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by

G.J. Kramer, R. Nazikian, and E. Valeo

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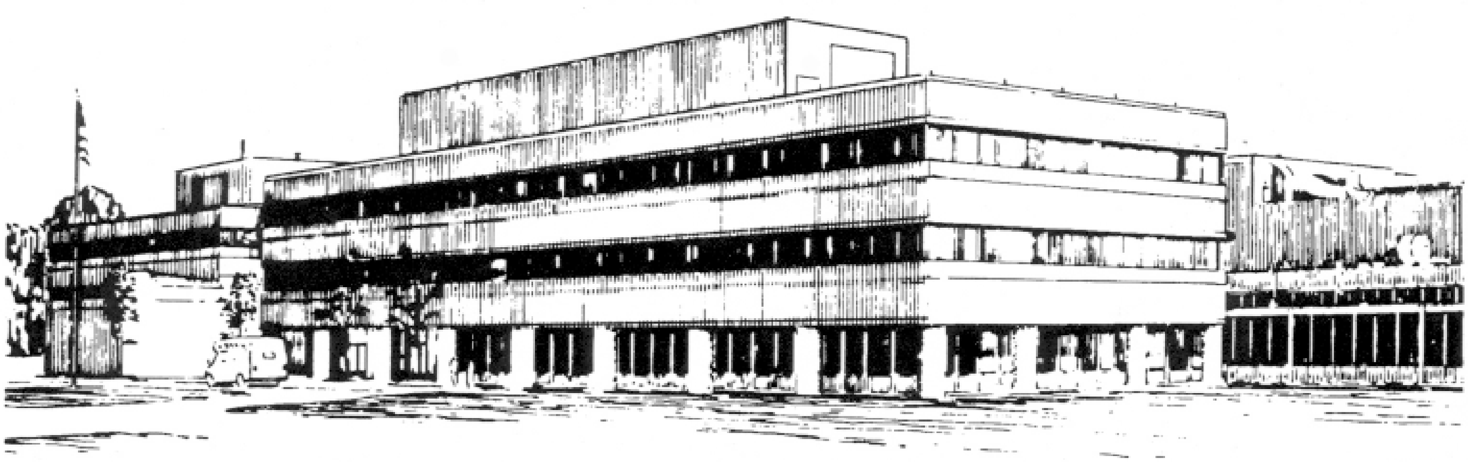

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LETTER TO THE EDITOR

Effects of finite density fluctuations and of the upper hybrid resonance on O-X correlation reflectometry

G J Kramer, R Nazikian, and E Valeo

Princeton Plasma Physics Laboratory Princeton NJ 08543-0451 USA

E-mail: gkramer@pppl.gov

Abstract. The correlation between O-mode and X-mode reflectometer signals is studied with a 1D reflectometer model taking into account the influence of finite density fluctuation levels and the upper hybrid resonance. It is found that a high level of O-X correlation can only be achieved for sufficiently small density fluctuation levels (typically much less than 1%) or very low magnetic field strengths. The influence of the upper hybrid resonance on the O-X correlation was found to also degrade the correlation between the O and X mode signals for very low magnetic field strengths or for very short density scale lengths. The extrapolation of these results to reactor scale parameters indicates that the magnetic field strength can reliably be measured in the core plasma provided the density fluctuation level is typically much less than 1%.

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1. Introduction

An essential physics parameter to determine in magnetic confinement systems is the plasma rotational transform or magnetic safety factor, q. In addition, the corrections to the toroidal magnetic field due to the finite pressure of the plasma is of interest, particularly in high-beta systems which are expected to produce a magnetic well. The standard method currently in use for q-profile measurements is the Motional Stark Effect (MSE) [1, 2] which provides a constraint on the magnetic field line pitch angle along the trajectory of a diagnostic neutral beam. Other methods make use of Faraday rotation [3] of a line integrated measurement or even the excitation of Alfvén Eigenmodes [4, 5, 6]. The MSE technique has been very effective in extracting equilibrium profiles, however, the need to develop alternative approaches is also necessary when considering the challenge of measuring the equilibrium profile in systems where a diagnostic neutral beam is technically difficult to implement or very costly.

In two recent articles [7, 8] an alternative approach to magnetic equilibrium reconstruction has been proposed based on the reflection of microwaves of different polarizations from a magnetized plasma. The method makes use of the ubiquitous presence of turbulence in the plasma column by measuring the peak correlation in the reflected signal between two modes of orthogonal polarization, the ordinary or O-mode and the extraordinary or X-mode. This method is shown schematically in figure 1. The correlation peaks near to where the two cut off layers coincide. From the frequency difference between the two orthogonal polarizations at the peak in their correlation the local magnetic field strength can be obtained. The reflection layer of the O-mode depends only on the plasma density whereas the reflection location of the X-mode depends both on the density and the magnetic field strength and weakly on the plasma temperature. By maximizing the correlation of the scattered signals between a fixed frequency O-mode channel and an X-mode channel that is scanned in frequency, a correlation as a function of the frequency separation can be obtained. The O-mode reflection layer can be obtained from the measured density profile and the wave frequency. From the frequency separation between the O- and X-mode at the peak of the cross correlation the local electron cyclotron frequency can be obtained which depends on the local magnetic field strength.

If this field strength can be resolved with sufficient precision, then the deviation of the magnetic field in the plasma from the vacuum field can be resolved. This deviation from the vacuum field can then be used as a constraint in an equilibrium solver in much the same way that MSE is used to constrain the numerical equilibrium.

