuthally symmetric modes of the bounding radiation structure. These simulations show a backward-wave instability to be more resilient to Doppler broadening of the beam-wave resonance than forward-wave coupling. This resilience has important implications when there is a cold, tenuous plasma in the resonant region. It would suggest that the auroral process may emit with backward-wave coupling giving a spectral downshift and thus avoiding the upper hybrid stop-band.

1. Auroral Kilometric Radiation

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. Electrons entering the Earth's magnetic dipole structure have a spread in their initial velocity. Those 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 and a region with a positive gradient in number density vs perpendicular velocity, $dn/dv_\perp$. Such horseshoe electron distributions have been measured in the Auroral Kilometric Radiation (AKR) [1-3] source regions within the polar magnetosphere. Part of the electron stream is 'mirrored', reversing its direction of motion along the magnetic field lines once all of its kinetic energy becomes associated with rotational motion providing a second energetic electron population in the auroral magnetosphere, the space bound component. Due to the correlation between the electron cyclotron frequency and the radio frequency, it has been hypothesized for some time that the emissions are due to a cyclotron instability [4].

2. Experimental studies

The AKR generation process was replicated in the laboratory in a scaled experimental apparatus [5-9]. The experiment was scaled to microwave frequencies by altering the electron cyclotron frequency through a proportionally increased magnetic field. A velvet coated cathode provides an injected electron beam through plasma flare emission; the beam is magnetically compressed by up to a factor of 30 and brought into resonance by a set of 6 DC magnet solenoids. Figure (1), illustrates the layout of the solenoids which create a convergent magnetic field reproducing the auroral geometry.

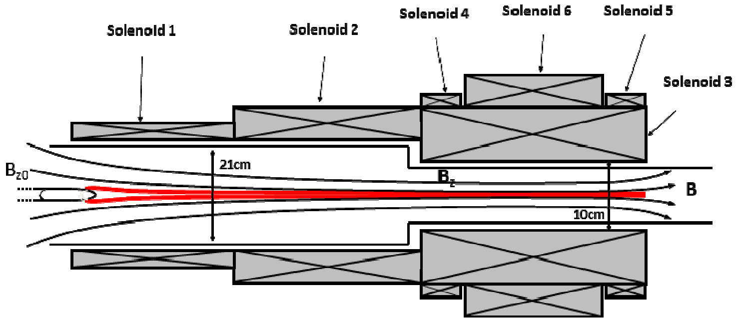


Figure 1: Experimental solenoid arrangement.

Two regimes of microwave generation were studied in these experiments. One regime was resonant at 4.42GHz, corresponding to a magnetic field of B=0.18T and for which the expected mode was the $TE_{0,1}$. In this regime the magnetic field may be increased to 0.48T to study the operating distribution function by progressive mirroring. The output spectrum from the experiment is shown in Figure 2. With a magnetic field plateaux of 0.18T the experiment generated 35kW from an electron beam of 37A and 75keV. The power & efficiency, ~1%, compares well with the efficiencies observed in the auroral cavity.

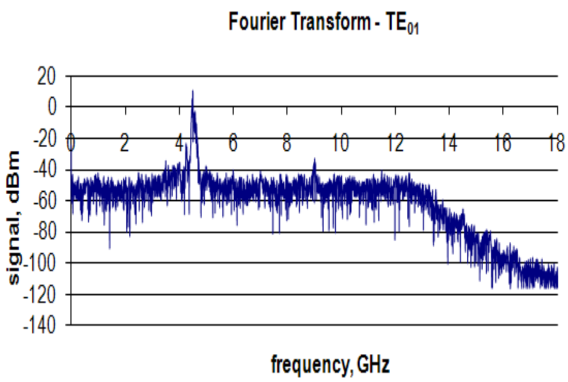


Figure 2: Spectrum of the output signal for 4.42GHz, second harmonic ~9GHz.

The second regime of microwave generation studied was 11.7GHz, corresponding to a magnetic field of B=0.48T and for which the expected mode was the $TE_{0,3.}$ This regime is highly overmoded making it more representative of the magnetosphere. The output spectrum from the experiment is shown in Figure 3. The experiment generated 30kW from an electron beam of 37A and 85keV. The power & efficiency, ~1%, compares well with the efficiencies observed in the auroral cavity.

