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POSSIBLE INFLUENCE OF EDGE DENSITY FLUCTUATIONS ON THE PROPOSED FAST ION AND ALPHA PARTICLE DIAGNOSTIC FOR JET

F.R. Hansen, J.P. Lynov, P. Michelsen and H.L. Pécseli

Abstract. The influence of random density fluctuations in a tokamak on the propagation of electromagnetic waves polarised in the ordinary mode is studied numerically. The study is of direct relevance for a proposed fast ion and α-particle diagnostic for JET relying on collective scattering of intense millimetre waves. The wave propagation is studied in the limit of geometrical optics by a ray-tracing code. For overall parameters specified by the contract, it is found that even low levels of relative density fluctuations may lead to a substantial broadening of an incoming wave beam. This effect is particularly pronounced for high values of the central plasma density. The wave beam broadening due to density fluctuations could lead to a degradation in the performance of the proposed diagnostic by limiting its spatial resolution.

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Contents

1 INTRODUCTION

In a few of the large tokamak experiments, operation with D-T plasmas has been planned in the near future. This has led to an increased interest in the possibility of diagnosing α-particles produced in D-T fusion reactions. In the case of JET, it was found by HUGHES and SMITH (1987) that scattering of waves in the millimetre wavelength range may be capable of providing useful information about the α-particle velocity distribution function, and it has therefore been proposed to develop such an α-particle diagnostic for JET.

In their work, HUGHES and SMITH found that the preferred candidate for a radiation source is a gyrotron operating at 140 GHz. A power level of several hundreds of kW is necessary in order to have enough scattered power for a reasonably high signal-to-noise ratio. Another factor limiting the signal-to-noise ratio is the size of the scattering volume. It is therefore of utmost importance to collimate the antenna wave beam used for the diagnostic. It was however noted by HUTCHINSON (1987), that wave refraction in the plasma could become a problem in attempts to reduce the scattering volume.

In addition to the effect discussed by HUTCHINSON, it is possible that random density fluctuations in the JET plasma can disturb wave propagation in such a manner that a collimated wave beam is broadened even more. Recent calculations by HANSEN *et al.* (1988) showed that the propagation of electron cyclotron waves in connection with electron cyclotron resonance heating of tokamak plasmas can be seriously affected by the small-scale density fluctuations inherently present in most plasmas. The numerical calculations revealed that even low levels of relative density fluctuations (around 1 per cent at the plasma edge) may result in a significant scattering of an incoming wave beam. The calculations were related to the PLT device and they are therefore not directly applicable to JET and the proposed α-particle diagnostic. The underlying principles in the calculations are however well suited to a similar study of the influence of density fluctuations on the proposed α-particle diagnostic for JET.

The purpose of this work is therefore to investigate the effect of density fluctuation on wave propagation in connection with the proposed α-particle diagnostic. Simple estimates will be given for the broadening of an ordinary polarised wave beam due to random density fluctuations for a wide range of parameters relevant for JET. The wave propagation is analysed in the limit of geometrical optics with a ray-tracing programme.

The present report is organised as follows: Section 2 contains the essential details of the ray-tracing programme used for our studies. In this section we also define the geometry adopted for our analysis. In Section 3 the numerical results are presented. Finally, Section 4 contains our conclusions including a discussion of the limitations of this work.

2 THE NUMERICAL CODE

The proposed fast ion and α-particle diagnostic for JET will rely upon an intense wave beam launched near the top of the torus and aimed towards the central region of the plasma. The beam will be injected almost perpendicular to the toroidal field. In the following, we neglect the poloidal field and assume that the waves propagate perpendicular to the toroidal field in the poloidal plane. As a further simplification, we consider a plasma that has a circular cross section and the cylinder co-ordinates r and θ will be used to refer to the position in this cross section.

Two models for the unperturbed plasma density are considered. In the first model (in the following referred to as model 1) the density is given by the expression

$$n(r) = \begin{cases} n_0\left(1 - (r/a)^2\right)^{\alpha} & \text{for } r \leq a \\ 0 & \text{for } r > a, \end{cases} \tag{1}$$

where $a = 1.20$ m is the plasma radius and n_0 the central plasma density. In this work the value for the parameter α is 0.7.

