Determination of internal radio frequency electric field profiles via millimeter wave reflectometry in the DIII-D Tokamak

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Millimeter wave reflectometry was employed to determine radio frequency wave electric field profiles in the DIII-D Tokamak. The method utilizes spatially localized X-mode reflectometer measurements in the 65–73 GHz frequency range to detect coherent fluctuations in magnetic field and density driven at the fast magnetosonic wave (FW) frequency (60 MHz). The FW electric field profiles were determined by adopting a geometric optics approach, which is appropriate for interpreting reflectometer data where the perturbing wavelength is longer than the probing wavelength. Successful measurements from this system were utilized to investigate FW propagation effects on DIII-D. The FW launch directionality necessary for current drive was confirmed at a position toroidally close to the FW antenna. © 1997 American Institute of Physics. [S0034-6748(97)63301-8]

I. INTRODUCTION

Reflectometry is a widely utilized diagnostic technique in magnetic confinement fusion since it only requires single port access which makes it ideally suitable for both existing and future devices such as ITER. Reflectometry was utilized to measure electron density profiles,1 microturbulence,2 and, more recently, ICRF waves.3,4 This article reports on an internal, nonperturbing determination of the electric field spatial profiles associated with externally launched radio frequency (rf) waves in fusion plasmas using reflectometry. Knowledge of the rf wave electric field profiles can enhance our understanding of coupling, propagation, mode conversion, and damping and, therefore, lead to improvements in the efficiency of rf heating and current drive. The experimental method developed and applied on the DIII-D tokamak is spatially localized extraordinary mode (X-mode) reflectometry, where coherent fluctuations in the magnetic field and density driven at the fast magnetosonic wave (FW) frequency (60 MHz) are monitored using heterodyne detection techniques. The relative FW electric field profiles are determined by adopting a geometric optics approach, which is appropriate for interpreting reflectometer data where the perturbing wavelength is longer than the probing wavelength.5 This article includes a description of the reflectometer system and the method for determining the FW electric field using reflectometry. Some illustrative examples of the determined FW electric field profiles are also presented.

II. EXPERIMENTAL APPROACH—MILLIMETER WAVE REFLECTOMETRY

A frequency tunable, heterodyne, tracking receiver reflectometer is employed to locally probe the fast wave propagation on DIII-D. A schematic is shown in Fig. 1. To obtain radial FW electric field profiles via a shot-to-shot frequency scan, millimeter wave frequency-tunable sources [two varactor tunable Gunn oscillators (65–73 GHz)] are separately employed as the probe beam and the local oscillator. A feed-forward tracking receiver technique is utilized to achieve frequency stability and is described in detail in previous work.3

To improve the signal-to-noise ratio, heterodyne detection is employed. Heterodyne detection is also essential in the elimination of direct electromagnetic pickup from the 60 MHz FW system. In homodyne detection the mixer output signal is identical to the FW frequency, making elimination of pickup a difficult task. On the other hand, in heterodyne detection the signal frequency is upshifted to an intermediate frequency (f_\text{IF}) that is offset from the FW frequency making direct pickup substantially easier to avoid. It should be noted that pickup can also appear in the upshifted signal frequency (f_\text{IF}+f_d) as a result of intermodulation products (f_\text{IF}+f_d) in the mixer. However, the pickup level in the upshifted signal frequency is decreased by the mixer intermodulation conver-
sion factor of \(>20\, \text{dB}\). Another advantage of heterodyne detection is that the overall sensitivity is improved over homodyne detection because the IF can be chosen to lie in a region where the 1/f noise (flicker noise) of the sources, detectors, and amplifiers is negligible.

Two internal horn antennas designed and fabricated by Oak Ridge National Laboratory (ORNL) were utilized during this work for transmission and reception. This bistatic configuration eliminated any spurious reflections and, together with heterodyne detection, provided a large dynamic range \( (>40\, \text{dB})\) for the total reflected millimeter-wave power in comparison to the background noise (e.g., electron cyclotron emission). This total reflected power appears at \(f_{\text{rf}}\) (200 MHz) in the heterodyne detection system, and is used to normalize the reflected FW signal power at \(f_{\text{rf}}+f_{p}\) (260 MHz), as described in Sec. III. The above horns produced a \(\sim 13^\circ\) half-angle at the 3 dB power point. The two horns were located at the midplane, 9.5 cm away toroidally from the edge of the last current strap of the FW antenna. The horns are electrically insulated from the FW antenna and the vacuum vessel wall. They are circular, with a diameter of 1.65 cm and length of 6.58 cm, and are connected to a WR-15 waveguide (0.188×0.376 cm) with a cutoff frequency 39.9 GHz.

