PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76CH03073

PPPL-3722
UC-70

PPPL-3722

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by

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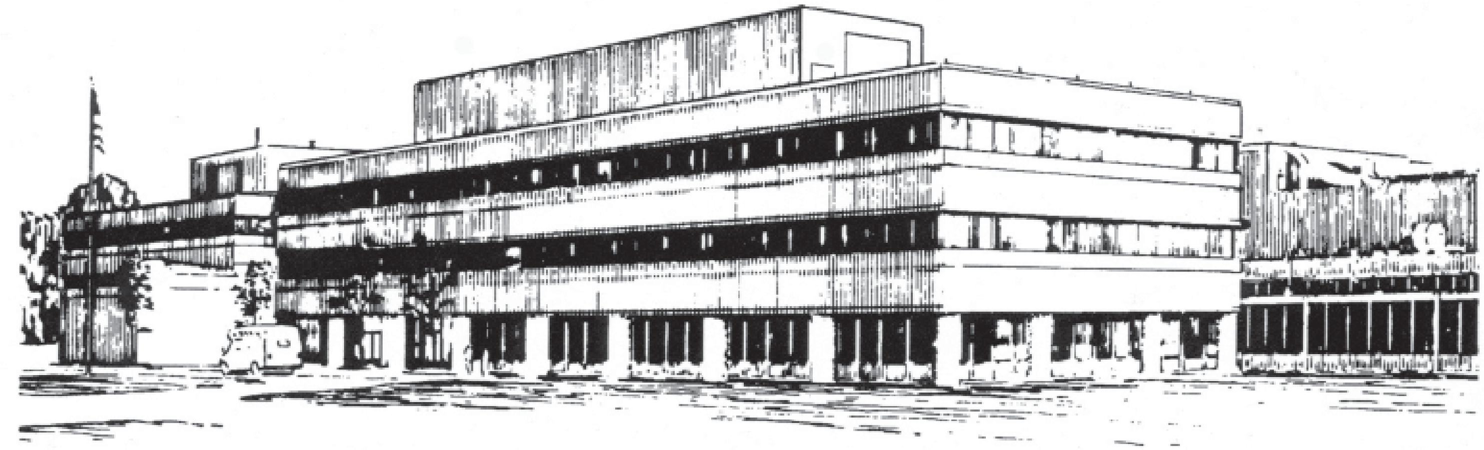
July 2002



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Correlation Reflectometry for Turbulence and Magnetic Field Measurements in Fusion Plasmas

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Abstract

For the interpretation of correlation reflectometry data a fast two dimensional full wave code has been developed in which realistic plasma geometries are used. Results of this code are compared with experiments and turbulence correlation lengths and fluctuation levels are extracted with statistical optics methods. It is shown that in general the measured reflectometer correlation length is not equal to the turbulence correlation length. The code is also used to study the posability of O-X correlation reflectometry in FIRE for the determination of the local magnetic field strength. It was found that this is only possible at very low fluctuation levels.

1 introduction

Correlation reflectometry has been performed for many years in both laboratory and fusion scale plasmas [1, 2, 3, 4, 5]. The aim of the laboratory scale experiments with its easy access for probes, is to compare fluctuation levels and correlation lengths deduced from reflectometer measurements with those from probe measurements. In fusion scale experiments, however, probe measurements in the core of the plasma for comparison with reflectometer measurements are no longer feasible, so the results from laboratory scale experiments have to be extrapolated to fusion scale experiments.

For this purpose we have developed a very fast 2-D reflectometer simulation code with realistic plasma geometry that can be used to study correlation reflectometry in detail [6]. With this model we can answer how robust the 1-D and slab geometry estimates [7, 8] of the fluctuation levels and correlation lengths are to details of the plasma profile and geometry. Slab models and 1-D models do not treat amplitude fluctuations, plasma curvature, finite aperture and alignment effects correctly.

We will present results of 2-D laboratory and fusion scale plasma simulations, compare it with experiments and 1-D models and show that 2-D effects are important in some cases for the interpretation of reflectometer experiments.

Correlations between O- and X-mode polarized signals can be used to measure local magnetic field strengths in plasmas [9]. We will also present results of a 2-D O-X correlation simulation and show that there is a good agreement with laboratory scale experiments. Extrapolation of these results to fusion devices show that it is far from certain that this technique will give reliable measurements of the local magnetic field in high field devices because of the very low fluctuation levels that are needed to obtain a significant correlation between the O- and X-mode signals.

2 Interpretation of correlation measurements

From correlation reflectometry two important quantities for the study of plasma turbulence and transport can be deduced. These are the turbulence correlation length, λ_T, and the density fluctuation level, $\tilde{n}/n$.

For correlation reflectometry two microwave beams with different frequencies are launched into the plasma and the cross correlation between the two reflected signals is studied (see figure 1). The two waves can either be launched in X-mode, usually to study the plasma core, O-mode, for edge measurements, or one channel in X-mode and the other in O-mode for the determination of the local magnetic field strength. In section 4, O-X correlations are studied in detail to obtain local magnetic field measurements in plasmas.

