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Electron cyclotron emission measurements at the stellarator TJ-K

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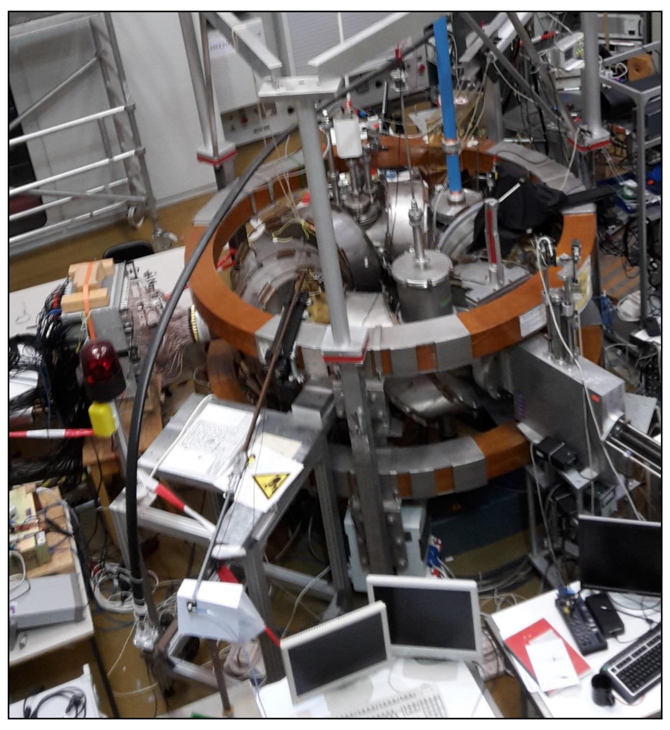
Introduction

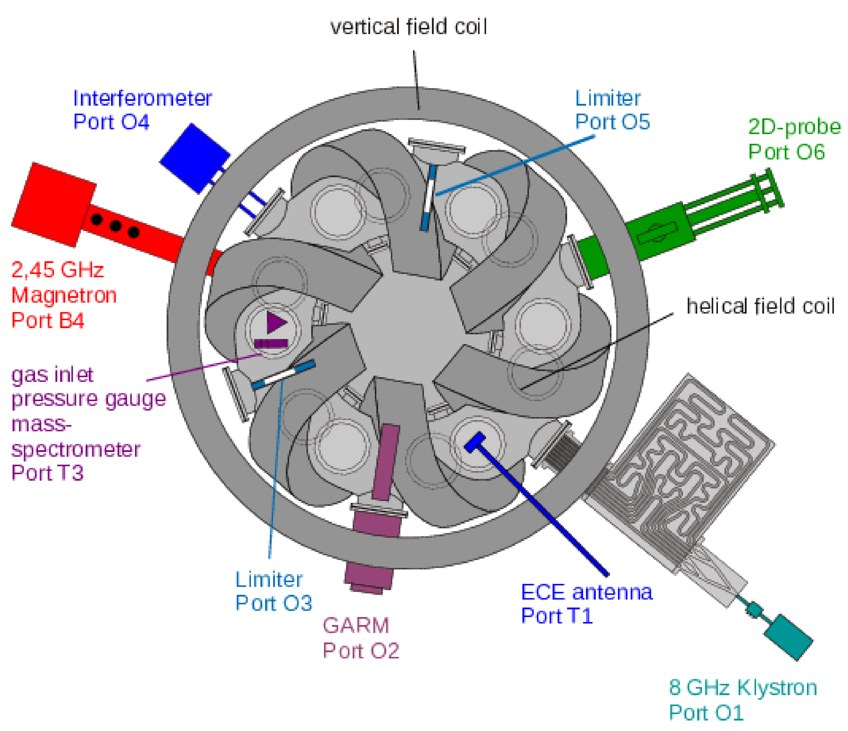
The electron temperature T_e can be measured by means of Langmuir probes for low temperatures only. The use of a Langmuir probe is an invasive procedure that could significantly perturb the plasma and the accompanying evaluation of the characteristics sets the minimum expenditure of time for T_e profile 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

