THz Techniques in Plasma Diagnostics

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Abstract — **THz techniques have been widely employed in magnetic fusion plasma diagnostics, including far infrared interferometry, polarimetry, and scattering to measure plasma electron density profiles, magnetic field strength profiles, and density fluctuations, respectively. The high magnetic field strength and high plasma densities anticipated for next generation fusion devices will further extend the applicability of THz techniques to the diagnostics of electron temperature profiles and fluctuations by electron cyclotron emission imaging, and electron density profiles and fluctuations by imaging reflectometry.**

I. Introduction

In magnetic fusion plasmas, the equilibrium profiles and the small amplitude fluctuations of plasma parameters, such as the plasma density, temperature, current, and magnetic field strength, are of fundamental importance because they determine the physics processes within plasmas. For example, it has been believed for decades that the unstable plasma equilibrium will lead to the development of plasma fluctuations, which subsequently result anomalous plasma transport, i.e., the plasmas lose their particles and energy at a rate much higher than predicted from Coulomb collisions [1]. However, this theoretical prediction has not been properly verified experimentally, due to limitations in plasma diagnostic techniques. To date, it remains a challenge to develop advanced diagnostic instruments with sufficiently high spatial and temporal resolution to diagnose these parameters in high temperature fusion plasmas. THz techniques are extremely useful in plasma diagnostics, as they are non-perturbative and have the advantages of negligible refractive effects and high spatial resolution.

In contemporary tokamaks and spherical tori such as TEXTOR-94 and NSTX, THz techniques are widely utilized in interferometry, polarimetry, and scattering diagnostic systems to measure plasma electron density profiles, magnetic field strength profiles, and density fluctuations, respectively. The general principles of these techniques can be found in numerous publications [2]-[5]. Therefore, only examples of the NSTX systems will be discussed in Secs. II and III.

Millimeter wave imaging diagnostic techniques have been recently developed and have already proven to be excellent tools for the study of plasma turbulence. These include Electron Cyclotron Emission Imaging (ECEI) and Microwave Imaging Reflectometry (MIR), as discussed in [6] and the references therein. In next generation tokamaks, such as the Fusion Ignition Research Experiment (FIRE) and the International Thermonuclear Experimental Reactor (ITER), the plasma characteristic frequencies, i.e., the electron cyclotron frequency and the plasma cutoff frequency, will be in the THz range due to the high magnetic field and high plasma density, and THz imaging techniques will be necessary. This can be seen from Fig 1, in which the characteristic frequencies for FIRE have been plotted. The third harmonic ECE, which is the most suitable for imaging radiometric diagnostics, has a frequency range from 0.65 to 1.15 THz. The right hand cutoff frequency extends from 0.25 to 0.4 THz, which is suitable for imaging reflectometry diagnostics. The possible application in these areas will be discussed in Secs. IV and V, respectively. A brief summary will be given in Sec. VI.

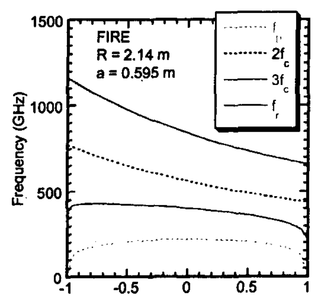

Fig. 1. Characteristic frequencies of FIRE plasmas.

II. Interferometry and Polarimetry

For interferometry and polarimetry applications, the frequency of the probe beam is much higher than the plasma characteristic frequencies. Therefore, the refractive index along the magnetic field direction can be approximated as [5,7]

