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プラズマのマイクロ波・ミリ波イメージングの現状
Present Status of Micro to Millimeter-Wave Imaging Plasma Diagnostics

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1. Introduction

Microwave to millimeter-wave diagnostics utilizing transmission/reflection, scattering, and radiation processes have been applied to various fields [1]. Application to remote sensing and in-vehicle systems for collision avoidance and automatic cruise control has been extremely fruitful due to the high transmissivity of microwaves under various atmospheric conditions in comparison with infrared and visible light. Microwave/millimeter-wave diagnostics have been utilized because they have the features of good accessibility, non-invasive nature, as well as good spatial resolution especially in the range direction. All of the above-mentioned features are extremely important for fusion plasma diagnostics and depend upon specific characteristics in plasmas, such as the electron cyclotron radiation and the cut-off density, where an electromagnetic wave launched into a plasma is reflected at the corresponding cutoff layer.

In the present paper, we focus on microwave imaging diagnostics and their application to fusion plasmas. The progress in microwave and millimeter-wave devices and circuits, such as monolithic microwave integrated circuits (MMICs), and data processing including computer technology has contributed to the rapid advancement in imaging diagnostic technology for the understanding of physics issues.

2. Microwave imaging system

There exists two-types of schemes in microwave imaging. One is synthetic aperture imaging and the other is optical imaging. The synthetic aperture imaging approach consists of a transmitting antenna and an array of receiving antennas. The signal reflected at a local point arrives at each of the antennas at a different time depending on the direction of the source. The Fresnel-Huygens formula is utilized in order to reconstruct the phase changes due to fluctuations at the cutoff layer [2]. The optical imaging approach uses large aperture optics to restore the wavefront at the receiver position [3]. In this paper, we describe the latter case.

Microwave imaging (microwave imaging reflectometry -MIR and electron cyclotron emission imaging-ECEI) uses a single set of optics and multichannel detector array instead of multichannel optical path with a single detector for each optical path. The position of transmitting and receiving point and distance between lenses/mirrors are determined from the accessibility condition to the machine. The optics design is characterized by using a ray tracing code, such as, Code V and Zemax and FDTD (finite difference time domain) simulation code [4]. In the recent system, the UC Davis Group has investigated the utilization of electronically controlling zooming optics to match the wavefront with curvature of the cutoff layer corresponding to the multi-frequency incident sources.

Figure 1 schematically illustrates the DIII-D MIR system [5], which is an extension to 2-D with 12 vertically separated sightlines and 4-frequency operation (four radial channels). Features of the system are: i) illumination frequencies that can be tuned within 500 μs over a range of 56 to 74 GHz, ii) an innovative optical design that keeps both on-axis and off-axis channels focused at the cutoff of 56 to 74 GHz, ii) an innovative optical design that keeps both on-axis and off-axis channels focused at the cutoff surface, and iii) shared port with ECEI, thereby permitting simultaneous measurements of electron temperature and density in the same volume of plasma. These key features permit visualization and quantitative diagnosis of density perturbations, including correlation length, wavenumber, fluctuation velocities, and dispersion.

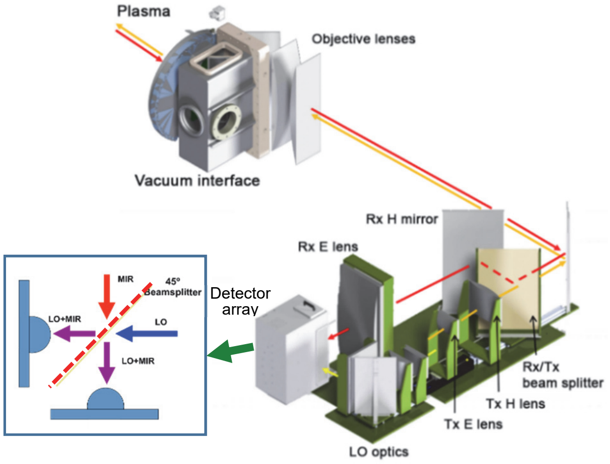

Fig. 1. Schematic of DIII-D imaging system [5].

