

# Polarisation of Electron Cyclotron Emission Spectra in LHD

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The complex structure of the magnetic field configuration in the Large Helical Device (LHD), which has a large shear, complicates the analysis of the ECE spectrum. The polarisation of the ECE spectrum has been numerically studied and the results will be presented in this paper. At high density mode conversion is negligible, but the polarisation of the ECE wave rotates in the laboratory frame. Furthermore, wall reflections causes mode conversion which may scramble the ECE measurement. However, by means of a polarisation rotator it is possible to select the second harmonic X-mode, and determine the temperature profile.

## 1. Introduction

Electron Cyclotron Emission (ECE) spectroscopy has proven to be a powerful tool to measure temperature profiles in thermonuclear fusion plasmas [1,2,3]. The temperature profiles in tokamaks can be obtained generally straightforward from second harmonic ECE spectra. At the Large Helical Device ( LHD:  $R_{axis}=3.75\text{ m}$ ,  $a=0.6 - 0.9\text{ m}$  ), ECE is used to measure the temperature profile. However, the complex magnetic configuration of a heliotron, like LHD, complicates the analysis.

The magnetic field is a non-monotonic function of the radius in the line-of-sight of the diagnostic antenna (see fig. 1). Thus, a single frequency can be emitted from two resonance's in the plasma. Furthermore, the field has a large shear. The ratio of the toroidal and poloidal magnetic field is of order unity in a heliotron. Hence, the two polarisation modes, X and O-mode, do not propagate independently. The coupled propagation may lead to mode conversion or polarisation rotation [4,5].

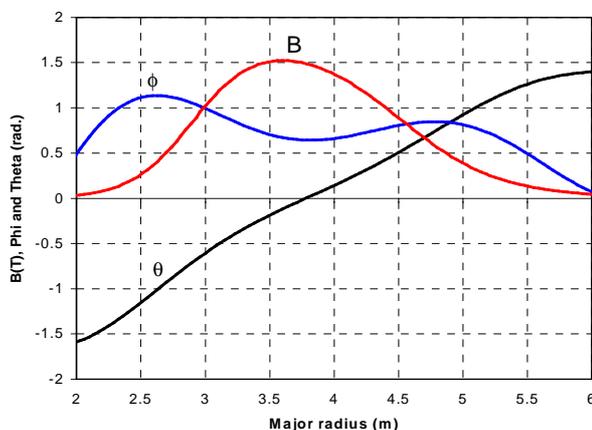
The propagation of second harmonic ECE waves in LHD has been numerically studied in order to estimate the mode conversion. Furthermore, absorption and emission from double resonance's and wall reflections have been included in the calculation. First, the details of mode propagation will be treated. Thereafter the polarisation of the complete LHD spectra will be discussed.

## 2. Wave propagation in LHD

The magnetised plasma is a refractive medium for microwaves. Furthermore, waves can be re-absorbed or reflected by resonance's and cut-off layers. The two polarisation modes, X- and O-mode have different refractive indices and thus different propagation velocities. Furthermore, the wave equations are coupled if they propagated in a sheared magnetic field [4,5]. By solving the wave equations as given in ref. [4]., numerically along the path towards the antenna, mode conversion can be studied. It is found that the mode conversion depends strongly on the plasma density.

Figure 1:

The magnetic field configuration in the line-of-sight of the diagnostic antenna. The magnetic field is a non-monotonous function of the radius and has a maximum at  $R = 3.6\text{ m}$ . For ECE frequencies and inside ( $R < 3.6\text{ m}$ ) and outside ( $R > 3.6\text{ m}$ ) resonance can be found. The magnetic shear is given as,  $\theta \equiv \text{atan}(B_{pol}/B_{tor})$  and  $\phi = d\theta/dR$ . At the plasma edge the ratio of the two magnetic field components is of order unity ( $\theta \approx 45^\circ$ ) in LHD.



