Reproduction of Auroral Cyclotron Emission Mechanisms in Laboratory Experiments and 3D Simulations

Karen Margaret Gillespie
BSc Hons., MSc., The University of Strathclyde

Department of Physics
The University of Strathclyde

Thesis submitted for the Degree of Doctor of Philosophy

2013

This thesis is the results of the authors' original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

The copyright of this thesis belongs to the author under the terms of the United Kingdom Copyright Acts as qualified by University of Strathclyde Regulation 3.51. Due acknowledgment must always be made of the use of any material contained in, or derived from, this thesis.

" *It's not that I'm so smart, it's just that I stay with problems longer.* "

Albert Einstein

Let us not lose heart and become tired in doing good, for in due time & at the appointed season we shall reap, if we do not loosen and relax our courage and give up.

Dedication

I dedicate this research & thesis to Brian, Patricia & Pamela, as a symbol of gratitude

for everything they have ever, & each individually, done for me throughout my life.

I am truly thankful.

And to my husband, Craig, for his love and laughter.

ABSTRACT

Efficient (~1%) electron cyclotron radio emissions are known to originate in the X-mode from regions of locally depleted plasma in the Earth's polar magnetosphere. These emissions are commonly referred to as the Auroral Kilometric Radiation (AKR). Two populations of electrons exist with rotational kinetic energy to contribute to this effect. The downward propagating auroral electron flux which acquires transverse momentum and a horseshoe or half shell distribution in electron velocity space, due to conservation of the magnetic moment, as it experiences increasing magnetic field and the mirrored component of this flux. It is now thought that the transverse momentum in the descending distribution can give rise to a cyclotron maser instability.

KARAT 2D & 3D particle in cell (PiC) simulations were used to enhance the understanding of results from a laboratory experiment built to reproduce the mechanisms of AKR generation. In these experiments the kilometric radiation was scaled to microwave frequencies by increasing the magnetic field strength. Results from the laboratory experiment demonstrated excitation of the $TE_{0,1}$ mode of a cylindrical waveguide at 4.42GHz and the $TE_{0,3}$ mode at 11.7GHz, consistent with the 2D PiC code simulations.

3D simulations represent a significant extension to the previous work, as a two dimensional cylindrically symmetric simulation cannot account for waveguide modes with azimuthal structure. 3D simulations, as presented in this thesis, were therefore able to provide a representation of the full interaction, which more accurately describes the laboratory experiment. 3D PiC codes have been used to successfully simulate the interaction between these complex electron beams and electromagnetic radiation.

These simulations have proven accurate in predicting the radiation modes and frequencies, polarisation and propagation behaviour. The simulations predicted wave excitation with efficiencies of ~2-3%, whilst the experiment measured conversion efficiencies of ~1-3%. They predicted excitation of near-to-cut-off TE modes ($TE_{0,1}$ at 4.42GHz and $TE_{0,3}$ at 11.7GHz) consistent with the experiment and with the wave propagation and polarisation observed by satellites in the magnetosphere.

Simulations were conducted and experimental investigation extended to investigate the potential for excitation of modes away from perpendicular propagation. These showed that at small increases of cyclotron frequency above resonance with a perpendicular wave mode yielded a preference for emission in a slightly backwards propagation regime, at some ~3% below the cyclotron frequency. Inclusion of a reflector for the backward wave raised efficiency to ~7%-11%, significantly above that observed in the absence of the reflector. This may have important implications suggesting AKR emissions may be able to avoid absorption in the upper hybrid stop-band.

R-X type emission was examined, showing efficient (up to 3%) emission into waves propagating at 55^{o} from the waveguide axis and polarised in dipole-like waves at very close to, but slightly below, the cyclotron frequency.

ACKNOWLEDGEMENTS

I would first of all like to thank my supervisor Dr. Kevin Ronald. I would particularly like to acknowledge his guidance, for all his times of advice and aid he gave me whilst conducting my studies. My second supervisor Prof. Alan Phelps is thanked for times of advice and support.

Special thanks go to Dr. Craig Donaldson for his advice & guidance with computer software packages. I would also like to mention my office colleagues during my PhD, Dr. Sandra McConville & Dr. David Speirs.

Furthermore, I would like to take the time to thank Mr David Barclay for his extensive skills in making modifications to the laboratory experiment and also the ABP Group for a pleasant and cheerful working environment and for making my PhD enjoyable and for providing an environment I could be productive and fruitful in.

The National Aeronautics and Space Administration (NASA) is thanked for access to photographs for illustration purposes in my thesis. The EPSRC should be thanked for funding throughout my studies.

Finally, I would like to thank my friends and family who have shown me support throughout my university career…from the first "…why for.. ?!" & all those times of filing, sawing, retrieving Stanley knives, or getting mucky under the floorboards. Or from examples of always giving your best effort in all situations…like getting several hundred pounds off a 70 foot cruiser even though you have no intention of buying it or have a place to put it….to all those times getting to exercise my inquisitive and troubleshooting mind trying to figure out just exactly what a "wiffleduster for a hoofledinger" was. Years and years later I am proud to be able to be doing a PhD…well as I was once told "...it's useful knowing a geek; you get to know a whole bunch of cool stuff without having to learn it first..." (Don't worry Keith I remembered it was all down to you really!)

Karen Gillespie, University of Strathclyde, Glasgow 2013.