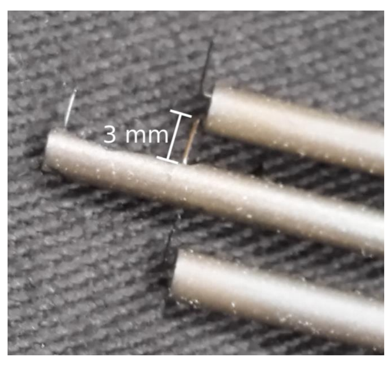
- Major radius: $R = 0.6\,\mathrm{m}$
- Minor radius: $a = 0.1\,\mathrm{m}$
- Magnetic field: $|\vec{B}_0| \leq 0.5\ \mathrm{T}$
- Microwave heating: 3 kW at 2.45 GHz, 3 kW at 8 GHz, 6 kW at 14 GHz
- Max. pulse duration: 45 min (2.45 GHz)
- Gases: H, D, He, Ne, Ar, Kr
- Electron temperature: $T_e \leq 20\ \mathrm{eV}$
- Ion temperature: $T_i \leq 1\ \mathrm{eV}$
- Electron density: $n_e \leq 5 \cdot 10^{18}\ \mathrm{m^{-3}}$
- Rotational transform: $\iota \approx 0.3$





T_e measurements with probes and ECE

- Langmuir probe measurements
  - 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



Langmuir probes

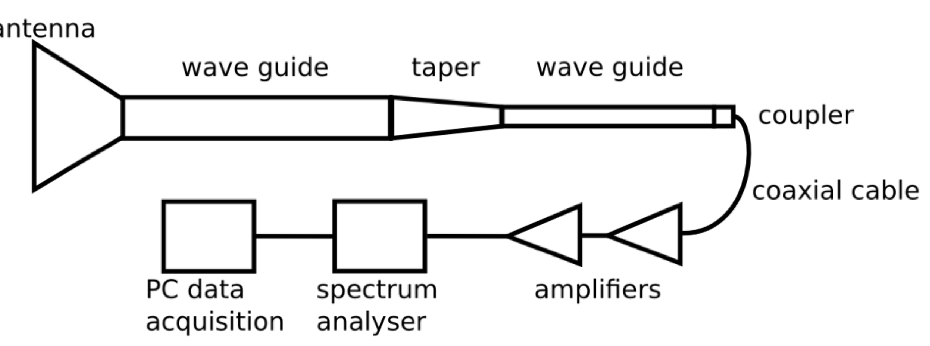
- Electron cyclotron emission measurements
  - Analysis of emitted radiation: power vs. frequency (non-invasive)
  - Fast information about temperature along line of sight
  - Time resolved measurements
  - Detection of non-Maxwellian energy distributions

Electron cyclotron emission theory

- Electron gyration as accelerated motion leads to emission of electromagnetic radiation
- Emitted frequency determined by the local magnetic field strength $\omega_{ce}(r) = \frac{eB(r)}{m}$
- Black body emission intensity approximated by Rayleigh-Jeans' law $I(\omega, T_e) \approx \frac{\omega^2}{8\pi^3 c} k_B T_e$
- The combination of $I(\omega, T_e)$ 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 τ: $I(\omega) = (1 - e^{-\tau}) \cdot I_{RJ}$
- 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