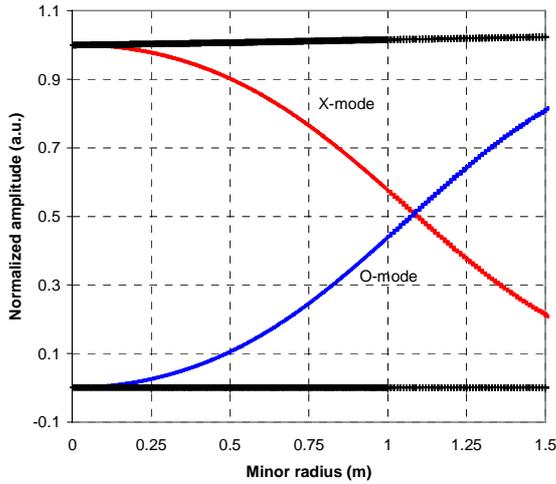
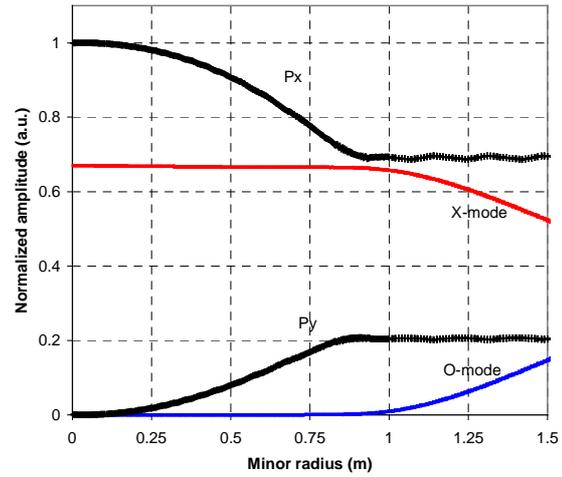


Fig. 2a: Mode conversion in vacuum.

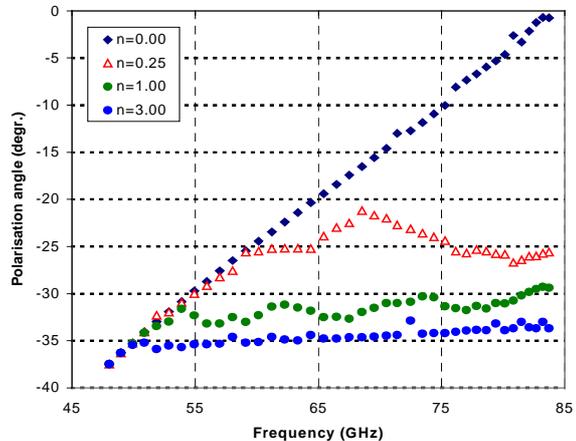

 Fig. 2b: Rotation in x/y-frame ( $n_e = 1 \cdot 10^{19} \text{ m}^{-3}$ )

Two examples for different densities are shown in fig. 2. Flat, squared parabolic density profiles have been assumed. Initial X-mode, emitted at the centre ( $r=0$ ) propagates radially outwards. In vacuum (fig. 2a), the electric field vector is constant in the fixed x/y laboratory frame, as is expected. The calculations show a conversion from X to O-mode, due to the different magnetic field vector. The situation changes in a dense plasma (fig. 2b), where the X-mode power is found to be conserved up to the edge of the plasma at  $r = a = 0.9 \text{ m}$ . The wave electric field vector rotates in the x/y frame, outside the plasma in the vacuum, no rotation is observed. The rotation with the magnetic field shear is called polarisation rotation. Outside the plasma ( $r > 0.9 \text{ m}$ ) the rotation stops.

Polarisation rotation is caused by the difference of the X and O-mode refractive indices in the coupled wave equations. Thus, it depends also on the plasma density. The polarisation angle,  $\alpha$ , for the ECE spectrum is shown in fig. 3. If X-mode is emitted, each frequency has a different polarisation angle at the resonance where it is emitted. The central frequency is emitted with the electric field in the x-direction. In vacuum this angle does not change during propagation and the polarisation angle at  $r=a$  is equal to that at the emission resonance. But at higher densities it rotates during propagation towards the edge. For densities,  $n_{e0} > 1.0 \cdot 10^{19} \text{ m}^{-3}$  the angle is approximately equal for all frequencies and it approaches  $35^\circ$ . This is equal to the magnetic field shear angle at the plasma outer edge. ( $\alpha = \theta(r=a) = 35^\circ$ ) The plasma functions as a polarisation rotator. It rotates the polarisation in the x/y frame.

