Shine-through in electron cyclotron emission measurements

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Introduction For magnetically confined fusion research Electron Cyclotron Emission (ECE) is one of the primary techniques for the measurement of the electron temperature (T_e) profile. Most commonly the T_e profile is inferred from the radiation temperature (T_{rad}) profile measured by the ECE assuming T_{rad} is equal to T_e at the cold resonance position [1]. However, this approach, called "classical ECE analysis" does not account for the frequency shift in the emission induced by the relativistic mass increase and the Doppler-shift. Hence, this treatment becomes inaccurate [2, 3], if the frequency shifted emission contributes significantly to the measurements. An example of such behavior is the shine-through of down-shifted emission through the cold resonance position. This effect and its importance for the accurate inference of T_e from the ECE measurements has already been studied in Ref. [2]. Here we extend upon the work of Ref. [2] and show three different origins of shine-through observed at ASDEX Upgrade and their interpretation with the extended radiation transport model from ref. [3].

ECE measurements and their data analysis at ASDEX Upgrade At ASDEX Upgrade a 60-channel heterodyne radiometer is used for ECE measurements. The antennae of the ECE system view the plasma on the mid-plane and are located on the low field side (LFS) of the plasma vessel. The radiometer is calibrated using a hot and a cold source which allows it to deliver T_{rad} measurements with a 7 % systematic uncertainty. The ECE measurements are analyzed using radiation transport modeling in the framework of integrated data analysis Ref. [2]. With this approach all effects causing the shine-through described in this paper are considered in the inference of the T_e profile from the measurements. The radiation transport is solved along a single, geometrical optics ray for each ECE channel [3]. The absorption coefficient is given by equation 8a) of Ref. [4] and the emissivity is calculated from the absorption coefficient via Kirchhoff's law assuming a thermal plasma. Wall reflections are modeled by an infinite reflection model according to Ref. [2] and only X-mode emission is considered. The evaluation of the ECE measurements is coupled with the evaluation of the Lithium beam spectroscopy [5] and plasma interferometry [6] in the framework of Integrated Data Analysis (IDA) [7], because the forward modeled T_{rad} also depends on electron density (n_e). Measurements within a time window of 1 ms are considered for the profiles shown in this paper. Accordingly, the error bars in T_{rad} include the standard deviation from this time window plus the systematic uncertainties from the calibration.

The "classic" shine-through peak in H-mode discharges The "classic" shine-through peak in T_{rad} is a peak structure in the near scrape-off layer (SOL), which is commonly seen in H-mode, due to the steep gradients in T_e and n_e [2]. Figure 1 shows the T_e profile inferred from the ECE measurements $T_{rad,ECE}$ for discharge # 32100 at t =3.71 s and the forward modeled measurements $T_{rad,mod}$. The ECE channels are mapped to the cold resonance positions. The synthetic data reproduces the shine-through-peak in the ECE measurements well even though all channels with $1.0 < \rho_{pol}$ were disregarded in the IDA. The birthplace distribution of observed intensity (BPD), as defined in ref. [3], show that the emission observed by the channels outside of the confined regions originates from the pedestal top and the pedestal edge (not shown).

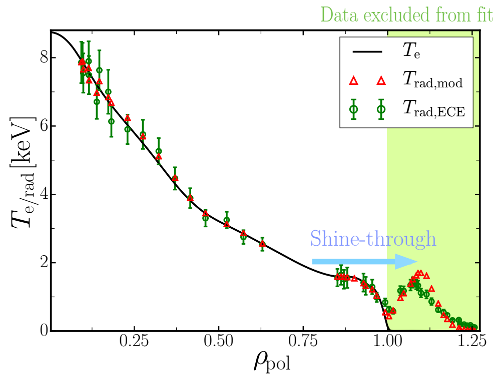

Figure 1: *T_e profile as inferred from the ECE measurements $T_{rad,ECE}$ and modeled data $T_{rad,mod}$ for # 32100 t =*3.71 s.