The O-X correlation method was studied extensively at the LArge Plasma Device (LAPD) [9] at magnetic fields up to 0.18 T, electron densities up to $3.0\,10^{18}$ m^{-3} and density scale lengths between 0.05 and 0.20 m. Experimentally, it was found that the X-mode frequency corresponding to the maximum correlation did not coincide with the X-mode frequency at the O-mode reflection layer but was shifted toward lower frequencies than calculated from independent measurements of the magnetic field. This shift was reproduced well with a 1D full wave model taking into account the measured density correlation lengths [7]. In addition a degradation of the maximum coherence was observed with increasing magnetic field strengths. Experimentally, it was found that the decrease of the coherence depends on the magnetic field as was shown in figure 9 of reference [7]. From the decrease of the coherence with the magnetic field strength the applicability of this method for magnetic field measurements in fusion scale plasmas needs careful consideration. An important question to address is whether the degradation in the correlation is a feature of 2D scattering or whether the correlation can be accounted for within the context of 1D full wave analysis and geometrical optics or both.

In the following we present results of 1D simulations incorporating the upper hybrid (UH) resonance and finite density fluctuation levels. With this code we have found two mechanisms that can lead to the degradation of the O-X correlation. The first mechanism is the effect of a significant level of density fluctuations (i.e. $\tilde{n}/n > 1\%$) and the second mechanism is the influence of the UH resonance on the X-mode scattering which is important at low magnetic fields when the UH resonance is close to the X-mode cut off. Our simulation results indicate that finite fluctuation levels can strongly influence the O-X correlation whereas the effect of the UH resonance is negligible unless the magnetic field is very low or the density scale length is very short.

2. 1D-modeling

The 1D simulation code is based on a tri-diagonal implicit method [10] in which the scalar wave equation

$$\left(\frac{\partial^2}{\partial x^2} + k_0^2 \varepsilon(x)\right) E(x) = 0$$

for the electrical field, $E(x)$, is solved for a wave with a vacuum wave vector $k_0 = 2\pi/\lambda_0$ (λ_0 is the vacuum wave length). This wave equation is valid for waves that propagate perpendicular to the magnetic field. The upper and lower X-mode permittivity, $\varepsilon(x)$, is given by

$$\varepsilon = 1 - \frac{(U-X)X}{(U-X)U - Y^2}$$

with $X = (\omega_{pe}/\omega)^2$, $Y = \omega_{ce}/\omega$, $U = 1 - \mathrm{i}\nu_{ei}/\omega$, $\omega_{pe} = (n_e e^2/\varepsilon_0 m_e^*)^{1/2}$ the plasma frequency, $\omega_{ce} = eB/m_e^*$ the electron cyclotron frequency and ν_{ei} the electron-ion collision frequency. The O-mode permittivity is obtained when Y is zero. The finite electron-ion collision frequency is included to account for the pole at the UH resonance. The effective electron mass, $m_e^* = m_e(1 + 5\,T_e/511)^{1/2}$, is corrected for finite electron temperature effects as outlined in [12, 11] (T_e the electron temperature in keV).

For the solution of the wave equation an incoming and outgoing wave are taken in the vacuum region outside the plasma as

$$E(x) = \exp(\mathrm{i}k_0 x) + \exp(-\mathrm{i}(k_0 x + \phi))$$

and integrated into the evanescent region beyond the cut-off to determine the (complex) phase, ϕ, which reflects the density fluctuations.

In 1D geometric optics the phase is given by

$$\phi_{geo} = 2k_0 \int_0^{x_c} \sqrt{\varepsilon(x)}\, dx \tag{1}$$

where the integration is performed from the edge of the plasma to the cut off layer at x_c. In the following we will compare the full wave results with the geometric optics approximation and find that the latter is applicable when the UH resonance is separated well from the reflection layer.

For the simulation of the density fluctuations we have added to the equilibrium profile a spectrum of fluctuations which gives the following density correlation function

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

with $(\tilde{n}/n)_{x_1}$ the fluctuation amplitude, x_1 (x_2) the fixed (variable) frequency cut off layer position, λ_c the 1/e width of the correlation and $k_{\mathrm{fl}} = 2\pi/\lambda_{\mathrm{fl}}$ where λ_{fl} is the characteristic fluctuation wave length.

A set of N (typically 500) random density distributions, $\tilde{n}(x)$, are generated from the correlation function (equation 2). The wave equation is then solved numerically for each of these distributions to generate an ensemble of complex phases, ϕ, for the outgoing wave. This is repeated for each frequency and each mode of propagation. Then the correlation of the complex signal of the outgoing waves, $E = \exp(\mathrm{i}\phi)$, is obtained where the normalized correlation, γ, is given by

$$\gamma = \frac{|\langle E_O E_X \rangle|}{\sqrt{\langle |E_O|^2 \rangle \langle |E_X|^2 \rangle}}.$$

Similarly, the correlation for 1D geometric optics is obtained from the complex signal $E_{geo} = exp(\mathrm{i}\phi_{geo})$ where ϕ_{geo} is the phase obtained by solving equation 1 for 1D geometric optics.

3. Density fluctuation effects

In the following we investigate the effects of finite density fluctuation levels for parameters similar to those obtained in the LAPD experiments [7]: the density scale length, $L_n = 20$ cm, the fluctuation width $\lambda_c = 1.57$ m, and $k_{\mathrm{fl}} = 0$ m^{-1}. We have scanned fluctuation level, $\tilde{n}/n$, at two magnetic fields: $B = 0.10$ and 0.18 T. The results of these calculations are shown in figure 2.