In the second model (model 2) the unperturbed plasma density is expressed as

$$n(r) = \begin{cases} n_0 & \text{for } r < d \\ n_0\left[1 - (r-d)/(a-d)\right] & \text{for } d \leq r \leq a \\ 0 & \text{for } r > a, \end{cases} \tag{2}$$

where the parameter d is 1.00 m.

For both models a similar representation for the density fluctuations is chosen. An expression for the density including fluctuations is obtained by superimposing a sinusoidal varying term on the unperturbed densities.

$$\tilde{n}(r,\theta) = n(r)\left[1 + (r/a)^{\beta} v \sin(m\theta + \phi_0)\right], \quad \beta \geq 1. \tag{3}$$

With this choice the relative density fluctuations increase monotonically from zero in the centre to a maximum value at the plasma edge. This ensures that the relative density fluctuation level is largest where the density gradient is largest as appropriate, for instance, for electrostactic drift wave type fluctuations. By the model in Eq. (3) we assumed that the density fluctuations vary in the radial and poloidal direction only, while toroidal variations are negligible. Note however, that the radial dependence of the relative density fluctuation level enters only through the factor $(r/a)^{\beta}$ in Eq. (3). A more general expression including a sinusoidal variation in radial direction also, can be found in HANSEN *et al.* (1988). The important parameters in Eq. (3) are the poloidal mode number, m, and the relative density fluctuation level controlled by v.

As mentioned in the introduction, the numerical investigations are based on ray-tracing calculations. The rays are calculated using the ray-tracing programme

CONRAY (HANSEN *et al.* (1985)) which solves the set of ray equations

$$\frac{d\vec{r}}{dt} = -\frac{\partial D}{\partial \vec{k}} / \frac{\partial D}{\partial \omega} \tag{4}$$

$$\frac{d\vec{k}}{dt} = \frac{\partial D}{\partial \vec{r}} / \frac{\partial D}{\partial \omega} \tag{5}$$

for the position $\vec{r}$ and the local wave vector $\vec{k}$. The local dispersion function is denoted by D and the angular wave frequency by ω. In this work we consider waves with ordinary polarisation that are injected in the poloidal plane. Since we neglect the poloidal field and because there are no density fluctuations that can scatter the waves out of the poloidal plane the wave vector will remain in the poloidal plane. We therefore use the dispersion function for electromagnetic waves with ordinary polarisation propagating perpendicular to a magnetic field,

$$D(\vec{r}, \vec{k}, \omega) = c^2 \vec{k} \cdot \vec{k} + \omega_{pe}^2(\vec{r}) - \omega^2, \tag{6}$$

where the electron plasma frequency is denoted by ω_{pe}. We would like to point out that this dispersion function for ordinary waves is valid only when the waves propagate strictly perpendicular to the magnetic field.

Throughout this work the wave frequency, f, is kept constant at 140 GHz, and the parameter in Eq. (3) specifying the radial dependence of the relative density fluctuation level is $\beta = 2$.

3 NUMERICAL RESULTS

In the following, we consider a beam launched from an antenna located near the plasma edge. The beam is aimed directly toward the centre of the plasma. The antenna is assumed to radiate its power uniformly in a single direction with a beam width equal to 6 cm. The antenna radiation pattern has to be represented by a finite number of rays and two such representations are considered.

In the first representation a fairly large number of rays are used to model the antenna radiation pattern. The rays are injected in parallel with a constant distance between neighbouring rays. Each ray thus carry the same fraction of the total power radiated by the antenna. In Figure 1a we show this representation with the number of rays, N, being equal to six. A simpler representation of the antenna radiation pattern is shown in Figure 1b. In this case two rays with a separation of 3.46 cm is used to model the radiation pattern. A justification of this representation will be given later.

As mentioned above, we consider a beam that is aimed toward the centre of the plasma. The actual azimuthal position, θ, of the antenna is however of no importance in this analysis. This is because the ray trajectories depend on the density

