2-5 Millimeter Wave Imaging Diagnostics of Plasma Turbulence

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Abstract Novel millimeter wave imaging diagnostic techniques for the study of plasma turbulence, i.e., the Electron Cyclotron Emission Imaging (ECEI) of plasma electron temperature fluctuations, and the Microwave Imaging Reflectometry (MIR) for plasma density fluctuation measurements, are discussed. Illustrative experimental results of ECEI are presented.

1. Introduction

Anomalous plasma transport remains an outstanding issue in magnetic fusion studies. One of the main reasons limiting the understanding of this important phenomenon is the difficulty in acquiring detailed fluctuation data, especially in the high temperature plasma core region [1,2]. It was not until 1993 that plasma core electron temperature fluctuations ($\tilde{T}_e$) were measured by applying the intensity interferometric technique to Electron Cyclotron Emission (ECE) diagnostics [3]. However, it was soon realized that relatively poor spatial resolution (compared to that required by fluctuation studies) and the one-dimensional nature of conventional ECE radiometers have limited the available information of $\tilde{T}_e$ [2,4]. This has led to the appearance of a novel ECE diagnostic, Electron Cyclotron Emission Imaging (ECEI), which utilizes compact millimeter wave imaging arrays as the heterodyne receivers [2,5,6]. This unique two-dimensional diagnostic has excellent spatial resolution, and has been successfully applied to fluctuation studies in the TEXT-U and RTP tokamaks [2, 5,6]. New information such as poloidal wavenumbers and 2-D structures of the fluctuations have been obtained [2,7].

In a separate development path, microwave reflectometry has been utilized to study plasma density fluctuations ($\tilde{n}_e$) for more than two decades [8]. However, this radar-like method retrieves the target information from the group delay of the reflected microwave signal along the sight line. This inevitably is modulated by the plasma fluctuations transverse to the sightline, so that quantitative interpretation of the data is very difficult [8]. Recently, it has been proposed that the imaging approach can solve the ambiguity in reflectometric measurements of plasma density fluctuations [8,9].

In Sec. 2, the main aspects of the implemented ECEI diagnostic systems are described, along with representative experimental results. New developments in imaging diagnostics, which includes microwave imaging reflectometry (MIR), and the combined three-dimensional ECE and reflectometric imaging diagnostic, are discussed in Secs. 3 and 4, respectively.

2. ECE Imaging of Plasma Electron Temperature Fluctuations

2.1ECE Imaging Diagnostic

Electron cyclotron emission (ECE) radiometers have been standard diagnostics for measuring plasma electron temperature profiles in tokamaks since 1974 [10]; and recently, the have been utilized to study the electron temperature fluctuations in the plasma core [3,4,11]. Conventional ECE diagnostics measure electron temperature profiles by using a single antenna/receiver aligned along a horizontal chord in the direction of the major radius. Therefore, 2-D measurements are impossible with this single sight line arrangement. The spatial resolution of such a system in the transverse direction of the sight line is limited by the divergence of the Gaussian beam pattern of the antenna, typically about 2 to 5 cm for small to medium size tokamaks [12]. As the sample volumes of conventional ECE radiometers are aligned radially, it is impossible to measure the poloidal wavenumbers of the turbulence, which is essential for understanding the relation between drift wave turbulence and anomalous transport of tokamak plasmas [2,11]. Thus, it is desirable to construct diagnostics with poloidally separated sample volumes. It is expected that drift wave fluctuations have peak power at poloidal wavenumbers of about $k_\theta \sim 2cm^{-1}$ [13]. Therefore, it is important to improve the spatial resolution of the ECE diagnostics to $\leq$ 1 cm, so that the systems are sensitive to fluctuations of $k_\theta \leq 3cm^{-1}$.

To meet the above requirements, a novel ECE radiometer, the ECE Imaging diagnostic, has been developed and applied to the TEXT-U and RTP tokamaks [2,5,6]. The principle of the diagnostic is illustrated in Fig. 1. Instead of a single receiver located in the tokamak midplane as in conventional ECE radiometers, the ECEI systems utilized the hybrid millimeter wave imaging arrays as the receiver/mixers. Shown in Fig.2 is the mask layout of the ECEI arrays. In the system, the elements of the arrays are aligned vertically, and measure at the same frequency, so that the sample volumes of the imaging systems are vertically aligned in the plasma. The horizontal position of the sample volumes are determined by the magnetic field strength and the ECE frequency, or the LO frequency of the diagnostic systems. By varying the magnetic field strength or the LO frequency, the sample volumes can be scanned through the plasma cross section to achieve two-dimensional measurements. As all the sample volumes are positioned at the focal plane of the imaging optics, i.e., the Gaussian beam waist location, excellent spatial resolution of about 1 cm is achieved.