CONTENTS

Dedication..IV

Abstract...V

Acknowledgements...VII

Figure List..XV

List of tables..XXVIII

Nomenclature...XXIX

Acronyms and definitions...XXXIII

Satellites referred to in thesis...XXXVI

1. Introduction..1

1.1 Auroral Kilometric Radiation (AKR) and astrophysical sources of cyclotron radiation...2

1.1.1 AKR and other wave polarisation and propagation properties in the magnetosphere..8

1.2 Satellite observations of AKR source regions...10

1.3 The terrestrial auroral lights..15

1.4 The magnetosphere and the magnetotail...17

1.5 Principles of a scaled laboratory experimental reproduction...........................19

1.5.1 Previous AKR research at the University of Strathclyde.............................20

1.6 Research pursued in this thesis..22

2. Theory of guided electromagnetic waves, cyclotron electron beams and beam-wave instabilities...24

2.1 Electromagnetic (EM) waves...25

2.1.1 Introduction...25

2.1.2 Maxwell's Equations..26

2.1.3 Free space propagation..26

2.2 Waveguide mode theory and dispersion..28

2.2.1 Transverse electric and magnetic modes...28

2.2.2 Rectangular waveguide mode theory...29

2.2.2.1 Cut-off and boundary conditions...30

2.2.2.2 Rectangular transverse electric and magnetic modes...............................30

2.2.3 Cylindrical waveguide mode theory..31

2.2.3.1 Cylindrical transverse electric and magnetic modes.................................33

2.3 Electron cyclotron maser theory..36

2.3.1 Introduction...36

2.3.2 Particle orbit theory..38

2.3.3 Magnetic moment..40

2.3.4 Magnetic mirrors..41

2.3.5 Resonance relationships..42

2.3.6 Energy extraction & instability mechanism...45

2.3.7 Cyclotron resonance maser (CRM) instabilities – Azimuthal bunching.........46

2.3.8 Weibel instabilities – Axial bunching...48

2.3.9 The autoresonance condition……………………….................................50

2.3.10 Evolution of horseshoe electron distribution..50

2.3.11 The loss cone...52

2.3.12 Instabilities in loss cone and horseshoe distributions..................................52

3. Electron beam sources and physics..55

3.1 Emission regimes..56

3.1.1 Thermionic emission...56

3.1.2 Schottky effect..59

3.1.3 Space charge limited..60

3.2 Field emission..61

3.2.1 Fowler-Nordheim equation..62

3.2.2 Field enhancement...62

3.2.3 Latham hot electron model..63

3.3 Explosive electron emission...65

3.3.1 Cathode flare formation..65

3.3.2 Flare expansion velocity..65

3.3.3 Interaction between emission sites..66

3.4 Electron beam transport...68

3.4.1 Phase space...69

3.4.2 Liouville's theorem..69

3.4.3 Laminar and non-laminar beams..70

3.4.4 Phase fluid...72

3.4.5 Beam emittance...72

3.4.6 Busch's theorem..75

3.5 Beam focusing..76

3.5.1 Focusing with magnets – the solenoid...77

4. Experimental apparatus & diagnostics...80

4.1 Experiment overview..81

4.1.1 Overall experimental set-up...81

4.2 Experimental vacuum and interaction region..87

4.2.1 Velvet coated cathode...88

4.3 HT pulsed electrical diagnostics & supply..90

4.3.1 Blumlein generator...92

4.3.2 Ionic ($CuSO_4$) resistor...96

4.3.3 Rogowski coil...98

4.3.4 Current shunt resistor...100

4.3.5 Faraday cup...101

4.3.6 Thyratron..102

4.3.7 Spark gap..103

4.4 Solenoids...105

4.5 Microwave detection...110

4.5.1 Spectral analysis...110

4.5.2 Attenuators...110

4.5.3 Echosorb foam attenuators...112

4.5.4 Receiving antenna, antenna pattern and power analysis...........................113

4.5.5 Rectifying diodes...115

4.6 Numerical simulation...117

4.6.1 KARAT and its modelling method..117

4.6.1.1 KARAT introduction...117

4.6.1.2 Finite difference scheme of modelling..............................118

4.7 Using Maple to solve the simulation magnetic field configuration...................121

5. Results and analysis..122

5.1 Initial 3D simulations...123

5.2 Analysing the impact of beam current, detuning and velocity distribution..........33

5.3 Matching electron velocity distributions of 4.42GHz experiments and simulations...141

5.4 Experimental measurement & numerical mapping of the electron beam distribution in velocity space for B=0.11T & revised B=0.18T resonance configurations...146

5.4.1 Matching electron number density of new experimental data to simulations..148

5.5 3D simulation of electromagnetic emissions from realistic electron horseshoe distributions...151

5.6 Simulation of mode competition in high frequency experiments.......................154

5.7 Investigation of backward wave instability..160

5.7.1 Experimental and numerical comparative investigations of backward wave nature of the instability...164

5.7.2 Experimental measurements of wave polarisation, propagation and power..168

5.8 O-mode and R-mode type resonances...173

6. Discussions, conclusions and future work..181

6.1 Overview...182

6.2 Simulations demonstrating importance of velocity distribution.........................183

6.3 Experimentally consistent electron velocity distribution...................................184

6.4 Experimentally consistent 3D simulation of wave generation...........................184

6.5 Preferential backwards wave emission..186

6.6 Emission into R-like modes...188

6.7 Comparison to the magnetosphere..189

6.8 Future work...191

References...192

Appendix 1: Additional material..205

Terrestrial auroral processes...206

The aurora phenomenon...206

Experimental technical details...209

Safety interlocks...209

Vacuum systems………..210

Rotary vane pump...212

Diffusion pump...213

Vacuum gauge diagnostics...215

Backward wave coupling...216

Kinetic theory of backward-wave coupling...216

Appendix 2: Maple script...222

The Maple script used to calculate the magnetic field of the experiment in KARAT simulations...223

Appendix 3: Published papers & achievements..229

Published papers...230

Achievements throughout PhD...231

LIST OF FIGURES

1. Introduction

Figure 1.1: Representation of the AKR source region and terrestrial auroral process and the production of visible aurora as the electrons enter the ionosphere..................2

Figure 1.2: Dispersion diagrams for wave propagation, $k_\perp$ B, showing the X, O & Z branches...9

Figure 1.3: Dispersion diagrams for wave propagation, $k_{//}$ B, showing the R & L branches...9

Figure 1.4: Orbit of FAST satellite crossing the AKR region..................................12

Figure 1.5: Predicated normalised growth rates for X, O, Z mode cyclotron emissions for the range of (ω_p/ω_{ce}) mapped by ISIS...14

Figure 1.6: (a) Image of the aurora taken during a geomagnetic storm from International Space Station (ISS) (b) Aurora above the Earth taken from the ISS illustrating the green aurora [NASA space agency]...16

Figure 1.7: Illustration of auroral arcs (a) Aurora Australis captured by NASA's IMAGE satellite, (b) Image taken from Cluster satellite [NASA space agency].......16

