Electron Cyclotron Emission (ECE) and Correlation ECE diagnostic on TCV

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The electron cyclotron emission (ECE) and correlation ECE diagnostics in TCV have been upgraded during its 2014 shutdown; this paper will provide a brief overview on their updated architecture and capabilities. The ECE system is equipped with two radiometers, each with 24 channels (750 MHz bandwidth) looking at the plasma both from the low and high field side covering the whole vessel. Of particular interest is the possibility of acquiring signals through a vertical line of sight and a two-axis steerable antenna to study electron distribution function (EDF) in plasmas with ECCD or ECRH. The correlation ECE system has been equipped with a new independent front end connected to the steerable antenna. The main characteristics of the radiometer are the six YIG independently tunable (between 6-18 GHz) 170 MHz bandwidth channels that can be moved on the whole LFS of the vessel. Using correlation analysis techniques it is possible to study very small temperature fluctuations. A brief presentation of some applications where these capabilities have been exploited in past TCV experiments for the study of micro instabilities characteristics is also included.

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1. Introduction

Tokamak à Configuration Variable (TCV) is a medium sized machine for the study of the physics of magnetically confined plasmas for nuclear fusion applications. Its most relevant characteristics are the possibility of working in a large range of different plasma shapes, its versatile heating system and the large variety of diagnostic systems available for the study of the plasma. In the past year the Electron Cyclotron Emission (ECE) diagnostic system has been significantly upgraded. This kind of diagnostic allows the measurement of local electron temperature with high spatial and temporal resolution. The dependence of the resonant frequency on the local value of the magnetic field makes it possible to associate the different frequency components of the measured signal with different radial positions allowing spatially resolved measurements of T_e. In reality though it must be taken into account that radiation frequency coming from a constant B surface will be broadened by relativistic effects (i.e. suprathermal electrons emission) and Doppler shift [1] [2]. The present paper provides a brief overview of the ECE (section 2) and CECE (section 3) systems of TCV together with examples of applications.

2. ECE

TCV has been equipped for the first time with ECE diagnostics in 2002 (HFS) and 2003 (LFS). In the following section we will describe the current status of the ECE systems on TCV.

2.1 Lines of sight

The ECE system of TCV is composed of two separate radiometers looking respectively from HFS and LFS perpendicular to the magnetic field. Each of them can be connected to one of two antennas, one on the mid plane of the tokamak ($z = 0$) and the other at $z = 21$ cm. The ECE antennas consist of a focusing element and the waveguide transmission line : an oversized waveguide ending in a rectangular section. The LFS line of sight on the mid plane plane uses as a focusing element a thermoplastic (TMPX) lens with 20 cm focal length while the one at $z = 21$ cm uses an elliptical mirror. Mirrors, antennas and some waveguide components are inside the vacuum vessel, separated by a window from the outside. The HFS lines of sight are similar to the second LFS one with the difference that the waveguides run behind the tiles of the wall and bring the signal towards the upper part of the vessel where the vacuum break is provided by a 200 μm Mylar foil.

2.1.1 Alternative lines of sight

In addition to these four antennas TCV is equipped with a steerable receiver, connected to the LFS and CECE radiometers, and a vertical receiver, whose signal can be transmitted to both HFS and LFS radiometers. Both lines of sight can be used to obtain information on the electron density distribution function. The vertical line of sight consists of a focusing ellipsoidal mirror and a telescope system with a view from the top of the vessel, perpendicular to the magnetic field. At the bottom of the vacuum chamber is placed a beam dump (reflectivity $< 0.1\%$). This receiver can be considered to be looking along a surface of constant magnetic field. Neglecting the non ideal antenna pattern and Doppler shifted emissions, the signals coming at different frequencies can be related to electrons with different kinetic energies (relativistic broadening) [3]. This antenna is
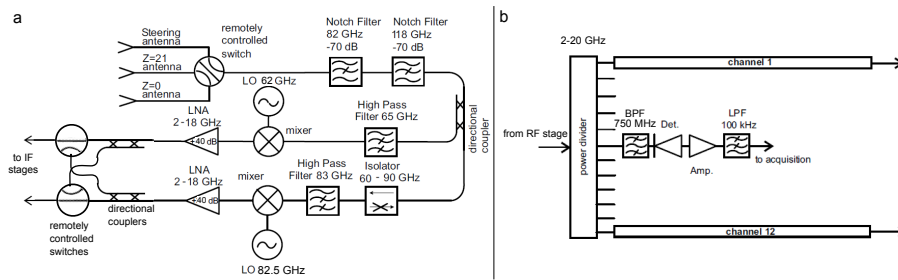
FIGURE 1: Schematics of the RF (a) and IF (b) stages of the LFS ECE radiometer. The HFS radiometer is identical except for the antenna connections and the working frequencies of LOs and other components.

