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Differential Phase Reflectometry For Edge Profile Measurements on TFTR

G. R. Hanson, J. B. Wilgen, T. S. Bigelow, I. Collazo,[a] A. C. England, M. Murakami, D. A. Rasmussen, J. R. Wilson[b]

Fusion Energy Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

Edge electron density profile measurements, including the scrape-off layer, have been made during ICRF heating with the two-frequency differential phase reflectometer installed in an ICRF antenna on 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} to 3×10^{13} cm^{-3} in high-field (4.5- to 4.9-T) full size (R_0 = 2.62 m, a = .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.

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[a]Georgia Institute of Technology, Atlanta, GA

[b]Plasma Physics Laboratory, Princeton University, Princeton, NJ.

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Introduction

A detailed measurement of the density profile in the scrape-off region of the plasma is essential to study such phenomenon as 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 make this measurement 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 region of the plasma. In order 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 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 the phase shift incurred by the higher frequency probing signal propagating in the plasma 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 nearly 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, obtaining the difference phase provides a 'natural' averaging of the phase variations due to the density fluctuations, and therefore, the difference phase provides a better representation of the mean density profile.

The TFTR Two-Frequency Differential-Phase Reflectometer

To provide the capability to measure the edge density profile in the range of $\lesssim 1.0 \times 10^{11}$ to 3.0×10^{13} cm^{-3} in high-field (4.5- to 4.9-T) full size (R_0 = 2.62 m, a = .96 m) TFTR plasmas, a frequency range of 90 to 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 (i.e. $R_0 + a$ = 3.59 m) have shown the capability of measuring the density down to values of less than 1.0×10^{11} cm^{-3}. In Fig. 1 we show three shaded regions representing the typical radial range covered by the 90 to 118 GHz frequency sweep of the reflectometer for toroidal field coil current values of I_{TF} = 62, 67, and 72 kA, which correspond to vacuum field values of 4.16, 4.50, and 4.83 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 greater than 2×10^{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) 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 radius of the reflectometer launcher apertures. Corrections to the vacuum field for the poloidal field will shift these curves slightly outwards.

To obtain the desired probing signals, the reflectometer starts with a swept frequency source of 7.8- to 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 effected. Additionally, the frequency spacing determines the maximum number of fringes which 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 electron cyclotron resonance alone, and 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 and waveguide transmission system have 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 x 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 the 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 and 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 through 40 cm away from the launcher aperture, are between 15 and 30 dB.

Profile Reconstruction From Differential Phase Data

The measured differential phase can be written as

$$\Delta\varnothing = \varnothing_H - \varnothing_L \qquad \text{Eq. 1}$$

where $\varnothing_H$ is the total phase shift incurred by the higher frequency signal, and $\varnothing_L$ is the total phase shift incurred by the lower frequency signal. This can be written as

$$\Delta\varnothing = \frac{4\pi}{c}\left[f_H \int_{R_{ref}}^{R_H} \mu(R, f_H)\,dR - f_L \int_{R_{ref}}^{R_L} \mu(R, f_L)\,dR \right] + \Delta\varnothing_{WG} \qquad \text{Eq. 2}$$

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_{ref} up to the higher and lower frequency cutoff radii, R_H and R_L respectively, and $\Delta\varnothing_{WG}$ 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

$$\Delta\varnothing = \frac{4\pi}{c} f_H \left[\int_{R_{ref}}^{R_L} \mu(R, f_H) dR + \tfrac{1}{2} \Delta R \mu(R_L, f_H) \right] - \frac{4\pi}{c} f_L \int_{R_{ref}}^{R_L} \mu(R, f_L) dR$$

Eq. 3

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 since 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. This data is from a single 10 ms sweep, although only the last 6.8 ms of the sweep (99 to 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 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 ΔR of the two cutoff layers calculated from the differential phase using Eq. 3 above for the fixed difference frequency of 125 MHz. These three plots illustrate how changes in the density gradient effect the radial separation of the two cutoff layers and therefore the differential phase. In this case, the radial separation is seen to vary from 0.5 mm 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) is seen to increase 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 which shows up as a constant 2 mm separation on this plot.

