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Differential-phase reflectometry for edge profile measurements on Tokamak fusion test reactor

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Edge electron density profile measurements, including the scrape-off layer, have been made during ion cyclotron range of frequency (ICRF) heating with the two-frequency differential-phase reflectometer installed on an ICRF antenna on the Tokamak fusion test reactor (TFTR). This system probes the plasma using the extraordinary mode with two signals swept from 90 to 118 GHz, while maintaining a fixed-difference frequency of 125 MHz. The extraordinary mode is used to obtain density profiles in the range of 1×10^{11}–3×10^{13} cm^{-3} in high-field (4.5–4.9 T) full-size ($R_0=2.62$ m, $a=0.96$ m) TFTR plasmas. The reflectometer launcher is located in an ICRF antenna and views the plasma through a small penetration in the center of the Faraday shield. A 26-m-long overmoded waveguide run connects the launcher to the reflectometer microwave electronics. Profile measurements made with this reflectometer system will be presented along with a discussion of the characteristics of this differential phase reflectometer and data analysis. © *1995 American Institute of Physics.*

I. INTRODUCTION

A detailed measurement of the density profile in the scrape-off region of the plasma is essential to study such phenomena as ion cyclotron range of frequency (ICRF) power coupling to the plasma, H-mode edge profile modifications, and impurity transport at the plasma edge. Consequently, there is significant interest in obtaining detailed measurements of the shape of the edge-density profile, and it is of particular interest to measure this in the ICRF antenna environment. In general, reflectometry profile measurements in the plasma edge region are unreliable due to the phase scrambling effects of the large density fluctuations present in this plasma region. To overcome the undesirable effects of the density fluctuations, a two-frequency differential-phase technique was developed.[1,2] This technique was chosen because the multiplicity of fringes is greatly reduced, and phase fluctuations arising from density fluctuations in the plasma are significantly reduced. Both of these attributes are essential for reliable phase tracking of multiple-fringe phase data.

In this differential-phase technique, two swept microwave signals with a fixed-difference frequency probe the plasma. After reflection from the plasma, these two signals are beat against one another to obtain the differential phase between them. This differential phase consists of (1) the difference in the propagation phase shifts of the two signals in propagating up to the lower frequency signal's cutoff in the plasma and back to the receiver with a scale length of order of the beat wavelength, plus (2) the phase shift incurred by the higher frequency probing signal propagating in the phasma region between the lower frequency signal's cutoff and its own cutoff. The latter is the phase shift due to the density gradient and occurs on a scale length of order of the probing signal wavelength. In general, the phase shift due to the separation between the two cutoff layers is much larger than the propagation phase shift, so differential-phase measurements are almost a direct measurement of the electron density gradient. By obtaining the difference phase in the microwave electronics, the run-away fringe problem observed by most reflectometers is eliminated. Additionally, a good representation of the time-averaged density profile can readily be obtained by simply acquiring a sufficiently large data sample so that the phase fluctuations can be averaged out.

II. TFTR TWO-FREQUENCY DIFFERENTIAL-PHASE REFLECTOMETER

To provide the capability to measure the edge-density profile in the range of $\lesssim1.0\times10^{11}$–3.0×10^{13} cm^{-3} in high-field (4.5–4.9 T) full-size ($R_0=2.62$ m, $a=0.96$ m) Tokamak fusion test reactor (TFTR) plasmas, a frequency range of 90–118 GHz is used with the extraordinary mode of polarization. Measurements with the launcher located at a major radius of 3.61 m in full-size plasmas have shown the capability of measuring the density down to values of $<1.0\times10^{11}$ cm^{-3}. In Fig. 1, the three shaded regions represent the typical radial range covered by the 90–118 GHz frequency sweep of the reflectometer for vacuum toroidal field values of 4.16, 4.50, and 4.84 T for $R_0=2.62$ m. For each shaded region, the lower boundary is the radius of the electron cyclotron resonance (ECR), and the upper boundary is the cutoff radius for a fixed density of 2×10^{13} cm^{-3}. The reflectometer typically measures the density profile up to density values $>2\times10^{13}$ cm^{-3}. In the limit of zero density, the ECR represents the minimum radial starting point of the reflectometer measurements, and where it crosses the minimum probing frequency of 90 GHz indicates the maximum probing radius (in the limit of zero density using the vacuum field only) that the reflectometer will see. For the highest accuracy in locating the measured profiles, it is desirable to have this maximum radius be greater than or equal to the

