2-D ECE IMAGING EXPERIMENTS ON TEXTOR

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Recently a real-time 2D ECE Imaging (ECEI) system has become operational at the TEXTOR tokamak in Germany. This novel diagnostic combines ECEI techniques and broadband radiometry to measure the electron temperature and fluctuations in 16 × 8 sample volumes. The total plasma area imaged on the detector array is 16 cm (vertically) by 5 to 9 cm (radially). The system is wideband tuneable and covers a total detection range of 98 to 128 GHz to match a wide variety of magnetic field conditions. First results obtained at TEXTOR demonstrate the feasibility of 2D ECE imaging.

Introduction

Ongoing sophistication of theory and simulations of fusion plasma physics in toroidal devices, have led to three dimensional (3D) models and visualizations of plasma parameters [1,2,3]. However, experimental verification of the 3D models is often incomplete, for instance in the case of transport models where complex turbulence physics is presumably playing a dominant role. Unfortunately, one of the established diagnostics to measure electron temperature, namely Electron Cyclotron Emission (ECE) radiometry, is still a 1D diagnostic in most experiments. This is an unsatisfying situation because assumptions are required to be able to reconstruct 3D phenomena from 1D ECE data, such as the assumption of rigid body rotation [4].

Due to advances in millimeter wave technology [5], especially in the development of compact detector arrays with excellent broadband properties, it has now become feasible to perform true 2D ECE measurements. This has been accomplished by the combination of the merits of ECE imaging (ECEI) and conventional broadband ECE radiometry, applied to each of the array detector elements. In ECEI [6], optical elements, like mirrors and lenses, image a vertical chord of ECE radiation on a detector array. On the other hand, conventional ECE explores the radial dependency of the electron cyclotron frequency. The combination of both techniques leads to a 2D measurement.

This novel 2D ECEI system has been developed in a collaboration between UC Davis, PPPL and FOM, and is operational at the TEXTOR tokamak in

Germany. The TEXTOR ECEI system has been combined with a Microwave Imaging Reflectometer (MIR) [7], to measure simultaneously temperature and density fluctuations and their correlations. In this paper the attention is focused on the ECEI part of the system only.

System description of the 2D ECEI system at TEXTOR

In order to image the second harmonic X-mode ECE radiation onto the detector array, several optical components have been used, as shown in Figure 1. The quartz window (30 by 40 cm) and the first two large focussing mirrors are shared with the MIR system. The window forms the limiting aperture of the imaging system. All optics is designed to make use of the full window aperture. After the second mirror, a beamsplitter is used to separate the ECE radiation from the MIR signals. The high-density polyethylene (HDPE) lenses between the beamsplitter and the array serve to maximize the coupling of the received radiation with the antenna pattern of the detector array. Just in front of the array, a quasi optical notch filter has been inserted to protect the array against stray radiation from the 1 MW 140 GHz gyrotron used for Electron Cyclotron Resonance Heating (ECRH).

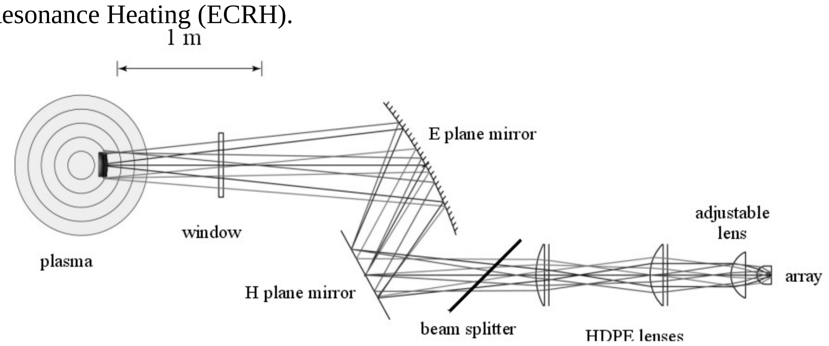

Figure 1. Schematic overview of the optical components of the 2D ECEI system.

The detector array [8] consists of 16 dual dipole antennas, positioned on a dielectric substrate. The dual dipole antenna offers a number of advantages over the bowtie-type antenna that has been used in previous ECEI experiments: it has a better H-plane pattern, it has a wider IF bandwidth and it is more compact, which enables the design of a densely packed array. Schottky diodes are connected to the dual dipole antennas for the down conversion of the ECE frequencies to intermediate frequencies (IF) from 3 to 7 GHz. The IF bandwidth of the current system is limited by the bandwidth of the IF electronics, but could be extended to 13 GHz with the current dual dipole antenna design. The down conversion process is performed in single sideband, where the upper sideband is used. To suppress the lower sideband, a dichroic plate is applied as a quasi-optic highpass filter. Local oscillator (LO) power is supplied from the backside of the array. The LO source is a backward-wave oscillator (BWO) that can be tuned in frequency between plasma shots. The sideband filter needs to be exchanged if the LO frequency becomes too high or too low.