O-mode waves are reflected at the plasma frequency cut off layer which depends on the local electron density whereas X-mode waves are reflected at the left- and right-hand cut off layers which depend on the local electron density and magnetic field strength. The radial separation between the two channels is obtained from the frequency difference and the density, and in the X-mode case, magnetic field profiles. These profiles can be determined from other diagnostics.

Instead of studying the amplitude and phase fluctuations of the reflected signals separately, we have chosen to use statistical optics methods [10] for both the experimental and simulated data. It has been shown that the amplitude fluctuations in the reflected signal are introduced by interference effects of the scattered waves [11].

From the correlation reflectometer signals we can calculate two signals that are important for the interpretation the measurements: the normalized cross correlation, γ, and the coherent reflection, G. The normalized cross correlation is defined as

$$\gamma = \frac{|\langle E_1 E_2^* \rangle|}{\sqrt{\langle |E_1|^2 \rangle \langle |E_2|^2 \rangle}}$$

with E_1 and E_2 the (complex) signal of reflectometer channel 1 and 2, respectively, and $\langle \cdots \rangle$ stands for ensemble averaging. The normalized cross correlation can be used to estimate the radial correlation length of the turbulence. Until now the 1/e width of the measured cross correlation distribution is used as a measurement of the radial turbulence correlation length but in the following we will show that in general the radial correlation length as measured with a reflectometer is not equal to the turbulence correlation length.

The coherent reflection is given by

$$G = \frac{|\langle E \rangle|}{\sqrt{\langle |E|^2 \rangle}} \tag{1}$$

and can be used as an indicator of the density fluctuation level.

In the following we study the relationship between the experimentally determined γ and G and the theoretical quantities λ_T and $\tilde{n}/n$ and we show that both γ and G are needed together with 2-D (or 1-D) modeling to determine λ_T and $\tilde{n}/n$ uniquely.

3 Turbulence simulations

Correlation reflectometry has been performed in the edge of laboratory scale plasmas [3] and in the core of large scale fusion devices [2, 12]. In some of those experiments the measured reflectometer correlation length is interpreted as the turbulence correlation length. In this section we present exhaustive 1-D and 2-D reflectometer modeling and show that in general these two correlation lengths are different. We will also show a benchmark of the 1-D and 2-D codes with an experiment performed at the LArge Plasma Device [13].

We have simulated the behavior of microwave reflection from the edge of a plasma with a 1-D [8] and a 2-D code [6]. In our calculations we have taken a cylindrical plasma, radius 60 cm, a density scale length of 10 cm, and O-mode polarized waves with a frequency of 12 GHz. These waves were reflected from a layer 10 cm inside the plasma. On top of the equilibrium density profile a spectrum of density fluctuations was added which gives the following density correlation function

$$\langle \tilde{n}(x_2)\, \tilde{n}(x_1) \rangle / n^2 = \left(\frac{\tilde{n}}{n} \right)^2_{x_1} \exp(-(x_2 - x_1)^2 / \lambda_T^2) \cos(k_{\mathrm{fl}}(x_2 - x_1))$$

with $(\tilde{n}/n)_{x_1}$ the fluctuation amplitude, x_1 (x_2) the fixed (variable) frequency cut off layer position, λ_T the 1/e width of the turbulence correlation and $k_{\mathrm{fl}} = 2\pi/\lambda_{\mathrm{fl}}$ where λ_{fl} is the characteristic fluctuation wave length. In a similar manner a 2-D spectrum of density fluctuations (spectral locations k_x and k_y and widths Δk_x and Δk_y) was added to the 2-D density equilibrium profile for the 2-D calculations [6].

In our simulations we have varied the theoretically important variables $\tilde{n}/n$ between 0.1 and 12% in steps of 1% and λ_T between 0.5 and 2.5 in steps of 0.5 times the width of the Airy fringe at the cut off layer which is given (for O-mode) by $w_{\mathrm{Airy}} = 0.48\, L_n^{1/3} \lambda_0^{2/3}$.

The 1-D correlations were calculated on 401 equally spaced radial points over an interval of six correlation lengths. The radial grid for the 2-D simulations was an equally spaced grid of 13 points with a spacing of 0.5 cm. For the 1-D calculations a set of 6000 random density distributions, $\tilde{n}(x)$, were generated from the correlation function whereas for the 2-D simulations an ensemble of 300 realizations was used.

In figure 2 the relation is shown between λ_T and the inferred reflectometer correlation length, λ_R, at different density fluctuation levels. It can be seen that in general λ_T is not equal to λ_R. At low fluctuation levels and short turbulence correlation lengths, λ_R is larger than λ_T whereas at high fluctuation levels and long turbulence correlation lengths λ_R is smaller than λ_T.

When one measures only λ_R, the corresponding λ_T is not determined uniquely, because of the $\tilde{n}/n$ dependence. We can resolve that ambiguity by not only measuring λ_R but also the coherent reflected power, G, which is correlated with $\tilde{n}/n$. A clear way to represent this, is to map the quantities of the turbulence, (λ_T,$\tilde{n}/n$), to the (λ_R,G)

plane, which are both experimental quantities, as shown in figure 3. First of all, there is a remarkable similarity between the 1-D and 2-D simulation results. From figure 3 it can also be seen that if $\tilde{n}/n$ increases at constant λ_T, G decreases. G also decreases when $\tilde{n}/n$ is kept constant and λ_T is increased. In a similar way λ_R decreases when $\tilde{n}/n$ increases at constant λ_T.