### III. Determination of Internal FW Electric Field Profiles

The reflectometer system operates in \(X\) mode to locally monitor coherent fluctuations in density and magnetic field induced by the FW electric field inside the DIII-D plasma. The reflection position (right-hand cutoff) for \(X\)-mode propagation depends on electron density \(n_e\) and total magnetic field \(B\) and responds to local changes in \(n_e\) and \(B\). The FW modulates both the local density and magnetic field at the launched FW frequency (60 MHz). In order to determine the internal rf electric field structure, a geometrical optics approach is adopted in this work. This approach was as appropriate for interpreting reflectometer signals for long perpendicular wavelength perturbations, where the spot size of the probe beam is less than the parallel wavelength of the perturbation. The FW in the DIII-D has a perpendicular wavelength of \(\sim 10\, \text{cm}\), while the reflectometer wavelength is \(\sim 0.5\, \text{cm}\). Therefore, our experimental conditions well satisfy the first constraint. The parallel FW wavelength is expected to be about 1 m from the calculated antenna launch spectrum \((N_c=5)\). On the other hand, the spot diameter of the beam incident on the reflecting region is estimated to be \(\sim 5\, \text{cm}\) near the separatrix \((R_{\text{maj}}=2.28\, \text{m})\) and \(\sim 25\, \text{cm}\) near the plasma center \((R_{\text{maj}}=1.8\, \text{m})\) from the measured reflectometer horn pattern. Thus, the second condition is satisfied over the full spatial coverage of the reflectometer, i.e., \(R_{\text{maj}}=2.28–1.8\, \text{m}\).

The FW electric and magnetic field components are given by

\[
E_{\theta}(t) = \tilde{E}_{\theta} \sin \omega_{\text{FW}} t, \quad B_{z}(t) = \tilde{B}_{z} \sin \omega_{\text{FW}} t. \tag{1}
\]

Using the electron continuity equation in the cold plasma approximation and slab geometry \((k_{\theta}=0)\), it can then be shown that

\[
\frac{\tilde{n}_e}{n_e} = \frac{\tilde{E}_{\theta}}{\omega B_t} = \frac{\tilde{B}_{z}}{B_t} \times n_e^{0.5}. \tag{2}
\]

Here, \(\tilde{n}_e\) is the modulus of the resulting density fluctuation at the FW frequency. The subscripts \(r\), \(\theta\), and \(z\) represent the radial, poloidal, and toroidal directions, respectively. The FW radial wave number is \(k_r\), \(n_e\) is the plasma electron density, and \(B_t\) is the toroidal magnetic field. It should be noted that \(\omega k_r\) can be approximated as the Alfvén velocity \((\approx B_t/n_e^{0.5})\).

The reflectometer phase response due to a long wavelength FW perturbation is obtained from

\[
\delta \phi = \delta \phi_{\text{FW}} \sin \omega_{\text{FW}} t \approx \left( \frac{k_0(\tilde{n}_e/n_e)+(\tilde{B}_z/B_t)f_{c0}/f_p^2}{1+f_c+f_p/|f_p^2|/B_t^2} \right) \sin \omega_{\text{FW}} t, \tag{3}
\]

where \(L_n\) and \(L_B\) are, respectively, the density and magnetic field gradient scale lengths, \(f_c\) is the electron cyclotron frequency, \(f_p\) is the electron plasma frequency, and \(f_0\) \((k_0)\) is the reflectometer probe frequency \((\text{wave number})\). Then, by combining the above two equations, the modulus of the reflectometer phase response due to the cutoff layer movements induced by the density and magnetic fluctuations driven by the FW electric field is given by

\[
\delta \phi_{\text{FW}} \approx \left( \frac{k_0(1+f_c/f_p^2)}{1+f_c+f_p/|f_p^2|/B_t^2} \right)^{0.5} \tilde{E}_{\theta}. \tag{4}
\]

Let us now relate the heterodyne reflectometer signal \((S)\) to the phase response described above. The heterodyne reflectometer signal \((S)\) can be written by

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**FIG. 1.** The schematic diagram of the frequency tunable, heterodyne, tracking receiver millimeter wave reflectometer.
where $G_{sys}$ is the system gain, $\phi_{dc}$ is the phase change associated with the density profile, and $A(t)$ and $\phi(t)$ are the low frequency (<1 MHz) amplitude and phase fluctuations associated with microturbulence. Note that $G_{sys}$ includes the effects of the microwave beam, the mixer conversion loss, propagation, and refraction. Equation (5) can be approximated using the fact that $\sin(\delta \phi_{FW} \sin \theta) \approx \delta \phi_{FW} \sin \theta$ when $\delta \phi_{FW} \ll 1$:

$$S = G_{sys} \left[ 1 + A(t) \right] \sin \left[ \omega_{FW} t + \delta \phi_{FW} \sin (\omega_{FW} t) + \phi(t) + \phi_{dc} \right].$$

$$S = G_{sys} \left[ 1 + A(t) \right] \sin \left[ \omega_{FW} t + \phi(t) + \phi_{dc} \right] + 0.5 \delta \phi_{FW} \sin \left[ (\omega_{FW} + \omega_{t}) t + \phi(t) + \phi_{dc} \right] - 0.5 \delta \phi_{FW} \sin \left[ (\omega_{FW} - \omega_{t}) t + \phi(t) + \phi_{dc} \right].$$

