# Electron Cyclotron Emission Measurements at the Optically Thin Plasmas of the Stellarator TJ-K

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## Introduction

A standard diagnostic system for magnetically confined fusion-related plasmas is the electron cyclotron emission (ECE) measurement. This method can be used to investigate time-resolved electron temperature profiles $T_e(\vec{r})$ along the line of sight $\vec{r}$ of an antenna and also detect non-thermal electrons. In large fusion experiments, the second harmonic X-mode emission is measured from optically thick plasmas. In the case of the stellarator TJ-K the second harmonic ECE propagates in an optically thin plasma. This allows for multiple passes of the microwaves through the plasma and reflections at the curved vessel walls before reaching the antenna.

This paper describes the set-up of the ECE-diagnostics in the frequency range of 9.5 to 19.5 GHz for the optically thin plasmas in TJ-K and its application for $T_e$ measurements as well as the detection of non-thermal electrons. It is furthermore planned to investigate the fast electrons with the ECE diagnostic which are thought to be responsible for toroidal net currents measured in previous experiments. Additionally, the electron trajectories are investigated numerically.

## Electron Cyclotron Emission

In plasmas confined by a magnetic field $\vec{B}$ the electrons are accelerated by the Lorentz force leading to a circular motion. As a consequence of this acceleration, electromagnetic radiation is emitted at the electron cyclotron frequency

$$f_{\mathrm{ce}} = \frac{e|\vec{B}(\vec{r})|}{2\pi \cdot m_{\mathrm{e}}}. \tag{1}$$

Due to the non-zero Larmor radius, emission also appears at the harmonic frequencies $n \cdot f_{\mathrm{ce}}$. The radiation propagating in the plasma undergoes absorption, described by the absorption coefficient $\alpha$, and further emission. Therefore, the intensity is modified along the path $s$ from emission to the antenna on account of the optical thickness $\tau := \int_{e\to a} \alpha(f)\mathrm{d}s$ resulting in the intensity $I(f)$ at the antenna [1]:

$$I(f) = I_B(1-\mathrm{e}^{-\tau}) \approx \begin{cases} I_{\mathrm{B}}, & \tau \gg 1. \\ I_{\mathrm{B}} \cdot \tau, & \tau \ll 1. \end{cases} \tag{2}$$

For large $\tau$ the received intensity is given by the black body intensity $I_B$ while for a small optical thickness the intensity is smaller by the factor $\tau$.

In TJ-K the magnetic field strength varies monotonically along the line of sight of the antenna. Therefore, for a given antenna the place of origin of the ECE can be derived from its frequency using Eq. (1) and thus the measured intensity spectrum can be converted to a temperature profile along the line of sight. The spatial resolution depends on the gradient in the magnetic field strength, the frequency resolution of the detection system and on the shape of the emitted line.

## ECE Signals from Optically Thin Plasmas

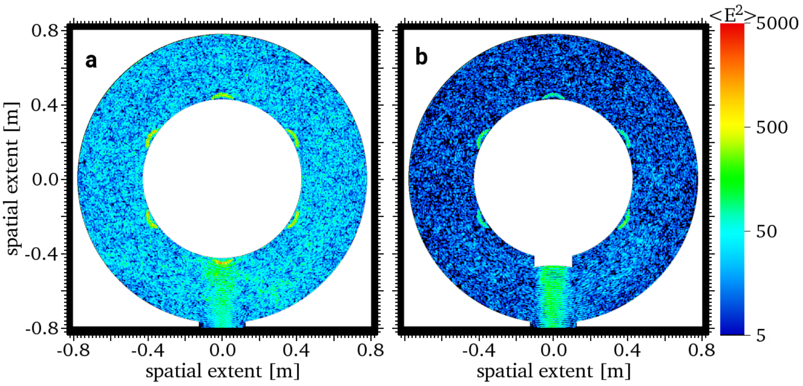

Figure 1: *Field distribution of a 16 GHz microwave injected from a port into a torus with TJ-K dimensions. A mirror at the inner vessel wall restricts the microwave distribution clearly.*

For optically thin plasmas, $\tau$ needs to be known either experimentally or theoretically in order to normalise the temperature profiles. When a direct path from the emission to the antenna can be assumed, the emitted intensity in an optically thin plasma is very low. Additionally, in TJ-K electron densities are below the cut-off density of the ECE. Therefore, the radiation can propagate in all directions through the plasma. This leads to ECE from the entire torus reaching the antenna after several reflections at the vessel wall as demonstrated in Fig. 1 a. Due to low-loss reflections the full black body intensity can be approached, especially in a resonator, even for plasmas with low density $n_e$ while reflections eliminate the polarization [2]. Additionally, the point of origin cannot be determined as directly as in the optically thick case. The geometry in TJ-K will be modified by the installation of a mirror with optimized curvature opposite the antenna as shown in Fig. 1 b. With this geometry the spatial resolution can be obtained. In principle, a resonator with a partly transmitting mirror directly in front of the antenna increases the measured intensity. The limited bandwidth of such a resonator restricts the effect to a frequency interval that cannot cover the second harmonic ECE range from approximately 9.5 to 19.5 GHz of our stellarator.

## Observed Toroidal Net Currents

In the stellarator TJ-K, unexpected toroidal net currents up to 30 A have been found previously. To analyze the origin of these currents, ECE measurements will be used to investigate the correlation of non-thermal electrons and toroidal net currents. Simulations are employed to predict toroidal net currents by directional losses due to the shape of fast electron drift orbits. The orientation of the velocity of a fast electron compared to the magnetic field determines the direction of its gradient and curvature drift velocities. This leads either to a drift orbit larger or smaller than the flux surfaces that the electron starts on. In the case of smaller orbits the electron is well confined in the plasma. Larger orbits can lead to electron losses due to leaving the confinement region.