From figure 2 (a) it can be seen that the decorrelation between the X-mode and O-mode signals depends on the fluctuation level and the decorrelation is stronger at higher magnetic field strengths. This decorrelation is also found from the geometrical optics analysis (dotted lines in figure 2).

The location where the correlation peaks depends also on the fluctuation level as shown in figure 2 (b) and the position moves away from the equilibrium fixed channel location when $\tilde{n}/n$ increases. Even at low fluctuation levels there is a separation between the fixed channel and the peak correlation position for the full wave solution. This shift at low fluctuation levels is much smaller in the geometrical optics analysis, however, at higher fluctuation levels, geometrical optics reproduces the additional shift that is observed in the full wave analysis. One consequence of this analysis is the need for detailed comparison with experiment to determine if the separation of the O- and X-mode cut off layers indeed increases with fluctuation levels as the 1D simulations indicate.

The separation between the equilibrium fixed frequency O-mode reflection point and the point of maximum correlation at low density fluctuation levels can be explained successfully with the phase matching arguments as presented in reference [7]. Moreover, the excursions of the O- and X-mode reflection points at the maximum correlation due to low fluctuation levels are very similar as can be seen in figure 3 (a) where $\tilde{n}/n = 0.01$. The distribution of the actual O-mode reflection point is distributed symmetrically around the reflection point without fluctuations, whereas the distribution for the X-mode reflection point is shifted strongly as can be seen in figure 3 (b). At high fluctuation levels these distributions broaden and shift away from the equilibrium location toward the reflectometer antennas as is shown in figure 3 (d) for $\tilde{n}/n = 0.20$. Here again the plots are made at the maximum correlation. The location of the O- and X-mode reflection points decorrelate as can be seen from the large scatter of points above the straight diagonal line in figure 3 (c), which is consistent with the decreased O-X correlation.

4. Upper hybrid resonance effects

When the UH resonance is close to the X-mode reflection layer, it will modify the X-mode wave solution and influence the O-X correlation. The wave solution in the evanescent region behind the cut off layer can be approximated with an exponentially damped wave

$$E(x) = E_c \exp(-(x - x_c)\,\delta_X) \qquad\qquad (x > x_c)$$

with E_c the wave amplitude at the cut off [13]. The 1/e width of the X-mode decay length, δ_X, is given by

$$\delta_X = \left(\frac{2k_0^2}{L_n}\right)^{1/3}$$

for a plasma with a constant magnetic field (i.e. the magnetic scale length is infinite [13]) and the density scale length, L_n, is evaluated at the X-mode cut off. The distance between the UH resonance and the X-mode cut off is then given by

$$\Delta r = 2L_n\Omega(\sqrt{\Omega^2 + 1} - \Omega)$$

with $\Omega = \omega_{ce}/2\omega_{pe}$. When $\Delta r\,\delta_X \gg 1$ the UH resonance does not influence the X-mode wave solution at the reflecting layer. In the case of low magnetic fields ($\omega_{ce}/2\omega_{pe} \ll 1$) the separation between the UH resonance and the X-mode cut off can be approximated by $\Delta r = 2L_n\Omega$. By decreasing the magnetic field strength the UH resonance can be moved very close to the X-mode cut off as is shown in figure 4. When the magnetic field is zero the O-mode solution is recovered while for 0.1 Tesla the UH resonance is already well enough separated from the cut off so that it does not influence the X-mode wave solution. In these calculations an electron-ion collisionality of 1 MHz was used. It was found in the simulations that when the collisionality decreased, the wave amplitude at the resonance increased. Thus the results should be sensitive to the collisionality when the resonance is important.

When the magnetic fields are strong as is the case for tokamaks, $\Delta r \approx L_n$ (i.e. independent of Ω) and the condition that $\Delta r\,\delta_X \approx (2k_0^2\,{L_n}^2)^{1/3} \gg 1$ is easily fulfilled because of the large values of k_0. The density scale length where the influence of the UH resonance becomes detectable, is less than 9 mm for a machine with an edge magnetic field of about 2 T, less than 6 mm for a machine with an edge magnetic field of about 3 T and 4 mm for a machine with an edge magnetic field of about 4 T. Such small density scale lengths cannot be ruled out in the edge transport barriers.

5. O-X correlations at high magnetic fields

In order to investigate the possibility to use O-X correlation reflectometry as a diagnostic tool for the deviation of the magnetic field strength from the vacuum field strength in tokamak plasmas we have calculated the peak in the O-X correlation for an ITER like plasma as a function of the magnetic field strength for different density fluctuation levels. The results are shown in figure 5. In these calculations the following parameters were used: major radius 4.0 m, minor radius 1.5 m, parabolic density profile with central density of $1.0\,10^{20}$ m^{-3} and a fixed frequency O-mode channel at 75 GHz which is reflected at 4.79 m. The correlation length, λ_c, was chosen to be 0.01 m and $k_{\mathrm{fl}} = 0\ \mathrm{m}^{-1}$. At six different values for the density fluctuations ($\tilde{n}/n = 0.1$, 0.4, 0.7, 1.0, 1.5, and 2.0%) the magnetic field was varied between 0.01 and 10.0 T.

From figure 5 it can be seen that the O-X peak correlation is strongly affected by the level of density fluctuations. At magnetic fields above one Tesla the correlation is only significant when the density fluctuations are less than 0.5% and this number drops even further with higher field strengths. At low magnetic fields the correlation is also degraded due to the presence of the UH resonance.

In figure 5 results are also shown for the geometric optics approximation as dotted curves. Above about 0.05 T the geometric optics results agree very well with the full wave calculations. At lower magnetic field strengths the UH resonance (behind the reflection layer) is affecting the full wave results. This effect is not present in the geometric optics approximation in which is only integrated to the cut off layer.