The microwave imaging instrument usually uses a heterodyne receiver to obtain an intermediate frequency (IF) signal. One of the important issues is to supply sufficient LO power (1-10 mW) to a mixer to achieve low conversion loss for good signal to noise ratio. In the conventional ECEI and MIR, the LO power is also fed quasi-optically to a mixer together with radiation and reflected signals using focusing optics. However, it is rather difficult to uniformly irradiate LO power on an array detector depending on the array size.

A conventional system and an improved system [6] are depicted in Fig 2. Figure 2 (a) shows that both the RF wave

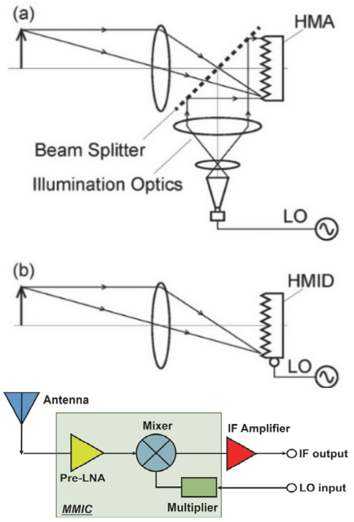

Fig. 2. The feeding method of LO: (a) conventional method, (b) new method. [7].

(reflected wave and LO wave) enter an array detector. In order to provide sufficient LO power to each channel, the LO power should be very high, and this increases the cost of the system. Figure 2 (b) shows an improved system, which uses the technology to combine waveguide and microstrip line for heterodyne detection radiometer. The weak ECEI and MIR signals are at first amplified by using low-noise microwave amplifier as shown in the bottom figure, which supplies significant noise reduction (-10dB) and system gain (+40dB).

3. Examples of results obtained by ECEI and MIR

The ECEI systems have enabled visualization of a variety of MHD instability structures in the poloidal cross-section of the tokamak plasma. Local and nonlinear dynamics immanent in MHD instabilities such as sawteeth, tearing modes, Alfven eigenmodes and edge localized modes (ELMs) have been revealed.

A high-confinement discharge on DIII-D with ELMs is presented here to demonstrate some of MIR's capabilities. Inter-ELM density fluctuations, such as the upward sweeping modes, are clearly seen from interferometry as well as with the MIR system as shown in Fig. 3. The core-localized tearing mode at 70 kHz produces a prominent magnetic fluctuation (Fig. 3 (c)) but is not strong from the perspective of ECE, interferometry, or MIR. Each diagnostic detects a coherent fluctuation at 100 kHz, but MIR also readily detects a neighboring mode at 110 kHz (Fig. 3(d)), which is near the noise level in the other diagnostics. One possible explanation for the clear signature on MIR is that its high sensitivity to small density perturbations and its highly-localized spatial measurement allows MIR to detect fluctuations that line-averaged measurements (such as interferometry) and external measurements (such as Mirnov coils) cannot.

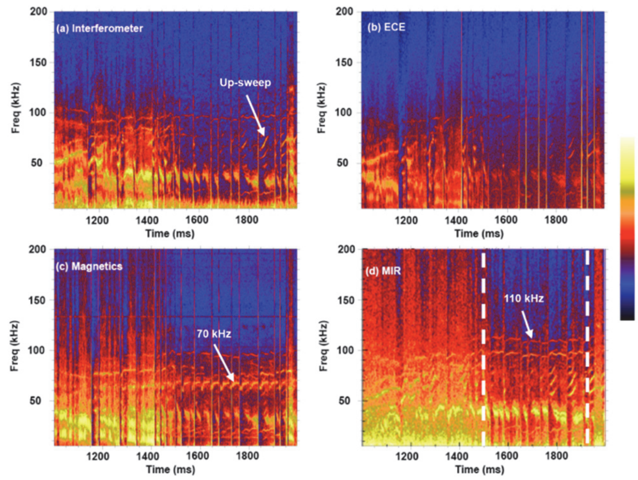

Fig. 3. Spectrograms obtained by (a) interferometer, (b) ECEI, (c) magnetic probe, and (d) MIR. [1].

4. Summary

Microwave imaging system (ECEI and MIR) have been applied to various magnetically confined plasmas such as DIII-D, LHD, KSTAR, ASDEX-U, and EAST, and have made important contributions to understanding of fusion science regarding fluctuation phenomena. Details will be reported at the symposium.

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