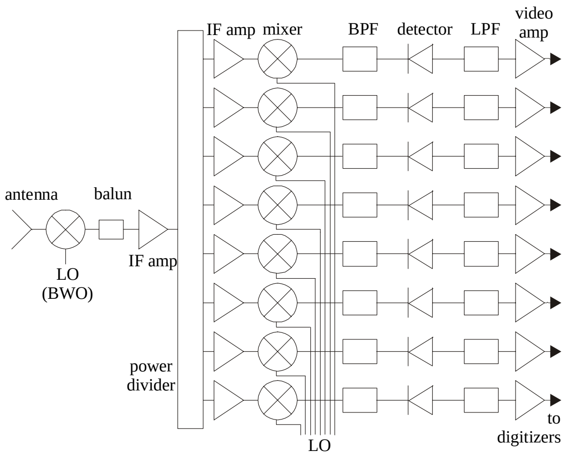

Figure 2. 2D-ECEI electronics, shown for one array detector element.

The ouput of each of the 16 Schottky diodes is connected with a 8 band receiver, see Figure 2. After pre-amplification, the 16 IF signals are transmitted by lowloss coaxial cables to a location outside the TEXTOR bunker where the remaining electronics is installed. Each IF signal is split into eight parts and down converted with eight different LO frequencies that cover the range from 3.2 to 6.8 GHz with 500 MHz separation. This secondary down conversion is a double sideband process that corresponds to a RF bandwidth of 300 MHz due to the 5 to 150 MHz bandpass filters. The signals are then fed into microwave detectors. Post-detection electronics consists of amplification with remote controlled gain settings to match the signal level with the input range of the digitizers, and lowpass filtering. High-speed digitizers, with sampling rates up to 2 MSa per second and on-board memory of 2 MSa per channel are used to sample the signals.

Diagnostic capability

The 2D measurement of temperature profiles and coherent mode phenomena will allow direct observation of rotation without the assumption of rigid body rotation. Furthermore, to study electron temperature turbulence, the 2D ECEI system makes it possible to measure simultaneously and unambiguously the time averaged radial and poloidal wave numbers.

The radial range of the 2D ECEI measurements is determined by the detection bandwidth of 4 GHz. For a typical TEXTOR toroidal magnetic field B_T of 2.25 T at TEXTOR (major radius R_0=1.75 m; minor radius a=0.46 m), this corresponds to a radial range from 5 to 9 cm. The radial plasma range that is covered can be shifted by changing the LO frequency supplied to the array. Compositions of images with a larger total radial extension can be made this way. The effective power of the BWO limits the useful LO range from 102 to 121 GHz, which corresponds to a range of ECE frequencies of 105 to 128 GHz.

The vertical and toroidal spatial range is determined by the focal plane patterns of the optical system in the E- and H-plane respectively [5,8]. The E-plane channel spacing is 11 mm. Therefore the vertical range of the 2D ECEI system is about ± 8 cm around the tokamak midplane. The E-plane spot size is approximately 12 mm (full width at half maximum of the power) for the central channels to 13 mm for the outer channels. The side lobe levels are relatively low. The H-plane spot size is 9 mm. Even and odd channels are separated by 8 mm due to the zigzagged placement of the dual dipole antennas on the array substrate. The location of the focal plane in the plasma, with respect to the array location, can be changed by translation of one of the HDPE lenses close to the array. This way, the spatial resolution of the system can be optimized, for all positions of the ECE radiation layers that are diagnosed.

Fluctuations in electron temperature can be resolved up to 240 kHz, which is the maximum available video bandwidth. With a sampling rate of 1 MSa per second and 2 MSa of memory, the measurement period is limited to 2 seconds. To diagnose slower phenomena, a lower video bandwidth and sampling rate (e.g. 200 kSa per second) can be used to measure during 10 seconds, which is sufficiently long to sample a whole TEXTOR shot of typically 7 seconds.