We conclude from figure 3 that it is required to measure both λ_R and G to determine λ_T and $\tilde{n}/n$. Determining λ_R alone as a measure of λ_T, leaves one with a range of possible λ_T's.

The relation between correlation lengths determined from probes as a measure of the turbulence correlation length and the correlation lengths from reflectometer measurements has been studied exhaustively in a laboratory scale plasma at LAPD [3]. We have used the data of one of those measurements in our 1-D code as a benchmark. We have used the 1-D instead of the 2-D code because the the two codes give the same results for the parameter range that is covered in this simulation as was shown in figure 3. In our benchmark calculation we have used 1.7 cm for the turbulence correlation as was measured with the probes. Other experimental parameters that were used are a density scale length of 12 cm, 14 GHz X-mode polarized waves, and a magnetic field of 0.1 T. In our simulations we have varied the density fluctuation level between 5 and 19% and found that the 9% fluctuation level which was measured with the probes, fits the measured 1/e reflectometer width very well (see figure 4). In a separate study where measured O-X cross correlations were compared with 1-D and 2-D modeling and where 2-D effects were shown to be important, good agreement with the modeling and experiments was also found. Details of those simulations were reported in [8].

We conclude that simulations agree well with experimental results. A study is under way in which the the 1-D and 2-D codes are used to analize all the experimental and model sensitivities for reflectometer data that was measured in the core of a large scale fusion plasma, inside the internal transport barrier of a JT-60U plasma [2, 12]

4 Magnetic field measurements

Magnetic field measurements are essential for fusion devices. In the next generation of Tokamaks it will become very difficult to use Motional Stark Effect (MSE) measurements for the determination of the magnetic safety factor or q-profile [14, 15] because of the expected high plasma densities in which diagnostic neutral beams cannot penetrate to the plasma center.

In two recent articles [3, 4] an alternative approach to magnetic field measurements in hot plasmas has been proposed based on the reflection of microwaves of different polarizations from magnetized plasmas. In this method the omnipresent turbulence in the plasma is used by measuring the peak correlation in the reflected signal between ordinary or O-mode and extraordinary or X-mode polarized waves. The absolute value of the magnetic field, $|\mathbf{B}|$, at the reflection point can then be deduced from the electron cyclotron frequency, ω_c, and the measured O-mode, and right hand side X-mode frequencies, ω_O and ω_R,

$$\omega_c = \frac{-e|\mathbf{B}|}{m_e} = \frac{\omega_R^2 + \omega_O^2}{\omega_R}$$

with e and m_e represent the electron charge and mass respectively. In LAPD O-X correlations have been studied extensively [3, 4] with uniform magnetic fields between 0.1 and 0.18 T, densities up to $3.0\,10^{18}$ m^{-3}, and density scale lengths between 0.05 and 0.20 m. In these experiments, in which the X-mode frequency was scanned and the O-mode frequency kept fixed, it was found that the O-X correlation was reduced with increasing magnetic field strengths, and it peaked slightly in front of where the two cut off layers coincide. Both effects have been explained successfully with 2-D modeling [8].

Future burning plasma experiments such as FIRE and ITER, will operate at very high magnetic field strengths (10 T and 5.3 T, respectively), so it is not clear whether there is any O-X correlation left at these field strengths. To answer this question, we have performed extensive 1-D and 2-D simulations for an envisaged FIRE discharge with a toroidal magnetic field of 10 T, a central electron density of $4.9\,10^{20}$ m^{-3}, and a central electron temperature of 11.9 keV. The FIRE plasma shape has been designed to be: major radius 2.14 m, minor radius 0.60 m, ellipticity 2.0, and triangularity 0.49 [16].

In our 1-D and 2-D simulations we have chosen an O-mode frequency of 190.0 GHz which is reflected at r/a of 0.34 as can be seen from figure 5. The right hand side X-mode frequencies were scanned between 350.2 and 354.5 GHz. An isotropic spectrum of density fluctuations with a correlation length, λ_T, of 1.0 cm and fluctuation levels, $\tilde{n}/n$, of 0.1, 0.3, and 0.5% were added to the equilibrium density profile (for more details see [6, 8]). The antennas, about 1.1 cm in height, were located in the simulation at the low field side mid-plane and 50 cm from the plasma edge.

For the 1-D calculations an ensemble size of 3000 was used. Radially in 1-D, the O-X correlation was calculated for 10 cm before to 10 cm behind the O-mode reflection layer with a radial step of 0.25 mm. In the 2-D calculations the ensemble size was 300 and up to 25 different X-mode frequencies were used separated radially between 1.25 mm and 2.50 mm in such a way that the peak of the cross correlation is covered accurately.

In figure 6 the results of the 1-D and 2-D simulations are shown. It is quite amazing to find a significant O-X cross correlation in the 2-D simulations at 0.1% fluctuation level because the scattered wave fields for the two polarizations are very different as is shown in figures 7 and 8. The maximum 2-D cross correlation of 0.4 is reached 3 mm in front of the O-mode reflection layer which corresponds with a X-mode frequency shift of 0.34 GHz. There is a significant difference in the magnitude of the cross correlation between the 1-D and 2-D modeling (see figure 6). This can be explained by the fact that in the 1-D modeling only the phase fluctuations are taken into account whereas in the 2-D modeling both phase and amplitude fluctuations are present in the signal at the (software) antenna.