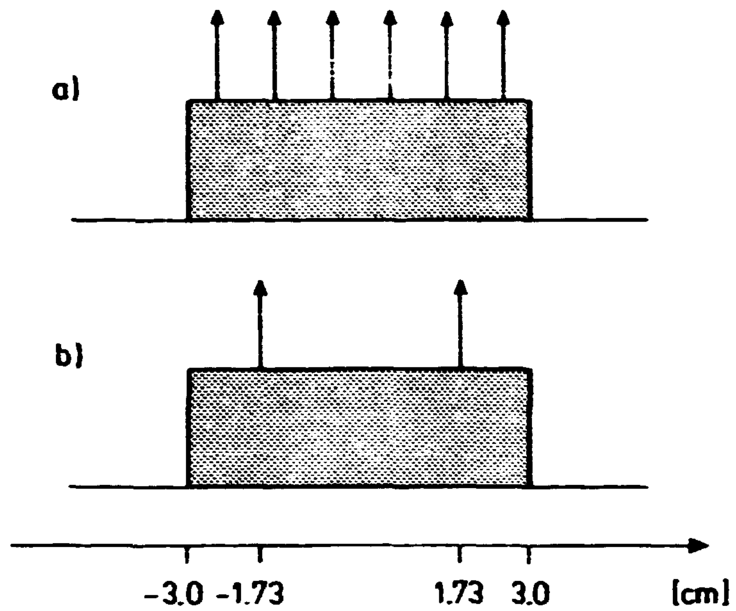

Figure 1: *Two representations of the antenna radiation pattern with a beam width equal to 6 cm. (a) Many rays with equidistant separation; (b) two rays separated by 3.46 cm.*

alone, and changing the value of θ can always be accounted for by changing the value of the phase ϕ_0 in Eq. (3). The results presented in the following will thus apply to a beam injected along an arbitrary diameter in the poloidal plane.

An example of ray trajectories calculated by the CONRAY programme is shown in Figure 2. Here is shown six rays using the representation for the antenna radiation pattern shown in Figure 1a. The unperturbed density corresponds to model 1 and the six rays are launched symmetrically around $\theta = 0$ and the arbitrary phase ϕ_0 equals zero in Eq. (3). We note that if there are no density fluctuations present, i.e. $v = 0$ in Eq. (3), the six rays will diverge slightly due to the variation in the bulk plasma density, but the beam will be symmetric around the x-axis.

In order to extract the statistical information from many plasma realisations we perform the following steps: A large number of plasma realisations are generated by keeping the amplitude v constant, but varying the arbitrary phase ϕ_0 uniformly in the interval $[0; 2\pi[$. For each realisation all of the rays used to represent the antenna radiation pattern are traced, and on the basis of all ray trajectories a probability distribution for the rays can be calculated. The basic physical model underlying this statistical treatment shall not be described in greater detail here. For a thorough discussion of this subject we refer to HANSEN *et al.* (1988).

In Figure 3 we show an example of an statistical analysis of the above-mentioned type. The results shown in the figure is based on 150 realisations of the plasma density with 11 rays used to represent the antenna giving a total of 1650 rays. All

