Recent Reflectometry Results from the UCLA Plasma Diagnostics Group

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Abstract

The UCLA Plasma Diagnostics Group has an active ongoing reflectometry program. The program is threefold, including 1) profile and 2) fluctuation measurements on fusion devices (DIII-D, NSTX, and others), and 3) basic reflectometry studies in linear and laboratory plasmas that seek to develop new measurement capabilities and increase the physics understanding of reflectometry. Recent results on the DIII-D tokamak include progress toward the implementation of FM reflectometry as a standard density profile diagnostic, and correlation length measurements in QDB discharges that indicate a very different scaling than normally observed in L-mode plasmas. The first reflectometry measurements in a spherical torus (ST) have also been obtained on NSTX. Profiles in NSTX show good agreement with those of Thomson scattering. Finally, in a linear device, a local magnetic field strength measurement based on O-X correlation reflectometry has been demonstrated to proof of principle level, and correlation lengths measured by reflectometry are in good agreement with probes.

I. INTRODUCTION

Reflectometry can provide both electron density profiles with high spatial and temporal resolution, and density fluctuation measurements from the plasma edge to the core. One proven method for density profile measurement is the FM radar technique.[1,2] The UCLA group currently operates FM radar systems on both the DIII-D tokamak and NSTX spherical torus. In Section II, recent profile measurements from DIII-D and NSTX are shown, and progress in implementing FM relfectometry as a standard diagnostic is briefly discussed.

Section III presents correlation reflectometry measurements from DIII-D. Radial correlation lengths, Δr, are compared in DIII-D L-mode and Quiescent Double Barrier (QDB) discharges,[3,4] and are found to exhibit different scalings.

Two aspects of basic reflectometry studies are discussed in Section IV. First, the development of a magnetic field strength, $|\underline{B}|$, diagnostic based on dual mode (O-X) correlation reflectometry is presented. It is shown that, in these experiments, $|\underline{B}|$ could be determined simultaneously with the radial correlation length, Δr. Second, comparisons between radial correlation lengths measured by homodyne reflectometry and a Langmuir probe array are presented. Good agreement is found between the reflectometer and probe.

II. FM PROFILE MEASUREMENTS

Significant progress has been made toward implementing profile reflectometry as a standard diagnostic on the DIII-D tokamak. Automatic profile analysis has been demonstrated, system spatial coverage has been optimized via polarization flexibility, and upgraded data acquisition has significantly extended the time coverage.

The profile reflectometers on DIII-D are Q- (33-50 GHz) and V-band (50–75 GHz) FM radars,[5,6] that operate in either O- or X-mode.[7] The data acquisition system and analysis software have been upgraded to allow profiles to be measured every 10 ms for an entire 5 s discharge, and analyzed between shots. O-mode measurements are able to access the plasma core, while X-mode scans the edge. The O-mode system has been particularly important in measuring the steep profiles found to occur in operating modes with internal transport barriers (ITB) with good time resolution. Fig. 1 shows an example of the time evolution of the electron density at an ITB.

In order to construct X-mode profiles, the start of reflection from the right-hand cut-off must be identified. For O-mode in the core, a reliable fit to Thomson Scattering (TS) profiles at the edge must be available. Furthermore, in cases where the O-mode begins to transmit above cut-off, this point in the time record must be identified. Software is now in place and operating to automatically determine this information, and to reconstruct the profiles between shots.[7] Note that the large volume of profiles, up to 10,000 per discharge, *requires* an automated analysis system. Currently, however, operator intervention is still required to obtain profiles showing detailed agreement with those of the TS system. Development of a fully automatic system is ongoing.