Only at very low fluctuation levels, there is a significant correlation between the O-mode and X-mode signals and the O-X correlation technique can used in the next generation of fusion devices. Moreover, the density profile should have such a shape that the O-mode waves can reach the locations where one wants to measure $|\mathbf{B}|$. Usually, this means a monotonically decreasing density profile from the center to the edge with a finite density gradient.

It should also be stressed that the fluctuation level must be low so that the coherent scattered power is significant and peak cross correlations is above the noise level as shown in figure 9. From this figure it is concluded that the fluctuation level for the FIRE equilibrium studied here should be well below 0.2% at a turbulence correlation length of 1.0 cm. When the turbulence correlation length is smaller the cross correlation increases as was shown in section 2. Experimentally, fluctuation levels of 0.2 to 0.5% have been found in large scale fusion experiments [12, 17, 18, 19, 20].

With the O-X correlation reflectometry method, the $|\mathbf{B}|$-profile is measured as a function of the electron density. for the determination of the $|\mathbf{B}|$-profile as function of minor or major radius, high spatial resolved and accurate measurements of the density profile are needed.

The accuracy of these magnetic field measurements can be expressed as

$$\frac{|\Delta\,\mathbf{B}|}{|\mathbf{B}|} = \frac{\Delta\omega_c}{\omega_c} = \frac{\omega_R}{\omega_R^2 + \omega_O^2}\Big(\frac{2\omega_O}{\omega_R}\Delta\omega_O + \frac{\omega_R^2 - \omega_O^2}{\omega_R^2}\Delta\omega_R\Big)$$

with $\Delta\omega_O$ and $\Delta\omega_R$ the experimental uncertainties in the O-mode and X-mode frequencies which includes the accuracy with which the peak of the cross correlation can be determined.

The change in the magnetic field in the above used FIRE equilibrium due to plasma effects is in the order of 0.25 T at the location where we have performed the simulation, which corresponds to a change in ω_c of 7 GHz. The estimated experimental uncertainties of 0.1 GHz for the O-mode and 0.2 GHz for the X-mode frequencies result in a $\Delta\omega_c$ of 0.25 GHz which in turn gives 0.01 T accuracy for $|\Delta\,\mathbf{B}|$.

5 Conclusions and further plans

Microwave correlation reflectometry has the potential to determine turbulence correlation lengths and fluctuation levels. From 1-D and 2-D simulations and statistical optics analysis methods, it was shown that for an unambiguous determination of fluctuation levels and turbulence correlation lengths both reflectometer correlation lengths and coherent scattered powers have to be determined experimentally. It was also shown that the measured reflectometer correlation length depends both on the turbulence correlation length and on the fluctuation level. Vice versa, the coherent scattered power depends on both the density fluctuation level and the turbulence correlation length.

1-D and 2-D reflectometer simulations for experiments performed at LAPD have shown an excellent agreement with the experimental results. However, for a more stringent comparison between experiment and simulations, the coherent scattered power has to be measured in future experiments together with the reflectometer correlation length.

Under certain conditions the absolute value of the local magnetic field can be deduced from O-X cross correlation measurements. Experimentally, this technique has been used successfully in LAPD at magnetic fields up to 0.2 T. For a good theoretical understranding of these experiments 2-D simulations had to be performed. 1-D simulations overestimated the maximum cross correlation significantly. We have used the 2-D simulation code to study the feasibility to use O-X cross correlations in a FIRE like plasma for local internal magnetic field measurements near the core. It was found that only at very low fluctuation levels, less than 0.2%, and short turbulence correlation lengths, 1 cm or less, sufficient high O-X cross correlation exists so that this technique can be used successfully there. In the low field spherical tokamak NSTX experiments are underway to use this technique as a local internal magnetic field measurement [21].

In the future, the 2-D code can and will be used to design new experiments such as imaging reflectometry experiments [22], poloidal scattering experiments [23] and to study the sensitivity to poloidal correlation lengths. Moreover, an investigation is underway to study the difference between homodyne and heterodyne detection systems from statistical ensembles that are calculated with the 2-D code.

This work was supported by DOE Contract No. DE-AC02-76-CH0373.