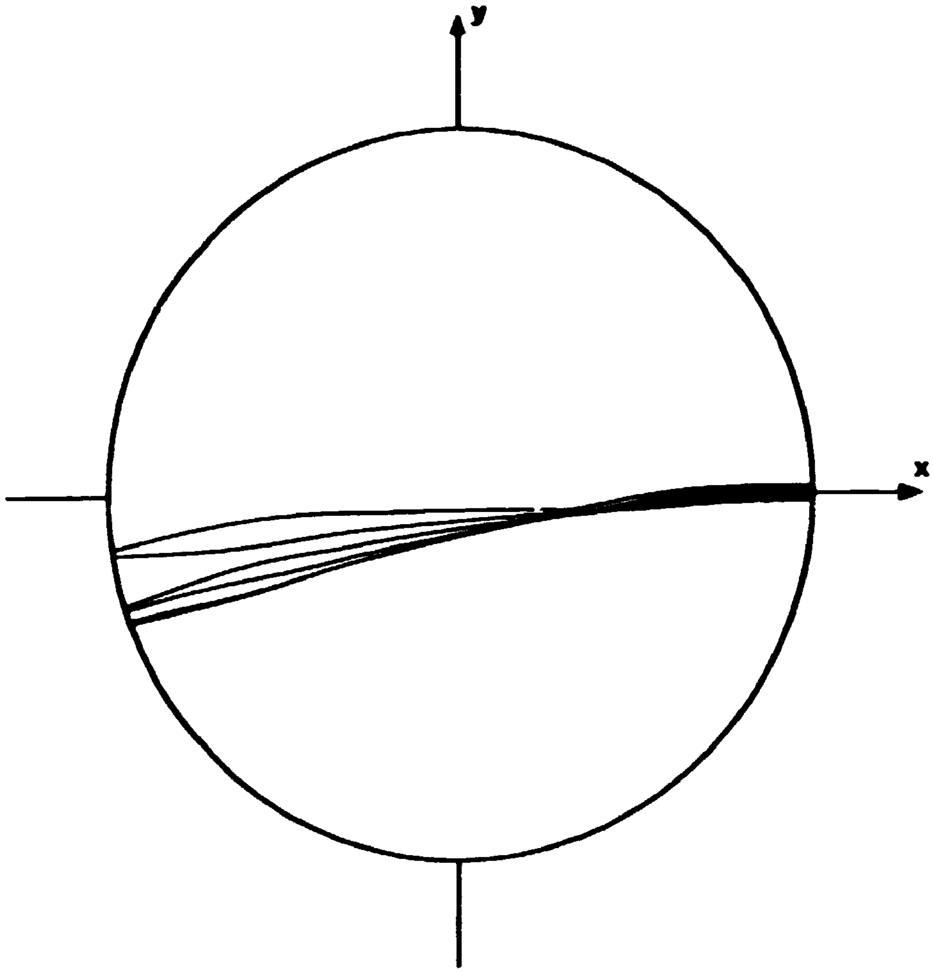

Figure 2: *The ray trajectories for six rays injected in parallel. The azimuthal mode number is $m = 30$ and the amplitude, $v = 0.07071$ corresponds to a relative density fluctuation level of 5 per cent at the edge of the plasma column. The unperturbed density corresponds to model 1 with a central plasma density, $n_0 = 15.0 \cdot 10^{19}$ m^{-3}.*

other parameters are the same as in Figure 2.

For a given probability distribution we are able to calculate the moments of the distribution. In this work only moments of even order will be of interest since odd order moments will be zero for symmetry reasons. In particular the second order moment $\sigma^2 = \langle y^2 \rangle$ is important because it measures the broadening of the beam. σ is known as the standard deviation or the root-mean-square (rms) deviation, and in the following it will be used as a direct measure of the beam width in the plasma (or rather half the beam width). Also of importance is the quantity called the kurtosis which is related to the fourth-order moment and measures the population of the wings of the distribution. The kurtosis is given by $K = \langle y^4 \rangle / \sigma^4$. For a uniform probability distribution we have $K = 1.8$ and $\sigma^2 = \frac{1}{12}\Delta^2$, where Δ is the width of the distribution. For $\Delta = 6$ cm we get $\sigma \simeq 1.73$ cm.