An FM profile reflectometer, consisting of three O-mode systems in the bands 12-18 GHz, 20-32 GHz and 33-50 GHz, has also been installed on the National Spherical Torus Experiment (NSTX),[8] and initial results have been obtained. All three NSTX systems utilize circular horn antennas, and rotating waveguide joints so that the polarization angle can be adjusted manually. During operation, the polarization is typically aligned with the expected edge magnetic field pitch angle. Figure 2 shows a recent reflectometer profile from NSTX together with Thomson scattering measurements. As can be seen, there is good agreement between the two measurements over most of the outer half of the plasma. Note that this is the first reflectometry measurement in an ST device. These initial results are encouraging since there were concerns about problems with reflectometry in the ST's resulting from O-X mode conversion due to the large magnetic field shear.[9]

III. CORRELATION MEASUREMENTS IN DIII-D

Although some questions regarding the interpretation of fluctuation and correlation data remain,[10] correlation reflectometry is now a mature enough diagnostic to be used reliably for physics studies in magnetically confined plasmas.

Figures 3 and 4 show two recent and interesting correlation results from DIII-D.[3,11] These measurements were made with a heterodyne frequency tunable V-band (50-75 GHz) system located on the outboard midplane.[12] First, Fig. 3 plots radial correlation length, Δr, measurements in DIII-D in typical L-mode and QDB discharges. The QDB discharge is a high performance mode that exhibits both edge and core transport barriers. The core barrier, as well as sheared flow due to radial electric field, exists over a large region of the core plasma.[3,4] In the L-mode case, Δr exhibits a scaling with either the poloidal ion sound gyroradius, $\rho_{\theta s}$ (i.e. the gyroradius using T_e instead of T_i), or approximately 5-8 times the total sound gyroradius, ρ_s. In contrast, the QDB case Δr's are significantly smaller than the L-mode scaling, which is consistent with reduced turbulent transport step size and improved confinement.

Second, a comparison between reflectometer measurements and a 3D toroidal electrostatic gyrokinetic simulation[13] is shown in Fig. 4. This comparison is an early result from a program to make experiment-model comparisons in detail. The initial simulated plasmas have been circular (DIII-D plasmas are shaped), however comparisons with shaped plasmas are now under way. Measured n_e, T_i, and q profiles were used in the simulation. Two simulation results are shown, both with and without self-generated, or zonal, flows included. Without zonal flows, correlation lengths are seen to be very long – in a fact a large fraction of the total 65 cm minor radius. When zonal flows are included, Δr can be seen to reduce to values near the experimental measurements. Although the agreement is intriguing, this is a very early stage of the comparison and more work remains. Nevertheless, this seems a clear indication of the importance of zonal flow effects in gyrokinetic modeling.

IV. BASIC REFLECTOMETRY STUDIES

A. Dual mode (O-X) correlation reflectometry

Basic studies of dual mode correlation reflectometry have been conducted in the LArge Plasma Device (LAPD) at UCLA.[14,15] In addition to fluctuation/correlation length measurements, O-X reflectometry can provide a local, nonperturbing measurement of $|\underline{B}|$. If O- and X-modes are launched and received through the same pair of antennas, one might expect the cross correlation of both fluctuating signals to maximize when the two reflecting layers overlap spatially. If each signal comes from its respective cut-off layer, then the X-mode frequency corresponding to cut-off at the same spatial location as the O-mode can be written in terms of f_o and f_x,

$$f_x = \frac{1}{2}\left(f_c + \sqrt{f_c^2 + 4 f_o^2} \right), \tag{1}$$

where f_o and f_x are the O- and X-mode frequencies respectively, f_c is the electron cyclotron frequency, f_p is the electron plasma frequency, and the right-hand cutoff, f_R, has been taken for X-mode. Since f_x and f_o are known from the cross-correlation, $|\underline{B}|$ can be determined from Eq. (1).

