EFDA–JET–CP(07)04-17

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** See annex of M.L. Watkins et al, "Overview of JET Results ",*
(Proc. 21 st IAEA Fusion Energy Conference, Chengdu, China (2006)).

Preprint of Paper to be submitted for publication in Proceedings of the
International Workshop on Burning Plasma Diagnostics, Villa Monastero,Varenna, Italy.
(24th September 2007 - 28th September 2007)

ABSTRACT.
Despite considerable effort, both theoretically and experimentally, a complete physical model to describe the particle and energy losses during ELMs is far from complete. On the experimental front, improved description of the spatial structure (poloidal asymmetry, radial distribution) and the dynamics of the ELM crash is a key requirement to answer some of the basic outstanding questions concerning the physics of ELMs. A significant number of diagnostics is now capable of fast measurements of the pedestal profile during an ELM, however, there is a lack of data from the inboard midplane, so assumptions of poloidal symmetry on the flux surfaces have often to be made. The aim of this work is to explore the capabilities of the Electron Cyclotron Emission (ECE) diagnostics to provide simultaneous measurements of the edge temperature for both inboard and outboard plasma midplane. Access to the inboard region of the plasma is achieved in JET by using 1st harmonic/O-mode polarization, as it is not affected by harmonic overlap with the 2nd harmonic. This paper focuses on the validation of the inboard ECE data and the identification of the limitations of the measurements and the data analysis.

1. ELECTRON TEMPERATURE MEASUREMENTS IN JET

Several diagnostics provide the electron temperature profile in JET: the Electron Cyclotron Emission (ECE) heterodyne radiometer [1], a core and edge LIDAR Thomson Scattering system [2] and a recently installed High Resolution Thomson Scattering (HRTS) system [3]. Both the HRTS and the edge LIDAR systems have a nominal spatial resolution of 1.5cm (at the pedestal region), for the core LIDAR the resolution is ~12cm. The ECE radiometer consists of 96 closely spaced channels (~1cm for the magnetic field gradient at JET) with an spatial resolution of ~3-6cm depending on the plasma conditions and the harmonic number (including spectral resolution of the instruments, relativistic broadening of the cyclotron emission and antenna pattern effects). For the experiments reported here a sampling rate of 5kHz was used. The radiometer is cross-calibrated against an absolutely calibrated scanning Michelson Interferometer (2nd harmonic, X-mode) during the ohmic phase of the discharge. All of these diagnostics provides local values of the electron temperature at various poloidal locations. In order to compare the radial temperature profiles from the different diagnostics, measurements are mapped onto the mid-plane using EFIT reconstruction. The objective of this paper is to report on a new set of recent measurements obtained at JET using high spatial and temporal resolution ECE data from both High-Field Side (HFS) and Low-Field-Side (LFS) midplane. Given the relative novelty of the technique, this paper focuses on the validation of the new ECE data measured at the HFS and the identification of the limitations of the measurements and the data analysis.

2. SIMULTANEOUS HFS/LFS TE MEASUREMENTS BY ECE

The radiometer in JET collects the emission using an antenna located on the low field side of the torus. It consists on 6 independent heterodyne receivers in the frequency range 69-139GHz. Each of the receivers can be independently set to measure O-mode or X-mode polarized radiation (for first and second harmonic respectively) which allows good radial coverage of the outer half of the plasma for a large range of toroidal fields (up to 4T).

ECE measurements using the 2nd harmonic have an intrinsic limitation due to the harmonic overlap with the 3rd harmonic, so the maximum radius at which reliable temperature measurements can be obtained in JET is limited to R>2.6m. However, for 1st harmonic O-mode polarization this limitation does not exist and access to the inboard plasma region can be achieved (see Fig.1). By using a combined O- and X-mode operation and for a sub-set of toroidal fields, simultaneous access to the plasma edge at both the High-Field-Side (HFS) and the Low-Field-Side (LFS) region is possible.

3. ANALYSIS OF THE ECE MEASUREMENTS FROM THE INBOARD REGION

One difficulty in the analysis of the ECE data from the HFS is that the standard scheme of cross calibrating the radiometer data (1st harmonic/O-mode) against the Michelson data (2nd harmonic/ X-mode) is not valid anymore, and a different technique must be implemented. Two independent calibration methods have been compared: cross-calibration with the Michelson interferometer using specific toroidal field ramp pulses and comparison to the data measured at the plasma LFS during L-mode. With the first method, the radiometer data is calibrated using pulses in which the O-mode channels are located in the LFS region (R<3 m) and therefore they can be cross- calibrated against the Michelson interferometer. This requires to carry out the calibration pulses (ohmic pulses with a magnetic field ramp) at a higher magnetic field than that used for the pedestal measurements and to select the appropriate radiometer configuration (the calibration factors depend on all the components along the heterodyne detection stage, i.e. the mixer, the IF amplifier, the IF filter and the video detector). However, due to the variability of the measured calibration factors (mainly due to lack of stability on the receiver's sensivity), it was necessary to develop an alternative calibration technique. With this second technique the radiometer channels located at the plasma HFS are calibrated by comparison with the channels at the plasma LFS during L-mode (assuming that the T_e is constant on a given flux surface). In order to obtain a reliable calibration the following conditions must be fulfilled: the method is restricted to the L-mode phase (reliable equilibrium reconstruction) where the gradients are nearly lineal (in this case the possible differences in calibration due to the different spatial resolution for O-mode and X-mode are minimized) and in the region where T_e >150eV (to guarantee high enough optical thickness). The errors for the calibration factors obtained using the second method (when it is compared with the absolute calibration technique) give typical uncertainties of less than 10%.