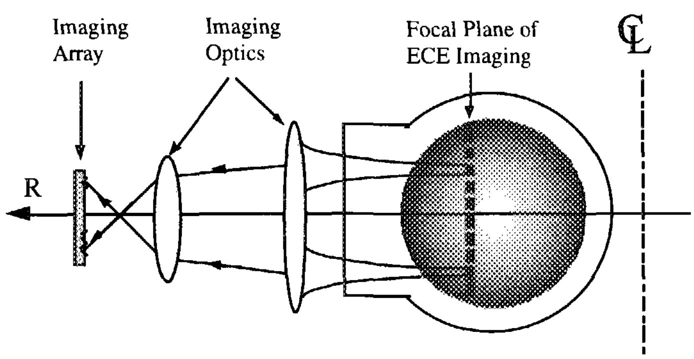

Fig.1 Schematic of the ECEI diagnostic, showing the imaging array and the imaging lenses. The sample volumes can be scanned horizontally (see text).

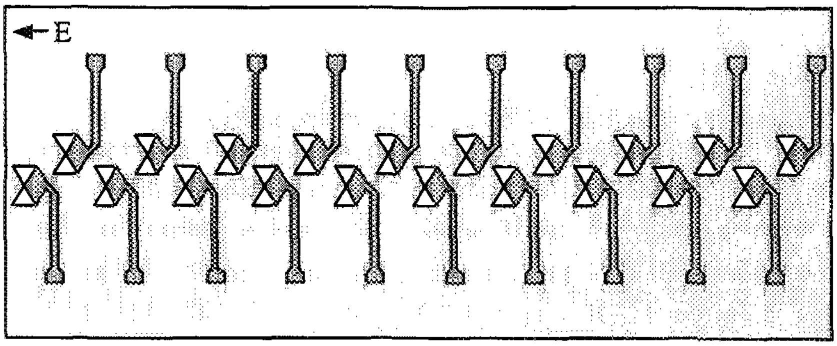

Fig. 2 Mask layout of the RTP ECE Imaging array.

Shown in Fig. 3 is the schematic of the RTP ECEI system. The motorized frames can be translated horizontally to maintain good spatial resolution, when the sample volumes are scanned across the plasma cross-section. From laboratory tests, it is found that for both the TEXT-U and RTP systems, the interchannel spacing is about 1.3 cm. The beam waist (diameter at 1/e intensity) is about 1 cm for the middle channels. This value increases to about 1.5 cm for the edge channels due to spherical aberrations and edge diffraction, mainly due to limited port size.

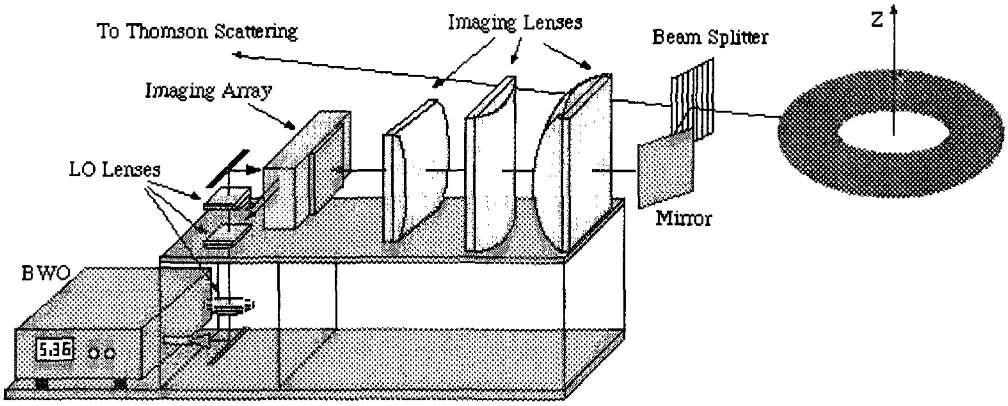

Fig. 3 ECE Imaging diagnostic system implemented on the RTP tokamak. The beam splitter allows the ECEI system and the Thomson scattering system to measure along the same vertical chord of the plasma.

2.2Examples of Experimental Results

Shown in Fig. 4 are the cross power spectral density and cross phases of T_e fluctuations measured by the ECEI system in TEXT-U [2]. Two sets of data are obtained from identical plasma conditions, except that in one set of the discharges, the ECEI system is translated horizontally so that the sample volumes are increased from 1 cm to 2.7 cm (defocused). It is seen that, with degraded spatial resolution, the measured cross power spectral density and cross phases are attenuated due to the sample volume effects [14]. This illustrates the advantage of high spatial resolution ECEI system in plasma fluctuation diagnostics. More results are presented elsewhere [2,7].