In practice, it was found that O-X cross-correlation peaked at an X-mode frequency (for fixed O-mode) less than f_R. Fig. 5 shows the results of a typical cross-correlation of homodyne signals, $\langle I_o I_x \rangle$, where $I = A\cos\varphi$. Here $f_o = 11.0$ GHz, B = 0.10 T, and f_x scanned over the range shown. A Guassian fit to the data gave an X-mode frequency of peak cross-correlation, $f_{x,pk} = 12.15 \pm 0.073$ GHz, while $f_R = 12.47 \pm 0.03$ GHz. Amplitude, $\langle A_o A_x \rangle$ and phase, $\langle \varphi_o \varphi_x \rangle$, correlations yielded $f_{x,pk} = 12.17 \pm 0.082$ and 12.15 ± 0.097

GHz respectively. In all cases $f_{x,pk}$ determined from amplitude, phase, and homodyne signals were equal to within the error bars.

Figure 6 shows the X-mode frequency of peak cross-correlation vs. magnetic field for fixed $f_o = 11.0$ GHz. As can be seen, $f_{x,pk}$ lies below the right-hand cutoff in every case. Therefore, $|\underline{B}|$ cannot be determined from the simple formula, (1). However, it has been found that $f_{x,pk}$ can be accurately reproduced by a one-dimensional full wave model (code),[14] as shown in Fig. 6. In order to accurately determine $f_{x,pk}$, the code requires inputs of L_n, the density gradient scale length ($\equiv ((1/n)dn/dx)^{-1}$), and Δk_r, the radial k-spectral width of the plasma fluctuations, $S(k_r) \propto \exp\{ k_r^2 / \Delta k_r^2 \}$. Note that Δk_r is measured directly in an O-X correlation experiment, since for a Guassian k-spectrum, $\Delta k_r = 2\sqrt{2} / \Delta r$, where Δr is the 1/e radial correlation length. Experiment and model show good agreement with variation of these parameters, though the range of Δk_r studied was limited.[14,15]

A practical $|\underline{B}|$ diagnostic would use the 1D model, run iteratively, to determine B at cut-off from measured $f_{x,pk}$ and Δk_r, together with L_n from another diagnostic (e.g. a profile reflectometer). In the LAPD experiments, the accuracy of B was 5%, which was dominated by statistical error. It is likely that statistical error will dominate any measurement, and must be carefully assessed in any experiment. In a hot plasma, a knowledge of T_e might also be required for a relativistic correction to f_R.

An effect found in the O-X experiment, which is not predicted by the code, is that the maximum cross-correlation *value* decreases with magnetic field strength.[14,15] In the LAPD experiments, $\rho_{ox} \approx 0.65$ maximum at 0.05 T, decreasing to $\rho_{ox} \approx 0.4$ at 0.2 T. The reasons for this are not yet understood and may be due to 2D effects, but, practically, this may limit the diagnostic to low B-field cases (B ~ 0.1 T).

B. Reflectometer-Probe Comparisons

Detailed comparisons of turbulent radial correlation lengths measured by reflectometry and probes in the LAPD have also been made.[10] A plot comparing Δr from homodyne reflectometry to that of a probe array is shown in Fig. 7. Here Δr is taken as the 1/e length. As can be seen, there is good agreement, to within 10-15%, between reflectometer and probe in O-O, X-X, as well as O-X modes. The measured correlation lengths fell in the range $0.6 \leq \Delta r/\lambda_0 \leq 1.2$, or $0.7 \leq \Delta r/W_{Airy} \leq 1.3$, where λ_0 is the reflectometer vacuum wavelength and W_{Airy} is the Airy width.[15] Note that correlation lengths less than the vacuum wavelength were accurately measured.

Homodyne reflectometer and probe measurements also showed good agreement in power spectra and coherency in overall character, while phase signals showed agreement only in cases of low fluctuation levels. In cases of high fluctuation levels, the phase was found to undergo a series of multi-radian phase discontinuities, or "jumps" (see ref. [16] for definitions of "low" and "high"). In these cases, the power spectra were found to approach an f^{-2} dependence, and Δr was much shorter than the corresponding probe measurements. These observations are consistent with the Random Phase Screen Model of reflectometry.[16] Finally, when a limited number of such phase jumps existed, they could be filtered out to recover power spectra and correlation lengths consistent with probe measurements.[15]

V. SUMMARY

Recent reflectometry results from the UCLA Plasma Diagnostics Group have been presented. FM density profile measurements have been presented from DIII-D and NSTX. Radial correlation measurements from DIII-D, now being used for physics studies, were also shown. Finally, basic reflectometry work on the linear LAPD on the development of a $|\underline{B}|$ measurement based on O-X correlation reflectometry, and comparisons with probes have been discussed.