Figure 1.8: Illustration of the Earth's magnetosphere; an area of space around a planet where the plasma dynamics are controlled by the planet's magnetic field [NASA space agency]...18

2. Electromagnetic waves and Electron beam-wave instabilities

Figure 2.1: Coordinate system used for rectangular waveguides.............................29

Figure 2.2: Diagram illustrates TE and TM modes in rectangular waveguides. Electric and magnetic fields are depicted by solid and dashed lines respectively...31

Figure 2.3: Coordinate system used for discussion of cylindrical waveguides.........32

Figure 2.4: Electric field amplitude profiles for various TE modes in a cylindrical waveguide. The different colours indicate the intensities of the electric field...........34

Figure 2.5: Field distributions of the TE modes in cylindrical waveguides.............34

Figure 2.6: Plot of the first four Bessel function...35

Figure 2.7: Beam-wave dispersion plots for two individual interaction scenarios…44

Figure 2.8: Electron cyclotron maser mechanism. Illustrated by orbits of particles in velocity space in the presence of a small external field (a) initial particle positions (b) bunched electrons after several gyrotron cycles...47

Figure 2.9 Phase bunches forming from the progression of CRM instability...........48

Figure 2.10: Representation of the Weibel instability..49

Figure 2.11: Beam cross-section and side profile of electron bunching occurring due to the Weibel instability..49

Figure 2.12: (a) shows a beam before entering the increasing magnetic field. (b) represents the horseshoe distribution that arises from the conservation of magnetic moment..51

Figure 2.13: Loss cone distribution in velocity space. As the guide magnetic field increases, the beam distribution function progressively develops a horseshoe-like profile with an increasing number of electrons residing across a positive gradient in transverse momentum at the tip of the distribution..52

Figure 2.14: A visual representation of the horseshoe distribution..........................54

3. Electron beam sources and physics

Figure 3.1: Plot representing various electron emission regimes in terms of applied electric field and resultant emitted current density...56

Figure 3.2: Energy level diagram for electrons near the surface of a metal.............57

Figure 3.3: Density of states as a function of energy..57

Figure 3.4: Fermi-Dirac distribution function..58

Figure 3.5: Kinetic energy distribution of thermionically emitted electrons.............59

Figure 3.6: Illustration of the Schottky Effect..59

Figure 3.7: Potential distribution with and without electrons in a parallel-plane diode..60

Figure 3.8: Illustration of the form of whiskers on the surface of stainless steel cathodes after exposure to fields of around 200kV/cm...63

Figure 3.9: The physical micro-regime assumed to be responsible for non-metallic electron emission processes..64

Figure 3.10: Illustration of the magnetic field effect on the cathode flare distribution density in a coaxial diode with a cylindrical graphite cathode, increasing from a magnetic field value of 0T to ~0.1T [K. Ronald]...67

Figure 3.11: Motion of beam particles viewed in configuration space (a) particle orbits in a laminar beam (b) downstream projection of particle orbits for a non-laminar distribution..71

Figure 3.12: Particle velocity/position distribution denoted by the grey area. The dashed line round the outside represents a minimum area ellipse, enclosing the distribution...73

Figure 3.13: Upright trace-space ellipse, enclosed emittance equals $x_0x'_0$ in units of π-m-rad...74

Figure 3.14: Schematic of solenoid magnet lens...78

4. Experimental apparatus & diagnostics

Figure 4.1: Photograph showing a frontal view of the full experiment and its position within the surrounding lead and concrete walls. The metre stick against the wall gives a sense of scale..82

Figure 4.2: Photograph showing different aspects of the laboratory experiment, the cathode region, solenoids and the interaction waveguide...82

Figure 4.3: Perspective drawing of experiment illustrating main components.........83

Figure 4.4: Drawing of experimental layout with position and relative size of various components in the lead and concrete shielded enclosure...84

Figure 4.5: Schematic diagram of experimental layout, showing the interconnection of key components including the power supplies, diagnostics, vacuum envelope and magnetic field systems...85

Figure 4.6: Detailed experimental layout, illustrating each component and relating this to the relevant section within the thesis..86

Figure 4.7: View of an annular dielectric velvet cathode surface, with schematic diagram illustrating dimensions and nose cone angle..88

Figure 4.8: Schematic of the velvet cathode emitter and acceleration gap................89

Figure 4.9: View of the anode mesh...90

Figure 4.10: HT pulse generation circuit..91

Figure 4.11: Experiment’s inverting double Blumlein pulse generator.....................92

Figure 4.12: Simple DC charged single cable pulser circuit…................................92

Figure 4.13: Blumlein cable pulser circuit...93

Figure 4.14: Inverting double Blumlein pulser circuit...94

Figure 4.15: Experimental inverting double Blumlein generator layout and winding arrangement...95

Figure 4.16: Blumlein ‘load’ side connections, the section inside the blue dotted lines are Rogowski belt current sensors transmitting to oscilloscopes along co-axial lines..96

Figure 4.17: Photograph of the copper sulphate ionic resistor connected to the output of the Blumlein..97

Figure 4.18: Arrangement of a Rogowski coil...98

Figure 4.19: Rogowski coil circuit, (a) Rogowski coil measurement taken of the current through $CuSO_4$ resistor, for analysis of the diode voltage. (b) Rogowski coil measurement taken along the ground return of the experiment for analysis of the diode current..100

Figure 4.20: Current shunt (a) the current shunt connected into the experiment (b) current shunt resistor, illustrating the arrangement of the resistors and copper plates with connections for current flow...100

Figure 4.21: Photograph of Faraday cup used in the experiment, surrounded by PTFE bush. This fits within the interaction waveguide of the experiment..............101

Figure 4.22: Faraday cup schematic illustrating the position of the resistor and the connection for the co-axial cable to the oscilloscope..102

Figure 4.23: Schematic of the inside of a thyratron...103

Figure 4.24: Photo of the spark gap, used as a closing switch in the double Blumlein circuit, in the experiment...104

Figure 4.25: Circuit diagram for the mid-plane spark gap.....................................104

Figure 4.26: Experimental solenoid arrangement (a) Photo of experimental solenoid arrangement, illustrating the various different coils (b) Schematic, with dimensions, of the solenoid arrangement illustrating position of the electron beam...................106

Figure 4.27: Illustration of the experimental solenoid arrangement showing the layers of the solenoids..107