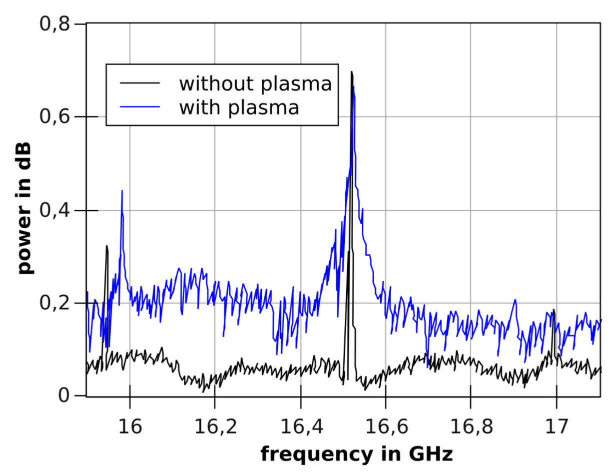
ECE measurements

- 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 $f_c \approx 9.5\ \mathrm{GHz}$ 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.

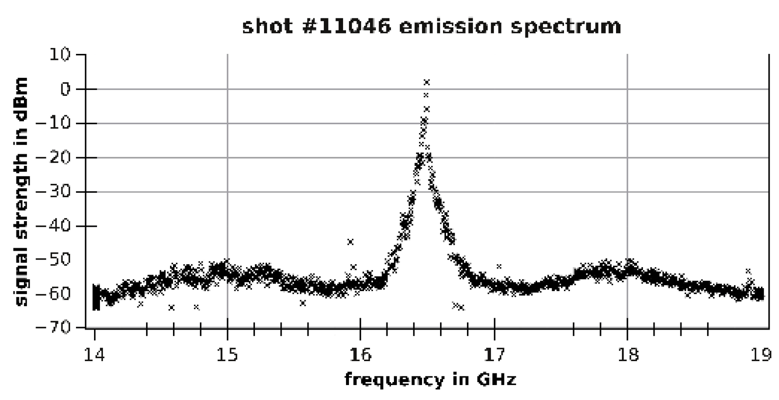


Measurement chain of the ECE diagnostic.

- Emission measurements show significant signal strengths compared to the measurements without plasma
- There is a strong peak at the second harmonic of the heating frequency



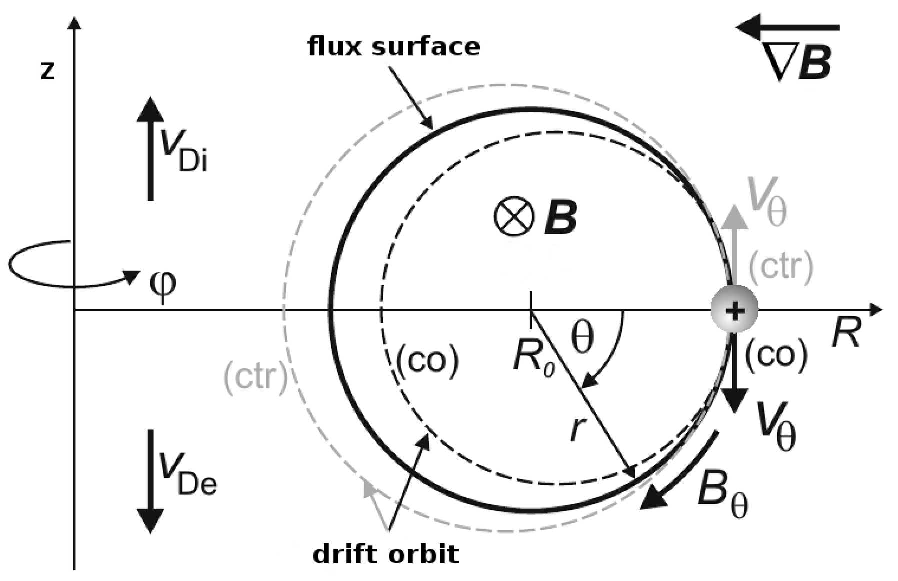
Comparison of the received spectrum with and without plasma around 16 GHz. Ar, 900 W 8 GHz, $p_0 \approx 8\ \mathrm{mPa}$.



Plasma emission from 14 to 19 GHz recorded without unwanted signals due to aliasing for an Ar plasma heated with 2.4kW.