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Figure Captions

FIG. 1. Example of the time development of a steep, localized internal transport barrier (ITB) in electron density, in a DIII-D negative central shear (NCS) discharge. The portion of the profile determined by the reflectometer system is shown by open circles.

FIG. 2. Electron density profiles in NSTX vs. major radius measured by O-mode FM reflectometry (line) and Thomson scattering (triangles). Shot 104503, 97-100 ms.

FIG. 3. Radial correlation lengths in the DIII-D core as a function of plasma radius (flux coordinates) in cases of L-mode and QDB[3,4] plasmas. Lines indicate the poloidal sound gyroradius, $\rho_{\theta,s}$, in each case.

FIG. 4. Comparison of radial correlation lengths from measurements in DIII-D and Gyrokinetic simulations, with and without zonal (self-generated) flows included.

FIG. 5. Homodyne O-X cross-correlation coefficient, ρ_{ox}, vs. X-mode frequency, f_x. Error bars denote 95% confidence intervals. $f_o = 11.0$ GHz, B = 0.10 T. Right-hand cut-off $f_R = 12.47 \pm 0.03$ GHz.

FIG. 6. X-mode frequency of peak cross-correlation $f_{x,pk}$ vs. magnetic field: experiment (phase) and simulation. $f_o = 11.0$ GHz in each. Dashed line indicates the right-hand cut-off frequency f_R corresponding to $f_p = 11.0$ GHz.

FIG. 7. Homodyne reflectometer 1/e radial correlation length vs. those measured by a Langmuir probe array in the LAPD.