connected with a mechanical switch both to the HFS and LFS radiometers allowing the use of both sets of channels [4]. Another possible line of sight is a steerable antenna positioned at $z = 45$ cm (upper lateral). The antenna itself is one of the gyrotron launchers and its detailed description was provided by Goodman [5]. The movable mirrors allow one to rotate the line of sight with respect to a major radius (θ_L) and around it (ϕ_L), describing a cone trajectory. θ_L can be swept during a shot from 7 to 55° in 500 ms. This receiver sends signals to the LFS or the CECE radiometer and can be used to perform oblique measurements of the EC radiation. This is particularly interesting for shots with ECCD since it is possible to study the difference between co and counter current emissions to get information on the effects of current drive on EDF.

2.2 Radiometer

The radiation collected by the antennas is second harmonic electron cyclotron radiation in extraordinary mode (X2). This is transported in waveguide to the two radiometers (whose scheme is presented in figure 1) after a couple of notch filters (X2 and X3 frequencies) that remove any interference from the ECRH system. The incoming radiofrequency (RF) power is divided in a directional coupler and directed to two mixers, each connected to a Local Oscillator (LO) working at a different frequency. High-pass filters reject the image frequencies below that of the LO frequency. The LOs work respectively at 94.5 and 76.5 GHz for the HFS and at 82.5 and 62 GHz for the LFS. In both radiometers the high frequency branch of the front end includes an isolator which prevents reflected low frequency signals from reaching back into the lower branch. The original RF signals are converted down to the 2-20 GHz interval and then transmitted through co-axial cables into the intermediate frequency (IF) stage of the radiometers. The RF bandwidths analysed by the HFS and LFS mixers are respectively 78 - 114 GHz and 65 - 100 GHz allowing us to acquire data over almost all the radial profile of TCV. The down converted signals are amplified in a low noise amplifier (LNA) with 40 dB gain over the 2-20 GHz interval. These LNAs show 1 dB gain compression at 20 dBm (P1dB) and 3rd harmonic distortion after 30 dBm (IP3). After the amplification the signals are directed to two power splitters. The resulting four signals are divided into two electronic switches so that both receive half of the signal from each mixer. These switches are connected to two twelve-way splitters which divide the incoming signal into the 24 output channels ; the switches allow one to choose which mixer signal goes into which set of channels, thus adding a degree of flexibility in the selection of the analysed plasma volumes. All of these split signals go through a 750 MHz bandwidth band-pass filter selecting the frequencies that will be
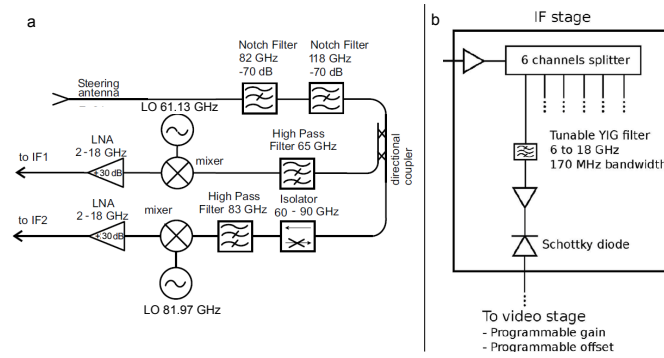
FIGURE 2: Scheme of the upgraded CECE radiometer. a : RF stage, b :IF stage

analysed ; in both radiometers the two 12 channels sets, whose center frequencies are separated by 1.5 GHz, span the 2-20 GHz interval. After being filtered the signals are rectified using a set of unbiased Schottky diodes, low pass filtered (100 kHz) and amplified in a remotely controlled variable gain amplifier. The response curve of the diodes is nonlinear up to -17 dBm and they work in the 2-18 GHz interval (2-26 for the four highest channels).

2.3 Capabilities

The ECE system in TCV has been used in a wide range of geometries, heating conditions and current induction regimes. Together, the HFS and LFS channels span the whole tokamak vessel. The 750 MHz bandwidth of an output channel corresponds to plasma volumes with different width as the magnetic field varies over the radial profile. In the core, one channel corresponds approximately to a 1 cm wide region while in the HFS or in the LFS it would respectively be smaller and larger. The poloidal spot size, instead, varies for the different lines of sight. The best focusing, considering $1/e^2$ width in intensity, is obtained for the LFS ECE at $r/a = 0.6$ and is less than 2 cm.[6] [7]

3. Correlation ECE

The correlation ECE system in TCV was installed in 2007 but only with the last upgrade did it acquire an independent front end from the LFS ECE. Its working principle is to apply spectral decorrelation to ECE signals coming from plasma volumes very close to each other but not overlapped : if the distance between the volumes is chosen correctly small scale modes will still be correlated while the thermal noise of the two channels will not. It is hence possible to lower the minimum fluctuation detectable by the radiometer ($\delta T_e/T_e$).