For the O-X peak correlation measurements to be a useful measure of the local value of q, we have also investigated the dependence of the peak correlation as a function of the density correlation length, λ_c. For this calculation we have used the same tokamak parameters as above at a magnetic field of 3 T. The results are shown in figure 6 for three density fluctuation levels ($\tilde{n}/n = 0.1$, 0.2 and 0.3%). From this figure it can be seen that the frequency where the correlation peaks depends very weakly on the density correlation length and on the fluctuation level when it is below 1%. The width of the peak, however, increases with the correlation length as can be seen from the Full Width Half Maximum (FWHM) contours in figure 6. It can also be seen that at a given density correlation length the width of the correlation peak decreases with increasing fluctuation level. The peak O-X correlation degrades slowly with increasing correlation length. Because the position of the O-X correlation peak does not depend on the density correlation length it can provide a robust measure of the local magnetic field strength.

6. Accuracy

An important question is how accurate the magnetic field stength can be measured from O-X correlations. For this we have to investigate how accurate the top of the O-X peak correlation can be determined and how this translates into an uncertainty for the magnetic field strength.

For the determination of the X-mode frequency where the O-X correlation peaks, a number of closely spaced correlation measurements are needed. For the calculations shown in figure 6 this means that the X-mode channel should be stepped in intervals of about 0.1 GHz in a 5 GHz range to resolve the correlation peak accurately. The final accuracy for the magnetic field strength measurements can be expressed as

$$\frac{|\Delta \mathrm{B}|}{|\mathrm{B}|} = \frac{\Delta\omega_X}{\omega_X}\left(\frac{\omega_X}{\omega_{ce}} + \frac{\omega_{pe}^2}{\omega_{ce}\omega_X}\right)$$

with ω_X the measured peak correlation X-mode frequency and $\Delta\omega_X$ its uncertainty. For large aspect ratio tokamaks with $\omega_{pe}^2 \ll \omega_{ce}^2$ (and $\omega_X \approx \omega_{ce}$) the relative uncertainty in the X-mode frequency is identical to the relative uncertainty in the magnetic field measurement. It is technically well possible to determine the peak of the O-X correlation with an accuracy of better than 0.1% which is needed to observe deviations from the vacuum magnetic field in tokamaks.

7. Conclusions

We have shown that the decorrelation of the O-mode and X-mode signals with increasing magnetic field strength can arise from a finite level of density fluctuations. Additionally, The UH resonance influences the upper X-mode wave solution at very low magnetic fields or very short density scale lengths leading to a further decorrelation of the X- and O-mode signals. It would be of interest in laboratory plasmas such as LAPD to test the effect of the UH resonance on the O-X correlation at reduced magnetic fields. In tokamaks the UH resonance is far enough behind the upper X-mode cut off that it does not influence the X-mode solution except possible in the edge region. It was shown that the geometric optics approximation works very well when the UH resonance is far enough behind the upper X-mode reflection layer.

For large scale fusion plasmas the correlation between the O-mode and X-mode reflection signals may be used to determine the magnetic field strength provided that the fluctuation level is sufficiently low.

The O-X correlation measurements for determining the magnetic field strength in plasmas is promising, and should be a valuable diagnostic in fusion scale plasmas provided that the peak in the correlation can be determined with sufficient accuracy. Further work should focus on the degree to which the peak correlation can be measured, which will relate directly to the accuracy of the magnetic field strength measurement and its effectiveness as a constraint to determine the MHD equilibrium.

Acknowledgments

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Figure captions

Figure 1. Schematic of O-X correlation reflectometry. Waves with O- and X-mode polarization reflect from different layers, separated by Δr, in the plasma. The O-mode reflection point depends only on the electron density, whereas the X-mode point depends on both the electron density and the magnetic field. When one of the reflectometer frequencies is varied the cross correlation, γ, between the O- and X-mode signals can be obtained as a function of Δr.

Figure 2. (a) Simulated O-X peak coherence as a function of the fluctuation level for the parameters given in the main text that are similar to the LAPD experiments at a magnetic field of 0.1 T and 0.18 T. (b) The location where the O-X correlation peaks relative to the fixed channel equilibrium O-mode location. The solid lines are from the full 1D calculation and the dotted lines are the geometrical optics approximation.

Figure 3. The distribution of the reflection points at the maximum of the O-X cross correlation relative to the fixed frequency location without fluctuations for an ensemble of 6000 points. (a) and (b) Fluctuation level 1%. (c) and (d) Fluctuation level 20%. (a) and (c) The location of the variable X-mode channel plotted against the fixed O-mode channel. (b) and (d) The distribution of the O-mode (white) and X-mode (shaded) reflection points relative to the O-mode location without fluctuations.

Figure 4. The X-mode wave solution at various values of the magnetic field whereby the influence of the upper hybrid resonance becomes more and more pronounced. All the other parameters are in the approximate range of the LAPD experiment (see text) and a collisionality of 1.0 MHz. Absorbtion at the upper hybrid resonance is most prominent at 0.02 T.

Figure 5. Simulated O-X peak coherence as a function of the magnetic field strength for different density fluctuation levels between 0.1 and 2.0% for a tokamak geometry as discussed in the text. The full wave solution is indicated with a solid line and the geometric optics approximation is shown as dotted lines.

Figure 6. (a) The degradation of the peak O-X correlation as a function of the density correlation length at fluctuation levels of 0.1% (——), 0.2% (- - - -) and 0.3% (— · —). (b) The location of the top, the low field side full width half maximum (LFS FWHM) and the high field side full width half maximum (HFS FWHM) contours for the same fluctuation levels as in (a) relative to the O-mode reflection layer (left) and X-mode frequency (right) as a function of the density correlation length.

