First measurements of oblique ECE with a real-time moveable line-of-sight on TCV

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Abstract. Electron cyclotron emission (ECE) radiometers viewing perpendicular to the magnetic field are common on nearly all tokamaks for measuring the electron temperature with good spatial-temporal resolution. Two such radiometers are installed on TCV; one looking from the low and the other from the high field side (LFS, HFS). The HFS radiometer is especially sensitive to non-Maxwellian emission in the presence of strong electron cyclotron current drive (ECCD) provided by the 3MW second harmonic (X2) EC system, as the non-thermal radiation is not reabsorbed by the bulk when passing to the receiver. Simultaneous HFS and LFS measurements allow higher order modeling of the electron distribution function as more constraints are provided by the dual measurements; however, the asymmetric nature of the electron distribution function required for ECCD to occur, is not directly put in evidence by these lines-of-sight. Oblique ECE measurements of an asymmetric non-thermal electron distribution, on the other hand, are expected to also be asymmetric and can provide important information on the current carrying features of the non-thermal population [1]. A dedicated receiving antenna has been installed allowing real-time swept oblique ECE on TCV in both the co- and counter- looking directions. Proof of principle experiments are described in which Doppler-shifted emission is measured.

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INTRODUCTION

Two heterodyne radiometers, viewing perpendicular to the magnetic field, one from the low field side [2] and high field side [3], have been used on the TCV tokamak to diagnose the electron cyclotron emission from plasmas heated with up to 3MW of electron cyclotron heating (ECH) and current drive (82.7GHz, 2nd harmonic, X-mode: X2). The dual observations have been crucial to the understanding of experiments in which 100% absorption of 3rd harmonic X-mode radiation (118GHz, 0.5MW) was measured under specific X2-ECCD pre-heating conditions [4,5]; due to their sensitivity to bulk and suprathermal electron populations, respectively. Furthermore, they have been used to demonstrate that a significant fraction of the magnetic energy released during the magnetic reconnection which occurs at the familiar sawtooth crash, can be transferred to fast-electrons [3,6].

In the interest of complimenting these views and enhancing the flexibility of the ECE system on TCV [7], a LFS launcher has been connected to the LFS radiometer via 1” circular waveguide and a microwave switch. One of the many possibilities opened up by this antenna is the ability to put into evidence the asymmetry in the electron distribution function generated during high power ECCD, by viewing the plasma with oblique ECE (i.e. with a viewing line which is not perpendicular to the magnetic field). This technique has been used on Tore Supra, PBX and the FTU tokamaks, and will soon be installed on JET [8 and ref.s, therein]. This paper describes the experimental setup as implemented on TCV, and shows first measurements taken with the real-time-movable, oblique-viewing receiver, during ECCD.

OBLIQUE ECE ANTENNA

A receiving antenna (Fig. 1, foreground) has been installed in TCV in sector 7 (of 16) which is identical to one of 6 existing X2 launchers. The normals of all 4 mirrors, seen in figure 1, are in one plane and that of the 4th mirror moves in said plane when actuated by rods running inside the tubes seen at the sides. The 4-mirror structure including the actuator rods can be rotated up to 360° about the axis of the input waveguide between shots. For power launch, the microwave beam from an open-ended, 63.5 mm diameter, HE_{11}, corrugated waveguide reflects from the 4 mirrors and exits the launcher at an angle to the axis, determined by the angle of the 4th mirror, closest to the plasma. The 1st and 3rd mirrors are focusing. The 4th mirror angle can be adjusted rapidly to provide a sweep of the beam angle, relative to the axis, between 7° and 55° within 500 ms. At typical angles this results in a deposition displacement of ~ 1mm/ms or, one full-width-half-maximum beam width in ~30 ms.

Measurements were taken with launcher 1 (X2L1) of the TCV X2 ECH system prior to the installation of the 7th launcher receiving antenna (X2L7). To do this, the section of the transmission line immediately before the launcher (between a high-power, vacuum, microwave switch and the tokamak gate valve) was removed: the vacuum is maintained in the remaining part of the line and the tokamak and the gyrotron is diverted to a high-power load. A short pumping section and window were installed at the all-metal gate-valve entry to the launcher, the section was pumped and the gate-valve opened; thus, providing a view of the plasma via the launcher. For the newly installed X2L7, the gate-valve is replaced permanently by a window.

Polarization

EC radiation was received outside the window by open-ended one-inch diameter waveguide. For oblique ECE, the required polarization is elliptical (major axis, a, minor axis, b) - defined by the angles α (rotation of a) and β ($=\tan^{-1}(b/a)$) - and may vary in time if the viewing line moves. The receiver polarization, however, was constant and was determined by one of the three waveguide configurations described below.