3.1 Line of sight and radiometer

The newly upgraded CECE system in TCV looks at the plasma through the steerable receiver already discussed in 2.1.1. The front end of the CECE radiometer is similar to those of the standard ECE : two notch filters stop the ECRH power from reaching the mixing stage, a directional splitter divides the power between two mixers connected with LOs at 81.97 and 61.13 GHz, the lower side band is rejected and the down converted signals are amplified in LNAs with 30 dB gain over

the 2-20 GHz interval and P1dB=10 dBm. Only one of the two signals coming from the mixers is sent to the IF stage and that can be manually switched between shots. The IF stage consists of a six-way power splitter leading to six YIG filters, whose band pass frequency can be remotely adjusted between 6 and 18 GHz and whose bandwidth is 170 MHz, followed by another stage of amplification (20dB gain, 20 dBm P1dB, 27 dBm IP3) and six unbiased Schottky diodes. The voltage signal goes then through video cards with programmable gain and offset. A scheme of the CECE radiometer is presented in figure 2.

3.2 Capabilities

The newly upgraded CECE diagnostic is a highly versatile system : it can cover the frequency intervals between 67 to 79 GHz or 88 and 100 GHz, depending on which mixer is being used, allowing to look at the whole LFS of the vessel. Moreover the channels' frequencies, and hence the plasma volumes analyzed, can be varied from one shot to another, further increasing the flexibility of the system. Having six simultaneous measurements allows to perform cross correlation analysis in up to three different plasma regions and estimate the correlation length of turbulent modes in a single shot. The radial resolution is mainly limited by relativistic effects, while in the poloidal direction the antenna pattern limits to modes with $k_\theta < 112 \ cm^{-1}$ at 500 kHz.

3.3 Applications

One of the main fields where these diagnostics are employed is the study of anomalous transport in plasmas caused by turbulent modes. The high sensitivity of CECE diagnostic makes it ideal to study micro instabilities, characterized by very small spatial extension. Some of the experiments focused on the effects of plasma shape on turbulence characteristics. The role of triangularity (δ) has been studied performing a scan from negative to positive values while keeping the density and electron collisionality constant and changing the frequency of the CECE channels to cover, where possible, the central part in the LFS ($0.35 < \rho_\psi < 0.8$). It was found that negative δ leads to a narrower turbulence frequency range and larger correlation length. These effect tend to be more evident for larger ρ_ψ since that is the region where the triangularity difference is bigger. In some of those experiments it was not possible to probe all the LFS but, with the new CECE front end, this limit could be overcome. Together with other diagnostics CECE has been used to characterize geodesic acoustic modes (GAM) in TCV. These modes have been seen for $\rho_\psi > 0.7$ and its frequency matches the results of other diagnostics as magnetic coils or tangential phase contrast imaging (TPCI) [8] (figure 3).

4. Conclusions

The ECE diagnostic is of fundamental importance in the study of plasma physics in magnetic confinement devices allowing the possibility of obtaining information on local electron temperature with very high spatial and temporal resolution. TCV is equipped with a very flexible system that is able to cover the whole plasma cross section looking from the HFS and from the LFS. An important asset of this system is the presence of two non conventional lines of sight, one looking at the plasma along a vertical direction, while the other is connected to an antenna steerable around two axis, one of which can be scanned during shots. TCV is also equipped with a CECE system that can be
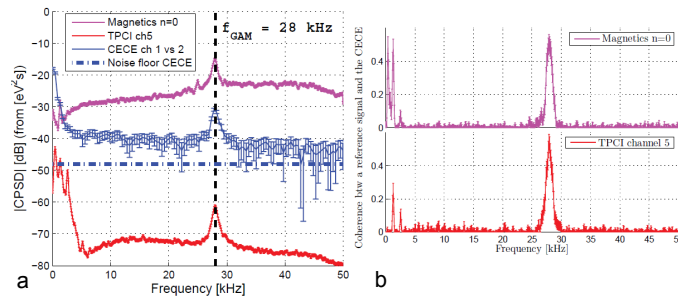
FIGURE 3: (a) Cross Power Spectral Density of magnetics, TPCI and CECE where the GAM is seen at the same frequency. (b) CECE coherence plots with magnetics and TPCI.

used to study microturbulence at very low spatial scale thanks to spectral decorrelation analysis. Future work will take advantage of the improved capabilities of the ECE and CECE diagnostic to overcome some of the main limitations encountered in past experiments.

Acknowledgements

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