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$$N_{L,R} \approx 1-(\omega_p^2/\omega^2)(1 \mp \omega_{ce}/\omega)/2 \qquad (1)$$

where the subscripts L and R denote the left hand and right hand circularly polarized eigen-states of magnetized plasmas, respectively. $\omega_p^2 \propto n_e$ is the plasma frequency, n_e is the plasma electron density, $\omega_{ce} \propto B$ is the electron cyclotron frequency, and B is the magnetic field strength. Therefore, if both R- and L-wave are launched to probe the plasma, as shown in Fig. 2, the plasma density n_e can be determined from their average phase shifts [7]:

$$\phi(x) = 2.8\times10^{-15}\lambda\int_0^x n_e(x')dx' \qquad (2)$$

In addition, the phase difference between the two eigen waves, i.e., the Faraday rotation angle, can yield information on the magnetic field [7]:

$$\psi_F(x) = 2.6\times10^{-13}\lambda^2\int_0^x n_e(x')B_{//}(x')dx' \qquad (3)$$

The tangential interferometer/polarimeter on NSTX is illustrated in Fig. 3. Three CH_3OH lasers operating at λ = 119 µm are pumped by a CW CO_2 laser. Two of the FIR lasers have circular waveguides, and the linearly polarized beams are converted to R- and L-waves by a quarter-wave plate to probe the plasma as illustrated in Fig. 2. The LO beam is produced by a third FIR laser, which is a Stark-tuned laser with a rectangular waveguide operating in the low pressure, low pump regime, in which the gain curve is broadened to about 7 MHz with about 30% power enhancement [8]. The high IF frequency allows the use of tracking techniques to accommodate cavity drifts. Corner cube Schottky diode mixers are utilized to detect the signals. The probing beams are arranged on the NSTX midplane so that the Faraday effect is induced by the toroidal magnetic field, the change of which can be utilized to study the plasma para- or diamagnetic effects. Preliminary density measurements using the system are illustrated in Fig. 4.

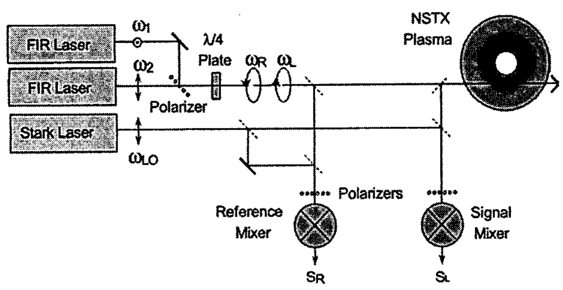

Fig. 2. Diagnostic principle of the far infrared (FIR) Interferometer/Polarimeter for NSTX.

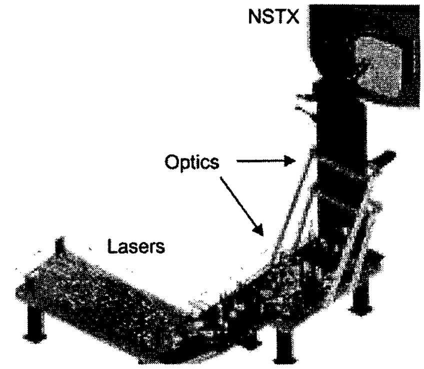

Fig. 3. Schematic of the far infrared (FIR) interferometer and polarimeter system for NSTX.

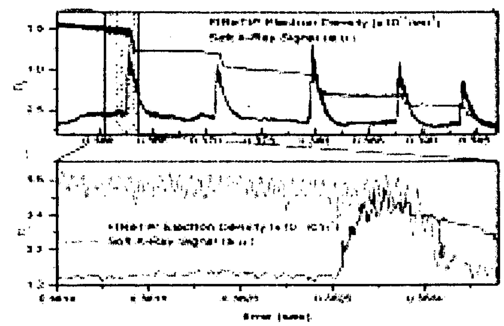

Fig. 4. Example of plasma density evolution on NSTX with sawteeth and Mirnov oscillations.

III. Collective Scattering

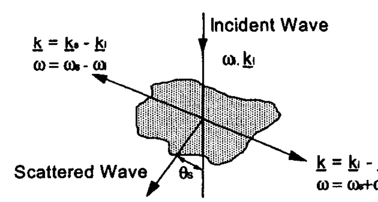

Fig. 5. Diagnostic principle of collective Thomson scattering.