Figure 4.28: Experimental solenoid arrangement..108

Figure 4.29: Experimental B-field measurement with corresponding Maple script predictions of B-field profiles..109

Figure 4.30: Screened room containing deep memory oscilloscopes, where microwave measurements were taken..110

Figure 4.31: Attenuators used in the experiment...111

Figure 4.32: Transmission loss diagram for one of the ‘Echosorb’ foam attenuators used in the 4.42GHz waveguide receivers...112

Figure 4.33: Waveguide antenna (in this case WG12) with rectifying diode..........113

Figure 4.34: Schematic circuit diagram of rectifying diode...................................114

Figure 4.35: (a) Schematic microwave detection set-up and (b) drawing of position in the experiment..115

Figure 4.36: Calibration curves for Narda and HP rectifying diodes, showing fitted 5th order polynomial..116

Figure 4.37: Vector representation of a field evaluated at the nodes of a lattice.....119

Figure 4.38: The Yee cell, this gives a representation of the integrated form of Maxwell’s equations..120

5. Results and analysis

Figure 5.1: Experimentally consistent simulation geometry, illustrating waveguide with the electron beam PiC particle trajectories of a pre-defined horseshoe distribution..124

Figure 5.2: Magnetic field profile for initial 4.42GHz simulations (peak B-field B=0.18T), 11.7GHz simulations used a similar profile with a peak B field of B=0.48T..125

Figure 5.3: Phase space plots of the electron beam in simulations, illustrating the spread in (a) transverse and (b) axial momentum due to horseshoe distribution......126

Figure 5.4: Beam current plot for 4.42GHz simulations, ~11A.............................127

Figure 5.5: KARAT output illustrating (a) Electric field vector plots from simulation illustrating excitation of the $TE_{0,1}$ mode (b) Spatial analysis of modes excited in the interaction. Here it can be seen the $TE_{0,1}$ is the predominant mode........................128

Figure 5.6: Fourier transform of electric field in a simulation tuned for 4.42GHz illustrating 2nd harmonic...129

Figure 5.7: Power output from 4.42GHz simulations, illustrating an average power ~28kW corresponding to an efficiency of ~3% which is comparable to experimental values..129

Figure 5.8: KARAT output predicting the modes excited in the high frequency (11.7GHz) interaction. Here it can be seen the $TE_{0,3}$ is the predominant mode.......131

Figure 5.9: (a) Electric field vector plots illustrating $TE_{0,3}$ mode. (b) Electric field vector plots illustrating $TE_{2,3}$ mode………………………………………………...131

Figure 5.10: Fourier transform of the E-field taken close to the source region at 0.05m over a period of t= 75-80ns, illustrating the primary resonance at a peak frequency of 11.6GHz. There is also a small peak at ~11.3GHz, indicating possible mode competition...132

Figure 5.11: Fourier transform of E-field of 1.2m downstream from the source region showing that several nanoseconds earlier the spectra has peaks at ~11.6GHz and ~12GHz...132

Figure 5.12: Output power for 11.7GHz simulations. Peak power around 17kW, which equates to an efficiency of ~2%, comparable to experiment and magnetospheric efficiencies. Note the power does not have a transient minima at zero due to the overmoding in the simulation………………………………………….133

Figure 5.13: KARAT simulation geometry used for investigation of the impact of the electron distribution function, beam current and detuning, illustrating the waveguide, the interaction solenoid, dielectric, and cross reference points and the simulation geometry. Also illustrated is the beam trajectory, and collection into the walls at z=100cm. The dielectric can be seen at z=135cm......................................135

Figure 5.14: KARAT simulation geometry illustrating electron distribution in velocity space in P_r, P_t and P_z..135

Figure 5.15: The magnetic field profile for the simulations. The plateau, B=0.1854T (which was varied in the simulations to control the detuning), is longer than the experimental magnetic field plateau of 20cm, this is to transport the beam through the tapered section in the geometry, the 'resonant' length remains 20cm................136

Figure 5.16: Electron distribution (for distribution 1) in velocity space, illustrating the injection and evolution of the horseshoe distribution from the start of the simulation t=20ns (prior to RF wave generation) to the end at t=120ns (saturated RF wave generation)..136

Figure 5.17: Resonant frequency and output power as a function of detuning ($(\omega_{ce}-\omega_{co})/\omega_{co}$), for Distribution 1 ($10^o$-$80^o$ horseshoe distribution)....................................137

Figure 5.18: Resonant frequency and output power as a function of detuning, for Distribution 2 (50^o-80^o horseshoe distribution)..138

Figure 5.19: (a) Resonant frequency and output power as a function of current for a uniform particle distribution in pitch angle (Distribution 1) and for a progressively increasing distribution (Distribution 3) for a detuning of 2.8%. (b) Fourier transform of electric field spectrum, illustrating the transition from incoherent to coherent emission with increasing time……………………………………………………..…140

Figure 5.20: Experimentally estimated variation of the electron line density as a function of pitch angle. Utilised in matching the electron distribution in 3D KARAT simulations..142

Figure 5.21: Beam current predicted by 3D KARAT simulations with electron distributions matched to experiment at a mirror ratio of 9. Fluctuation in the current at z=225-250cm is caused by an AC current in the absorbing dielectric.................143

Figure 5.22: Matching of simulation electron distribution to experimental data for a plateau/cathode mirror ratio of nine...144

Figure 5.23: Beam current input to 3D KARAT simulations for a plateau/cathode mirror ratio of 17. Fluctuation in the current at z = 225 - 250cm is caused by an AC current in the absorbing dielectric..145

Figure 5.24: Matching of simulation electron distribution to experimental data for a plateau/cathode mirror ratio of seventeen...145

Figure 5.25: Experimentally measured beam current for B=0.11T and B=0.18T regimes, mapped with increasing magnetic field, cathode B=0.01T.......................147

Figure 5.26: Experimental beam distribution for resonances at B=0.18T and B=0.11T plateau magnetic field...148

Figure 5.27: Experimentally measured beam current for B=0.11T and B=0.18T regimes, mapped with increasing magnetic field, cathode B=0.01T and the simulated beam current for B=0.11T...149