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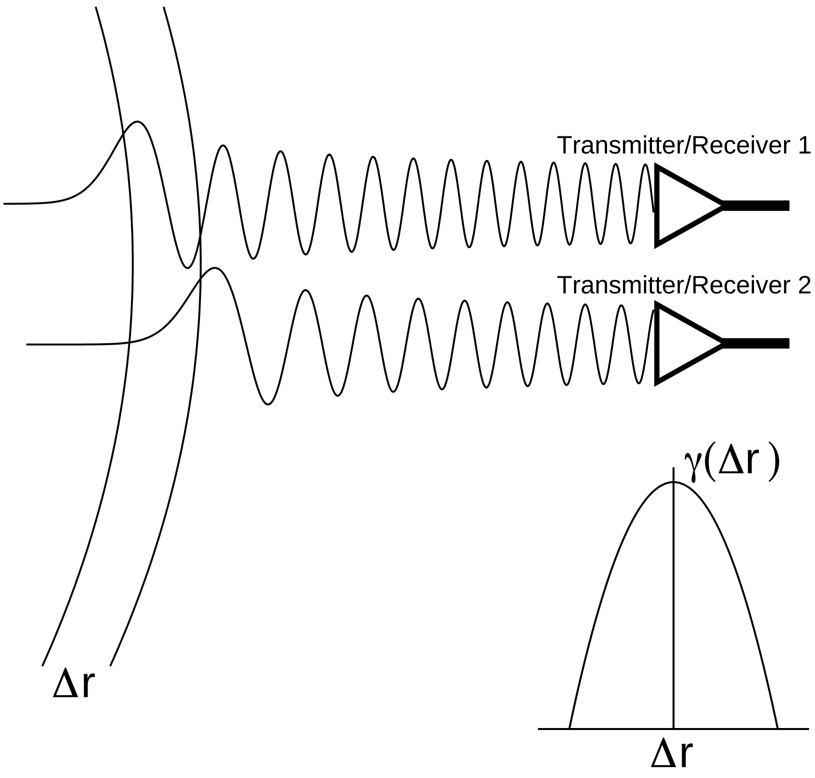

Figure 1: Schematic of correlation reflectometry. Microwaves reflect from different layers, separated by Δr, in the plasma. When one of the reflectometer frequencies is varied, the cross correlation, γ, between the signals can be obtained as a function of Δr whereby the radial separation is determined from diagnostics that measure the density (X- and O-mode) and magnetic field (X-mode) profiles.

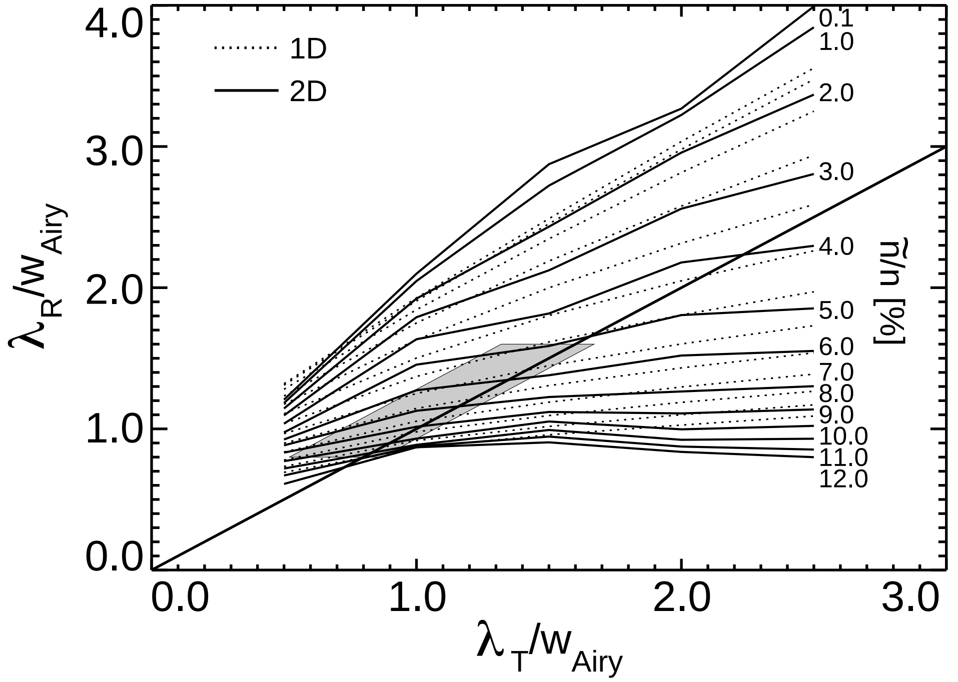

Figure 2: The reflectometer correlation length, λ_R, as a function of the turbulence correlation length, λ_T, for various values of the fluctuation level, $\tilde{n}/n$. The measurements from the LAPD experiments [3] fall within the gray box.