Initially, the geometry of the transmission line was such that a 22.5° rotation of the electric field away from the vertical resulted at the entrance to the receiver (radiometer input projected to the end of the transmission line). This gave $\alpha = -112.5°$ and, when added to the magnetic field line inclination resulting from the plasma current of 250 kA (~13°), resulted in a polarization rotation of ~35° away from "quasi" X-mode.

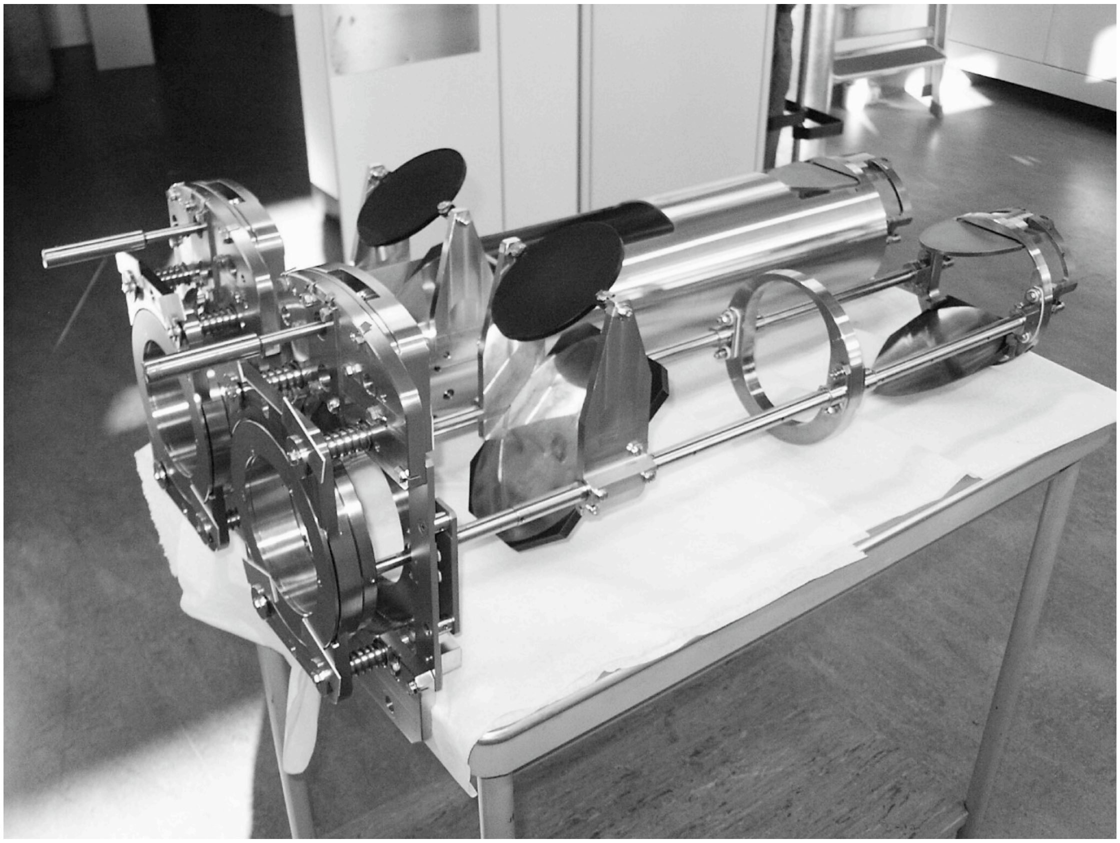

FIGURE 1. Two X2 launching antennas. Behind is a new version with fewer components allowing easier construction. In the foreground the 4 mirrors of the launcher/receiver can be seen. The plasma would be at the right in this photo.

The second polarization angle can be set to $\beta = [-45°,0°,45°]$. For the cases ±45° a "conversion section" consisting of a down-taper, circular-polarizer (axial ratio of 1.1 at ±10% bandwidth, center frequency 82.7GHz), rectangular-waveguide, rectangular-to-circular waveguide, and up-taper was used at the exit of the launcher. The conversion section selects one helicity of the wave and reflects the other. Without this convertor, the received power is transmitted through circular waveguide to a rectangular waveguide switch at the radiometer ($\beta = 0$).