Calibration of all types of ECE diagnostics is critically important for the interpretation of many measurements. However, the calibration less effects ECEI measurements of relative temperature fluctuations, and measurements of frequency and wavenumber spectra. So far the ECEI system at TEXTOR only has been cross-calibrated against Thomson scattering, where the benefit of spatial overlap of the Thomson scattering and ECEI measurement volumes is utilized [9]. Absolute and independent calibration by application of the hot/cold technique, with a hot source at 900 K and microwave absorption material at room temperature as blackbody sources, is planned for June 2004. With the calibration sources placed at the focal plane of ECEI, the calibration procedure is expected to be similar to the calibration of conventional (radiometer) ECE systems.

Initial experimental results.

As a first demonstration of 2D ECEI measurements, m=1 oscillations in a neutral beam heated TEXTOR plasma has been studied. Main plasma parameters were: plasma current I_p=400 kA, B_T=2.35 T, central electron density $n_e(0) \approx 3\times10^{19}\ m^{-3}$, and neutral beam power P_{NBI}=3 MW. The measured voltage of each channel, which is proportional to the local electron temperature, is normalized to the average value. About 10 identical sawteeth oscillations are averaged coherently to further reduce the noise level further. The 2D picture of the plasma behavior at various times before and after the sawtooth crash is shown in Figure 3. The part of the white circle indicates the location of the inversion radius. A hot island approaches the inversion layer before the crash. Heat spreads along the inversion radius and a cold island develops inside this radius. The 2D ECEI measurements will be very helpful to unravel the magnetic reconstruction physics associated with m=1 mode activity during a sawtooth crash. [10]

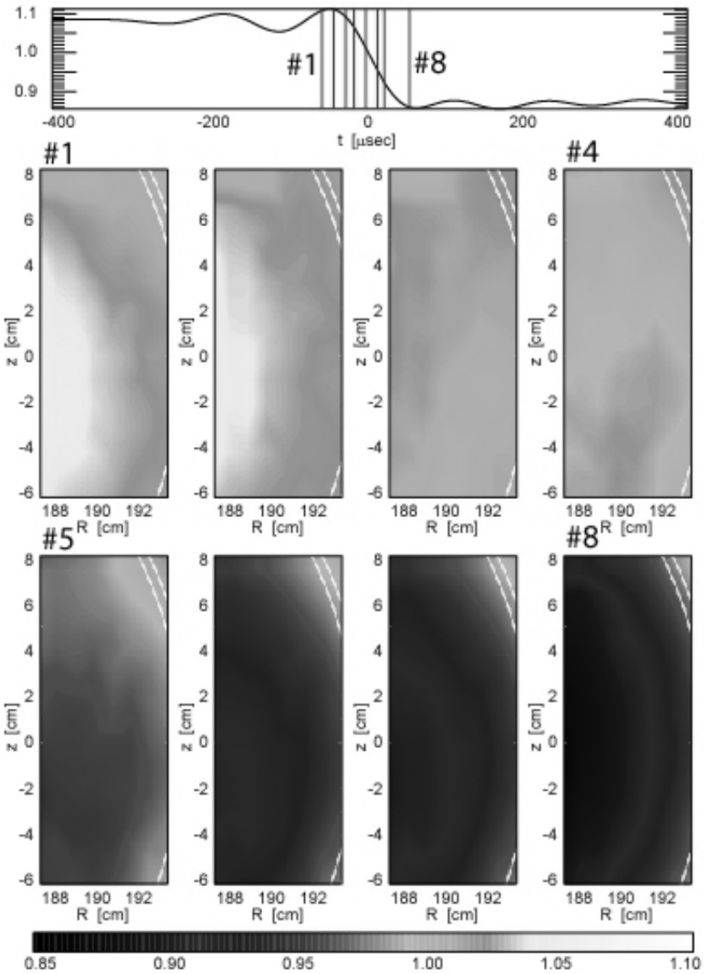

Figure 3. Crash of m=1 mode inside the inversion radius.

The feasibility to study electron temperature turbulence with the ECEI system by the application of correlation techniques has been studied. It has been shown that the current system is capable to resolve fluctuations down to a few tenth of a percent of the electron temperature. Initial fluctuation measurements are presented in [11].

Conclusions and outlook.

Advances in millimeter wave technology, especially in detector array improvement, have enabled the development of a true real-time 2D ECEI system. Real time 2D imaging of ECE radiation has been demonstrated recently at the TEXTOR tokamak. In combination with the MIR, the 2D ECEI system is ideal for the visualization and study of temperature and density fluctuations, due to MHD and turbulence, to verify 3D theory and simulations.

Future work on the system now operational at TEXTOR includes the absolute calibration of the system. A number of upgrades of the system are envisioned, such as the implementation of remote control of the BWO settings and the focal plane position. Furthermore, with additional investments, the full 10 GHz bandwidth of the detector array could be utilized to increase the detection bandwidth.

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