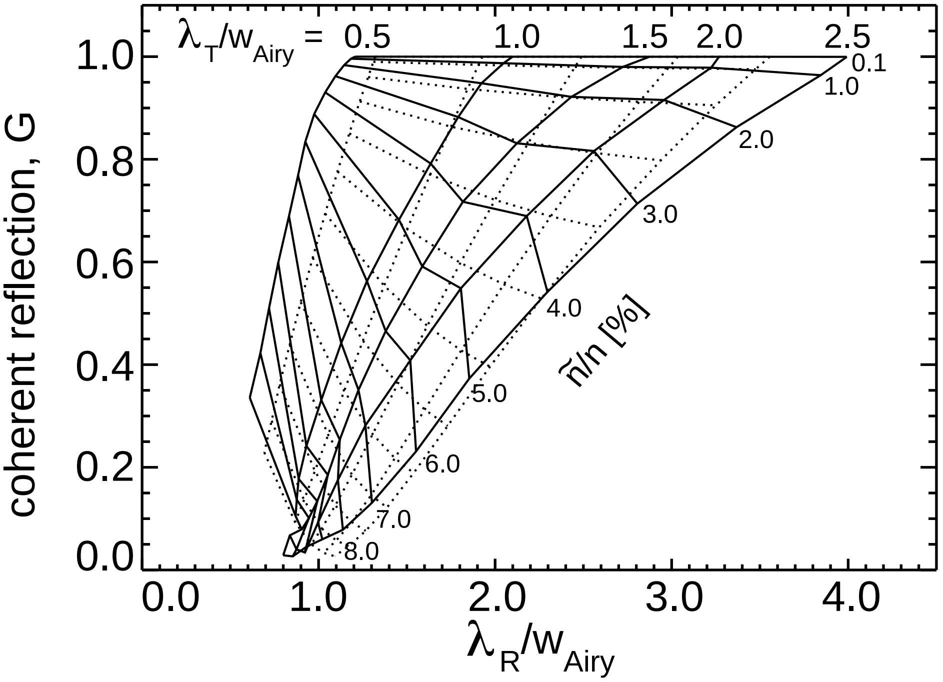

Figure 3: the mapping of the turbulence parameters, turbulence correlation length, λ_T, and fluctuation level, $\tilde{n}/n$, to the experimentally determined quantities, reflectometer correlation length, λ_R, and coherent reflected power G. λ_T and λ_R are normalized to the Airy width, $W_{\rm airy}$, of the last fringe at the cut off. The full lines are 2-D and the dotted lines are 1-D simulations.

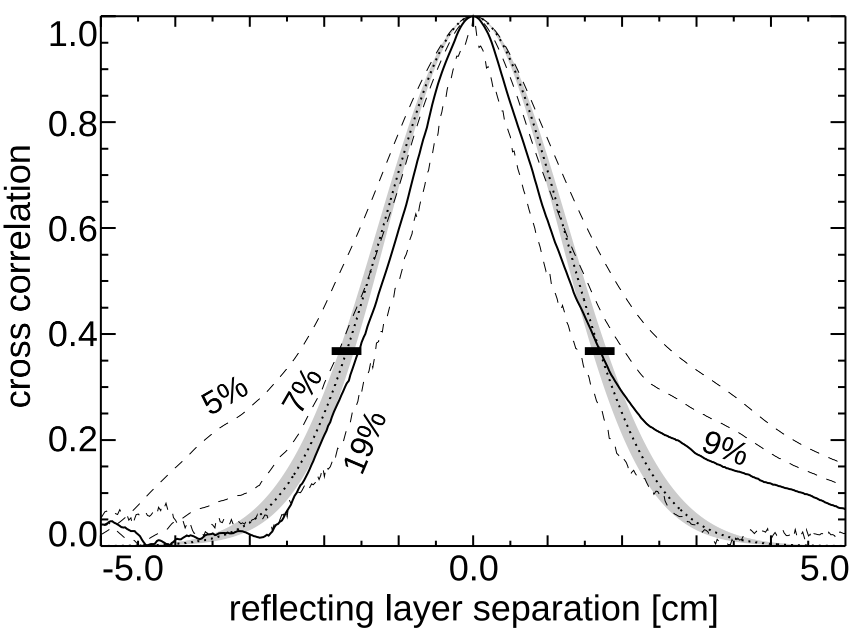

Figure 4: Calculated cross correlation for a LAPD experiment where both the turbulence correlation length and fluctuation level were measured with probes (dotted line, uncertainty: shaded area) and the reflectometer response a the measured fluctuation level of 9% (solid line). The measured reflectometer 1/e width and its uncertainty is indicated with the error bars at 1/e and agrees very well with the simulation. For comparison the three dashed curves are the simulated responses at $\tilde{n}/n = 5$, 7, and 19%.