A rectangular waveguide switch selects between one of three viewing lines for any given shot (perpendicular LFS via a lens at z=0.0 m, horn/mirror antenna at z=0.21 m, or the LFS launcher at z=0.0 m). For a constant source power, switching between lines introduces ±0.09 (±2%) uncertainty in the calibration of the radiometer.

Coupling

The TCV ECH Control System (ECHCS) automatically calculates the polarization required to couple to either quasi-X or quasi-O mode, hereafter referred to simply as X- or O-mode (elliptical polarization being understood), as a function of the launch angles and the plasma boundary, for all 7 X2 launchers. In the case of power *launch* this information is relayed to the two remote-controlled polarizer grating mirrors in the matching optics unit (MOU) of each gyrotron to ensure full absorption; generally, by coupling to the X-mode but in some experiments to the O-mode for O-X-B conversion to the electron Bernstein wave in overdense plasmas [9]. For the receiver, the information is simply used to calculate the coupling of each mode to the rectangular waveguide at the radiometer; dependent on the convertor section used during the shot.

For 2 discharges in which no conversion section was used, the calculated difference of the coupling *from one discharge to another* was less than 0.5% over all angles and frequencies, even though a more significant change was calculated as a function of receiver viewing angle for each discharge individually. As the calculations take into account the measured angles and plasma shape, 0.5% variation indicates good shot to shot reproducibility of the overall geometric configuration. The same is true if circular polarization is used, provided the helicity is flipped for shots having opposite viewing directions (i.e. each time receiving X-mode). This change requires disassembly and reassembly of some waveguide sections (requires ~5 minutes) and one can expect an additional ±2% variation as mentioned for the microwave switch, above. Finally, the circular polarizer increases the coupling by a factor of ~2 and provides better mode selectivity (hence localization); however, with additional front-end attenuation.

Calibration

The radiometer is not absolutely calibrated. To obtain a radiation temperature, a cross calibration of the radiometer channels to the Thomson Scattering (TS) profiles during the low power ECH, or Ohmic, phase of the discharge is performed. With the LFS antenna, we additionally impose that the calibration be carried out at the smallest toroidal angle (smallest $N_{//}$) to avoid Doppler-shifted reception. This is justified by comparison with the standard LFS viewing line at z=0.21m which has a much larger antenna divergence angle (12° vs. 4°), yet is not generally perturbed by fast-electrons: when calibrated prior to ECH, the ECE and TS temperatures also match during ECH.

EXPERIMENTS

Three shots were carried out initially; two with ECH heating and co- or counter-viewing; and one with ECCD in the co-direction (i.e. ECCD in the same direction as the plasma current). For all shots, the input power configuration was constant (power and injection angles); while the LFS viewing line was swept from 10° to 35° during 1s; once looking in the co-direction and once in the counter-direction. The first 2 shots had β=0° and were used to establish the reproducibility of the plasma as well as the difference in the ECE spectra measured when *viewing* a symmetric electron distribution function in *opposite directions*. Although there is an asymmetry due to the bulk drift velocity associated with the plasma current, this is negligibly small; or, at least, can be considered equivalent to a systematic “error” on the symmetry of the ECE spectra.

The ratio of the low-pass-filtered HFS signals (fixed viewing line) from one shot to the next during ECH is 1±10% over all radii (frequencies) and times. The ratio of the

LFS signals also varies by about ±10% except at the largest toroidal angles where refraction becomes important and even small differences in density are accentuated. Ratios of LFS signals greater that ±10% at the same angle can therefore be considered to be statistically significant and not due to irreproducibility between discharges.

A second pair of similar shots was executed using good X-mode selectivity and *swept co-viewing* (+10° to 30°; β=45°) for both discharges. Low power (250kW), small angle, ECCD was injected, once in the co(-10°) and once in the counter (+10°) directions. The ratio of the LFS signals was again calculated (cnt-eccd/co-eccd). It slowly decreases with increasing angle, from 1.0 to 0.85, at all optically thick frequencies. The radiation temperature of each shot initially follows the TS temperature, but decreases slightly with angle in each shot. The decreasing *ratio* might be an indication of an asymmetry associated with the ECCD but is not much different than the previous pair of shots; though the measurement is now more localized.