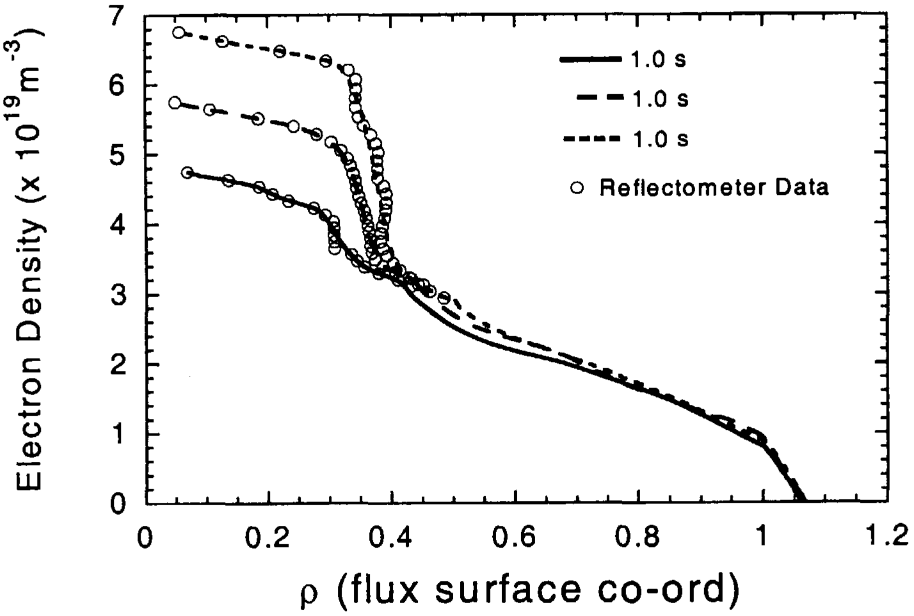


Figure 1

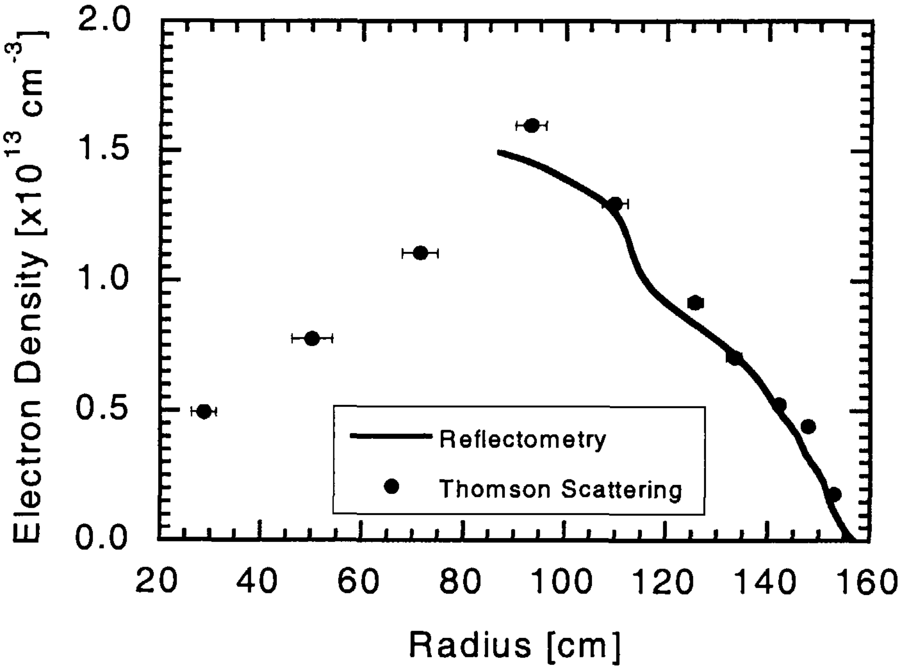


Figure 2

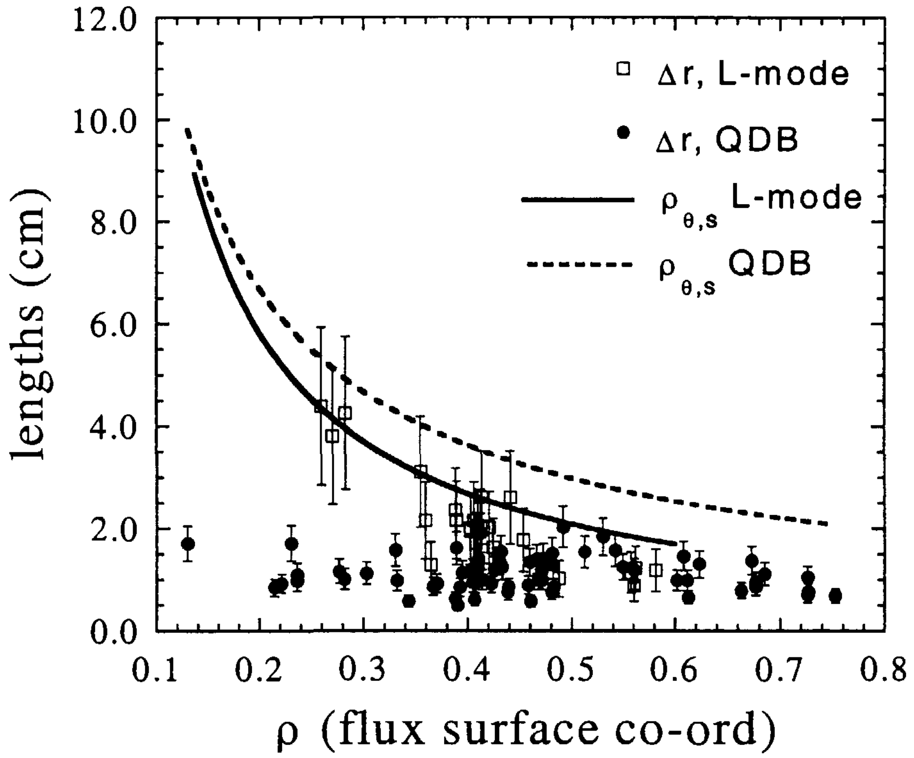


Figure 3