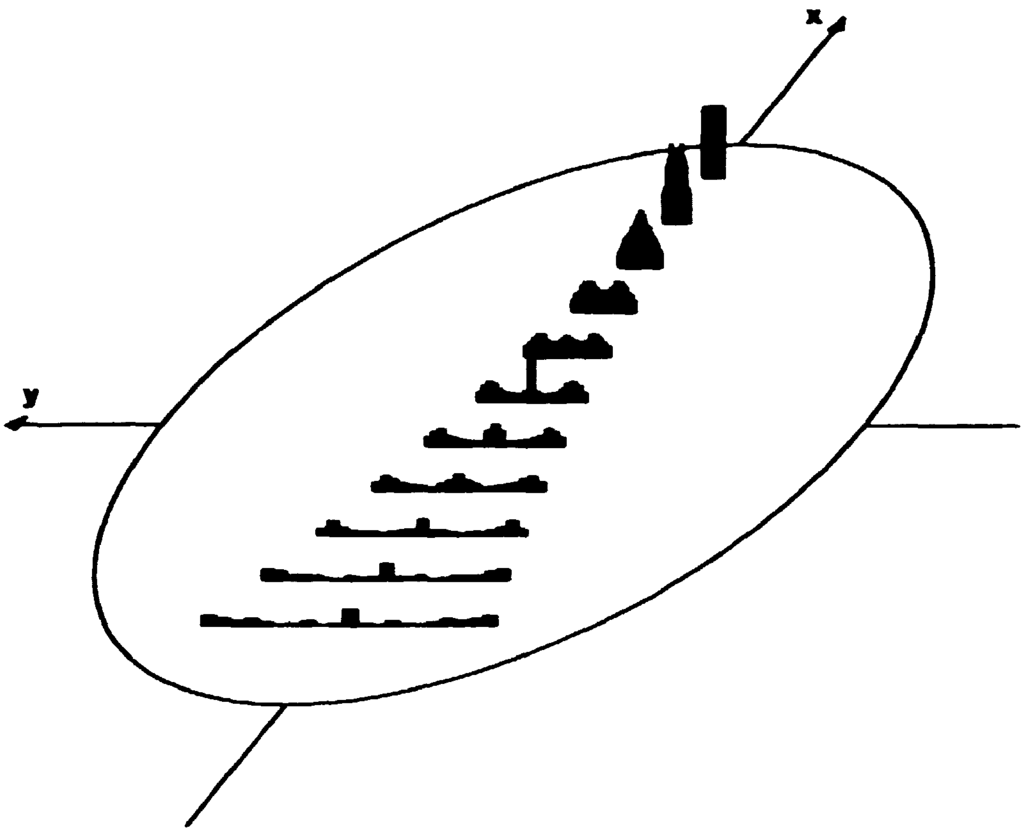

Figure 3: *Histograms representing the probability distribution of rays in 11 positions along a diameter. The parameters are the same as in Figure 2, except that* $N = 11$.

Figure 4 shows the variation of σ and K along the x-axis corresponding to the results presented in Figure 3. We note that the value of σ increases monotonically through the plasma column starting with a value of 1.73 cm and reaching a value of almost 30 cm. In the centre of the plasma column, i.e. at $x = 0$, $\sigma = 10.6$ cm and the beam width has thus increased by a factor of 6.1.

Instead of using the representation for the antenna shown in Figure 1a, it is possible to get just as good an estimate for the beam width using the simpler representation shown in Figure 1b. The distance between the two rays in Figure 1b is chosen in such a way that the value of the second-order moment, σ^2, matches the exact value of 3 cm^2 for a 6 cm wide continuous uniform distribution. In Figure 5 we show the variation of σ and K along the x-axis obtained by using the antenna representation in Figure 1b where the statistical average is based on 50 realisations of the plasma density. It should be noted here that with the chosen viewing direction it is possible to take advantage of the symmetry of the probability distribution around the reference axis. To extract the statistical information it is only necessary to calculate the part of the distribution of rays originating from one of the two rays used to represent the antenna.

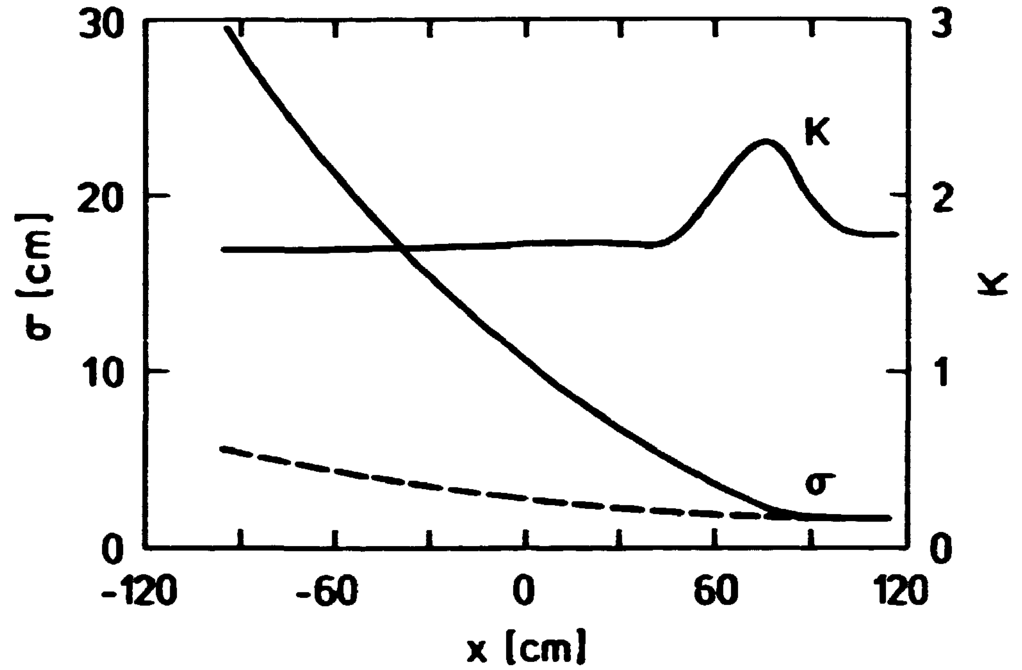

Figure 4: *Variation of σ and K along the x-axis. Parameters are the same as in the previous figure. The dashed line in this and the following similar figures indicates the broadening of the beam width due to the bulk plasma density variation, i.e. without density fluctuations.*