Coherent scattering of electromagnetic waves is a powerful technique, capable of providing a direct measure of the spectral power density of fluctuations. It was employed extensively in early studies of plasma turbulence, including the first detection of short scale fluctuations in tokamaks [9]. Consider an EM wave incident on a plasma (see Fig. 5). The reradiated power from an accelerated electron occurs at a frequency $\omega_s = \omega_i + (\underline{k}_s - \underline{k}_i)\cdot\underline{v}_e$ where $\underline{v}_e$ is the electron velocity. If the fluctuations have a frequency ω and wavenumber $\underline{k}$, the scattered wave must satisfy momentum and energy conservation, so that

$\omega_s=\omega_i\pm\omega$ and $\underline{k}_s=\underline{k}_i\pm\underline{k}$. For many cases of interest, $|\underline{k}_s| \approx |\underline{k}_i|$, so that $k = 2k_i\sin\theta_s/2$, the familiar Bragg relation.

In the case of a broad spectrum of waves, the fluctuation spectrum can be obtained with a multi-channel system which simultaneously probe a number of distinct scattering angles [10]. The optimum scattering source is in the 400 µm - 1 mm region, with source powers in the 1-5 W range for optimum sensitivity. Such a system has been proposed to study turbulent fluctuations on NSTX, initially employing a 200 mW, 280 GHz carcinotron source and later with a watt level gyrotron.

IV. Electron Cyclotron Emission Imaging

In magnetized plasmas such as tokamaks, the gyro-motion of the electrons results in plasma radiation at the electron cyclotron frequency $\omega_{ce} = eB/m_e$ and its harmonics. When the plasma density and temperature are sufficiently high, the plasma becomes optically thick to some harmonics of the electron cyclotron emission (ECE), so that the plasma electron temperature T_e and its fluctuations can be determined by measuring the intensity of ECE [5],[7],[11]. Since the magnetic field strength B is inversely proportional to the major radius of the tokamak R, spatially resolved measurement of electron temperature is achieved by resolving the ECE frequency along the horizontal sightline defined by the antenna pattern [5].

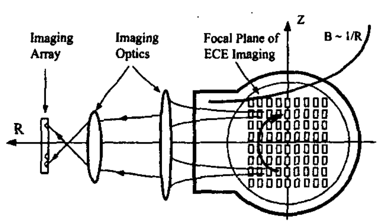

Fig. 6. Principle of the ECEI diagnostics.

An important recent new development in this area is the ECE imaging (ECEI) diagnostic, as shown in Fig. 6. Here, an array of mixers/antennas is utilized as the receiver, making it possible to extend the measurement in the vertical direction. A photograph of one of the imaging arrays is shown in Fig. 7, which is a monolithic array integrated with Schottky barrier diodes and slot bow tie antennas. With specially designed imaging optics, the ECEI technique has the unique advantages of high spatial resolution and two-dimensional capability, which have been shown to be essential in the study of plasma transport and fluctuation related phenomena [11]. The ECEI system implemented in the TEXTOR-94 tokamak is schematically illustrated in Fig. 8, in which a BWO source is utilized as the local oscillator. Figure 9 is an example of ECEI data showing that the ECEI diagnostic has the capability to resolve small plasma island structures of about 1 cm.

Fig. 7. Photograph of a monolithic imaging array for ECEI.

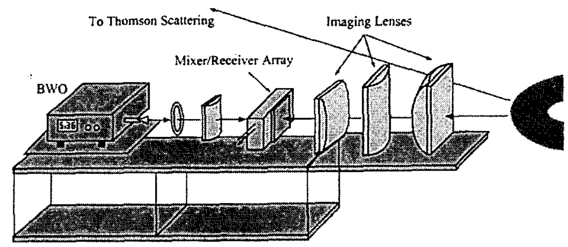

Fig. 8. Schematic of the ECEI system for TEXTOR-94.