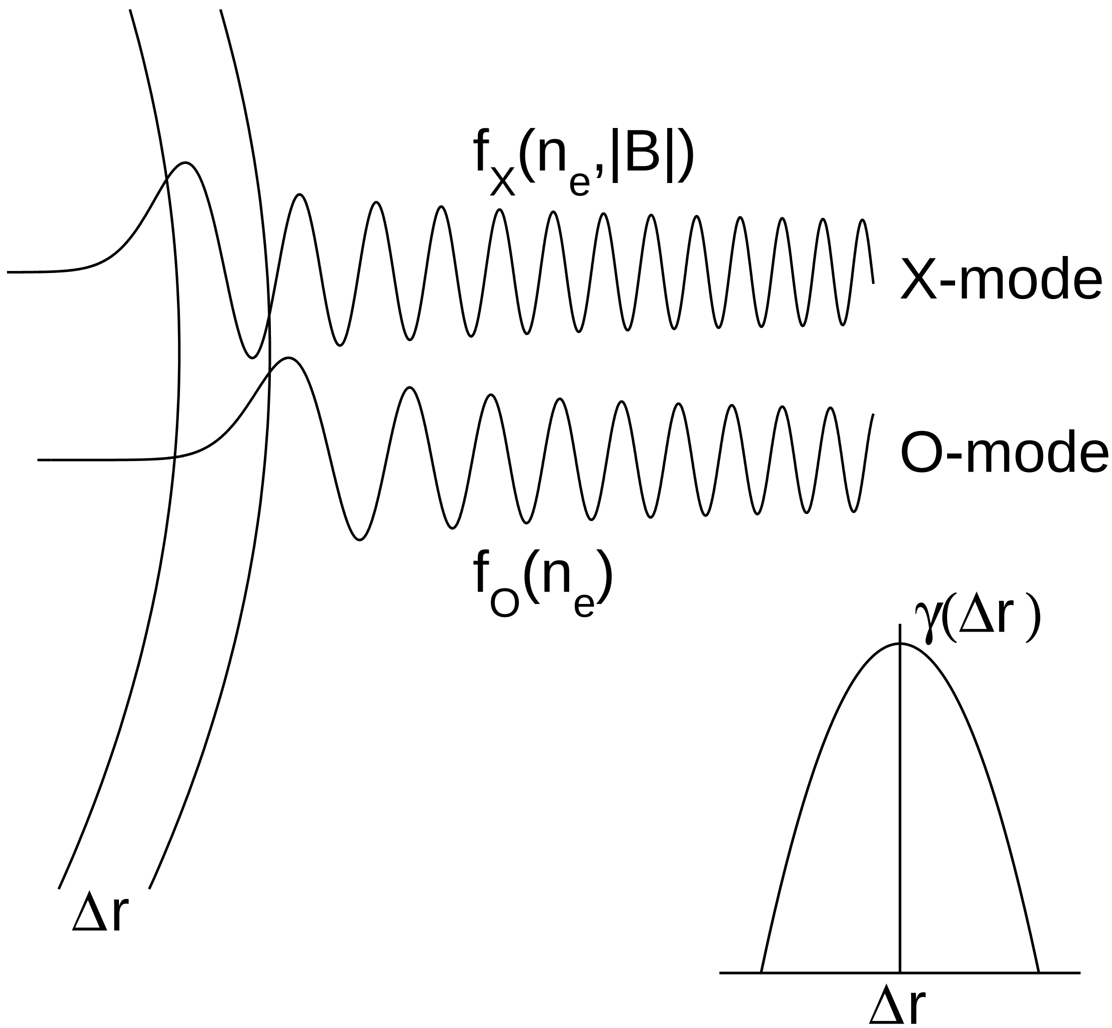

Figure 1

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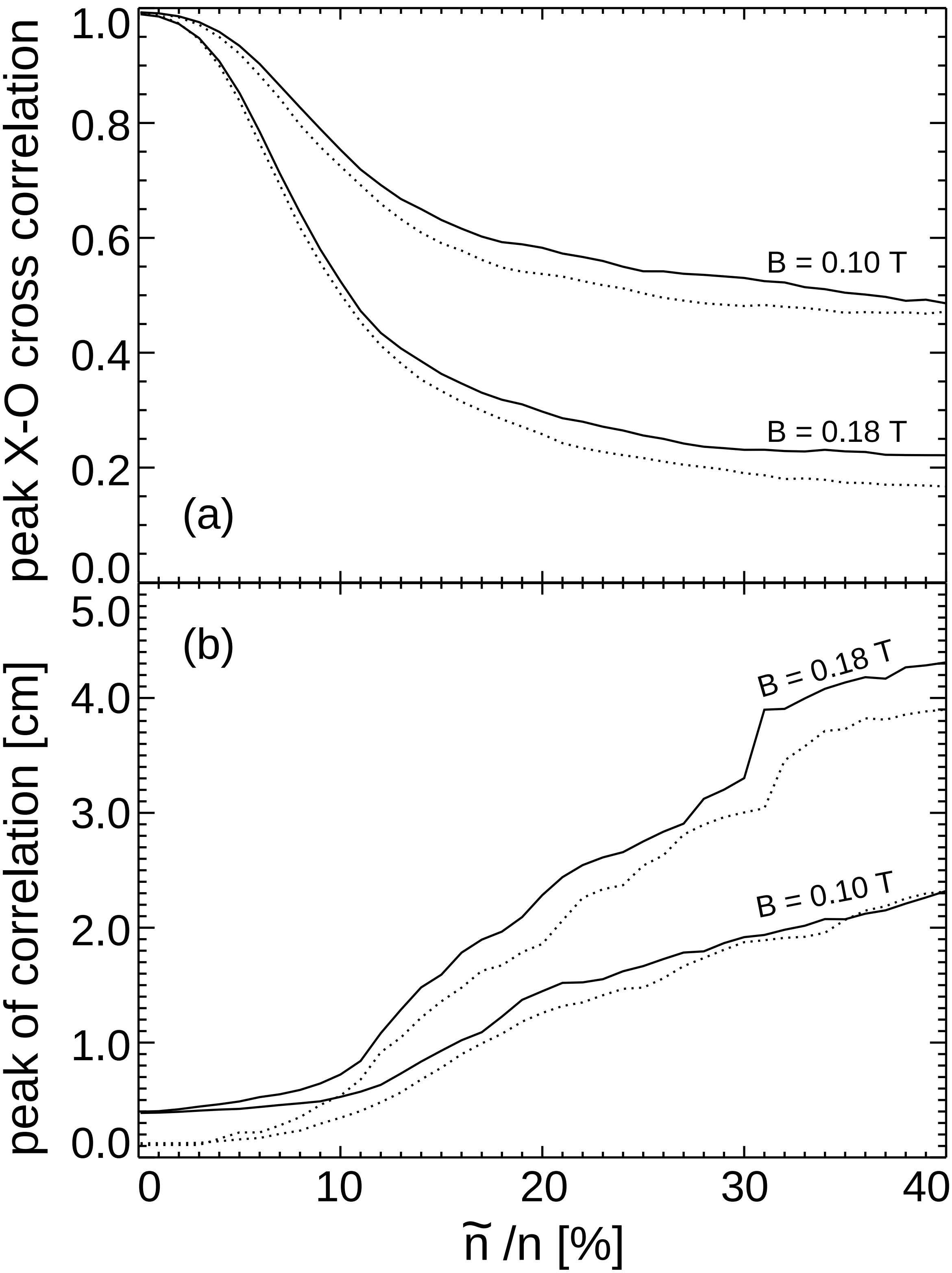

