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Laboratory Reproduction of Auroral Magnetospheric Radio Wave Sources.

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Laboratory Reproduction of Auroral Magnetospheric Radio Wave Sources

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Introduction - The Auroral Kilometric Radiation

- Intense RF emission at high altitudes (~1.5 – 3 Earth radii) within a large region of plasma depletion (the auroral density cavity), at frequencies of ~300kHz

- Discrete components of emission typically ~1kHz in bandwidth

- Within the source region the emissions have been observed to be polarised in the extraordinary (X) mode

- At certain altitudes, frequency components of emission are observed to extend down to the local relativistic electron cyclotron frequency $\Omega_{ce}/\gamma$

- These emissions are observed in conjunction with the formation of a horseshoe distribution function in electron velocity space

- Total RF output power ranges between $10^7 – 10^9$ Watts. Efficiency of emission is ~1-2% [Gurnett1974]
Electrons gyrate in close synchronism with a rotating electric field vector.

Bunching occurs due to modulation of the electron energy via the relativistic cyclotron frequency - this is fundamentally a relativistic phenomenon.

If the cyclotron frequency is slightly less than the wave frequency then net energy extraction may occur.

Saturation arises when phase trapping occurs.

$$\omega_c = \frac{eB}{\gamma m_0}$$
When an electron propagates into an increasing axial magnetic field a horseshoe distribution may arise.

Reason - conservation of the magnetic moment, $\mu$

Conversion of axial velocity $v_{//}$ into perpendicular velocity $v_{\perp}$, results in an increase in electron pitch factor, $\alpha$.

$$\alpha = \frac{v_{\perp}}{v_{//}}$$

$$\mu = \frac{mv_{\perp}^2}{2B_0}$$

$$\frac{\partial f_0}{\partial v_{\perp}} = +ve$$
Objectives

➢ To form in the laboratory an electron beam with velocity distribution comparable to the magnetosphere

➢ Scale radiation resonance to the microwave range

➢ Characterise the electron beam parameters and take microwave measurements as function of magnetic compression

➢ Compare with numerical simulation and magnetospheric results
Similar astrophysical radio sources

CU Virginis

- Recently observed by the telescopes at Jodrell Bank
- Highly reproducible L Band microwave emission from polar regions
- Strongly circularly polarised
Polarisation and dispersion

- Natural emission is in the X-mode, AC E-field and wavevector normal to static B-field
- Perpendicular wavevector can be achieved by waveguide modes near cut-off

$$\omega = \omega_{ce} + k_|| v_||$$

$$\omega_{ce} = 2\pi f_c = \frac{eB_z}{\gamma m_0}$$

$$\gamma = 1 + \frac{eV}{m_e c^2} = \left[1 - \frac{v^2}{c^2}\right]^{1/2}$$

Transverse field components for modes of cylindrical waveguides

- Near cut-off modes are required to give the correct propagation orientation and minimise the Doppler broadening
- TE modes have finite transverse electric field when $k_|| \to 0$
- TM modes have zero transverse electric field when $k_|| \to 0$
- Using TE modes near cut-off gives an approximation to the X-mode
Experimental schematic

- Corona shield
- Cathode Emitter
- Anode mesh assembly
- Water-cooled D.C. solenoid arrangement
- Solenoid 1
- Solenoid 2
- Solenoid 3
- Solenoid 4 (shim coil)
- Solenoid 5 (shim coil)
- Solenoid 6
- Faraday cup
- 25Bar, 1200 litres/min water pump
- Cooling radiators for recirculated water (120kW thermal capacity)
- Mylar output window
- cm-wave diagnostics
- Diffusion & Rotary pump
- Lead walls
- Blumlein Cable Pulsar
- 100 kV, 40 mA Power Supply
- Manually triggered pulse generator (5% rise)
- 30V, 250A Current Supply
- 70V, 300A Current Supply
- 70V, 300A Current Supply
- 70V, 600A Current Supply
- 200V, 310A Current Supply
- Screened Room

- 228 Ohm CaSO4 resistor
- 2.360 Ohm Current Slew
- Rogowski coil
- Pressurised midplane Spark-gap
- 100 MΩ
- 200 MΩ
- 1 MΩ
- Thyatron
Insulated OFHC copper tubing, 7mm OD, 2mm ID (total length >1km) wound on non-magnetic formers, tubing is core cooled by water at 20Bar