Comparing Figures 4 and 5 it is evident that the two different representations for the antenna give almost identical results for the rms-beam width, σ. Although the variation of σ is similar for the two antenna representations there is clearly a difference in the behaviour of K. The difference shows up in the values of K near the entrance point of the beam. This may be explained by the fact that the second-order moments for the the two discrete representations of the continuous uniform distribution are the same (at least in the limit of N going to infinity), whereas this is not true for the fourth- and higher-order moments.

For detailed studies of the beam shape in the plasma an antenna representation using many rays is clearly required. In this analysis, however, we are not interested in an accurate description of the shape of the beam, but only in an estimate of the beam width. As mentioned above, we will use σ to characterise the beam width, and in that respect it is immaterial which of the two representations for the antenna is chosen. The computational effort required when using the simple antenna representation is however much smaller than when using the one with many rays, and the simple representation is therefore adopted in the following calculations unless otherwise stated.

In order to get an overview of the parameter ranges where wave scattering by density fluctuations may be deleterious for the proposed α-particle diagnostic the

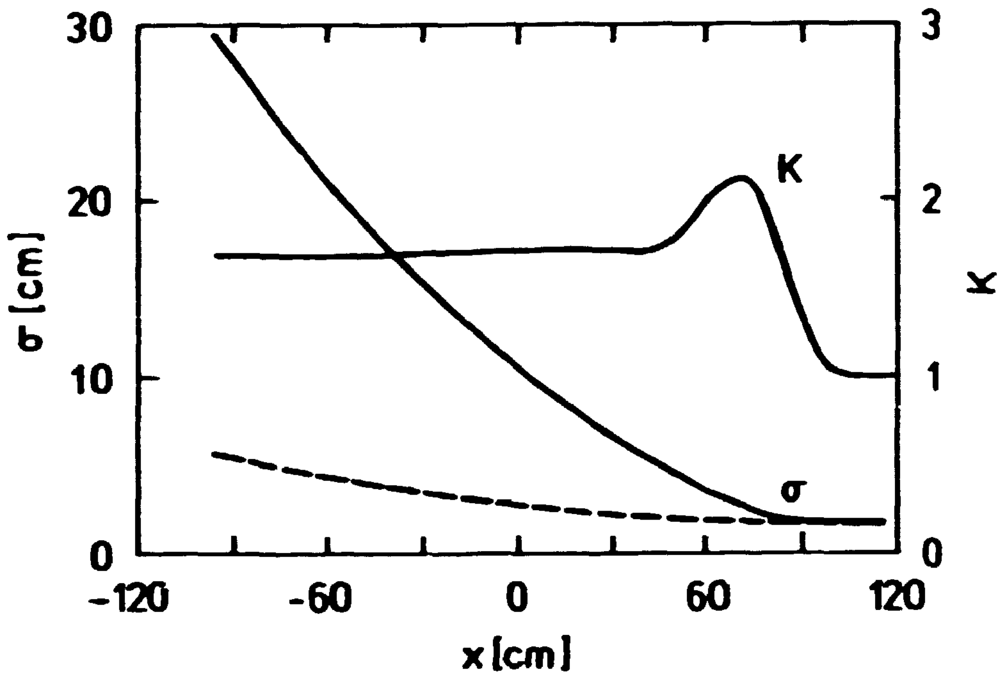

Figure 5: *Variation of σ and K along the x-axis. The plasma parameters are the same as in Figure 3. The representation of the antenna is the one shown in Figure 1b. The results are based on 50 realisations of the plasma density.*

following parameter study is carried out: For both models of the unperturbed density we consider three different values of the central density n_0, three different fluctuation levels $\delta n/n$, and three different mode numbers m, as specified by the contract. For all parameter combinations (27 for each model) the increase in beam width in the centre of the plasma due to the density fluctuations is determined. The results are summarised in Table 1.