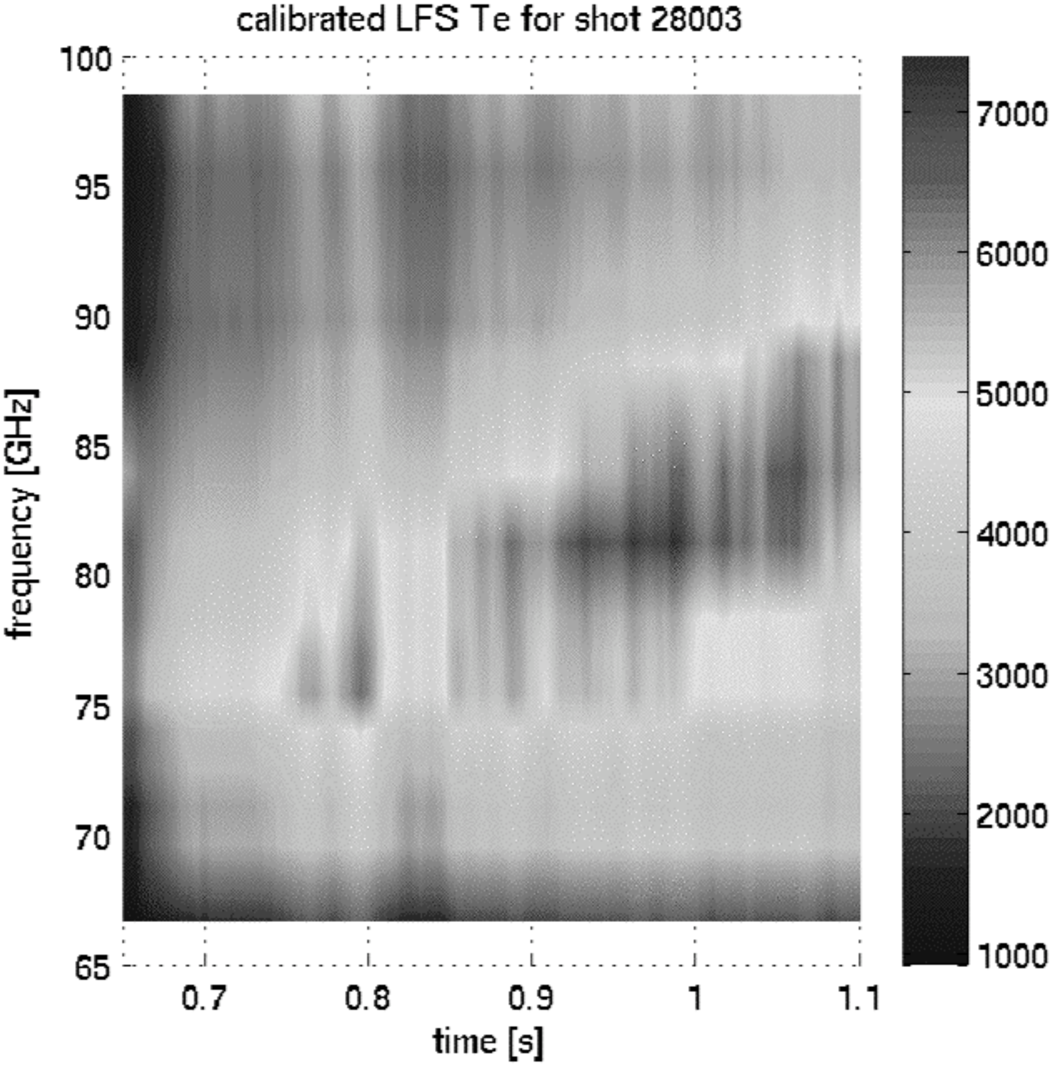

FIGURE 2. Radiation temperature from X2L7 radiometer during a real-time sweep of the co-view under constant current drive conditions (500kW co-ECCD). The viewing line is swept linearly from 10°

at 0.7s to 32.8° at 1.1s. The maximum radiation temperature shifts from ~75GHz to ~87GHz during the sweep while the HFS radiometer sees no shift in the same shot.

When 500kW co-ECCD at 25° is injected we compare the maximum in the LFS emission relative to the discharge with ECH for the same viewing angle sweep: the matching discharge with the opposite view is not available. The frequency of maximum emission intensity increases with angle (Fig. 2) whereas it remains nearly constant for the ECH discharge. This provides a first clear indication of significant Doppler-shifted emission due to the non-thermal electrons [2].

CONCLUSIONS

A LFS real-time movable ECE receiver has been successfully installed and used to measure Doppler-shifted suprathermal electron emission during ECCD by oblique viewing. Good shot-to-shot reproducibility has been confirmed allowing relative measurements despite the lack of absolute radiometer calibration. In the near future we plan to increase the measurement sensitivity by reducing the transmission line attenuation and adding low-noise amplification, and to complete a data set of co- and counter- viewing sweeps during strong ECCD at several difference injection angles.

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