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First measurements of the oblique ECE system at JET

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1. Introduction

Anomalies in the ECE spectra and discrepancies among different measurements in plasmas with high electron temperature have been reported in several experiments [1], suggesting that the electron distribution function could be significantly different from the Maxwellian one in the range of 1-3 times the thermal velocity. In this respect the new Oblique Electron Cyclotron Emission (ObECE) system at JET [2], entered operations during 2006, aims to resolve relatively small discrepancies among the ECE spectra measured at three toroidal angles, 0, 10 and 22 degrees with respect to the perpendicular to the toroidal field with 2 linear polarizations each. This technique enables the study of the electron distribution function in the low energy range. The spectral analysis of the EC radiation is performed over an extended bandwidth (75-800 GHz) using a six-channel Martin-Puplett interferometer. The time resolution is usually set at 10 ms/profile and the single line equivalent spectral resolution at 7.5-15 GHz. At present results from several experiments performed at different magnetic fields (1.8-3.2T) and aimed to reach high Beta normalized values with high fraction of non inductive plasma current are being analyzed. This paper deals particularly with a set of shots (see table 1) of the "hybrid regime with high electron heating" experiment. In all cases a substantial amount of auxiliary heating (up to 24 MW of NBI and ICRF) was used, with electron temperature in the range of 5-10 keV and electron density of 3-6 $10^{19}m^{-3}$.

Table 1 . (* data in ohmic plasma)

Pulse	B_t T	I_p MA	$n_e dl$ 10^{19} m^{-2}	T_e keV	P_{NBI} MW	P_{ICRH} MW	P_{LHCD} MW	β_N	H_{89}	t_{heat}	t_{oh}
68381	3.2	2.3	7.9	9.1	9.0	8.8	0.9	1.4	1.6	53.25	58.0
68385	3.2	2.3	13.0	6.9	9.0	8.7	0.7	1.3	1.3	53.25	57.0
68394	3.2	2.3	9.1	7.9	16.3	8.0	0.9	1.6	1.3	53.17	56.6
68382*	3.2	2.3	3.7	2.4	-	-	-	0.25	1.1	-	57.9

[*] See the Appendix of M.L.Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) IAEA, (2006)

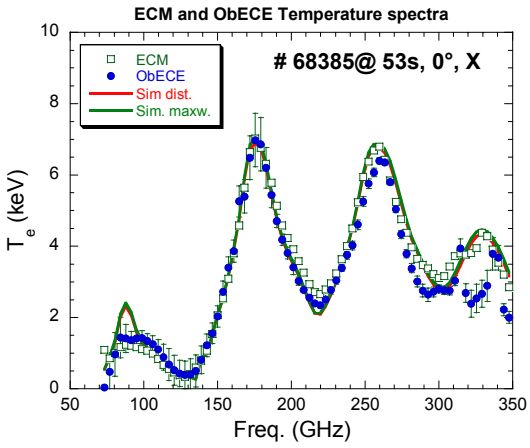

Fig. 1. X-mode, 0° spectrum during heating. Simulated spectra assuming Maxwellian (green line) and slightly distorted distribution [red line, u_d=-1(1), T_d=0.6(0.3), n_d=0.015(0.005)] are shown as well.

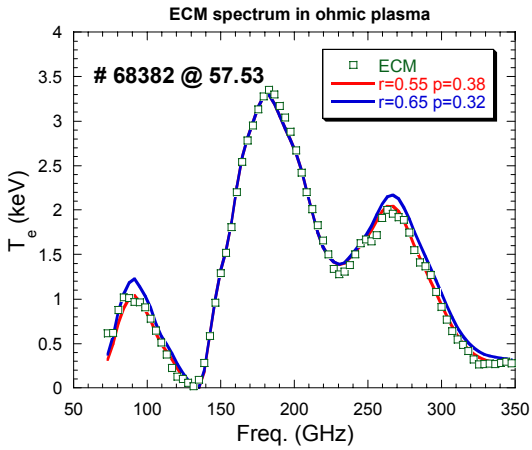

Fig. 2. ECM spectrum fitted with simulations using different values of polarization scrambling *p* and reflection coefficients *r*.