Figure 2

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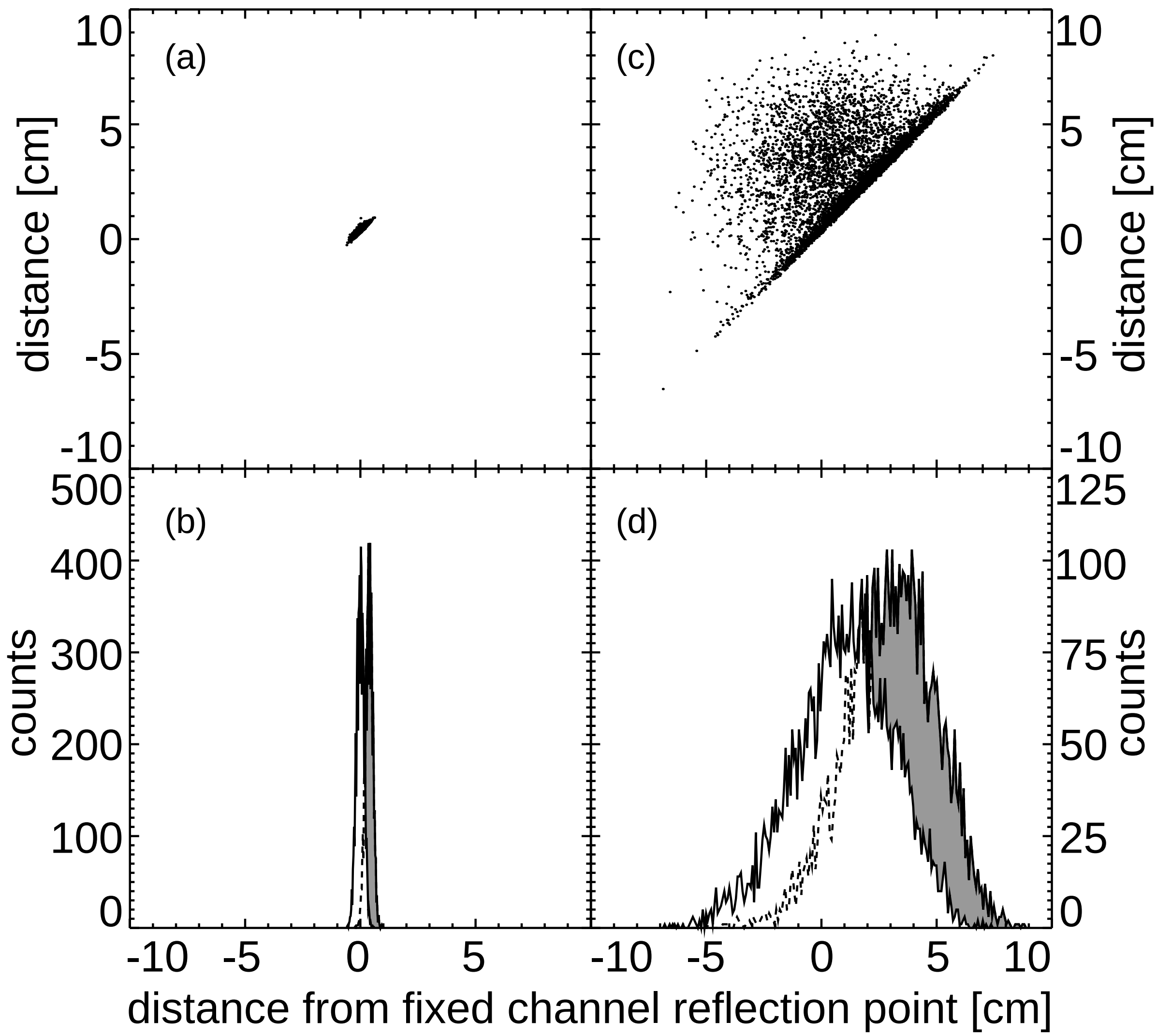

