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Visualization of Fusion Plasma Physics via Millimeter Wave Imaging Techniques

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Abstract—Advances in microwave technology and innovative ideas have enabled visualization of complex physics of the high temperature plasmas in magnetic fusion devices. ECE Imaging system becomes a powerful tool for MHD physics in various devices and the potential of the MIR system has been reassessed and a system design for KSTAR is in progress.

I. INTRODUCTION

Microwave technology has a long history of being an integral part of the fusion plasma diagnostics. In early days, applications such as interferometry/polarimetry, collective scattering and reflectormetry have utilized microwave region of the spectrum due to comfortable fringe counts/Faraday rotation angles, good spatial/wavenumber resolution, and suitable plasma cut-off frequency, respectively. In recent years, understanding of fusion plasma science has evolved in depth and the dynamics of the physics are shown to be much more complex as demonstrated via large scale 3-D simulations. In order to verify the theoretical models, it is imperative to have multi-dimensional experimental data that can be directly compared with the simulation results. Due to microwave technology advances during the last decade [1], sophisticated 2-D imaging diagnostics based on microwaves have been realized. To date two classes of imaging system have been explored: 1) Electron Cyclotron Emission Imaging (ECEI); a passive imaging technique based on electron cyclotron emission (ECE) which has been widely used in measuring the electron temperature of magnetized plasmas. 2) Microwave Imaging Reflectometry (MIR); an active imaging technique which is intended to overcome the shortcomings of the conventional radar reflectometry which utilizes the reflection of the waves from the cut-off layer in magnetized plasmas.

A prototype ECEI system combined with an MIR system was developed for the TEXTOR tokamak to visualize MHD events through real time 2D images of the electron temperature fluctuations[2]. After successful demonstration of new physics concerning the sawtooth oscillation from the TEXTOR experiment [3,4], an upgraded ECE imaging system [5] has been tested on the TEXTOR and verified the previous observations with improved image quality as well as new observations. The ECE imaging system on AUG at Germany[6] consists of a newly designed optics arrangement and the detection system from the prototype system and has been successfully applied to studies of the MHDs in AUG. New ECE imaging systems based on the tested upgraded system have been developed for DIII-D[7], and KSTAR[8]. In contrast to the highly successful operation of the ECEI system, the performance of the MIR system fell short in demonstrating a clear imaging of the cut-off layers. Therefore, the design characteristics of the MIR system have been reassessed with respect to its potential to measure 2-D images of density fluctuations. Laboratory tests of the MIR system aiming for KSTAR and DIII-D are in progress.

II. OVERVIEW

A. Electron Cyclotron Emission Imaging System

Radiometry based on Electron Cyclotron Emission (ECE) has been a reliable tool for electron temperature measurement in optically thick regions of magnetized plasmas for more than three decades. The principle of the ECEI system is based on ECE radiometry and the vertically extended region of the plasmas is imaged on 1-D array detector using large relay optics. Since ECE Imaging is a diffraction limited extension of optical imaging, it requires relatively large aperture optics for vertical localization of individual channels. ECEI systems have evolved from the ambitious prototype that was developed for the TEXTOR device where both the ECEI and MIR systems were combined to study fluctuations of $T_e$ and $n_e$ simultaneously. Considering a standing wave problem that may hamper the MIR system performance, reflective optics were introduced for the prototype system. Due to a tight focusing of the probe beam of the MIR system, the vertical extent of the ECEI system was somewhat limited. Application of the ECEI system in studies of the sawtooth oscillation visualized the crash phenomena in 2-D with unprecedented temporal and spatial resolution as shown in Fig.1. New findings include the high field side crash
which was forbidden in the Ballooning mode model[2], the long disputed reconnection process (x-point or y-point), and other details of the heat transport phenomenology. After decommissioning of the prototype TEXTOR imaging system, the ECEI detection system was moved to the AUG, Germany and has been operated with new optics. Recently it has produced valuable physics concerning ELM activity and Alfvén waves as shown in Fig.2. Meantime, the MIR system and reflective optics were moved to POSTECH for further study and this subject will be discussed in the following section. A new improved optical system based on refractive (lens) system, rather than reflective mirrors which were needed for the prototype MIR system, were introduced for the new upgraded ECEI system with a newly designed efficient detection system. In the course of commissioning of the upgraded system, new and interesting physics of a variety of crash patterns were observed in addition to the observations made in the prototype system such as the “high field side crash”. As an example of the new physics, the images of the tearing type post cursor were captured and illustrated in Fig. 3. Here, the m/n=1/1 mode slowly diminished in a resistive time scale (~10 msec.) after the first partial crash in Fig. 1 The details of Sawtooth crash at the high field side. The core heat escapes in collective manner. Black line represents the q=1 surface