The above normalization process can also be understood as follows. The FW reflectometer signal depends not only upon the local FW power, but also upon the power in the microwave beam, the mixer conversion loss, and propagation and refraction. In order to remove these, the total returned microwave signal power at $\omega_{p} + \omega_{t}$ [the second term in Eq. (6)] divided by the total reflection amplitude at $\omega_{t}$ [the first term in the parenthesis of the Eq. (6)] in the spectral domain, gives the value of $\delta \phi_{FW}$:

$$S_N = \frac{1}{\sqrt{2}} \delta \phi_{FW} \approx \frac{k_0 \left( 1 + f_c f_0 f_p^2 \right)}{1/L_n + f_c f_0 f_p^2 / L_B} \frac{n_{e}^{0.5}}{B_i} \bar{E}_\theta.$$  

IV. EXPERIMENTAL RESULTS

The normalized reflectometer signal ($S_N$) not only depends on the FW electric field but also depends on various local parameters: $n_e(r)$, $B_t(r)$, $L_n(r)$, and $L_B(r)$. Among these parameters, $L_n$ is the most sensitive to the reflectometer signal. The variables $n_e$ and $B_t$ are determined by the right-hand cutoff constraint $f_0^2 - f_c f_0 f_p^2 = 0$ for a given reflectometer probe frequency ($f_0$) and $L_B$ is also given by $R_m$ cutoff. Thus, $n_e$, $B_t$, and $L_B$ are almost constant in comparison to $L_n$ during a plasma discharge. The correlation of the normalized reflectometer signal to $L_n$ is observed as predicted in Eq. (7) and is illustrated in Fig. 2. The normalized signal amplitude peaked near 2450 ms and decreased later as $L_n$ decreased. The reflection position also changes from $\sim 2.1$ to $\sim 2.2$ m in the major radius during this time interval. It is important to note that the observed reflectometer signal reduction in this case is not a result of FW electric field changes. As illustrated in Fig. 4, the FW electric field over the range from $\sim 2.1$ to $\sim 2.2$ m is shown to be relatively constant.

FIG. 2. Correlation of the reflectometer signal to $L_n$ is shown. Note that the dashed line is the polynomial fit for $L_n$ data.

FIG. 3. The determined FW electric field profile using a shot-to-shot frequency scan. ($I_p=1$ MA, $B_0=2.0$ T, $\langle n_e \rangle \sim 3 \times 10^{19}$ m$^{-3}$.)
Figure 3 shows the determined FW electric field profile obtained with a shot-to-shot frequency scan using reproducible plasmas near the plasma edge region. The FW antenna is operated with \((0, \pi/2, \pi, 3\pi/2)\) phasing where FW is expected to be directed preferentially towards the toroidal location of reflectometer. Each datum was obtained by time averaging the signal over a period of \(~700\) ms when both the electron density and FW power were constant. The density profiles were measured via Thomson scattering. Once the detection position \(r\) is determined from the density profile, \(B_r = B_0 r_p/\left(R_0 + r\right)\) and \(L_p = R_0 + r\), respectively. The local density, \(n_r(x)\), is self-consistently determined using \(f_0 - f_c(r) f_0 - f_p(r)^2 = 0\). The local density gradient scale length, \(L_n(r)\), is then evaluated from the measured density profile. As can be seen, the data show that the FW electric field decreases toward the plasma edge (from \(R_m\sim 2.2\) to \(~2.28\) m).

Another example of the FW electric field profiles is shown in Fig. 4 using a density ramp. They were determined during a density ramp where \((r_{e}, n)\) varied from \(~2.2\times10^{19}\) to \(~2.9\times10^{19}\) m\(^{-3}\) within a single shot. As the density rises, the position of the right-hand cutoff layer moves radially outwards towards the plasma edge, e.g., the 70 GHz reflectometer detection position moves from \(R_{maj}\sim 2.16\) to 2.27 m. As can be seen, the determined FW electric field profiles again decreased toward the plasma edge. This edge decay is consistent with the calculated FW field pattern at the measurement location.\(^9\) The reflectometer signal is also observed to be significantly enhanced for a fast wave launched towards the detection position with \((0, \pi/2, \pi, 3\pi/2)\) antenna phasing, as compared to \((0, -\pi/2, -\pi, -3\pi/2)\) phasing, as illustrated in Fig. 4. The monitored total return powers are similar in both antenna phasing combinations indicating that the difference is indeed a result of the directivity of the FW launch. This is the first direct experimental evidence that a directed spectrum is in fact launched from a FW antenna in a Tokamak plasma.

V. SUMMARY

A new application of reflectometry to determine electric field profiles associated with externally launched rf waves was developed and applied to the FWCD experiment on the DIII-D Tokamak. The relative FW electric field profiles were determined by adopting a geometric optics approach, which has been determined appropriate for interpreting reflectometer data where the perturbing wavelength is larger than the probe wavelength. The correlation of the reflectometer signal with density gradient scale length was observed, as predicted by the geometric optics model. Using this technique, the FW launch directionality necessary for current drive was directly confirmed at a position toroidally close to the FW antenna.

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