Figure 3

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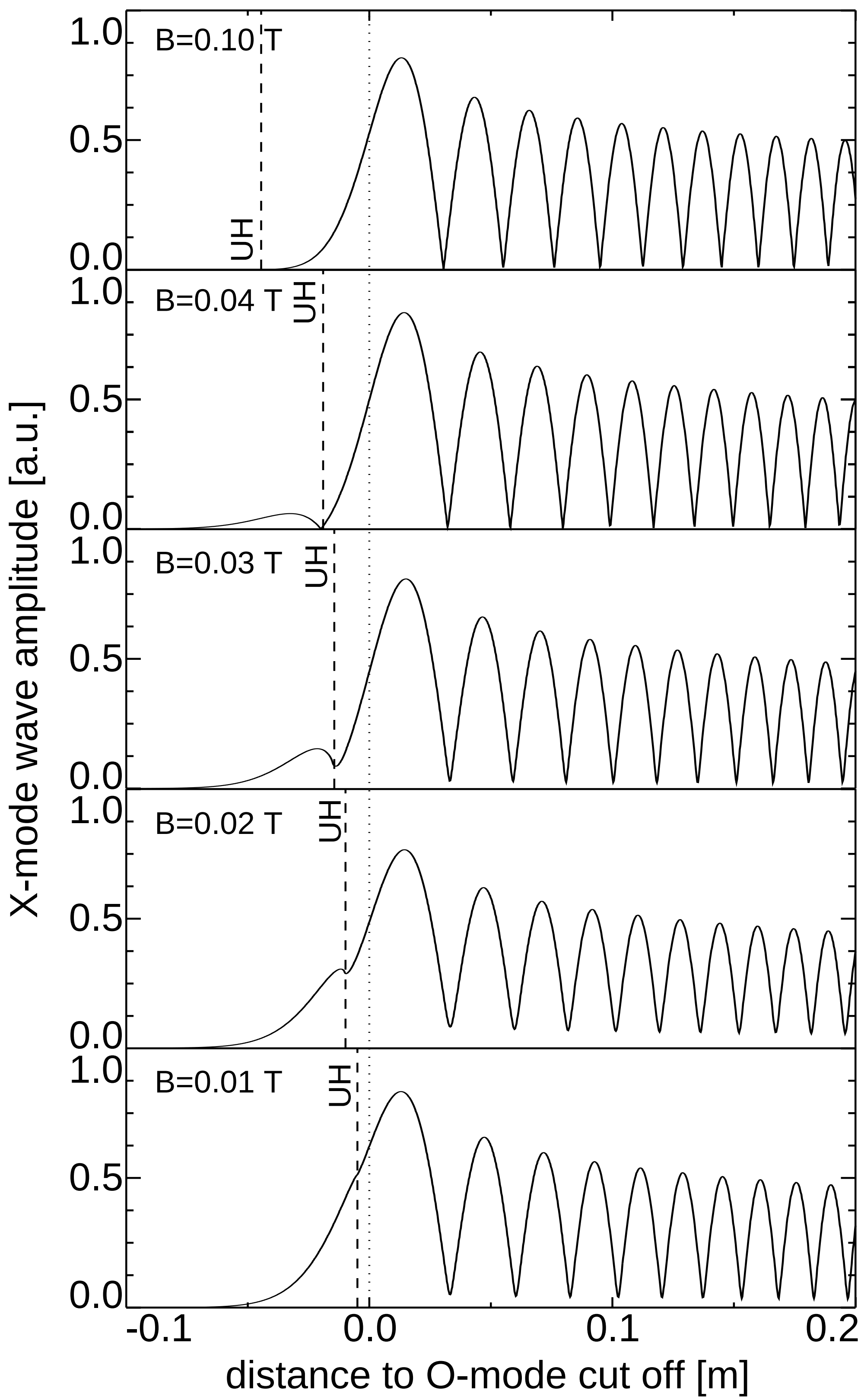