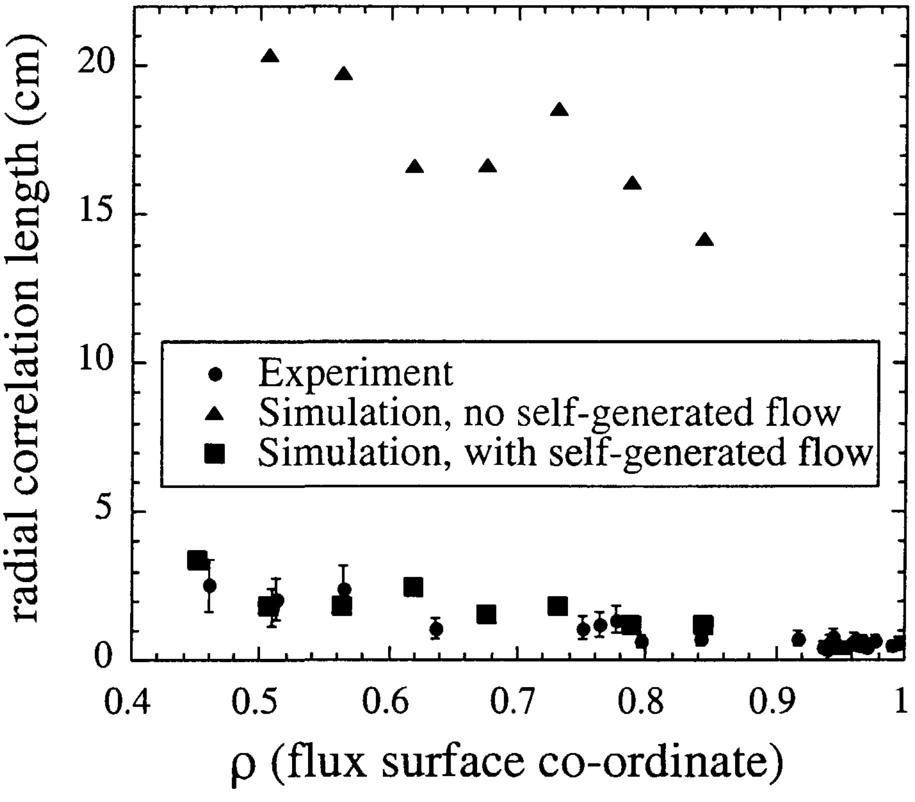


Figure 4

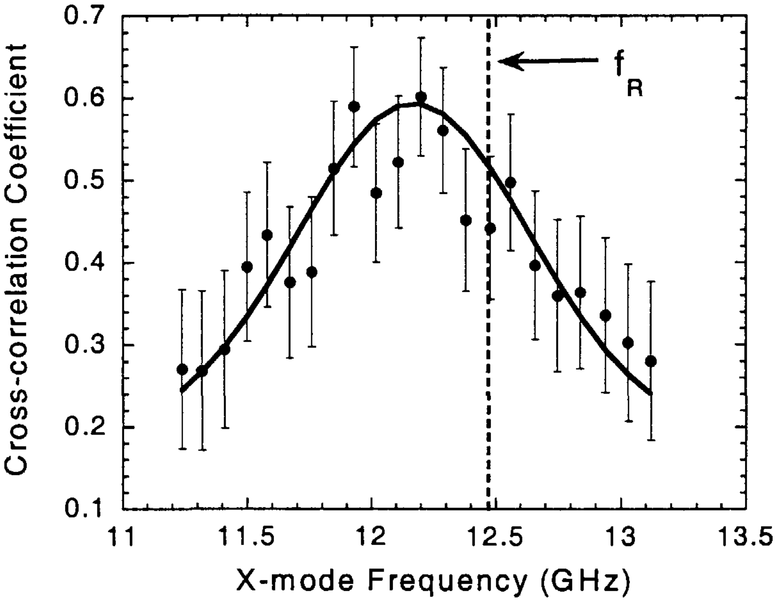


Figure 5

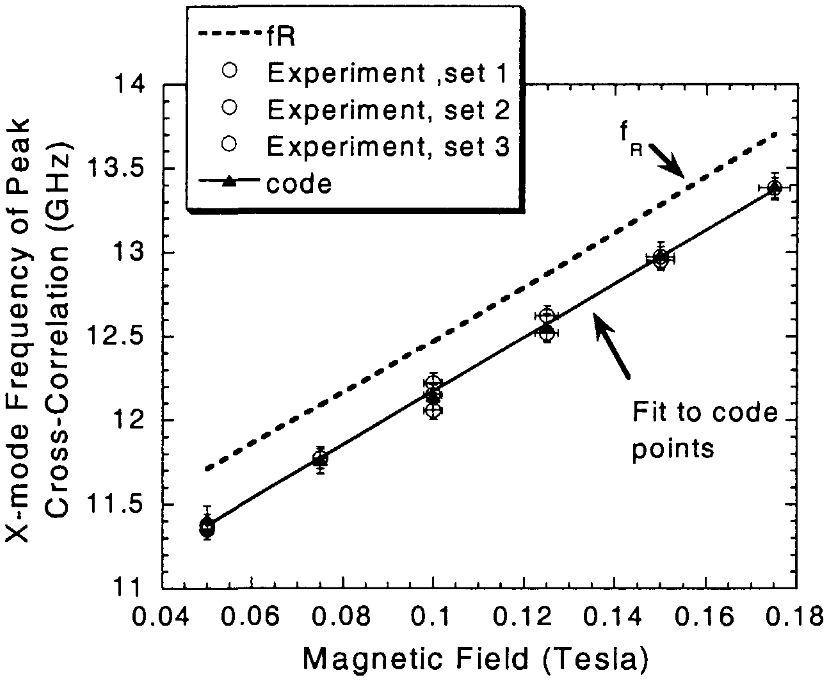