Figure 2 shows an example of the comparison between the T_e profiles measured by ECE (with the HFS calibrated using the second method described above), both in the LFS and the HFS, across the pedestal region and the data obtained with the HRTS system in JET for an ELMy H-mode plasma (B_0 = 2.7T, I_p = 2MA, P_{NBI} = 8.7MW, P_{ICRH} = 1.75MW, $n_{e0} = 6\times10^{19}$ m^{-3}). In general, good agreement is obtained between ECE and TS systems for relatively low density plasmas (where refraction effects are negligible). It is a general observation that the ECE profiles on the LFS are systematically shifted approximately 5 cm with respect to the TS profiles. This shift can be corrected by including an error of <1% in the value of the toroidal field, which is well within the uncertainty of its calibration. We have found that this correction also brings into alignment the inboard and outboard ECE profiles as it can be seen in Fig.2.

One of the main limitations for the use of the 1st harmonic O-mode ECE data is that it is closer to its cutoff frequency than the 2nd harmonic X-mode, which makes it more susceptible to cutoff and refraction effects. This limiting factor is stronger at lower magnetic fields (B = 2.7 T was found the best option in JET).

Refraction effects become important as the cutoff density is approached. In those conditions, the trajectory of the cyclotron radiation is bent causing the emission at a given frequency to come from a different region than expected from its nominal location along the antenna axis. This effect can be calculated using a beam tracing code [6]. In figure 3 an example of such kind analysis is shown for a high density H-mode plasma (B_0 = 2.7 T, I_p = 2.5 MA, P_{NBI} = 13.9MW, P_{ICRH} = 2MW, $n_{e0} = 9\times10^{19}$ m^{-3}). Figure 3a shows a clear asymmetry between the LFS and HFS temperature profiles mapped onto flux coordinates assuming that the emission comes from the cold resonance position along the antenna axis. When the location of the emission is corrected taking into account the refraction experienced by the emitted radiation, the resultant profiles are approximately equal in shape but they are shifted. This shift can be finally removed by including the error in the magnetic field mentioned previously.

CONCLUSIONS

In JET, a new set of ECE measurements of electron temperature profiles across the pedestal region at both HFS and LFS has been recently obtained. The access to the inboard side of the plasma is achieved by using 1st harmonic O mode emission which it is not affected by harmonic overlap. While it may seem obvious to use the O-mode electron cyclotron radiation to have access to the HFS, this task has hardly been taken on in the literature. Part of the problem is that the use of X-mode has been favored due to the better spatial resolution. In the case of JET the achievable spatial resolution on the HFS, calculated using the SPECE code [6], is poorer than for LFS data (<3cm in the LFS and <6m in the HFS pedestal region), but the measured data have shown that it is good enough for a comparative analysis of the inboard/outboard pedestal region in ELMy H-mode plasmas [4]. The difficulty of access to the inboard plasma region in large fusion devices makes this new ECE data measured at JET especially relevant, in particular for improving our understanding of ELM dynamics.This information can also provide a very valuable input for the equilibrium reconstruction before and after the ELM. Analysis of the temperature drop caused by the ELMs crash in both the inboard and outboard plasma region is in progress [4] and will be published elsewhere.

For ITER, the access to the inboard plasma midplane is restricted due to harmonic overlapping, effect that becomes more important as T_e increases [5,6]. Further analysis is in progress to asses the possible use of O-mode ECE from the inboard region during the first operation phase in ITER (with reduced plasma parameters).