Figure 5.28: 1D electron beam distribution as a function of beam pitch angle in the simulation for B=0.11T and B=0.18T plateau magnetic field.................................150

Figure 5.29: Comparison of simulation and experimental distribution of electrons in pitch angle...151

Figure 5.30: Simulated RF wave generation calculations consistent with the electron beam formed in the experiment at a mirror ratio of 9. 0% detuning corresponds to B=0.1769T..152

Figure 5.31: Simulated RF wave generation calculations consistent with the electron beam formed in the experiments at a mirror ratio of 17. 0% detuning corresponds to B=0.1769T..153

Figure 5.32: Mode content predicted by the simulations (a) $TE_{0,1}$ mode and corresponding electric field pattern predicted at a detuning of 2% (b) mode competition between the $TE_{0,1}$ and a strong $TE_{3,1}$ mode and corresponding electric field pattern predicted at a detuning of 8%. The electron beam was consistent with that used in the experiment at a cathode B=0.02T...154

Figure 5.33: Fourier transform of electric field illustrating the peak frequency of emission at 11.7GHz. There is also a small peak at around 12GHz indicating the possibility of mode competition……………………………………………………155

Figure 5.34: An example of the axial variation of the beam current, corresponding to an injected current of 13A, predicted by 3D KARAT simulations conducted for the mode competition analysis..156

Figure 5.35: 3D KARAT output illustrating the modes excited by a 37A electron beam at a magnetic field of B=0.48T. It can be seen that at 30ns the predominant mode is the $TE_{2,3}$ with a weakly excited $TE_{0,3}$ mode , however with the elapsing of time at 50ns, the predominant mode is the $TE_{0,3}$ and the $TE_{2,3}$ is now the smaller mode. This illustrates mode competition, associated with different growth rates and saturation limits of the wave emission in these two modes. At 40ns it is clear to see that there is competition between the modes..156

Figure 5.36: (a) 3D KARAT electric field vector plots predicted by the simulations, corresponding to an injected current of 37A and a magnetic field of B=0.48T, the pattern of the $TE_{2,3}$ is becoming disordered at 30ns showing the start of the competition between $TE_{2,3}$ and $TE_{0,3}$ modes and at 50ns it is illustrating the dominant excitation of the $TE_{0,3}$ mode. (b) Plot illustrating the power variation as the excited mode transitions from the $TE_{2,3}$ to $TE_{0,3}$ mode...157

Figure 5.37: Results for mode competition simulations, illustrating how power varies with beam current and detuning, around a central frequency of 11.7GHz...159

Figure 5.38: Fourier transform of electric field for B=0.46T (a) simulation spectrum for the backward wave (b) simulated spectrum for the forward wave. More energy is coupled into the backwards wave than the forward, indicating a backwards wave resonance. This is consistent with the form of the dispersion curves where the width of the forward wave resonance increases rapidly with detuning above cut-off whilst the backward wave resonance is less severely affected..162

Figure 5.39: Fourier transform of electric field for B=0.5T (a) simulated spectrum for the backward wave and (b) simulated spectrum for the forward wave. More energy is coupled into the backwards wave than the forward, indicating a backwards wave resonance. Note that both are less well defined than Figure 5.38..................163

Figure 5.40: Backwards and forwards radiation frequencies are almost equal for both resonance conditions implying high pitch angle electrons are determining the interaction. The backwards resonance shows remarkable resilience to Doppler broadening...164

Figure 5.41: (a) Accelerating potential and diode current pulse (b) Rectified microwave output signal...165

Figure 5.42: Fast Fourier transform of the AC wavepacket taken from the Oscilloscope. Illustrating a resonant frequency of 4.58GHz. This trace was taken from experiments conducted with a step reflector……………………………….166

Figure 5.43: Experimental measurement of emission frequency as a function of the magnetic field. It can be seen that the wave frequency increases more slowly than the cyclotron frequency suggesting a backward wave instability................................167

Figure 5.44: Variation in predicted radiation emission strength & frequency as the magnetic field is tuned through resonance. The frequency increases slowly with increasing magnetic field, illustrating a backward wave resonance........................168

Figure 5.45: Experimental measurement of signal entering the receiver waveguide, for each type of reflector used, as a function of magnetic field at an angle of 30^o in azimuthal polarisation..169

Figure 5.46: Variation of power incident on $5.6\text{x}10^{-4}\text{m}^2$ aperture of the receiving waveguide (both radially and azimuthally polarised) with angular position, at B=0.184T & B=0.192T, consistent with the $TE_{0,1}$ mode (at B=0.184T). This data is for a *straight reflector*..170

Figure 5.47: Intensity variation (both radially and azimuthally polarised) with angular position for azimuthal and radial polarisation, at a cyclotron frequency corresponding to B=0.184T and B=0.192T, clear radiation pattern maximum $\sim 25^o$ at B=0.192T, indicating a $TE_{0,1}$ mode. This data is for a *tapered reflector*................170

Figure 5.48: Variation of power incident on $5.6\text{x}10^{-4}\text{m}^2$ aperture of the receiving waveguide (both radially and azimuthally polarised) with angular position. At a cyclotron frequency of B=0.192T, power is primarily radiated down the centre implying a $TE_{1,1}$ like mode. This data is for *no reflector.* With B=0.184T the pattern is similar to a $TE_{0,1}$..171

Figure 5.49: Far field patterns for $TE_{0,1}$ and $TE_{1,1}$ modes......................................172

Figure 5.50: Predictions for power and frequency variation with magnetic field detuning for O-like and R-like excitation investigations, illustrating an output frequency ~2.7GHz..174

Figure 5.51: Simulation geometry, similar to the experiment with inserted taper, illustrating the waveguide and the electron beam PiC particle trajectories of the pre-defined horseshoe distribution 175

Figure 5.52: Simulation beam current, comparable to the experiment...................176

Figure 5.53: Representation of modes being excited in simulation, illustrating dominance of the $TE_{1,1}$..176

Figure 5.54: Fourier transform of the electric field illustrating a peak frequency of emission at 2.7GHz..177

Figure 5.55 Measurement of radiation frequency as the cyclotron frequency increases in “O-mode”/“R-mode” simulations..178