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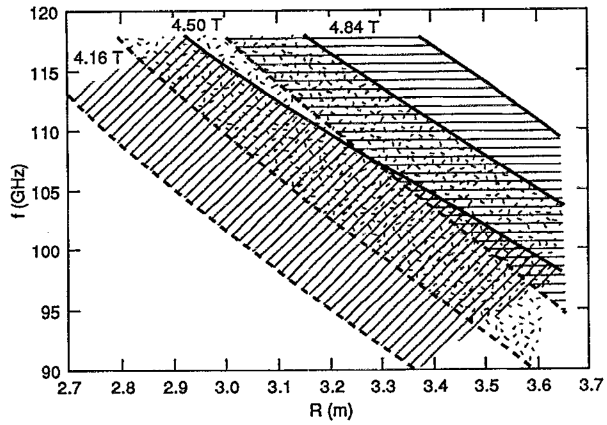

FIG. 1. Three shaded regions showing the reflectometer probing range for toroidal vacuum fields of 4.16, 4.50, and 4.84 T for R_0=2.62 m. For each region, the lower boundary represents the minimum cutoff radius for a given frequency, and the upper boundary indicates at what radius, for a given frequency, cutoff will occur for a density of 2×10^{13} cm^{-3}.

radius of the reflectometer launcher apertures. Corrections to the vacuum field for the poloidal field will shift these curves slightly outward.

To obtain the desired probing signals, the reflectometer starts with a swept frequency source of 7.8–12.5 GHz and then uses frequency upconversion and multiplication to provide the frequencies of interest. In this way, the frequencies of the two probing signals are simultaneously swept from 90 to 118 GHz, while maintaining a fixed frequency separation of 125 MHz. The frequency spacing determines the radial separation of the two cutoff layers in the plasma. This spacing should be kept small in comparison with the radial correlation length of the plasma density fluctuations if a reduction in the differential-phase fluctuation level is to be achieved. Additionally, the frequency spacing determines the maximum number of fringes that can occur. To provide a unique phase measurement, the maximum number of fringes should be kept small, in the range of two to three fringes. The maximum phase shift is estimated by calculating the differential-phase shift in the limit of zero density. Thus the maximum differential-phase shift is determined by the gradient of the ECR alone; for TFTR at 125 MHz, this gives a maximum phase shift of three fringes.

To facilitate scrape-off layer density profile measurements in the ICRF environment on TFTR, a reflectometer launcher has been installed into an ICRF antenna. The Bay-K ICRF antenna has a central diagnostic port on the center axis of the two-strap antenna that provides access through the antenna and Faraday shield. This diagnostic port provides access to the plasma edge for the reflectometer launchers. To eliminate the effects of spurious reflection on the reflectometer-phase measurements and to reduce the amount of differential-phase shift due to dispersive waveguide effects, a pair of oversized WR-90 rectangular waveguides (2.286×1.016 cm) are used with the "tall-guide" polarization (TE_{01}) for the transmitting and receiving antennas. The launcher apertures are recessed 3 mm behind the front surface of the ICRF antenna Faraday shield. Stainless steel waveguides are necessary to limit disruption forces; a single 3-mm-thick quartz window is used for vacuum feedthrough. With the exception of a downtapered section of WR-10 waveguide immediately outside of the vacuum window, which serves to filter higher-order modes, the waveguide run consists of 26 m of WR-90 waveguide leading to the reflectometer electronics located in the test cell basement. The waveguide transmission system has a measured round-trip transmission loss of ≤12 dB, excluding the window/launcher assembly. The coupling between the transmitting and receiving apertures (including the window and launcher assembly losses) measured by reflecting the transmitted signal off a metal plate located from 2 to 40 cm away from the launcher aperture, is between −15 and −30 dB.