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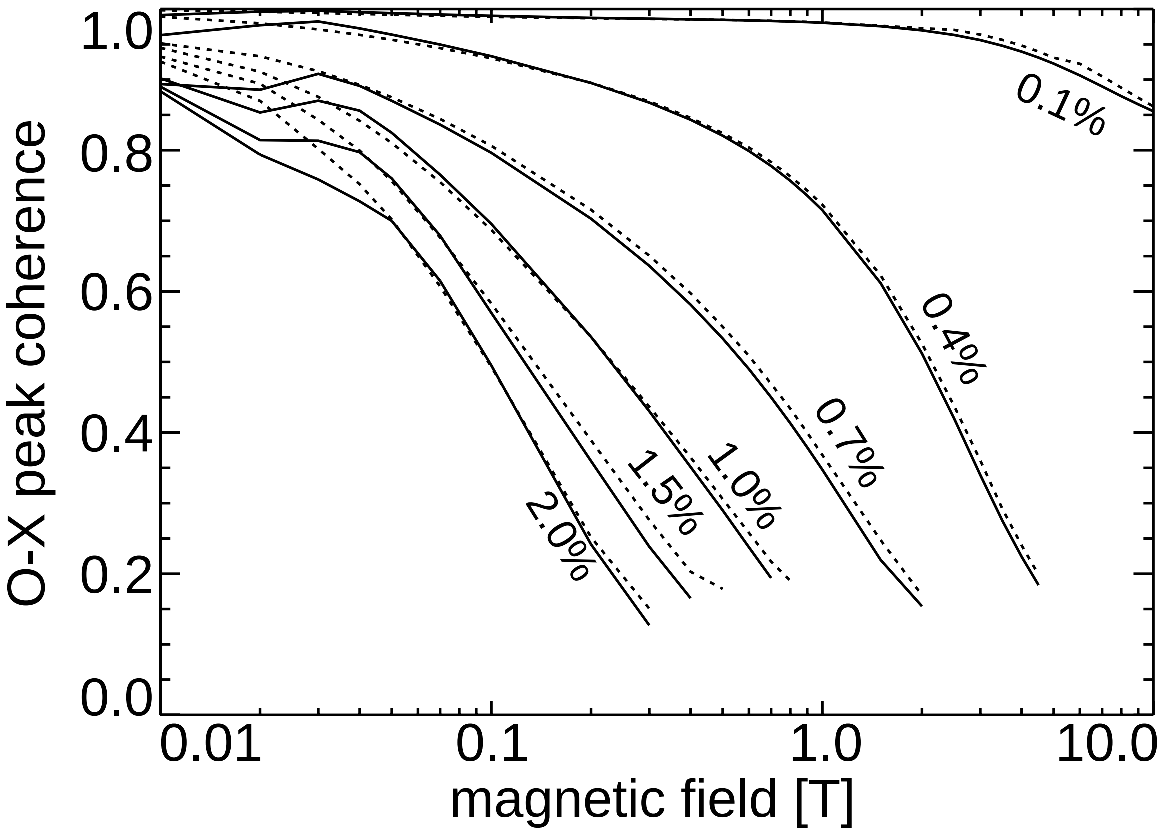

Figure 5

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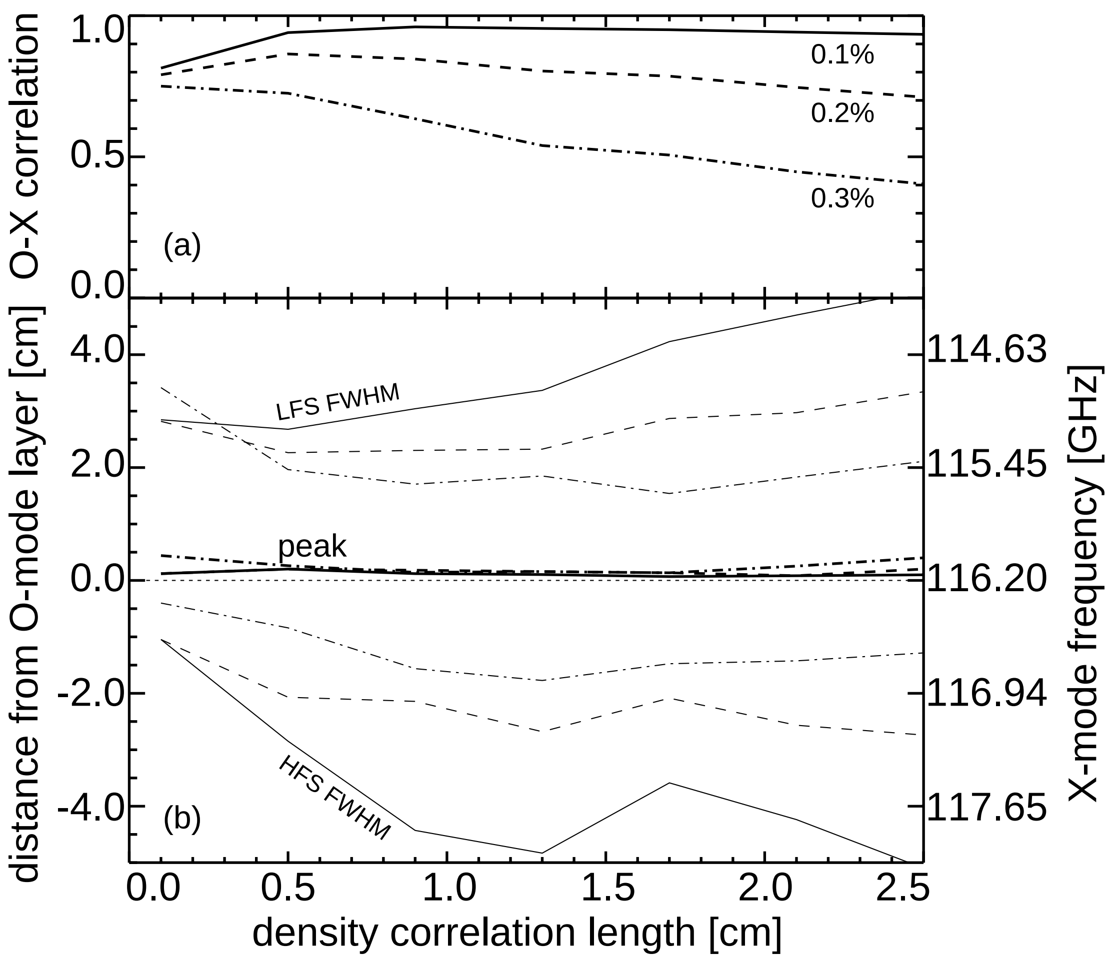

Figure 6

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