Figure 5.56: Fast Fourier transform of the AC wavepacket taken from the oscilloscope, illustrating a resonant frequency of 2.66GHz. These experiments were conducted to investigate the possibility of R or O-mode excitation........................178

Figure 5.57: Intensity variation with angular position for azimuthal and radial polarisation of the detector. Magnetic field B=0.116T..179

Figure 5.58: Measurement of power output with increasing magnetic field for the R and O-mode investigation experiments..180

LIST OF TABLES

Table 5.1: Parameters for initial 4.42GHz simulations..127

Table 5.2: Parameters for initial 11.7GHz simulations…......................................130

Table 5.3: Parameters for beam current and detuning simulations.........................134

Table 5.4: Initial simulation parameters used to mould the number density distribution to that of the experiment for mirror ratios of 9 & 17. B_o is the plateau magnetic field required for resonance with the EM radiation at 4.42GHz.............. 141

Table 5.5: Values taken from experimental mirror plots used to input into KARAT to match the beam distribution...142

Table 5.6: Full simulation parameters used to mould the number density distribution to that of the experiment for mirror ratios of 9 & 17...143

Table 5.7: Parameters for mode competition analysis simulations..........................155

Table 5.8: Results for mode competition simulations, illustrating how the excited modes varied with detuning and beam current..158

Table 5.9: Parameters for initial simulations conducted for backward wave investigations at 8.7GHz – 12.18GHz...161

Table 5.10: Simulation parameters for investigation of backward wave excitation...167

Table 5.11: Parameters of simulations conducted to investigate ‘R-mode’ and ‘O-mode’ AKR emission...174

NOMENCLATURE

A_o - Richardson’s constant *($1.202 \times 10^6 Am^{-2} deg^2$)*

B - magnetic flux density

c - speed of light *($2.998 \times 10^8 ms^{-1}$)*

C - capacitance

D - electric displacement field

e - electron Charge *(1.602×10^{-19} C)*

E - electric field

E_k - kinetic energy

E_T - thermal energy

f_{co} - cut-off frequency

f_e – population density function in phase space

f_{UH} - upper hybrid frequency

f_{ce} - electron cyclotron frequency

h - Planck’s constant *($6.626 \times 10^{-34} Js$)*

H - magnetic field intensity

H - Hamiltonian

J - current density

J_o - Richardson-Dushman current density

k - Boltzmann constant *($1.381 \times 10^{-23} m^2kgs^{-2}K^{-1}$)*

k - wavevector

$k_c / k_\perp$ - cut-off wavenumber component of the wavevector perpendicular to waveguide axis

$k_{//}$ - component of the wavevector parallel to waveguide axis

m_o - electron mass *(9.109 x 10^{-31} kg)*

p - Perveance

q - charge on a particle

R_E - Earth radii

r_L - Larmor radius

T - temperature

T_c - cyclotron period

v – velocity

v_e – expansion velocity

$v_{//}$ - velocity component parallel to a magnetic field

$v_\perp$ - velocity component perpendicular to a magnetic field

$\mathbf{v}_g$ - group velocity

V - potential

v_p - phase velocity

Z - impedance

Greek symbols

α - pitch factor of electron beam ($v_\perp$ / $v_{//}$)

α_i – coefficient for the imaginary part of the X-mode dispersion relation.

β - the ‘field enhancement factor’

γ - Lorentz factor

γ_A - adiabatic parameter

ε_0 - permittivity of free space *($8.854x10^{-12}$ Fm^{-1})*

ε_r – relative permittivity of a medium

κ - resistivity

λ - wavelength

μ - magnetic moment

μ_o - permeability of free space *(4π x 10^{-7} NA^{-2})*

μ_p - $p_{//}$ / p = cos θ , *where θ is the electron trajectory polar angle*

μ_r – relative permeability of a medium

ρ - phase space density

ρ_c – cathode material density

ρ_q - charge density

$\rho'_{m,i}$ - i-th root of the differentiated Bessel function of order ‘m’

ϕ - work function

χ - height of surface potential barrier

Ψ - magnetic flux

ω - angular frequency of electromagnetic radiation

ω_{ce} - angular electron cyclotron frequency

$\omega_{cut-off}$ - minimum frequency that can propagate in a waveguide

ω_D - Doppler shifted cyclotron angular frequency

Ω_{e0} - non-relativistic electron cyclotron angular frequency

ω_L – angular Larmor frequency

ω_0 - relativistic electron-cyclotron angular frequency

ω_p - angular plasma frequency

ACRONYMS AND DEFINITIONS

AC - Alternating Current

AKR - Auroral Kilometric Radiation, a non-thermal radio emission of very high intensity that is generated by the Earth’s Auroral zone.

BNC connector - Bayonet Neill-Concelman Connector, the BNC (Bayonet Neill-Concelman) connector is a common type of RF connector. It is used for coaxial cable which connects much radio, television and other radio-frequency electronic equipment. It is usually applied for frequencies below 3GHz.

CARM - Cyclotron Auto-Resonance Maser

Classes of beam-wave instability

CRM - Cyclotron Resonance Maser

CW - Continuous Wave, term describing an experiment which produces output radiation indefinitely.

DC - Direct Current

ECM - Electron Cyclotron Maser

EE - Explosive Emission, a mode of electron emission from a cathode which involves the explosive sublimation/vaporisation of part of the cathode surface, commonly as a result of overheating of an enhanced emission site.

EM - ElectroMagnetic

FAST - Fast Auroral Snapshot Explorer Satellite, the second mission in NASA's Small Explorer Satellite Program (SMEX), is a satellite designed to study the Earth's aurora.

FEL - Free Electron Laser, a free-electron laser, or FEL, is a laser that shares the same optical properties as conventional lasers such as emitting a beam consisting of coherent electromagnetic radiation which can reach high power. It uses oscillation of free electrons in a periodic magnetic field as its gain mechanism.

HT - High Tension, high voltage electricity, for example power supply systems >1kV may be referred to as an H.T. power supply.

ID - Inner Diameter.

LRL – Line – Reflect - Line - calibration technique used for Vector network analysers (VNA).

MIG - Magnetron Injection Gun, a type of tri-electrode configuration used commonly in many C.R.M. experiments, viewed along the axis of symmetry they physically resemble a magnetron.