Drive 5 solenoids independently up to 300A with 120kW DC power supplies

Flexible control of the magnetic field configuration
Solenoid 1: 4 Layers, Length = 0.5m, $R_i = 0.105m$, Current = 75A.
Solenoid 2: 2 Layers, Length = 0.45m, $R_i = 0.105m$, Current = 60A.
Solenoid 3: 10 Layers, Length = 0.5m, $R_i = 0.05m$, Current = 250A.
Solenoid 4: 2 Layers, Length = 0.11m, $R_i = 0.12m$, Current = 250A.
Solenoid 5: 2 Layers, Length = 0.11m, $R_i = 0.12m$, Current = 250A.
Vacuum spark electron injector

- Velvet electron emitter secured to a planar metallic surface facing a sparse mesh
- Cathode energised by a double Blumlein pulser generating over 75kV
- Field emission from velvet fibres combined with dielectric avalanche and surface flashover leads to a cathode plasma flare
- Space charge limited emission into vacuum gap
- Mesh concentrates electric field close to cathode
Solenoid sizes set by power and cooling constraints
- Sets dimensions of the rest of the apparatus
- Electron gun region 16cm in diameter
- Resonant region 8cm diameter and 20cm length
- Maximum possible fill factor ~50% (radius)
- Evacuated to <10⁻⁶mBar
Electrical diagnostics

➤ Diode voltage:
  Matching resistor (230Ω) in shunt with accelerator
  Current measured by a Rogowski belt

➤ Diode current:
  Rogowski belt (in ground connection of anode)

➤ Beam current:
  Faraday cup feeding 50Ω shunt resistor

➤ Cup shaped to inhibit secondary escape
Microwave detection: Amplitude and Spectrum

- Waveguide 12 (single mode at 4.42GHz) or Waveguide 18 (single mode at 11.7GHz) antenna in far field of experiment output
- Fitted with calibrated attenuators
- Signals delivered to calibrated rectifying diodes
- Rectified signals measured on a 1.5GHz digital oscilloscope
- Spectrum measured by FFT of AC waveform captured by 12GHz DSO
Microwave detection: Polarisation and Propagation

- Waveguide stub receiving antenna - output pattern and polarisation
- Waveguide attenuators and rectifying diodes - operating efficiency
Experimental and numerical studies

➤ Beam formation investigated, numerically and experimentally

➤ Two regimes of radiation generation were studied:

➤ 4.42GHz resonance, plateau B=0.18T
   - Expected mode $\text{TE}_{0,1}$
   - Relatively low order mode and magnetic flux density
   - Potential to measure the electron velocity distribution

➤ 11.7GHz resonance, plateau B=0.48T
   - Resonant mode $\text{TE}_{0,3}$
   - Highly overmoded, $\lambda \ll D$, high magnetic flux density
   - Chosen as most representative of magnetosphere
Experimental results: Beam formation

0.18T on main coil, beam voltage 75kV:
- Mirror Ratio of 17 gave $I_{beam}$ of 12A
- Mirror Ratio of 9 gave $I_{beam}$ of 34A
- Mirror Ratio of 4 gave $I_{beam}$ of 44A
Progressive decrease in current with increasing mirror ratio

-Demonstrates formation of horseshoe distribution
Estimation of 1D number density

Line Density vs pitch angle

- Cathode B=0.02T
- Cathode B=0.011T

Pitch angle is $\arctan\left(\frac{v_\perp}{v_z}\right)$
4.42GHz Numerical simulations

- Geometry programmed into KARAT, a 2D axi-symmetric PiC (Particle in Cell) code
- Highest $\eta$ at 1% cyclotron detuning
  - Cathode B=0.011T, power ~20 kW, $\eta=1.7\%$
  - Cathode B=0.02T, power ~50kW, $\eta=2\%$
2D Simulations: Electron velocity distributions
4.42GHz 3D Simulations
Microwave spectral measurements - 4.42GHz

- 12GHz Real-time oscilloscope
- AC waveform captured
- Fourier transform gives frequency

AC signal - TE\textsubscript{01}

+ Spectral peak at \sim 4.42GHz
+ Close to cut-off for TE\textsubscript{01}
+ Second harmonic at \sim 8.84GHz
Microwave amplitude and polarisation measurements at 4.42GHz