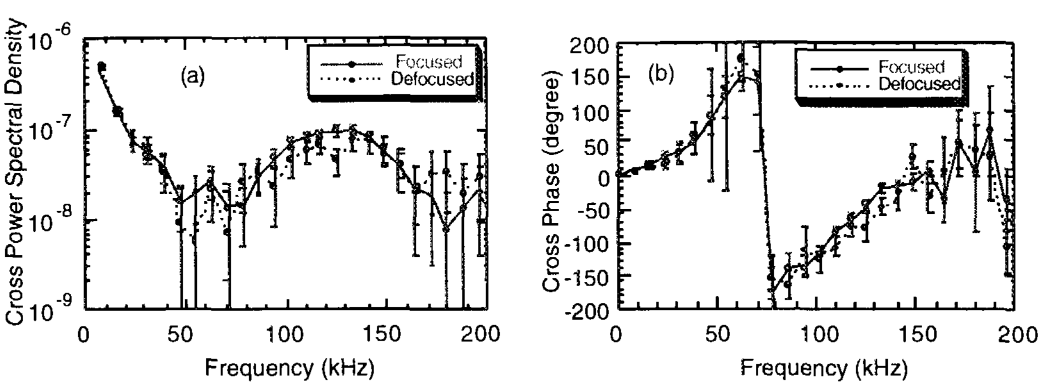

Fig. 4 Sample volume effects in the measurement of drift wave fluctuations (70-170 kHz). The measured cross power spectral density (a) of T_e fluctuations is decreased by ~30%, while the cross phases (b) are decreased by ~10% when the sample volumes are increased from 1 cm to 2.7 cm.

3. Microwave Imaging Reflectometry of Plasma Density Fluctuations

As conventional radar-type reflectometers measure the reflected wave at a single point far away from the plasma cutoff layer, it is impossible to resolve the complicated interference pattern originating from complicated plasma fluctuations [8,9]. Therefore, accurate interpretation of the data is impossible. In view of this difficulty, Mazzucato has recently proposed the concept of imaging reflectometry [9], in which the plasma reflection layer is imaged onto the detector array. Equivalently, an array of detectors simultaneously measure at the plasma cutoff layer, so that the fluctuation structures can be resolved. Shown in Fig. 5 is a schematic of a microwave imaging reflectometer (MIR) being designed for the TEXTOR tokamak. It differs from the ECEI system [Fig.(1)] in that optics is required for illumination of the plasma cutoff layer, and that the imaging optics needs to be designed to match the curvature of the cutoff layer, which may vary with plasma conditions as well as the frequency of measurement.

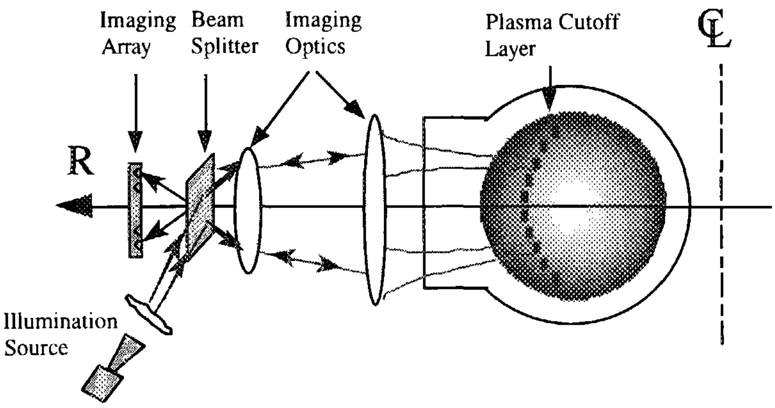

Fig. 5 Schematic of Microwave Imaging Reflectometry.

4. 3-D ECE and Reflectometric Imaging of Plasma Turbulence

As a next step of the millimeter wave imaging diagnostic development, two dimensional imaging arrays will be developed and will be utilized to construct 3-D microwave imaging diagnostic systems, as shown in Fig. 6 [2,9,15]. These systems will combine the ECE imaging diagnostic and the reflectometric imaging diagnostic, so that both the electron temperature and density fluctuations as well as the correlation between these fluctuation quantities can be measured simultaneously. It is expected that new information obtained in this fashion will further advance the understanding of plasma microturbulence and related anomalous transport phenomena [2,9,15].

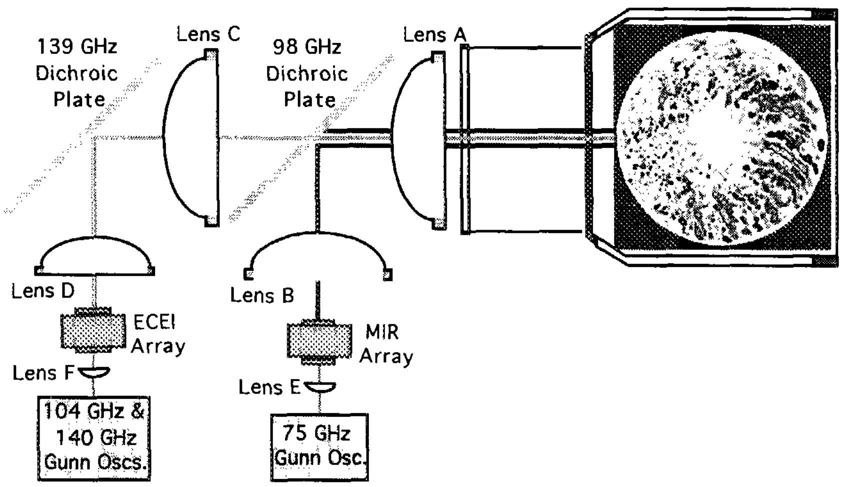

Fig. 6 Schematic of 3-D ECE and Reflectometric Imaging Diagnostic

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