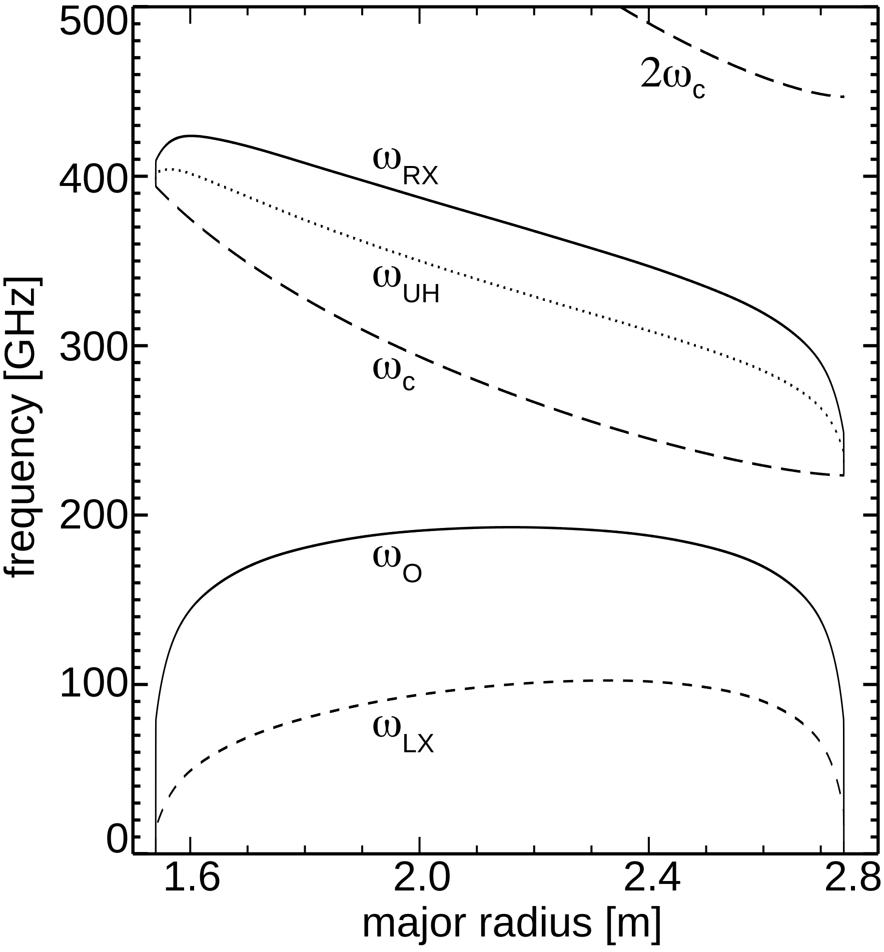

Figure 5: Frequency profiles for various resonant and cut off layers from the FIRE equilibrium used for the O-X correlation study. From bottom to top: ω_{LX} the left-hand side X-mode cut off, ω_{O} the O-mode cut off, ω_{c} the cyclotron resonance, ω_{UH} the upper hybrid resonance, ω_{LX} the right-hand side X-mode cut off, and $2\,\omega_{\mathrm{c}}$ the second harmonic cyclotron resonance.

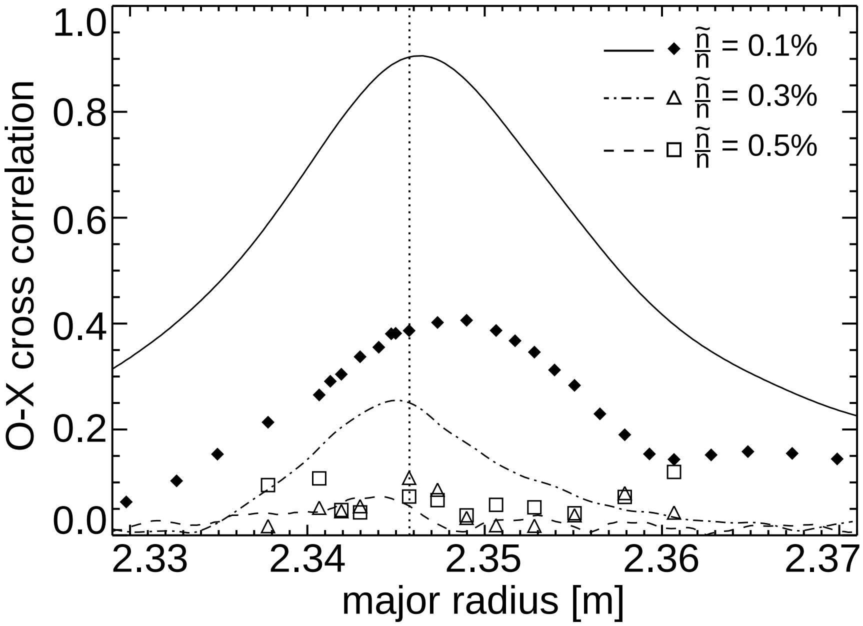

Figure 6: 1-D and 2-D O-X correlation simulations for the standard FIRE equilibrium at different fluctuation levels. The solid, dash dotted, and dashed lines are 1-D simulations for $\tilde{n}/n = 0.1$, 0.3, and 0.5%, respectively, whereas the diamonds, triangles, and squares are the 2-D simulations for the afore mentioned fluctuation levels. The vertical dotted line is the 1-D O-mode reflection location at 190 GHz.

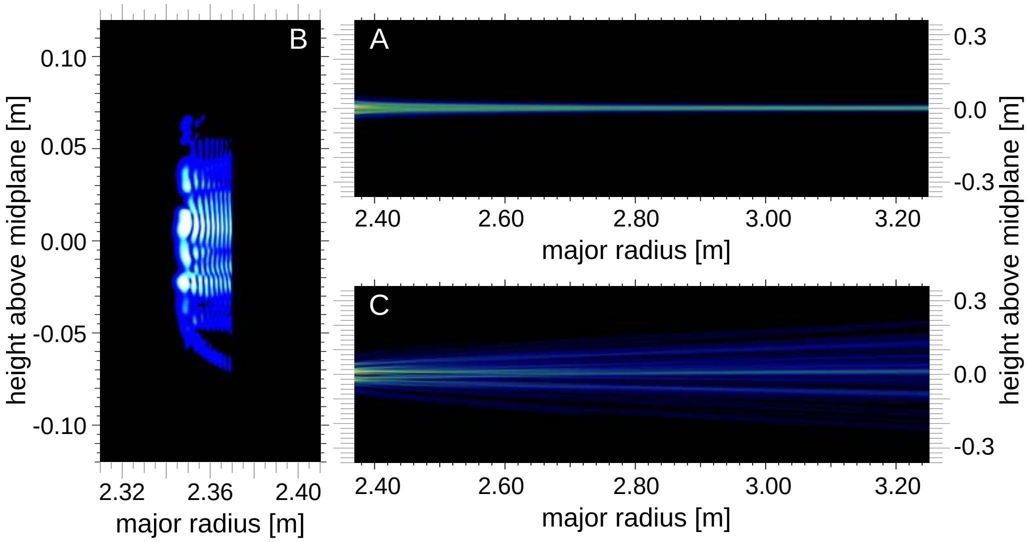

Figure 7: The intensity of the electric field for 352.6 GHz X-mode waves propagating in the plasma. (A) the paraxial solution of the incoming waves, (B) the full wave solution near the cut off, and (C) the paraxial solution of the outgoing waves. Note the difference in vertical scale between this figure and figure 8.