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 higher for the ICRF case; and 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, as shown in the inset in Fig. 3b. Both of these differences can be seen in the measured differential phase shown in Fig. 3a. For this data, the total ICRF power is 2.1 MW distributed over 3 antennas with 0.6 MW on the Bay K antenna, and applied with $0-\pi$ 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 electron cyclotron resonance for the lowest usable probing frequency was less than 1 cm away from the front of the Faraday shield, and therefore the two profiles are located to an accuracy of less than 1 cm. The relative positioning of the two profiles is based on the fact that the phase data from 93 GHz to 103 GHz is nearly identical for both cases, and so we assume the two density gradients corresponding to this data must also be the same and choose the starting points for the profile reconstruction appropriately.

Acknowledgements

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Figure Captions

FIG. 1. These three shaded regions show the reflectometer probing range for toroidal field coil currents of 62, 67, and 72 kA. For each region, the lower boundary represents the minimum cutoff radius for a given frequency, while the upper boundary indicates at what radius for a given frequency cutoff will occur for a density of 2×10^{13} cm^{-3}.

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 = 4.6 T, I_p = 2.0 MA, NL = 5.2 x 10^{15} cm^{-2}, P_{NBI} = 20 MW, and P_{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).

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, NL = 6.7 x 10^{15} cm^{-2} without ICRF and NL = 7.0 x 10^{15} cm^{-2} with ICRF, P_{NBI} = 27 MW, and P_{ICRF} = 2.1 MW for the ICRF case.