Figure 3:

The polarisation angle, i.e. the angle which the electric field vector makes with the x-axis at  $r=a$  in the x/y-frame is given for the ECE spectral components. X-mode emission from the outside resonance is regarded. In vacuum, the angle is equal to that at the resonance position. At  $R=3.6 \text{ m}$ , for  $f=83 \text{ GHz}$  it is defined:  $\alpha=0^\circ$ . In dense plasma the angle changes. For high densities, all frequencies exit the plasma under approximately the same angle. The electric field vector rotates up to the edge with the magnetic field shear.



In order to detect X-mode emission, the polarisation component perpendicular to the magnetic field at  $r=a$  should be selected. For all frequencies the X-mode exits the plasma under an angle of  $\alpha=34\pm 4^\circ$  with the x-axis for densities  $n_{eo} > 1.0 \cdot 10^{19} m^{-3}$ .

In LHD, a single frequency may have a double resonance. Emission from the inside resonance may shine through the outside resonance viewed by the diagnostic antenna. It will disturb the temperature profile reconstruction. In order to estimate these effect on the ECE spectrum, absorption has been included in the calculations. The wave equations are solved along the propagation path for each spectral frequency. Inside a narrow region around the resonance, the power of the X and O-mode component are reduced according to the local absorption. Optical thickness and absorption coefficient from ref. [3] have been used.

The shine-through fraction of the inside resonance depends on the density as shown in fig. 4. If the density is low ( $n_{eo} < 1.0 \cdot 10^{19} m^{-3}$ ) a part of the inside X-mode emission will be converted to O-mode at the outside resonance, and not be fully re-absorbed. Furthermore, at low densities the outside resonance will also become optically thin for X-mode. For a density of  $n_{eo} = 1.0 \cdot 10^{19} m^{-3}$  a maximum 10% of the outside resonance will shine-through, mainly due to a low optical depth.

Complete simulations of second harmonic ECE spectra, including emission, re-absorption, double resonance and mode conversion have been carried out. The maximum percentage of mode conversion was found to be negligible ( $< 0.9\%$ ) for  $n_{eo} > 1.0 \cdot 10^{19} m^{-3}$ . In order to keep the shine-through level below 5% a density of  $n_{eo} > 1.4 \cdot 10^{19} m^{-3}$  is required such that the outside resonance is optically thick. Than the X-mode emission is proportional to the temperature at the outside resonance. At moderate temperatures ( $T_{eo} < 2 keV$ ) and densities O-mode emission is negligible in LHD. Similar to emission from the inside resonance, waves that are reflected by the vessel wall might disturb the measurement of the ECE spectrum. This will be treated in the next section.

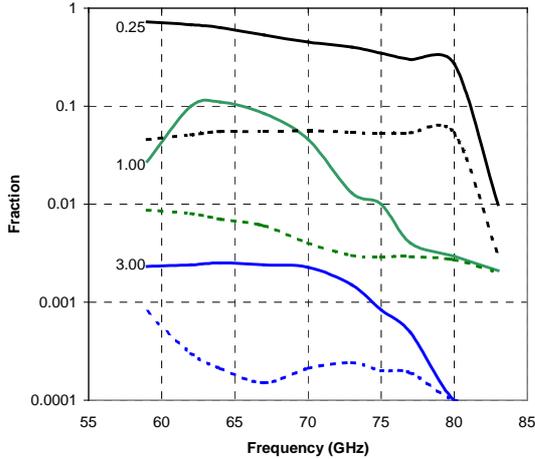


Figure 4:

Shine-through fraction for three different densities is shown (full lines). The maximum percentage of mode conversion (dashed lines) for the three densities were found to be 6% for  $n_{eo} < 0.25 \cdot 10^{19} m^{-3}$  and 0.9% for  $n_{eo} = 1.0 \cdot 10^{19} m^{-3}$ . Nevertheless, because of low optical depth a shine-through fraction of 10% is found for  $n_{eo} = 1.0 \cdot 10^{19} m^{-3}$ . Frequencies emitted from the high-density central resonance's are hardly affected.