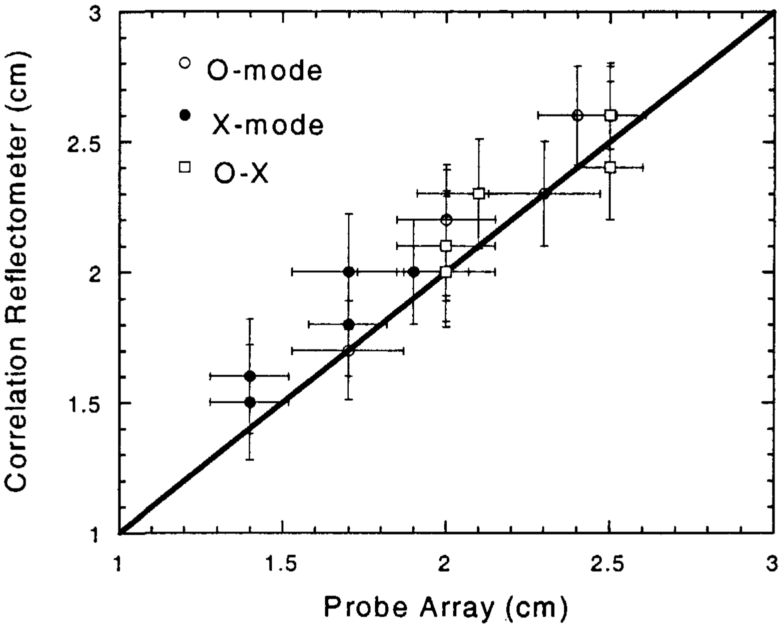


Figure 6



3
2.5
2
1.5
1
1
1.5
2
2.5
3
○ O-mode
● X-mode
□ O-X
Correlation Reflectometer (cm)
Probe Array (cm)

Figure 7