III. PROFILE RECONSTRUCTION FROM DIFFERENTIAL-PHASE DATA

The measured differential phase can be written as

$$\Delta\phi=\phi_H-\phi_L, \tag{1}$$

where ϕ_H is the total phase shift incurred by the higher frequency signal, and ϕ_L is the total phase shift incurred by the lower frequency signal. This can be written as

$$\Delta\phi=\frac{4\pi}{C}\left(f_H\int_{R_{\rm ref}}^{R_H}\mu(R,f_H)dR-f_L\int_{R_{\rm ref}}^{R_L}\mu(R,f_L)dR\right)+\Delta\phi_{\rm WG}, \tag{2}$$

where $\mu(R,f_H)$ and $\mu(R,f_L)$ are the indexes of refraction for the higher and lower frequency signals, respectively; the two integrals are from the phase reference plane $R_{\rm ref}$ up to the higher and lower frequency cutoff radii, R_H and R_L, respectively; and $\Delta\phi_{\rm WG}$ is the differential-phase shift incurred in the waveguide run and electronics and is removed by absolute phase calibration. Once the calibration differential-phase shift is subtracted from the measured phase, profile reconstruction can be performed. Assuming that we know the index of refraction for both signals up to R_L, we can use a trapezoidal (or polynomial, if desired) approximation to estimate the index of refraction for f_H between R_L and R_H.[3] This can be written as

$$\Delta\phi=\frac{4\pi}{C}f_H\left(\int_{R_{\rm ref}}^{R_L}\mu(R,f_H)dR+\frac{1}{2}\Delta R\mu(R_L,f_H)\right)-\frac{4\pi}{C}f_L\int_{R_{\rm ref}}^{R_L}\mu(R,f_L)dR,$$

where ΔR is the radial distance between R_L and R_H, and $\mu(R_L,f_H)$ is the index of refraction for the higher frequency signal at R_L. Finally, Eq. (3) can be solved for ΔR, and then ΔR added to R_L to obtain R_H. Once we have R_H, the local density value can be calculated from the extraordinary mode dispersion relation because we now know the probing frequency and cutoff radius. This procedure can be repeated for each phase data point to reconstruct the measured profile.

In Fig. 2, an example of the measured differential phase (after undergoing filtering, fringe counting, and calibration correction) is shown with the corresponding reconstructed density profile. These data are from a single 10 ms sweep,

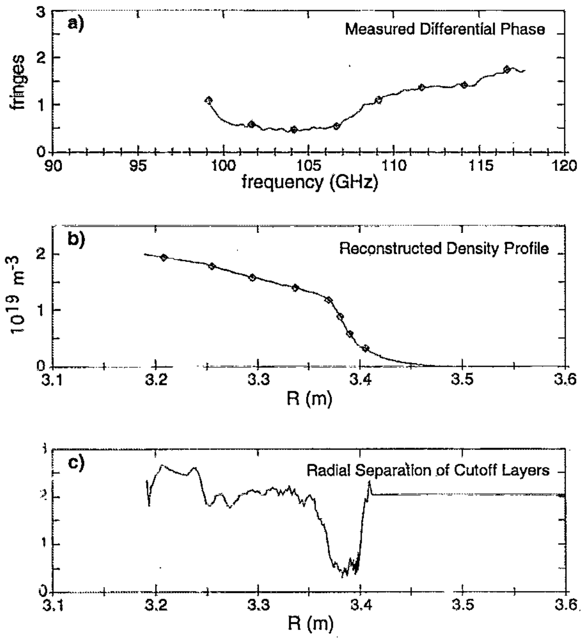

FIG. 2. Example of the reflectometer data: (a) measured differential-phase shift as a function of frequency, (b) the corresponding reconstructed edge-density profile, and (c) the radial separation of the two cutoff layers calculated from the measured differential phase. Plasma conditions include: R_0=2.52 m, B_0=4.67 T, I_p=2.0 MA, $n_e l$=5.2±10^{15} cm^{-2}, $P_{\rm NBI}$=20 MW, and $P_{\rm ICRF}$=0. The diamonds shown on the phase and density data are markers to allow mapping from the phase data to the density profile [e.g., the marker at 99 GHz in part (a) corresponds to the marker at 3.41 m in part (b)].