OFHC - Oxygen Free High Conductivity - oxygen free high conductivity copper is produced under carefully controlled conditions to prevent any contamination of the pure oxygen-free metal during processing. Characteristics are high ductility, high electrical and thermal conductivity, good creep resistance, and low volatility under high vacuum.

PiC - Particle in Cell, a particle in cell method refers to a technique used to solve a certain class of partial differential equations. PIC methods were already in use as early as 1955, even before the first Fortran compilers were available. In plasma physics applications, the method amounts to following the trajectories of charged particles in self-consistent electromagnetic (or electrostatic) fields computed on a fixed mesh.

RAL - Rutherford Appleton Laboratory, the Rutherford Appleton Laboratory (RAL) is near Didcot in Oxfordshire. RAL supports research in areas including materials, light sources, astronomy and particle physics.

RF - Radio Frequency, commonly taken to indicate the electromagnetic oscillations of frequency below ~1-3GHz.

RMS - Root Mean Square, in mathematics, also known as the quadratic mean, is a statistical measure of the magnitude of a varying quantity.

SCL – Space Charged Limited, a regime in a vacuum diode in which the current only depends on the voltage and geometry and not the material properties of the cathode.

SWR - Standing Wave Ratio, the ratio of the amplitude of a partial standing wave at an antinode (maximum) to the amplitude at an adjacent node (minimum), in an electrical transmission line. SWR is used as an efficiency measure for transmission lines, electrical circuits that conduct radio frequency signals. It is used to assess the effective connecting of radio transmitters, receivers & distributing cable. **VSWR** – **Voltage Standing Wave Ratio,** The SWR is usually defined as a voltage ratio called the VSWR.

TE - Transverse Electric, refers to solutions for bounded EM oscillations where there is no electric field in the direction of propagation.

TM - Transverse Magnetic, refers to solutions for bounded EM oscillations where there is no magnetic field in the direction of propagation.

TEM - Transverse ElectroMagnetic, refers to solutions for bounded EM oscillations where neither electric nor magnetic field is in the direction of propagation

HV/UHV – (Ultra) High Vacuum, vacuum systems can be divided into subsections for different ranges of pressures as vacuum technology extends over more than fifteen orders of magnitude. UHV corresponds to 10^{-8}mbar to 10^{-12}mbar. The AKR experiment discussed within this thesis is under high vacuum: 10^{-3}mbar to 10^{-8}mbar.

WG XX - WaveGuide, The British Standard definitions for rectangular waveguides for electromagnetic waves. The frequency range and physical dimensions are defined by the digits XX – e.g. WG 12; 3.95 - 5.85GHz.

SATELLITES REFERRED TO IN THESIS

The following passage summarises the satellite missions that have provided data for the evidence of AKR, this information is derived from NASA records.

AKEBONO - The purpose of this mission was to investigate the particle acceleration regions above the auroral zone in order to develop a better understanding of the acceleration mechanism and of its relation to substorm phenomena. The spacecraft was spin-stabilized with a rotation rate of 7.5 rpm. The attitude was magnetically controlled with the spacecraft axis pointing to the sun. All onboard operations such as command and data acquisition were controlled by an onboard computer permitting automatic operations for a full week. The satellite control and main telemetry station is at Kagoshima. **Launch Date: 21st February 1989**.

CLUSTER - The Cluster II mission is an in-situ investigation of the Earth's magnetosphere using four identical spacecraft simultaneously. It will permit the accurate determination of three-dimensional and time-varying phenomena and will make it possible to distinguish between spatial and temporal variations. Cluster II's main goal is to study the small-scale plasma structures in space and time in key plasma regions: solar wind and bow shock, magnetopause, polar cusp, magnetotail, auroral zone. **Launch date: 16th July 2000.**

DE1 - Dynamics **E**xplorer. This mission's general objective was to investigate the strong interactive processes coupling the hot, tenuous, convecting plasmas of the magnetosphere and the cooler, denser plasmas and gases co-rotating in the Earth's ionosphere, upper atmosphere, and plasmasphere. Two satellites, DE 1 and DE 2, were launched together and were placed in polar coplanar orbits, permitting simultaneous measurements at high and low altitudes in the same field-line region. The DE 1 spacecraft (high-altitude mission) used an elliptical orbit selected to allow (i) measurements extending from the hot magnetospheric plasma through the plasmasphere to the cool ionosphere; (ii) global auroral imaging, wave measurements in the heart of the magnetosphere, and crossing of auroral field lines at several Earth radii; and (iii) measurements for significant periods along a magnetic field flux tube. **Launch date: 3rd August 1981.**

FAST - Fast **A**uroral **S**napshot **E**xplorer is the second of the Small-Class Explorer (SMEX) missions. Its purpose was to investigate the plasma physics of the auroral phenomena which occur around both poles of the Earth. This was accomplished by taking high data rate snapshots with electric and magnetic field sensors, and plasma particle instruments, while traversing through the auroral regions. **Launch date: 21st August 1996.**

FREJA - The Freja spacecraft carried instruments to better understand: the processes responsible for transverse energisation of ions over the auroral oval; the nature of plasma cavities and their consequences for hot/cold plasma interactions; low-altitude electron/ion acceleration; the processes that germinate fine structures over the oval; wave phenomena and wave-particle interactions. The mission was jointly sponsored by Sweden and Germany, as a follow up to the Viking mission. It carried eight instruments to monitor the auroral phenomenon and processes. **Launch date: 6th October 1992**.

GEOTAIL - The GEOTAIL mission is a collaborative project undertaken by the Institute of Space and Astronautical Science (ISAS) and the National Aeronautics and Space Administration (NASA). Its primary objective is to study the dynamics of the Earth's magnetotail over a wide range of distance, extending from the near-Earth region (8 Earth radii (Re) from the Earth) to the distant tail (about 200 Re). The GEOTAIL spacecraft was designed and built by ISAS. **Launch date: 24th July 1992**.

HAWKEYE - The Hawkeye spacecraft (or Explorer 52) carried a payload of three scientific instruments: a plasma wave receiver, a fluxgate magnetometer, and a low energy proton-electron differential energy analyser. It was designed, built, and tracked by personnel at the Department of Physics and Astronomy, University of Iowa. The spacecraft was launched into a polar orbit with initial apogee over the north pole and re-entered on April 28, 1978 after 667 orbits or nearly four years of continuous operation. **Launch date: 3rd June 1974**.