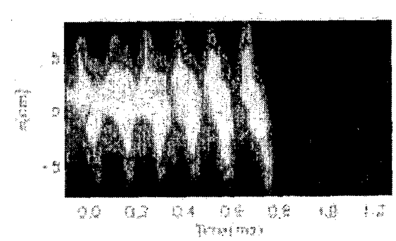

Fig. 9. ECEI measurement of T_e on TEXTOR-94.

In future fusion devices such as FIRE, the ECE frequency will be in the THz range (see Fig. 1). Therefore, THz imaging arrays will be required for ECEI measurements, and lessons learned from earlier plasma phase imaging interferometry will be utilized [12]. To achieve the requisite LO power and frequency bandwidth, quasi-optical frequency multiplier arrays is the most promising approach. Output powers of 5 W have been achieved in a tripler array [13] at 99 GHz in a pulsed proof-of-principle experiment. A maximum output power of 24 mW (pulsed) has been achieved at 1 THz [14] by Moussessian *et al.*

V. Imaging Reflectometry

From (1) and Fig. 1, it is seen that when the probe beam frequency is on the order of the plasma frequency and the electron cyclotron frequency, the beam launched from the tokamak low field side will encounter its cutoff layer, i.e., at which location the refractive index is zero and the beam will be reflected. This is the basis on which microwave reflectometers have been widely developed to determine plasma density profiles via determination of the group delay for varying frequencies, and density fluctuations from the modulation of the reflected signals [15],[16]. However, due to the complex fluctuation structures of plasmas, the reflected wave will be randomly modulated both in amplitude and phase, making it extremely difficult to derive the plasma density fluctuation information from the detected reflection [15]. This long outstanding issue was recently resolved by the application of reflectometric imaging techniques [16]. From theoretical model calculations, it is found that, by placing the detector array in the image plane of the 'virtual cutoff' layer, at which location the reflected wave has minimum amplitude modulation, the density fluctuation information can be recovered from the phase modulation of the reflected wave [15].

A first proof-of-principle system of this kind was successfully tested on TEXTOR-94 (see Fig. 10). The imaging receiver array is similar to that utilized for ECEI, except for the different frequency range. In addition, an illumination source is required to launch the probe beam, which is transformed to an elliptical beam by focusing optics to cover the plasma volumes to be measured.

In next generation fusion devices, the plasma cutoff frequency will be around 0.5 THz (see Fig.1); imaging receiver arrays in this range will thus be required. Also, high power sources with wide frequency bandwidth will be required both as probe beam and local oscillator. In order to minimize the insertion loss in the lenses, large aperture mirrors will replace lenses used in the millimeter range. This is also essential in present MIR systems as to eliminate spurious reflections from lens surfaces.

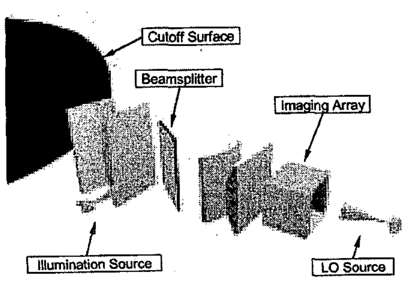

Fig. 10. Schematic of the MIR system on TEXTOR-94.

VI. Conclusion

THz techniques have been playing an indispensable role in plasma diagnostics, due to the ideal wavelengths that match the requirements for interferometry/polarimetry, and collective scattering. In next generation fusion devices, the applicability of THz techniques will be extended to electron cyclotron emission imaging and reflectometry imaging diagnostics. New imaging arrays in the THz range will be developed as receivers. Multiplier grid arrays will be developed as high power broadband sources.

Acknowledgement

This work is supported by the U.S. Department of Energy under contracts No. DE-FG03-95ER-54295 and W-7405-ENG-48, and by NWO and EURATOM.

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