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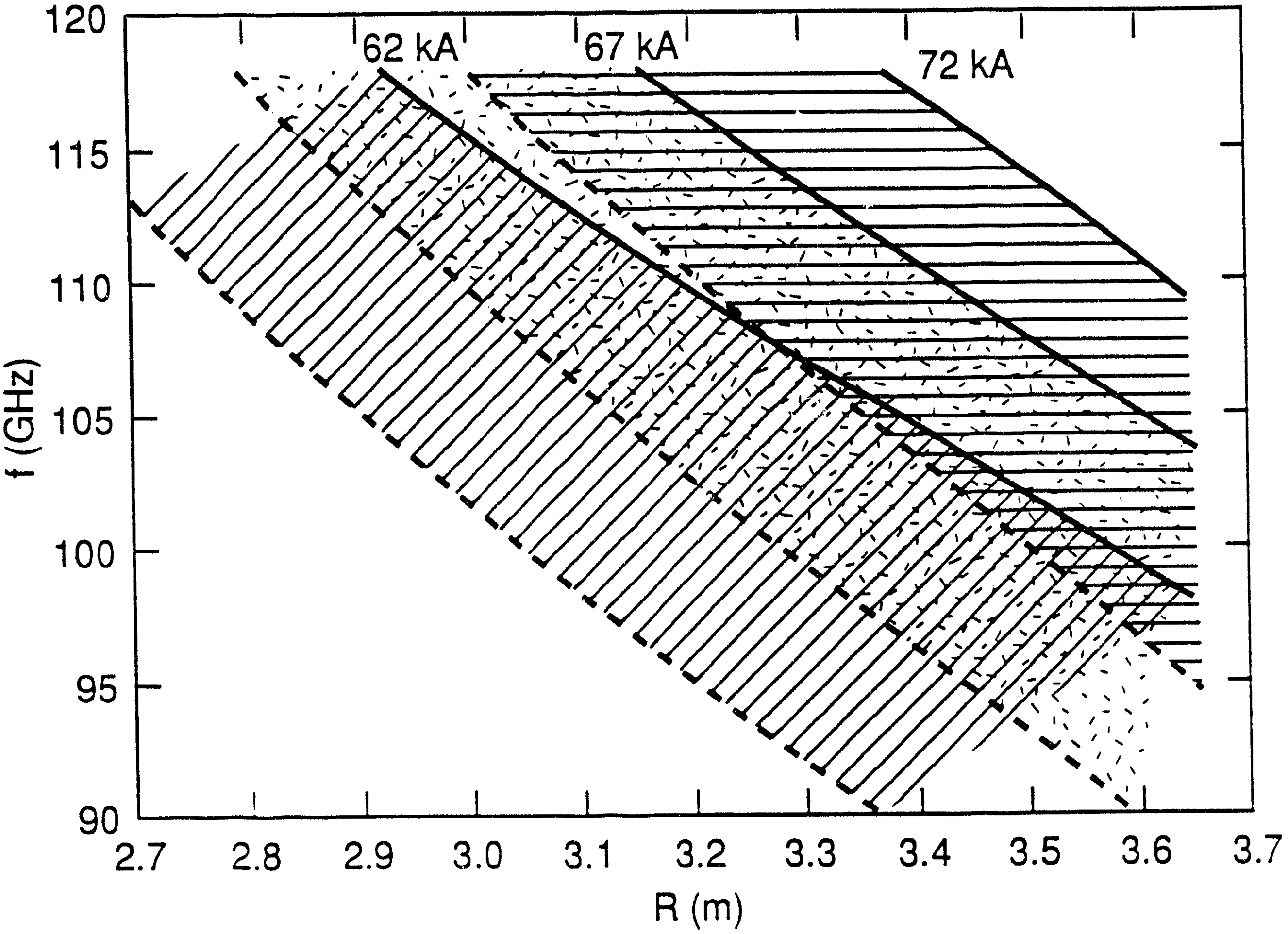
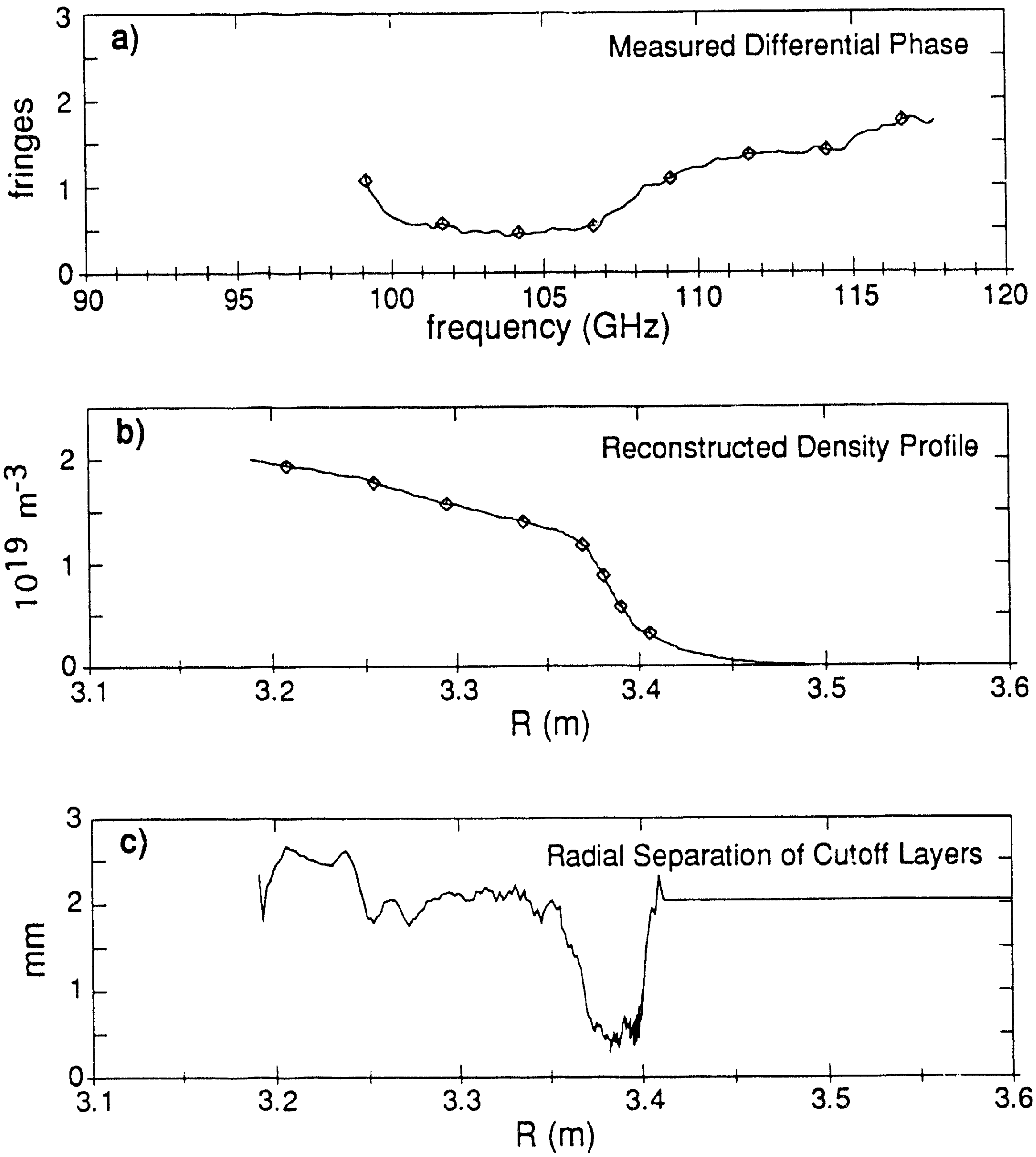
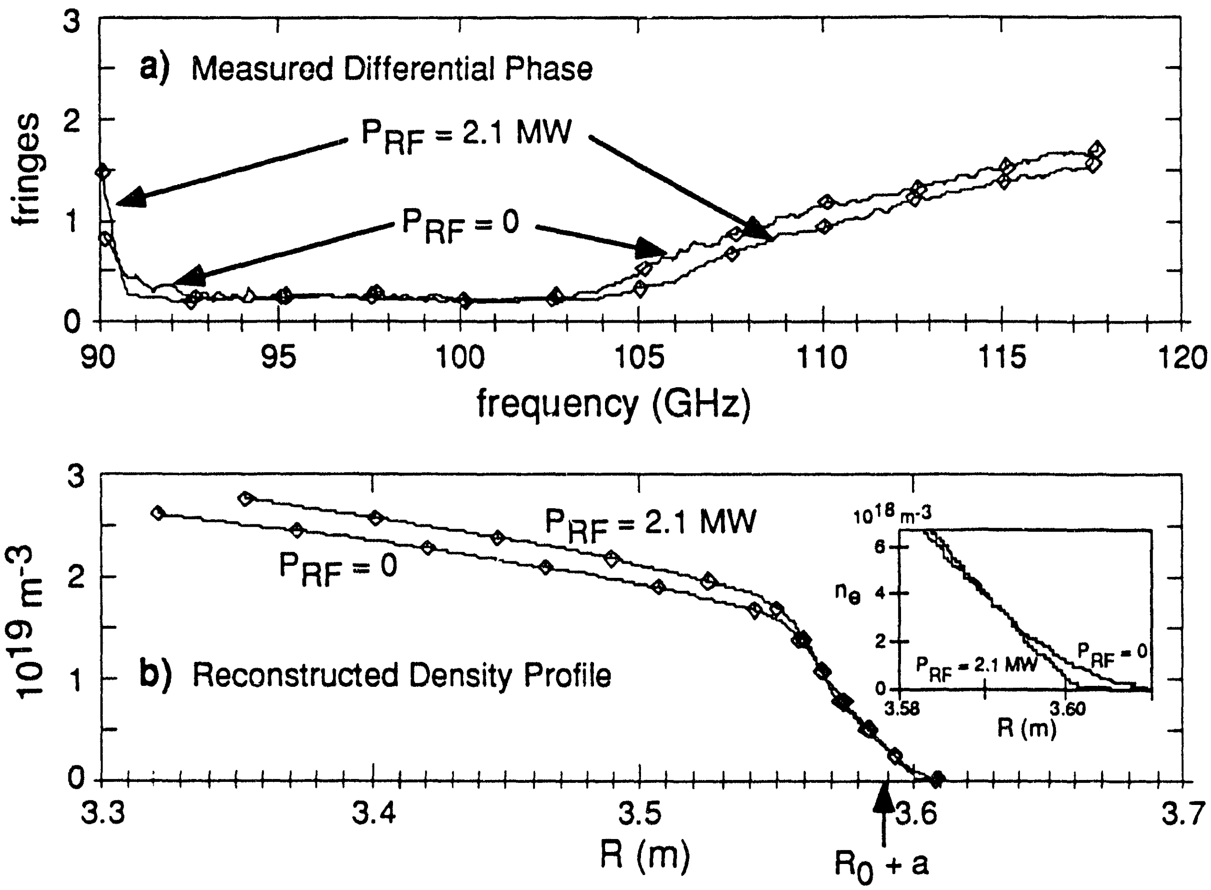


Fig. 1


a)
Measured Differential Phase
fringes
0
1
2
3
90
95
100
105
110
115
120
frequency (GHz)
b)
Reconstructed Density Profile
10^{19} m^{-3}
0
1
2
3.1
3.2
3.3
3.4
3.5
3.6
R (m)
c)
Radial Separation of Cutoff Layers
mm
0
1
2
3
3.1
3.2
3.3
3.4
3.5
3.6
R (m)



a) Measured Differential Phase
fringes
P_RF = 2.1 MW
P_RF = 0
frequency (GHz)
b) Reconstructed Density Profile
10^19 m^-3
P_RF = 2.1 MW
P_RF = 0
R (m)
R_0 + a
10^18 m-3
n_e
P_RF = 2.1 MW
P_RF = 0
R (m)

Fig. 3

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