Oblique spectra

The ObECE system needs an accurate spectral calibration in order to obtain useful data. The cross-calibration of the 0 degrees channel of the system has been performed through the comparison with the ECE spectra acquired with the absolutely calibrated Michelson interferometer (ECM) for a large number of ohmic plasmas at different magnetic field (1.7-3.2 T). The result of such procedure is shown in fig. 1 where the spectra obtained with both the diagnostics are compared for shot 68385. The simulations performed with the SPECE code [3] using ECM electron temperature profiles and LIDAR profiles for the density and assuming thermal plasma show large discrepancy with the experimental data on 1st and 4th harmonics (around 90 and 330 GHz), and differences in the 4th harmonic between ECM and ObECE in the data concerning the heating phase are present as well. The behavior of the first harmonic is still not clear at this phase of the analysis while the discrepancies in the 4th harmonics are probably related to the poor quality of the calibration in that region of the spectrum. For these reasons results here discussed mainly rely on 2nd harmonic spectra. The calibration of the oblique channels is based instead on the comparison with the computed EC emission for ohmic plasmas once it has been corroborated with the measured 0 degrees emission. This procedure for the oblique channels has been refined using one plasma discharge (68382) of the same experimental session of the data we are discussing in this paper. The simulation has been tuned with a proper choice of the empirical parameters r and p, which describe the reflection of the radiation on the walls and the scrambling of the polarization (fig. 2). As expected the variation of r and p on the calculated spectrum is relevant for the optically thin harmonics only (1st and 3rd at low temperature and 1st and 4th at

high temperature). Simulations assuming the minimum and the maximum of the error bars of the LIDAR density profile have been performed to evaluate the effect on the oblique spectra, resulting in a 5-7% variation on the optically thin harmonics.

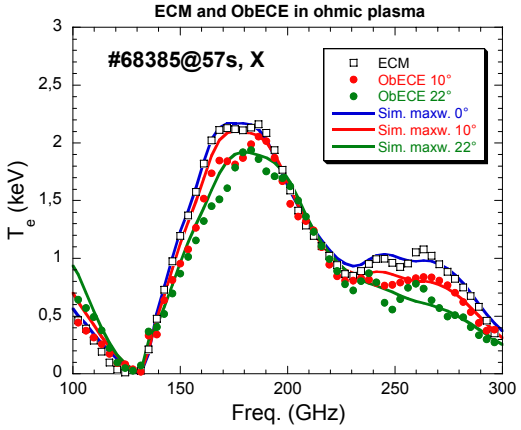

Fig. 3. X-mode, ohmic spectra at 0°, 10°, 22° with heating. Solid lines represent simulations with Maxwellian distribution.

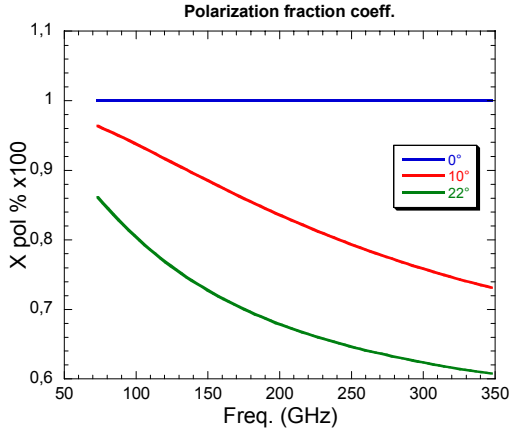

Fig. 4. Fraction of X-mode coupled to the vertical polarization of the antenna

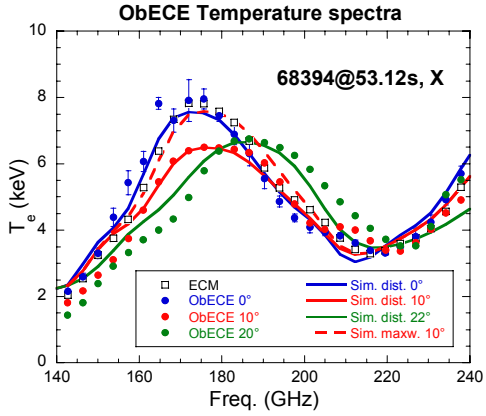

Fig. 5. X-mode, 10° spectrum with heating. Distorted distribution (red line): Distorted distributions: u_d=±1.2, T_d=0.23, n_d=0.015. A 7% error on the temperature has been assumed to fit the data.

