Abstract

Over the years, the efforts to develop Microwave Imaging Reflectometry (MIR) for nuclear fusion devices, have been extensively documented in the literature [1-9]. This paper intends to be a short overview of the MIR concept, the MIR instrumentation for TEXTOR, and preliminary results obtained so far.

1. Introduction

Reflectometry is a highly sensitive diagnostic for the localized measurement of density fluctuations in the core of tokamak plasmas. However, fluctuations (especially 2D fluctuations where the plasma permittivity varies both perpendicular and parallel to the direction of propagation of the probing beam) also complicate the interpretation of reflectometry data, due to the interference between reflected wave components.

A model that has been proposed to handle the effects of fluctuations on reflectometry measurements, describes the reflected field with a phase modulation that is caused by fluctuations mostly close to the cut-off layer and which magnitude is given by 1D geometric optics. Numerical studies [2, 4, 8] have shown this model to be valid when the amplitude of the fluctuations is smaller than a certain value, set by the spectrum of wave numbers. It has also been demonstrated that for an observer at the plasma edge, the reflected waves seem to originate from a “virtual” cutoff, located behind the actual cutoff. The reflected electromagnetic field consists of a group of scattered waves that propagate in various directions and a wave propagating in the direction of specular reflection. The amplitude of this specular reflection will decrease as the variance $\sigma^2_\phi$ of the phase modulation becomes larger than unity. The scattered waves produce a complicated interference pattern when observed at a distance from the virtual cutoff layer larger than the diffraction length. Therefore, even when the above mentioned model is valid, the backward field needs necessarily to be measured as close as possible to the virtual cutoff. Experimentally, this could be achieved by collecting a significant part of the scattered waves by a large-aperture optical system and by imaging the object plane of the system, located at the virtual cutoff, onto a phase detector at the image plane. This concept has led to the development of the microwave imaging reflectometry (MIR) technique.
2. MIR instrumentation at TEXTOR

A MIR instrument has been developed for the TEXTOR tokamak. The layout of the diagnostic, which is combined with an Electron Cyclotron Emission Imaging (ECEI) receiver, to measure simultaneously electron density and temperature fluctuations, is shown in Figure 1. The ECEI part of the system is described elsewhere [10].

![Figure 1: The combined MIR/ECEI system with the TEXTOR poloidal cross section.](image)

The MIR employs large-aperture front-end optical components (the cylindrical mirrors a and b in Figure 1) to collect the reflected waves over an extended range of scattered angles. The limiting aperture is formed by the 42 cm × 20 cm TEXTOR vacuum window. The same focusing mirrors are used to match the wave front curvature of the probing beam to the cutoff surface, thus improving the robustness of the system to variations of the location of the cutoff surface and reducing the effect of plasma refraction. A dichroic plate (c) is used to separate the higher frequency (> 95 GHz) ECEI signal from the lower frequency (< 90 GHz) MIR signal. Each subsystem has its own detector system, located at (g) and (f) respectively, including several lenses to improve the image quality and to match the image to the detector characteristics. A significant advantage of the imaging scheme is the possibility to perform multi-point measurements on an extended poloidal range of the cutoff surface by using a multi-element detector array. This way, the instrument will not only be able to perform measurements in the presence of poloidal fluctuations, but also of the poloidal fluctuations themselves.

The TEXTOR MIR instrument has a fixed frequency probing beam, launched in X-mode, of 88 GHz that covers a ≤ 15 cm poloidal range. The reflected waves are measured with a 16-channel detector array, leading to a spatial resolution of ~1 cm and a theoretical poloidal wavenumber $k_\theta$ resolution up to 3 cm$^{-1}$. 
Before installation, the MIR instrument has been tested in the laboratory using a rotating corrugated reflecting target of known shape to simulate the fluctuating plasma reflection layer [6]. This test clearly illustrates the property of the MIR technique where the detection plane is moved to a location that is remote from the target surface and physically accessible for a detection system.

3. Preliminary results

Figure 2 shows the results of a pilot experiment, where the electron density was ramped up during an Ohmic plasma discharge, to shift the virtual cutoff surface through and beyond the focal plane of the MIR optics [5]. The focal plane of the optics was held fixed, and all plasma parameters, apart from the density ramp, were held fixed. The figure shows I/Q plots from a single channel recorded over several 3 ms time windows during the density ramp. The striking difference between plots (a, d) and (b, c) is in the level of amplitude fluctuations. The smaller level of amplitude fluctuations in plots (b, c) is attributed to the in-focus condition of the virtual cutoff layer, as is confirmed by the agreement between the calculation of the virtual cutoff position and and the position of the MIR focal plane. Remarkable is also the difference between the power spectra of the signal phase. When the cutoff is in-focus (Figure 2f), the phase power spectrum is dominated by large coherent MHD fluctuations, while the spectrum becomes a featureless 1/f² spectrum when the focus goes out-of-focus (Figure 2e).

![Figure 2: I/Q-plots of a single MIR channel during a density ramp in an Ohmic discharge (a, b, c and d) and its phase power spectra (e and f).](image)

Recently, preliminary results on the measurement of phase spectral coherence, poloidal correlation lengths, poloidal wave number and poloidal phase velocity have been reported [9].
4. Discussion and conclusion

The latest version of the MIR system has been installed on TEXTOR in the summer of 2002. Due to a number of unforeseen and lengthy shutdowns, the experimental time that could be devoted to technical commissioning of the system was very limited. Moreover, during the few scheduled MIR test sessions, it has been very difficult to achieve the optimum plasma conditions. In the majority of test discharges, the system was out-of-focus, where the focal plane does not overlap the virtual cutoff. Obviously, more experimental time with improved plasma conditions is needed to fully explore the possibilities of MIR.

Recently, flexibility has been added to the MIR system to shift both the launching beam focal position and the detection system focal plane independently. Plans for the near future include the utilization of this flexibility to find optimum settings for both launching and receiving focal positions under optimized plasma parameters.

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References