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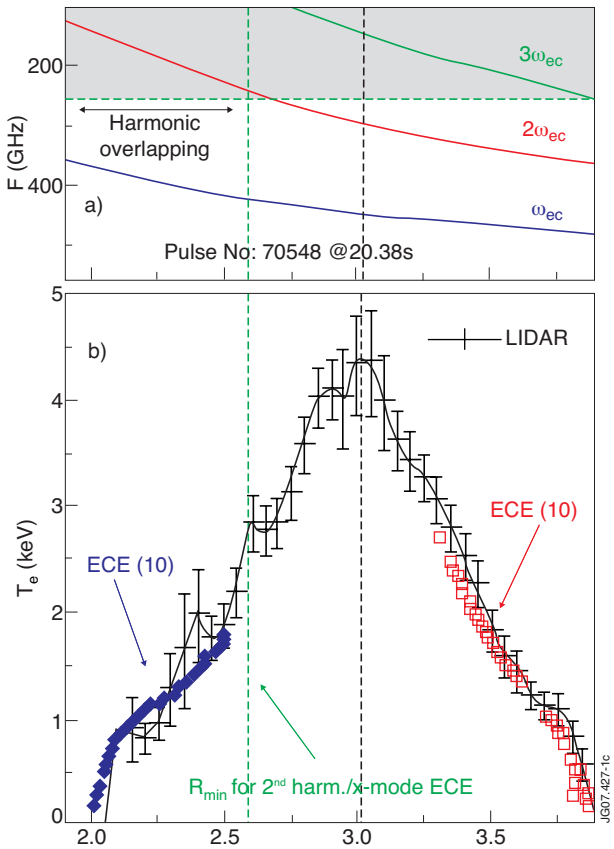

Figure 1: (a) Harmonics of the electron cyclotron frequency showing the region where 2nd and 3rd harmonic overlap, (b) Te profile measured by LIDAR and ECE: 2nd harmonic/X-mode is used for access to the LFS region and 1st harmonic/O-mode for access to the HFS region.

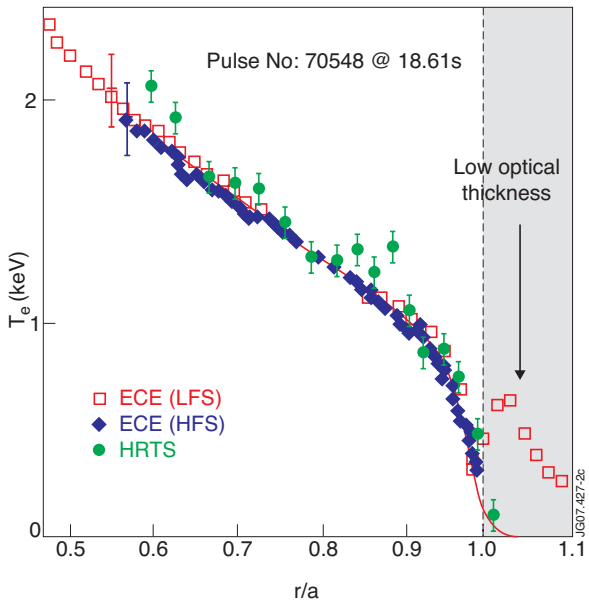

Figure 2: T_e profile measured by ECE (for both HFS and LFS) and HRTS for a low density ELMy H-mode discharge. The position of the ECE profiles has been calculated increasing the total magnetic field by 0.7%

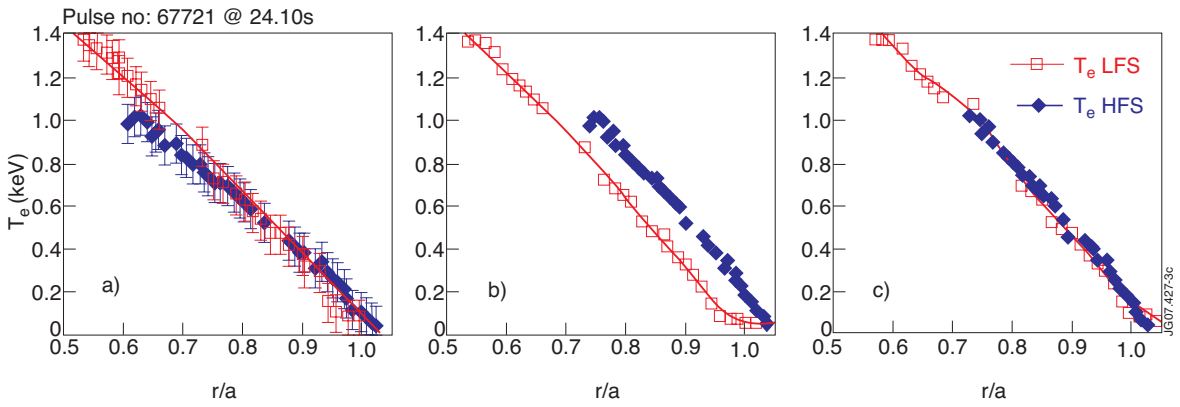

Figure 3: Temperature profiles measured by ECE and mapped onto flux coordinates for the LFS (red, open symbols) and HFS (blue, closed symbols): (a) assuming that the emission location is given by the cold resonance along the antenna line of sight, (b) correcting the emission location taking into account the refraction effects and (c) the same than b) including magnetic field error of ~1%.