Shine-through from the plasma core to the plasma edge ECE channels A shine-through peak observed at the plasma edge does not necessarily have to originate from the pedestal top only. Given large core T_e (for ASDEX Upgrade $T_e > 5$ keV) or a significant population of fast electrons it is possible that the emission of electrons in the plasma core contributes to the measured frequencies associated with the plasma edge and SOL. This requires sufficiently small n_e at the plasma core to avoid cut-off of the low frequency emission, which was not the case in the previous example (# 32100 at t =3.71 s). Figure 2 shows the T_e profile inferred from the ECE measurements for discharge # 32097 t =2.29 s where core $n_e = 5.0 \times 10^{19}\,\mathrm{m}^{-3}$. The forward modeled T_{rad} assuming a thermal, relativistic Maxwell-Jüttner distribution $T_{rad,mod}$ [Maxwell-Jüttner] describe the measurements over the entire range of ρ_{pol} including the shine-through peak reasonably well. Measurements with resonance positions $\rho_{pol} > 1.0$ were discarded in the IDA. Approximating the distribution function by a non-relativistic Maxwellian, as was done for the radiation transport model presented in Ref. [2] is inadequate for this scenario. $T_{rad,mod}$[Maxwell] largely overestimates the shine-through peak. This large discrepancy in T_{rad} between the radiation transport model presented in ref. [3] and the model from ref. [2]

only occurs for large T_e and sufficiently small core n_e. For the scenarios presented in ref. [2] the non-relativistic approximation of the distribution function is appropriate.

Relativistic broadening for hot and tenuous plasmas and its connection with shine-through Another problem arises for "classical ECE analysis" for ECE measurements of tenuous, high temperature plasmas [8, 9]. Under these plasma conditions the relativistic mass shift induces a pseudo radial displacement [9] of the ECE measurements. A method to overcome this problem is to perform "classical ECE analysis" with shifted measurement positions, which include the pseudo radial displacement. The necessary shift can either be obtained through approximations [10] or by solving the radiation transport for a known T_e profile [3, 11]. In the following it will be discussed that the relativistic broadening of the core ECE can be interpreted as another form of shine-through.

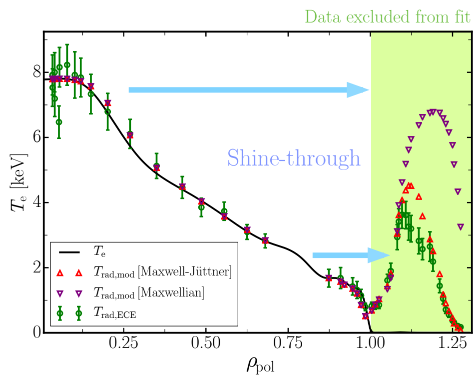

Figure 2: T_e *profile as inferred from the ECE measurements* $T_{rad,ECE}$, *modeled data assuming the relativistic Maxwellian* $T_{rad,mod}$[*Maxwell-Jüttner*] *and modeled data assuming a non relativistic Maxwellian* $T_{rad,mod}$[*Maxwell*] *for # 32097* t =2.29 s.

