Electron cyclotron emission measurements at the stellarator TJ-K

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Introduction
The electron temperature $T_e$ can be measured by means of Langmuir probes for low temperatures only. The use of a Langmuir probe is an invasive procedure that could significantly perturb the plasma, and the accompanying evaluation of the characteristics sets the minimum expenditure of time for $T_e$ profile measurements. As an alternative, the temperature can be measured using the electron cyclotron emission (ECE) that is generated by the gyration of electrons in magnetised plasmas. Magnetic field gradients in the plasma lead to a spatial distribution of emission frequencies and thus the possibility to relate the measured intensity at a given frequency to its point of origin. The temperature dependence of the intensity then leads to a temperature profile along the line of sight when a Maxwellian velocity distribution is present. When no Maxwellian velocity distribution is present, the emission spectrum changes heavily so that non-thermal electrons can be detected. It is shown by simulations that these non-thermal electrons move on drift orbits which can lead to toroidal net currents. Such currents have been previously observed in TJ-K.

The stellarator TJ-K
- Major radius: $R = 0.6\ m$
- Minor radius: $a = 0.1\ m$
- Magnetic field: $B_\| \leq 0.5\ T$
- Microwave heating: $3\ kW$ at $2.45\ GHz$
- $6\ kW$ at $14\ GHz$
- Max. pulse duration: $45\ min$ (2.45 GHz)
- Ion temperature: $T_i \approx 20\ eV$
- Electron density: $n_e \approx 5 \times 10^{19}\ m^{-3}$
- Rotational transform: $\eta = 0.3$

$T_e$ measurements with probes and ECE
- Insertion of an electrode into the plasma
- Measurement of $I(V)$ characteristics
- Perturbation of the plasma parameters (invasive)
- Limited to moderate temperatures and densities
- Local measurement, obtaining radial profiles is time consuming
- Electron cyclotron emission measurements
  - Analysis of emitted radiation: power vs. frequency (non-invasive)
  - Fast information about temperature along line of sight
  - Time resolved measurements
  - Detection of non-Maxwellian energy distributions

Electron cyclotron emission theory
- Electron gyration as accelerated motion leads to emission of electromagnetic radiation
- Emittted frequency determined by local magnetic field strength $\omega_{ce}(r) = \frac{eB(r)}{m_e}$
- Black body emission intensity approximated by Rayleigh-Jeans’ law $I(\nu, T_e) = \frac{2}{3} k_B T_e$
- The combination of $I(\nu, T_e)$ and $\omega_{ce}(r)$ can be used to calculate the $T_e(r)$ profile along the line of sight
- Reduction of measured intensity compared to black body intensity due to small optical depth $\tau_e$. $I(\nu) = (1 - e^{-\tau_e}) \times I(\nu)$
- Optical depth for $16\ GHz$ in TJ-K on the range of $10^{-4}$
- Further factors to determine: radiation transport, appropriate velocity distribution function, non-thermal electrons, Doppler broadening and relativistic broadening

ECE measurements
- The $8\ GHz$ klystron at TJ-K is used to heat the plasma via electron cyclotron resonance heating.
- Electron cyclotron emission measurements are conducted in the range from $10$ to $19\ GHz$ in order to detect the second harmonic of the emission.
- The emission is received by a horn antenna and fed to a waveguide. A waveguide with a cut-off frequency of $f_c = 9.5\ GHz$ is used to block the high power $8\ GHz$ heating radiation in order to protect the electronics.
- The signal at the waveguide output is amplified with a low noise broadband amplifier, fed to a spectrum analyser and recorded by a PC data acquisition system.

Linking ECE to net currents
- Particles starting at the outer side of the torus with clockwise winding $B$ are considered
- Gradient drift $\approx \nabla T_e$ and curvature drift $\approx \frac{V_B}{c}$ show drift orbits that significantly deviate with speed $\nu$ and the magnetic field $B$
- Drift orbits larger than the flux surfaces can lead to particle losses due to electrons leaving the confined region
- Losses of electrons with one orientation lead to a net current

Numerical simulations
- Drift orbits are calculated using a field line tracing code.
- Electron trajectories (guiding centre approximation) are computed with particle injection parallel and antiparallel compared to the magnetic field for various ratios $\eta$ and various speeds.
- Detection of the maximum distance between drift orbit and flux surface
- Relativistic electrons show distances in the centimetre range

Summary
- First ECE measurements at the second harmonic were successfully conducted
- More sensitive measurements will be conducted
- Simulations for high energetic electrons in TJ-K show drift orbits that significantly deviate from the flux surfaces
- Drift orbits are believed to explain previously observed toroidal net currents