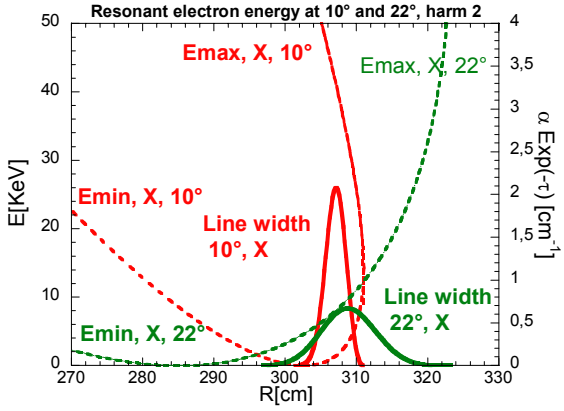

Fig. 6. Resonant electron energy at the central frequency of 2nd harmonics (179.3 GHz) for shot 68394, at 10° and 22°.

Fig. 3 shows the spectra during the ohmic phase of plasma 68385 measured at different angles and compared with the simulation assuming Maxwellian distribution. Data follow the behavior of simulation, in particular the frequency shift for increasing angles and the reduction of the measured peak temperature. This result is in agreement with detailed simulations reported in [1, 4]. The reduction of the peak for Maxwellian case with increasing angle is related to the reduction of the X-mode fraction coupled to the antenna. The ECE signal collected at each antenna for a given linear polarization is a combination of Ordinary and eXtraordinary waves. The fraction of X-mode coupled to the vertical polarization of the antennas is shown in fig. 4. The behavior of the X spectra in high temperature plasma 68394, in which density is lower and heating power is higher than in 68385, is shown in fig. 5. The

measurements are again in agreement with the simulations reported in [1], where the effect of a possible distortion of the electron distribution in the low energy range is discussed. In this plasma data for increasing angles are progressively farther from the Maxwellian spectra. In fig.5 this behavior is compared with preliminary simulation work performed introducing a pair of secondary Maxwellian dependent on three parameters representing the drift velocity u_d, the temperature T_d and the population n_d in relative units with respect to the bulk values in the region $\psi<0.3$. The parameters that best fit the data are included in the captions. Fig. 6 includes information on the energy of the electrons contributing to the emission at fixed frequencies, corresponding to the peak of the 2nd harmonic for 3.2 T at 10 and 22 degrees. For X-mode, perpendicular emission the maximum and minimum energy curves (not shown) collapse in a single line. The bell-shaped curves represent the line width of the emission at the given frequency for X-mode, while the dashed curves represent the minimum/maximum energies of the resonant electrons. As shown the spatial region that contributes to the emission for the 22° X-mode is wider than for 10° X-mode (poorer spatial resolution), and consequently the resonant electrons have a wider energy range, including the lowest energy region.

4. Conclusions

First data analyzed from JET Oblique ECE diagnostics show good agreement between measured and calculated spectra in ohmic plasmas assuming Maxwellian distribution, but differences beyond possible uncertainties related with the spectral details of the calibration arise when substantial heating power is added. These differences appear more remarkable for oblique emission, corresponding to wider energy range, and for higher heating/lower density. Fitting of the data assuming the distribution function being distorted with a simple receipt is possible, and gives indications about the typical energy of the distortion.

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References

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[2] C.Sozzi et al. Fus. Eng. & Des. 74 (2005) and Proc. 14th Workshop on ECE and ECRH (EC-14), (2006)

[3] D.Farina, L.Figini et al., to be presented at Int. Conf. on Burning Plasma Diagn. Varenna, Sept. 24-28, 2007

[4] V.Krivenski et al, Proc. 12th Workshop on ECE and ECRH (EC-12) (2002).