Fig. 2 ECEI experimental results from AUG (a) 2D images of ELMs (b) 2-D images of Alfvén eigenmodes (B&W is amplitude and the color is phase information

which the m/n=1/1 mode is reduced to 1/3 of the original size. During a long period of post cursor period, a trace of the heat continuously accumulated in the mixing zone has been observed through out the entire post cursor oscillation time. This fact indicates that the reconnection state is sustained through out the resistive time scale. This physical process of the tearing type crash is quite similar to the original Kadomtsev model[9] in which the m/n=1/1 mode is diminished without abrupt crash. However, the crash time scale is much longer than the reconnection time predicted by Kadomtsev model.
With a large access to the plasma and no stringent constraints in arrangement of the optical elements in DIII-D and KSTAR devices, a new optical system was designed for more versatility (high field side and low field side) and dynamic vertical range (zooming capability). Major improvements in the optical coupling schemes of ECEI diagnostics have allowed for the implementation of a wide range vertical zoom capabilities of as much as 3:1, and image focusing from the plasma edge to regions well to the inboard side of the core. Each of these features is implemented while meeting an appropriate wavelength dependent compromise between small viewing beam widths for adequate channel resolution and long confocal lengths for uniformity over the radial extent of the imaged plasma. Figure 4 provides an illustration of the complicated optical arrangements for the KSTAR ECEI cassette between the plasma and the first table. Dual array boxes are followed after splitting the signal and LO sources are located in the back.

### B. KSTAR MIR System

An innovative electron density fluctuation diagnostic, Microwave Imaging Reflectometry (MIR)[10], was developed for TEXTOR envisioning the potential of ameliorating the interpretation problem of reflectometry measurements, particularly in the plasma core. Characterization tests in the laboratory[11] using corrugated reflective surface illustrated both the difficulties of interpreting conventional reflectometry data (and the possibility of erroneous conclusions regarding core fluctuations as well as the edge) and the solutions offered by the MIR approach. Most importantly, the preliminary test results confirmed the design specifications of the TEXTOR MIR system. The initial application of the MIR system on the TEXTOR plasma to understand the concept of imaging of the fluctuating behaviors of the cut-off layer of the plasma was performed. At a fixed position, the dispersion relation of drift waves on the poloidal plane was deduced from the correlation study of the 16 channels of the vertical array in which the cut-off layer of the plasma is imaged [2]. However, the performance of the imaging characteristics was relatively poor when the focusing position on the cut-off layer was changed.

In order to understand the poor performance in the TEXTOR plasma tests, the MIR system has been intensively tested at POSTECH and a number of issues have been identified that might have hampered the performance of the prototype MIR system[12]. The first finding is the curvature matching problem between the cut-off layer and probe beam. As shown in Fig. 4, the smallest curvature of the beam with the original optics was ~50 cm which is the curvature of the cut-off layer at the very edge of the plasma. This is the most critical requirement to form a proper image of the cut-off layer of in the core of the plasma at the imaging plane. The second finding is the vertically skewed profile of the reflected beam. This is largely due to the optical aberration originating from the arrangement of the optical elements (staged with an angle). The third contribution is the phase interference introduced by the imperfect surface of the optical components. In addition to these findings, extensive comparative studies of the numerical methods that have been used to compare the laboratory test results from the reflective surface that has matched curvature to the probe beam and known corrugation. The corrugated target (k = 1.25 cm^{-1} with the radius of curvature R = 30 cm) that was used in previous laboratory test was employed to measure the...
amplitude modulation level at the target position. The detected modulation level appeared to be somewhat higher than expected. The measured high amplitude modulation level comes from the fact that the poloidal mirror could not collect the full diffracted beam from the
corrugated target due to the rapid expansion of the diffracted beam. In order to verify the validity of the Bessel function method used in simulation of the diffraction pattern, results from two different simulation codes are compared; Finite Difference Time Domain (FDTD) and Bessel function method. The test of these codes has been performed for the corrugated target that we have used (k = 1.25 cm⁻¹) and the equivalent corrugation level is ~0.5%. The comparison between the two results is in good agreement even though the two algorithms are completely different as shown in Fig. 5a and 5b. As the corrugation amplitude is increased (~2%), the difference between the two methods is clearly illustrated in Fig. 5. The discrepancy stems from the assumption used in the Bessel function expansion method. In FDTD, the scattering process of the ray at the surface of the corrugated target is considered where as this is ignored in the Bessel function expansion method.

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