## Identification of the Electron Cyclotron Emission

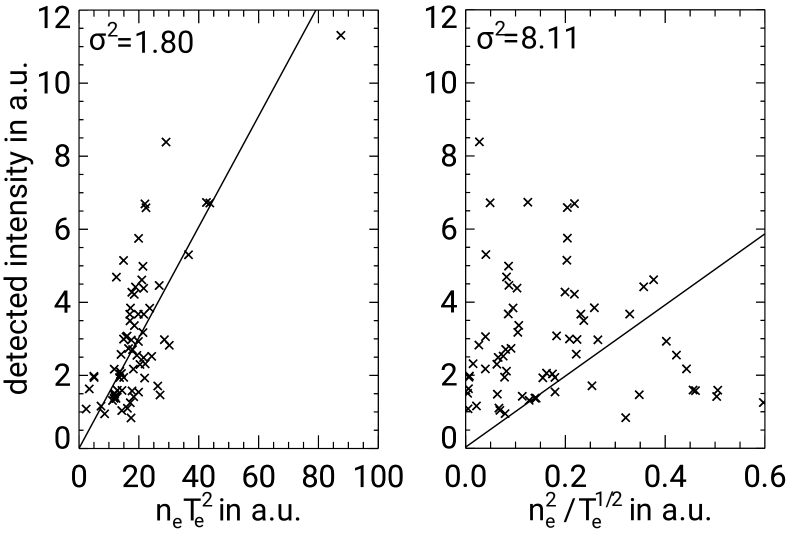

Figure 2: *The dependence of the emitted power on density and temperature is closer to a proportionality to* $n_e T_e^2$ *as predicted for ECE than* $n_e^2/\sqrt{T_e}$ *as predicted for bremsstrahlung.*

In contrast to large fusion experiments with high temperatures, emission in the frequency range of the second harmonic ECE of TJ-K plasmas can also be caused by Coulomb bremsstrahlung. To identify the dominant process, the temperature and density dependence of the radiation has been investigated. The results illustrated in Fig. 2 show that the intensity follows more closely the relation for second harmonic ECE $I(f) \sim n_e T_e^2$ than the relation $I(f) \sim n_e^2/\sqrt{T_e}$ that is predicted for Coulomb bremsstrahlung [3]. Furthermore, heating power modulation experiments have been carried out. When the heating is switched off, the microwave signals in the ECE frequency range drop on time scales in the $\mu$s range whereas the plasma density has not yet noticeably decreased. This points to the ECE nature of the emission because in the case of bremsstrahlung an increase of the intensity would be expected due to its $1/\sqrt{T_e}$ dependence. It is concluded that ECE is the dominant process.

As expected in a geometry with multiple reflections at non-planar walls like shown in Fig. 1 a, measurements of the emitted microwaves without a mirror show no dominant polarization.

## Simulated Electron Trajectories in TJ-K

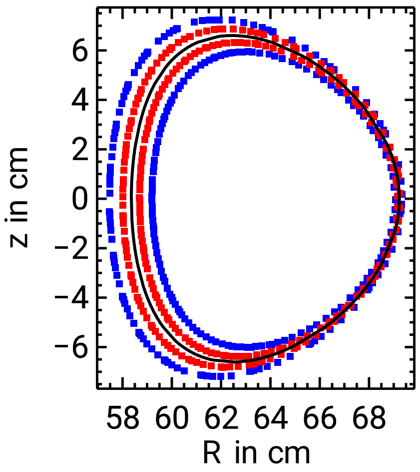

Figure 3: *Poloidal Rz-plane with electron drift orbits in TJ-K for 1 keV (red) and 7 keV (blue) parallel and antiparallel to the magnetic field, compared to the flux surface (black).*

Field line tracing is used to simulate electron trajectories in TJ-K. Figure 3 shows that drift orbits larger and smaller than the flux surface at the starting point were found for high energy electrons with opposite direction. The horizontal distance between the flux surface and the drift orbits increases from less than the simulated resolution of 1$\mu$m at 10 eV electron energy up to several cm in the $10^5$ eV range. Large drift orbits can lead to electron losses outside the separatrix. However, even electrons with more than 400 keV were found to be confined for TJ-K parameters. As a consequence, collisions outside the separatrix or unfavorable starting conditions are needed to generate direction-dependent particle losses.
First simulations with several Maxwellian velocity distributions for different temperatures were conducted with electrons starting equally distributed on a poloidal plane. These results will be extended by a realistic density profile to estimate the contribution of electron drift orbits to toroidal net currents.

## Summary and Outlook

The microwave emission from the optically thin plasmas of TJ-K in the frequency range from 9.5 to 19.5 GHz has been identified as second harmonic ECE by heating modulation measurements and the dependence of the emission on $n_e$ and $T_e$. In order to get spatial information about the temperature, measurements with a reflecting mirror will be conducted to minimize the reflections at the vessel wall. Absolute temperature values can be obtained either from knowledge of $\tau$ or a normalization with noise sources.
The simulations of electron trajectories show deviations from the flux surfaces that increase with the electron velocity. Whether the orbits are smaller or larger than the flux surface depends on the direction of motion compared to the magnetic field. The estimate of possible toroidal net currents due to electron losses will be done with realistic electron density profiles and compared to experimental findings.

## References

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