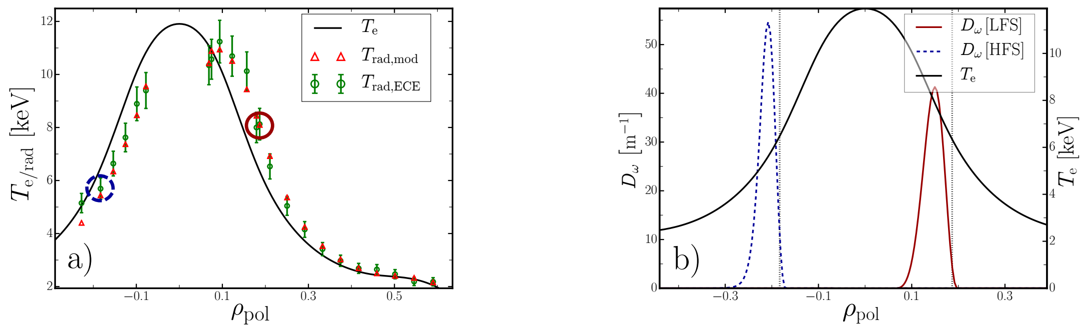

Figure 3: #30907 t = 0.73 s*: Figure a) shows measured* $T_{rad,ECE}$, *forward modeled* $T_{rad,mod}$ *and* T_e *as functions of the normalized radius. Frequencies with the cold resonance on the HFS have negative normalized radii. Figure b) shows the BPD* D_ω *for the two* $T_{rad,mod}$ *encircled in a).*

In figure 3 the measured $T_{rad,ECE}$, the T_e profile inferred from the measurements and the forward modeled T_{rad} are shown for discharge #30907 at 0.73 s, where $n_e \approx 1.2 \times 10^{19}\,\mathrm{m}^{-3}$ near the magnetic axis. T_{rad} with the cold resonance position on the HFS are given a negative sign in ρ_{pol}. For the inferred T_e profiles $T_{rad,mod}$ is in good agreement with the measurements $T_{rad,ECE}$. The BPDs in figure 3 show for the measurements encircled in figure 3 that the observed emission for these channels originates from positions shifted from the cold resonance position toward the HFS. Hence, plasma layers at positions with larger magnetic fields shine down-shifted emission through the plasma layer near the cold resonance position.

The mechanism of this shine-through is slightly different from the two previously discussed cases, because even though the cold resonance lies inside the confined region, the reabsorption near the cold resonance position is not strong enough to mitigate the shine-through. The occurrence of the shine-through is best discussed using an example for which the lines of sight (LOS) geometry and frequency of the channel, which is encircled in blue in figure 3, is chosen. For this channel the part of the LOS that ranges from 1 cm before to 1 cm after the cold resonance position has an optical depth of $\tau_\omega = 0.3$. Hence, this section of the LOS is optically thin and can only reabsorb 20 % of any incoming radiation. The reason for the weak absorption is the combination of large T_e with small n_e. While lowering n_e linearly decreases the overall electron count, increasing T_e redistributes the electrons from low energies to high energies. Near the cold resonance position electrons are only resonant if their velocity is small, otherwise the relativistic mass-increase and the Doppler-shift will shift the electron off resonance. For this particular measured frequency, LOS and T_e profile only 7 % of the electrons that are resonant to the measured frequency on the LOS reside inside the 2 cm section near the cold resonance position. If T_e is halved this fraction increases to 17 % while tripling T_e reduces the fraction 1.5 %. Hence, for large T_e absorption becomes weak in the vicinity of the cold resonance position allowing radiation to shine-through the plasma layer close to the cold resonance position.

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References

[1] I.H. Hutchinson. 1987.

[2] S. K. Rathgeber et al. *Plasma Physics and Controlled Fusion*, 55(2):025004, 2013.

[3] S. S. Denk et al. In *19th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating 2016 (EC19)*, 2017.

[4] F. Albajar et al. *Plasma Physics and Controlled Fusion*, 49(1):15–29, 2007.

[5] M. Willensdorfer et al. *Review of Scientific Instruments*, 83(2), 023501, 2012.

[6] A. Mlynek et al. *Nuclear Fusion*, 52(11):114012, 2012.

[7] R. Fischer et al. *Fusion Science and Technology*, 58(2):675–684, 2010.

[8] D.V. Bartlett. In *Diagnostics for experimental thermonuclear fusion reactors*, pages 183–192, 1996.

[9] M. Sato et al. *Journal of the Physical Society of Japan*, 67(9):3090–3099, 1998.

[10] J. L. Ségui et al. In *Electron Cyclotron Emission and Electron Cyclotron Heating*, pages 209–214, 2003.

[11] G.D Garstka et al. *Fusion Engineering and Design*, 53(1–4):123–128, 2001.