IMAGE - Imager for Magnetopause-to-Aurora Global Exploration was a MIDEX class mission, selected by NASA in 1996, to study the global response of the Earth's magnetosphere to changes in the solar wind. IMAGE was launched March 25, 2000 into a highly elliptical polar orbit with initial geocentric apogee of 8.2 Earth radii and perigee altitude of 1000 km. IMAGE used neutral atom, ultraviolet, and radio imaging techniques to: (a) identify the dominant mechanisms for injecting plasma into the magnetosphere on substorm and magnetic storm time scales; (b) determine the directly driven response of the magnetosphere to solar wind changes; and, (c) discover how and where magnetospheric plasmas are energized, transported, and subsequently lost during substorms and magnetic storms. **Launch Date: 25th March 2000.**

IMP 6 – **I**nterplanetary **M**onitoring **P**latform 6. The IMP-6 satellite was placed in an elliptical orbit with an apogee of more than 200,000 km. The 16-sided spacecraft was 182 cm high and 135 cm in diameter. The spin axis was normal to the ecliptic, with a spin period of 10.5 seconds. The satellite was powered by solar cells and chemical batteries. The spacecraft re-entered the Earth's atmosphere on 2 October 1974. However, the gamma-ray instrument failed on 26 September 1972. **Launch date: 14th March 1971**.

IMP 8 - **I**nterplanetary **M**onitoring **P**latform 8. IMP-8 was instrumented for interplanetary, magnetotail, and magnetospheric boundary studies of cosmic rays, energetic solar particles, plasma, and electric and magnetic fields. The objectives of the mission were to provide solar wind parameters as input for magnetospheric studies and as a 1-AU baseline for deep space studies, and to continue solar cycle variation studies. IMP 8 was built and operated at Goddard, and provided important space physics data as part of NASA's Sun-Earth Connection research program.
Launch date: 25th October 1973.

ISS - **I**nternational **S**pace **S**tation, the ISS is an internationally developed research facility that is being assembled in low Earth orbit. It serves as a research laboratory that has a microgravity environment in which crews conduct experiments in many areas of science, as well as astronomical and meteorological observations. **Launch date: 20th November 1998**.

ISEE - The Explorer-class mother spacecraft, International Sun-Earth Explorer 1, was part of the mother/daughter/heliocentric mission (ISEE 1, ISEE 2, ISEE 3). The purposes of the mission were: (1) to investigate solar-terrestrial relationships at the outermost boundaries of the Earth's magnetosphere, (2) to examine in detail the structure of the solar wind near the Earth and the shock wave that forms the interface between the solar wind and the Earth's magnetosphere, (3) to investigate dynamics of the plasma sheets, and (4) to investigate the effects of cosmic rays and solar flares in the interplanetary region near 1 AU. The 3 spacecraft carried a number of instruments for making measurements of plasmas, energetic particles, waves, and fields. The mission thus extended the investigations of the previous IMP spacecraft. **Launch Date: 22nd October 1977**.

ISIS 1 - An ionospheric observatory instrumented with sweep- and fixed-frequency ionosondes, a VLF receiver, energetic and soft particle detectors, an ion mass spectrometer, an electrostatic probe, an electrostatic analyser, a beacon transmitter, and a cosmic noise experiment. The sounder used two dipole antennas (73 and 18.7 m long). **Launch Date: 30th January 1969**.

ISIS 2 - An ionospheric observatory instrumented with a sweep- and a fixed-frequency ionosonde, a VLF receiver, energetic and soft particle detectors, an ion mass spectrometer, an electrostatic probe, a retarding potential analyser, a beacon transmitter, a cosmic noise experiment, and two photometers. Two long crossed-dipole antennas were used for sounding, VLF, and cosmic noise experiments. **Launch Date: 1st April 1971**.

POLAR – was a NASA science spacecraft designed to study the polar magnetosphere and aurora. It continued operations until the program was terminated in April 2008. The spacecraft remains in orbit, though it is now inactive. Polar is the sister ship to GGS Wind. **Launch Date: 24th February 1996**.

PROGNOZ 8 - This spacecraft was a member of a continuing series to measure charged particles, plasma, magnetic fields and electromagnetic radiation. The study of solar UV, X-ray, and gamma-ray emissions was undertaken along with the monitoring of electrons and protons in interplanetary space and the magnetosphere. **Launch Date: 25th December 1980**.

PROGNOZ 10 - Designed to study the Earth's bow shock and interplanetary shocks. Carried out research in the structure of the quasi-parallel shock wave front, consisting of both the extended region of acceleration and the more narrow region of the magnetic field jump. Topics of interest included the number density and temperature of the plasma from which particles are injected into the acceleration region. It also studied other thin boundaries in the magnetosphere, magnetopause jumps of the electric field, and plasma parameters in the auroral magnetosphere**. Launch Date: 26th April 1985.**

VIKING - Viking Sweden, the first Swedish national satellite, was a polar-orbiting research satellite for exploration of magnetospheric phenomena which take place in the altitude range of 1-2 Earth radii above the auroral zones. The objective of the mission was to investigate the interactions between the hot collisionless plasmas and the cold collisionless plasmas on auroral zone magnetic field lines and to relate these processes to the detailed auroral characteristics. To investigate these phenomena, Viking Sweden was instrumented for simultaneous in situ measurements of fields, particles, plasmas, and waves. In addition, an ultraviolet imager recorded the auroras. **Launch Date: 22nd February 1986**.

VOYAGER 1 and 2 - Voyager 1 and 2 are a pair of spacecraft launched to explore the planets of the outer solar system and the interplanetary environment. Each Voyager had as its major objectives at each planet to: (1) investigate the circulation, dynamics, structure, and composition of the planet's atmosphere; (2) characterize the morphology, geology, and physical state of the satellites of the planet; (3) provide improved values for the mass, size, and shape of the planet, its satellites, and any rings; and, (4) determine the magnetic field structure and characterize the composition and distribution of energetic trapped particles and plasma therein. **Voyager 1 launch Date: 5th September 1977. Voyager 2 launch Date: 20th August 1977.**