although only the last 6.8 ms of the sweep (99–118 GHz) is used. The measured phase data below 99 GHz had a high differential-phase noise due to the long gradient lengths in this region of the plasma, and they could not be used. The density gradient outside of 3.41 m must be assumed for the profile reconstruction and is approximated as an exponential decay. Also shown is the radial separation of ΔR of the two cutoff layers calculated from the differential phase using Eq. (3) for the fixed-difference frequency of 125 MHz. These three plots illustrate how changes in the density gradient affect the radial separation of the two cutoff layers and therefore the differential phase. In this case, the radial separation varies from 0.5 to 2.5 mm between 3.4 and 3.2 m. Outside of 3.4 m, the separation is rapidly increasing, and the differential-phase noise level (not shown) increases correspondingly until it reaches a level at which the phase can no longer be tracked. Outside of 3.41 m, the assumed density gradient uses a fixed radial separation that shows up as a constant 2 mm separation on this plot.

IV. RESULTS FROM PROFILE MEASUREMENTS WITH ICRF

To illustrate the capabilities of this diagnostic, Fig. 3 shows two-edge density profiles obtained on TFTR with and without ICRF power but otherwise the same plasma conditions. Two differences are observed between these profiles. First, the central plasma density is higher with ICRF, and so the density profile inside the scrape-off region is slightly

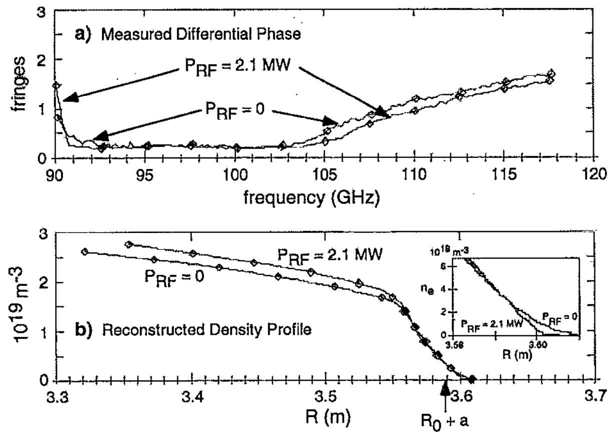

FIG. 3. Reflectometer data for two shots with and without ICRF: (a) measured differential-phase shift as a function of frequency, and (b) the corresponding reconstructed edge-density profile. Plasma conditions include: R_0=2.62 m, B_0=4.5 T, I_p=1.8 MA, $n_e l$=6.7×10^{15} cm^{-2} without ICRF and $n_e l$=7.0×10^{15} cm^{-2} with ICRF, $P_{\rm NBI}$=27 MW in both cases, and $P_{\rm ICRF}$=2.1 MW for the ICRF case.

higher for the ICRF case; second, a small modification of the edge-density profile within 2 cm of the Faraday shield at densities of 2×10^{12} cm^{-3} and less, is shown in the inset of Fig. 3(b). Both of these differences can be seen in the measured differential phase shown in Fig. 3(a). For these data, the total ICRF power is 2.1 MW distributed over three antennas, with 0.6 MW on the Bay-*K* antenna, and applied with 0–π phasing. Although the modification of the density profile is small, the related phase change is large due to the very small densities involved. For both profiles, the ECR for the lowest usable probing frequency was <1 cm away from the front of the Faraday shield, and therefore these two profiles are located to an accuracy of <1 cm. The relative positioning of the two profiles is based on the fact that the phase data from 93 to 103 GHz are nearly identical for both cases, and so we assume that the two density gradients corresponding to these data must also be the same and choose the starting points for the profile reconstruction appropriately.

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