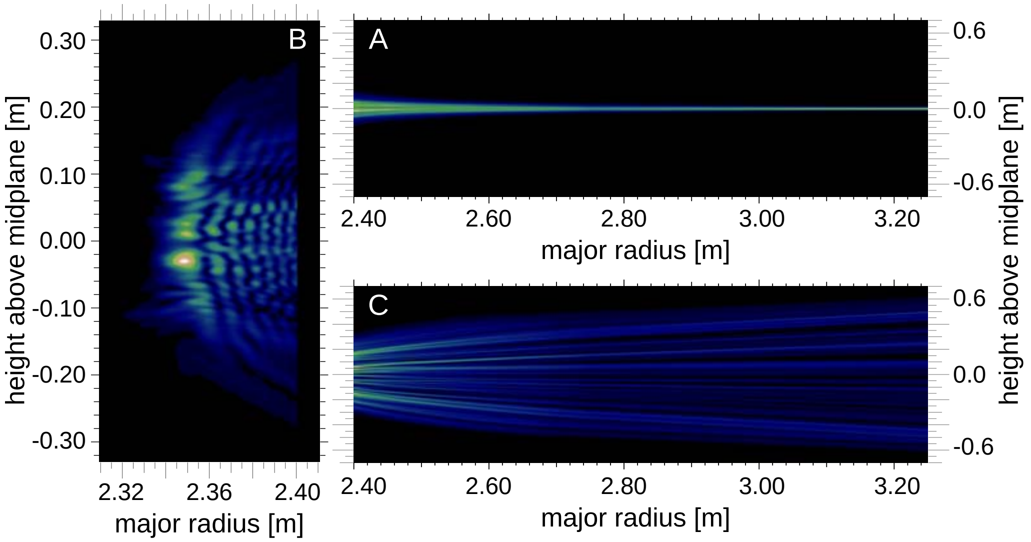

Figure 8: The intensity of the electric field for 190.0 GHz O-mode waves propagating in the plasma. (A) the paraxial solution of the incoming waves, (B) the full wave solution near the cut off, and (C) the paraxial solution of the outgoing waves. Note the difference in vertical scale between this figure and figure 7.

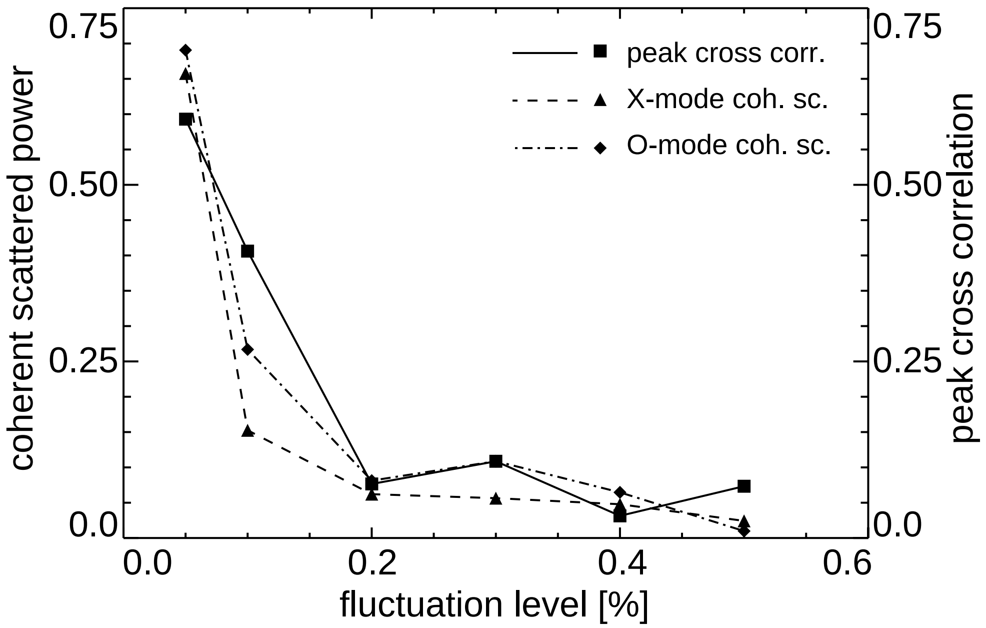

Figure 9: Peak O-X cross correlation (solid line) and coherent scattered power for X-mode (dashed line) and 0-mode (dashed dotted line) as a function of density fluctuation level for the FIRE equilibrium at $r/a = 0.34$.

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03/26/01

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