Integrated antenna pattern:

Radial polarisation gave no output

Azimuthal polarisation:
  Cathode B=0.011T ~ 19 kW
  Cathode B=0.02T ~ 35 kW

Results consistent with 1D number density measurements

Max efficiencies of ~2% for mirror ratio of 17, despite lower power

Highest $\eta$ at cyclotron detuning 2.4%
Comparison of numerical and experimental results

1D Number Density Distribution with pitch angle

- Cathode flux density 0.01T, Op I = 11.57A
- Cathode flux density 0.02T, Op I = 33.92A
- Cathode flux density 0.01T, Op I = 16A
- Cathode flux density 0.02T, Op I = 34A

Pitch angle/Deg

For cathode flux density 0.01T

<table>
<thead>
<tr>
<th>Exp</th>
<th>Num</th>
</tr>
</thead>
<tbody>
<tr>
<td>I_{in} = 121A</td>
<td>I_{in} = 18A</td>
</tr>
<tr>
<td>I_{out} = 11.57A</td>
<td>I_{out} = 16A</td>
</tr>
<tr>
<td>P_{out} = 19kW</td>
<td>P_{out} = 20kW</td>
</tr>
</tbody>
</table>

For cathode flux density 0.02T

<table>
<thead>
<tr>
<th>Exp</th>
<th>Num</th>
</tr>
</thead>
<tbody>
<tr>
<td>I_{in} = 208A</td>
<td>I_{in} = 35A</td>
</tr>
<tr>
<td>I_{out} = 33.92A</td>
<td>I_{out} = 34A</td>
</tr>
<tr>
<td>P_{out} = 35kW</td>
<td>P_{out} = 50kW</td>
</tr>
</tbody>
</table>

Pitch angle is arctan(v_{⊥}/v_{z})
11.7GHz 2D Numerical Results

Fourier transform of Etheta over the time interval 45 - 50ns @ z = 1.4m

Axial Poyntings flux measured at z = 2.5m

Efficiency 1%

Power (MW)

Time (ns)

Frequency (GHz)

Efficiency 1%
11.7GHz 3D Numerical Simulations

- Power (MW) vs. time (ns)
- Ey (relative amplitude) vs. F (GHz)
- 3d AKR simulation at time = 90.00 ns
- 3d AKR simulation at time = 45.00 ns
Microwave Spectral Measurements - 11.7GHz

- Spectral peak at 11.7GHz
- Evidence of backward wave Doppler downshift component
- Close to cut-off for TE_{03}
- Close to CRO Bandwidth
- Check with waveguide filters

AC output 0.48T
\(\frac{B_z}{B_{z0}} = 16\)

Rectifying crystal output with filters

Fourier Transform of AC wave

Time (ns)

Amplitude (V)

Frequency (GHz)

Relative amplitude (dB)

Signal amplitude (V)

Time (ns)
Microwave amplitude and polarisation measurements at 11.7GHz

- Antenna Pattern indicated complex mode mixture
- Dominant mode changed with time
- Mode competition and hopping
- Radiation in both polarisations
- TE_{03} and TE_{23} modes present
- Integration of antenna pattern
- Max efficiencies of ~1% with peak output power ~20kW
Conclusion

- Succeeded in forming electron beam with Horseshoe velocity distribution
  - Number density mapped as a function of pitch angle
- Numerical simulations predict instabilities with efficiencies ~1-2%
- Microwave measurements confirmed instability of distribution to cyclotron emissions
  - Radiation frequency slightly > relativistic cyclotron frequency
- The antenna pattern measurements illustrated near cut-off TE modes as numerically predicted
- Experimental efficiencies comparable with the numerical predictions
- Wave polarisation, propagation similar to X mode
- Generation efficiencies compare well with some auroral estimates
Future work

Investigate Doppler shifted regimes of resonance
- Measure the resilience of the instability to parallel propagation
- Build convective experiment to measure spatial growth rate

Bridge gap to unbounded geometry
- Numerical simulations underway to study cyclotron instabilities in the absence of ‘hard’ radiation boundaries

Investigate influence of background plasma
- Numerical studies underway of magnetised-plasma loaded waveguides
- Experimental modification to include a plasma background- possibly a quasi-Penning trap

Acknowledgements

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