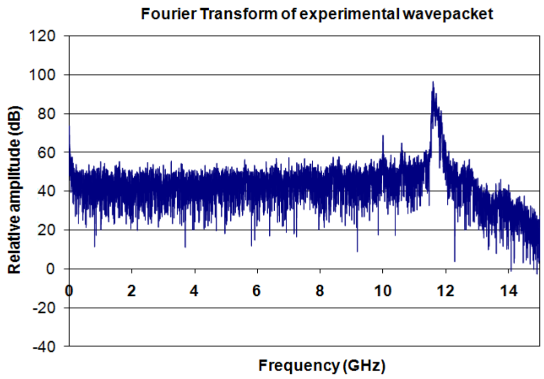
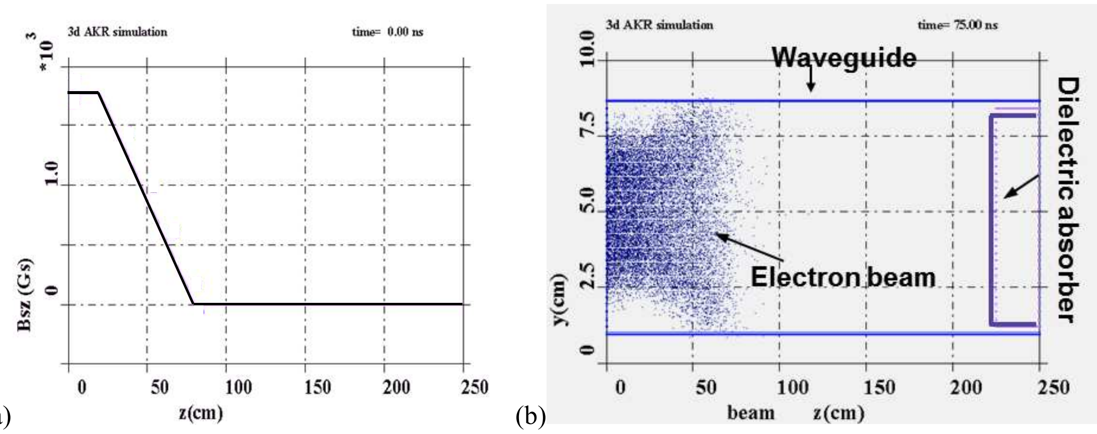


Figure 3: Spectrum of the output signal for 11.7GHz.

3. Simulation results

A uniform axial magnetic field profile was defined from 0-20cm with a linear decrease to 0T from 20-80cm as an initial condition for the PiC code, Figure 4. The 3D simulations have been used to study the excitation of radiation modes in both resonance regimes, which provide data to compare with experimental measurements and previous 2D simulations [10].



(a) (b)

Figure 4: (a) Axial magnetic field profile in simulation. (b) Simulation geometry with propagating electron beam.

In the case of the 11.7GHz regime, for a beam current of 37A, the predicted RF power output was in the range 30-180kW for a detuning of -3 to 3%. This corresponds to an RF conversion efficiency of ~1-6%, which is comparable with the previous 2D simulations and experiments. For the case of the 4.42GHz regime, the predicted RF power output was 35kW for a detuning of 2%. This corresponds to an RF conversion efficiency of ~2.6%, also comparable with the previous 2D simulations and experiments [11].

For the 11.7GHz resonance, simulations were conducted to analyse how various factors such as electron beam current and cyclotron-wave detuning influence mode excitation within the interaction region and the saturated rf output power. Typically the output power increased with detuning slightly below resonance, however, it decreased progressively with detuning above resonance. When the detuning is set slightly below resonance the peak power output is high, and it was seen that the recurring dominant mode was the $TE_{2,3}$. When the detuning increased above resonance the recurring mode excited was the $TE_{0,3}$ and the output power decreased. It was noticed that mode competition was more severe as the detuning increased above resonance.

5. Summary and future work

It has been shown that the 3D PiC codes are useful in simulating the interaction between a complex electron beam and electromagnetic radiation [10]. These new simulations have proven accurate in identifying the modes and the mode competition that existed in the experiment. The peak powers also agree well with those predicted in the experiment and previous simulations. This enhanced picture of the interaction region will prove valuable for further studies to improve the understanding of AKR and thus the general field of instability and waves in plasmas. Research will continue with simulations being conducted to refine these results investigating the sensitivity to the exact form of the electron distribution function. Analysis of experimental data will provide more insight to the mechanism of AKR and also confirm the results from simulations.

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7. References

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