Linking ECE to net currents

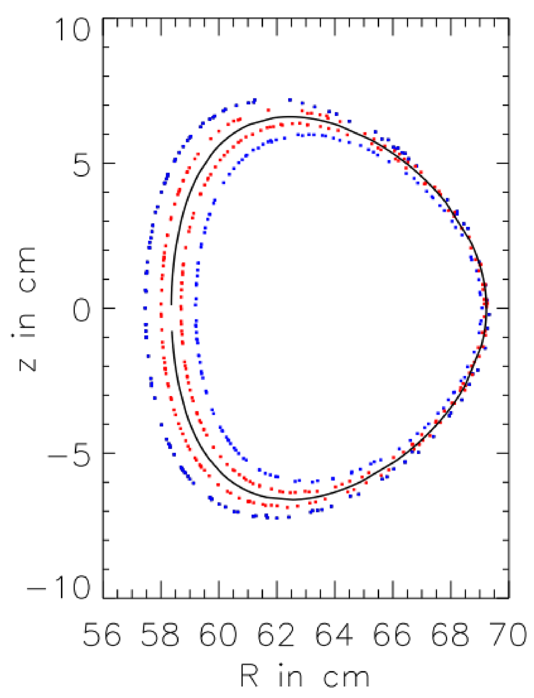
- Particles starting at the outer side of the torus with clockwise winding B are considered
- The combination of gradient drift and curvature drift results in a vertical drift velocity
- Gradient drift: $v_\nabla = -W_\perp \frac{\nabla B \times \vec{B}}{qB^3}$ curvature drift: $v_c = 2W_\parallel \frac{\vec{R} \times \vec{B}}{qR^2 B^2}$
- The drift direction is dependent on the charge sign: electron drift downwards, ion drift upwards
- Co-moving electrons: drift orbit larger than flux surface
- Counter-moving electrons: drift orbit smaller than flux surface
- 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



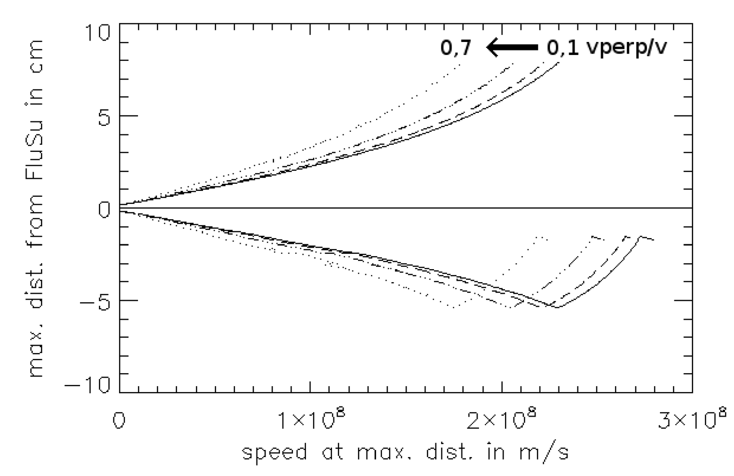
Drift orbits, modified from U. Stroth: *Plasmaphysik. Phänomene, Grundlagen, Anwendungen* (2011)

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 $\frac{v_\perp}{v}$ and various speeds.
- Detection of the maximum distance between drift orbit and flux surface
- Relativistic electrons show distances in the centimetre range



Example: Drift orbits in TJ-K for 1.1 keV (red) and 7.3 keV (blue) with $v_\perp \approx v_\parallel$. The flux surface is shown as black line.



Maximum distance from the flux surface for different speeds and ratios $\frac{v_\perp}{v}$ from 0.1 (solid) over 0.3 (dashed), 0.5 (dash-´dotted) to 0.7 (dotted).

Summary

- First ECE measurements at the second harmonic were successfully conducted
- More sensitive setup will be constructed
- 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

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