### 3. ECE spectrum and temperature profiles

In the previous section, we have seen that mode conversion is negligible for densities which are relevant for optical thick ECE spectra. Only rotation of the wave polarisation occurs in the x/y frame, which makes the understanding of ECE propagation easier. Under the assumption that polarisation rotation is perfect, ECE emission propagation can be treated in the same way as in a tokamak. However, the multiple resonance layers should be taken into account. The intensity of the spectral component with a frequency,  $\omega$ , is than given by.

$$T^{rad}(\omega) = T^{out}(1 - e^{-\tau^{out}}) \frac{1 - \rho e^{-\tau^{out}} e^{-\tau^{in}} + \rho e^{-\tau^{out}} e^{-2\tau^{in}}}{1 - \rho e^{-\tau^{out}} e^{-\tau^{in}}} + T^{in}(1 - e^{-\tau^{in}}) e^{-\tau^{out}} \frac{1 - \rho e^{-\tau^{out}} e^{-\tau^{in}} + \rho e^{-\tau^{in}}}{1 - \rho e^{-\tau^{out}} e^{-\tau^{in}}},$$

where different absorption properties for each resonance have been assumed and  $\rho$  is the wall reflectivity. If the outside resonance is optically thick, the right side can be neglected and the

intensity is proportional to the temperature at the outside resonance. As observed in early tokamak experiments, wall reflections can be mode converted and depolarise the ECE spectrum [6].

If we use the same considerations as in ref. [6], and assume O-mode emission and absorption to be zero, the measured O-mode component, due to mode converted wall reflections in LHD is given by,

$$T^{MCR}(\omega) = \frac{\pi\rho}{1 - \rho + \pi\rho} \left\{ T^{in} (1 - e^{-\tau^{in}}) + T^{out} e^{-\tau^{in}} (1 - e^{-\tau^{out}}) \right\}$$

where  $\pi$  is the mode conversion fraction. The wall reflectivity and mode conversion fraction are usually taken arbitrary,  $\rho=0.9$  and  $\pi=0.1$ , which predicts an O-mode component in the ECE spectrum, with an intensity of approximately 50% with respect to the X-mode intensity. Thus, wall reflections are expected to be the dominant factor that causes the de-polarisation of the ECE spectrum in LHD. As can be seen in the above equation, the O-mode intensity, due to mode converted reflections, is mainly related to the temperature at the inside resonance. Of course, in high temperature plasmas, O-mode emission from the plasma and re-absorption should be included in the calculations.

#### 4. Conclusions

At LHD three diagnostics, radiometer, grating polychromator and a Michelson interferometer are available to monitor the ECE spectrum [7]. Utilising second harmonic ECE spectra to determine the temperature is limited by the density. With a single antenna, only one part of the temperature profile can be measured. In LHD, the outside resonance is monitored. Calculations have been carried out to estimate the mode conversion due to the sheared magnetic field. Similar calculations have been carried out for microwave Electron Cyclotron Heating [5]. For ECE waves, the elliptisation of the waves, caused by Faraday rotation, was not relevant. This is only important if a fixed phase, between the X and O-mode wave, exists. A certain density,  $n_{eo} > 1.4 \cdot 10^{19} m^{-3}$ , is required to prevent mode conversion and a too low optical depth in the edge. Although, O-mode emission is small and mode conversion inside the plasma can be neglected, the ECE spectrum will be de-polarised due to mode converted reflections.

All ECE diagnostics at LHD measure a fixed polarisation mode. A polarisation rotator is installed in the waveguide system. In order to detect X-mode emission, this rotator should be aligned such that only the polarisation component perpendicular the magnetic field at  $r=a$  is monitored. Otherwise, a mix of part X-mode, mode converted reflections, O-mode emission is measured. The X-mode exits the plasma under an angle of  $\theta=34 \pm 4^\circ$  with the x-axis for densities  $n_{eo} > 1.0 \cdot 10^{19} m^{-3}$ . However, small errors may be caused by a misalignment of the rotator, a change in plasma edge position, or magnetic field configuration due to a large beta. An estimated error of  $10^\circ$  is expected during normal operation, which in turn will cause an error of less than 4% in the temperature measurement.

First results of temperature profiles have been determined in the last experimental campaign of LHD. Within the measurement error the profiles matched those, obtained from the Thomson scattering diagnostic. However, a significant reflected intensity was found to disturbed the measurement at low densities, as expected from our calculations.

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