In the table, σ refers to the value in the centre of the plasma column, and σ_0 denotes the value of σ for a vanishing fluctuation level. σ_0 thus represents a measure of the broadening of the beam due to the bulk plasma only (see e.g. dashed line on Figure 4). The increase in beam width due to the density fluctuations is measured in terms of the quantity σ/σ_0. The value of $\delta n/n$ in the table refers to the rms density fluctuation level at the edge of the plasma column. The value $v = 0.07071$ in Eq. (3) thus corresponds to a rms fluctuation level of 0.05. In all cases ensemble averages are taken over 50 plasma realisations.

Note that the detailed studies of the probability distribution of rays presented in Figures 3, 4 and 5 correspond to the choice of the parameters n_0, $\delta n/n$ and m listed in the row of Table 1 marked by the symbol †.

The data in Table 1 for the increase in beam width due to density fluctuations are represented graphically in Figure 6. Note that the scaling is different for the three

n_0	$\delta n/n$	m	σ_0	σ	σ/σ_0	
10^{19} m^{-3}	per cent		centimetre	centimetre		
2.0	5.0	4	1.81	1.82	1.00	
		10		1.86	1.03	
		30		2.12	1.17	
	10.0	4		1.84	1.02	
		10		2.00	1.11	
		30		2.85	1.57	
	20.0	4		1.94	1.07	
		10		2.48	1.37	
		30		4.42	2.45	
6.0	5.0	4	2.00	2.09	1.05	
		10		2.49	1.25	
		30		4.12	2.06	
	10.0	4		2.34	1.17	
		10		3.56	1.78	
		30		6.48	3.25	
	20.0	4		3.16	1.58	
		10		6.01	3.02	
		30		9.83	4.93	
15.0	5.0	4	2.80	3.79	1.35	
		10		6.49	2.32	
		30		10.6	3.79	†
	10.0	4		5.80	2.07	
		10		11.2	4.00	
		30		15.6	5.59	
	20.0	4		10.4	3.73	
		10		19.2	6.85	
		30		22.6	8.08	

Table 1: *Scattering results for model 1. The quantity σ/σ_0 represents the broadening of the beam in the centre of the plasma column due to the density fluctuations. The row marked by the symbol † corresponds to the combination of parameters used to produce the results presented in Figures 2 to 5.*

frames.

Looking at the data in Table 1 it appears that the wave scattering effect is almost negligible and thus unimportant in some parameter regimes, whereas in other regimes quite a substantial scattering takes place. The scattering effects are clearly most pronounced in the high density regime. This can be explained by the fact that the deflection of rays become increasingly important as the density approaches the cut-off density for the ordinary wave (the cut-off density for ordinary waves at 140 GHz is $24.3 \cdot 10^{19}$ m^{-3}). Rays that are scattered in the high density regime thus become further deflected due to the large density gradients in the bulk plasma.

It is also apparent from Table 1 and Figure 6 that high mode numbers are more effective in scattering the beam. This is in agreement with the observations made by HANSEN *et al.* (1988).

As mentioned previously, similar parameter studies are made for both density models. Table 2 contains the wave scattering results for model 2. As in the case of model 1, the data are visualised graphically, and the data corresponding to model 2 are depicted in Figure 7.

By comparing Figure 6 and Figure 7 it appears that for a fixed combination of parameters n_0, $\delta n/n$ and m, the scattering is always largest for model 2. This is probably because the density gradient for model 2 is larger than that for model 1 near the edge of the plasma column where significant scattering takes place. In all cases the increase in beam width due to density fluctuations for model 2 is larger than those for model 1 by a factor of approximately 1.5.

As in the case of model 1, one of the cases in the parameter study for model 2 is selected for a more detailed investigation of the probability distribution of rays. The parameters chosen are $n_0 = 15.0 \cdot 10^{19}$ m^{-3}, $\delta n/n = 5$ per cent and $m = 30$. This combination corresponds to the parameters in Table 2 in the row marked by the symbol ‡.

Figure 8 shows the histograms used to represent the probability distribution of rays at various positions along the reference direction. The representation for the antenna radiation pattern is now the one shown in Figure 1b with $N = 11$ and the number of plasma realisations is equal to 150.

In Figure 9 the spatial variation of σ and K along the reference direction is shown for the probability distribution found in Figure 8. Note that the growth of σ is nearly linear in a large part of the region. This region coincides essentially with the flat top region of the plasma for model 2 and we can therefore conclude that almost no scattering takes place here. The rays in the region of constant density simply disperse at a constant rate due to the scattering experienced by the rays before they entered the constant density region.

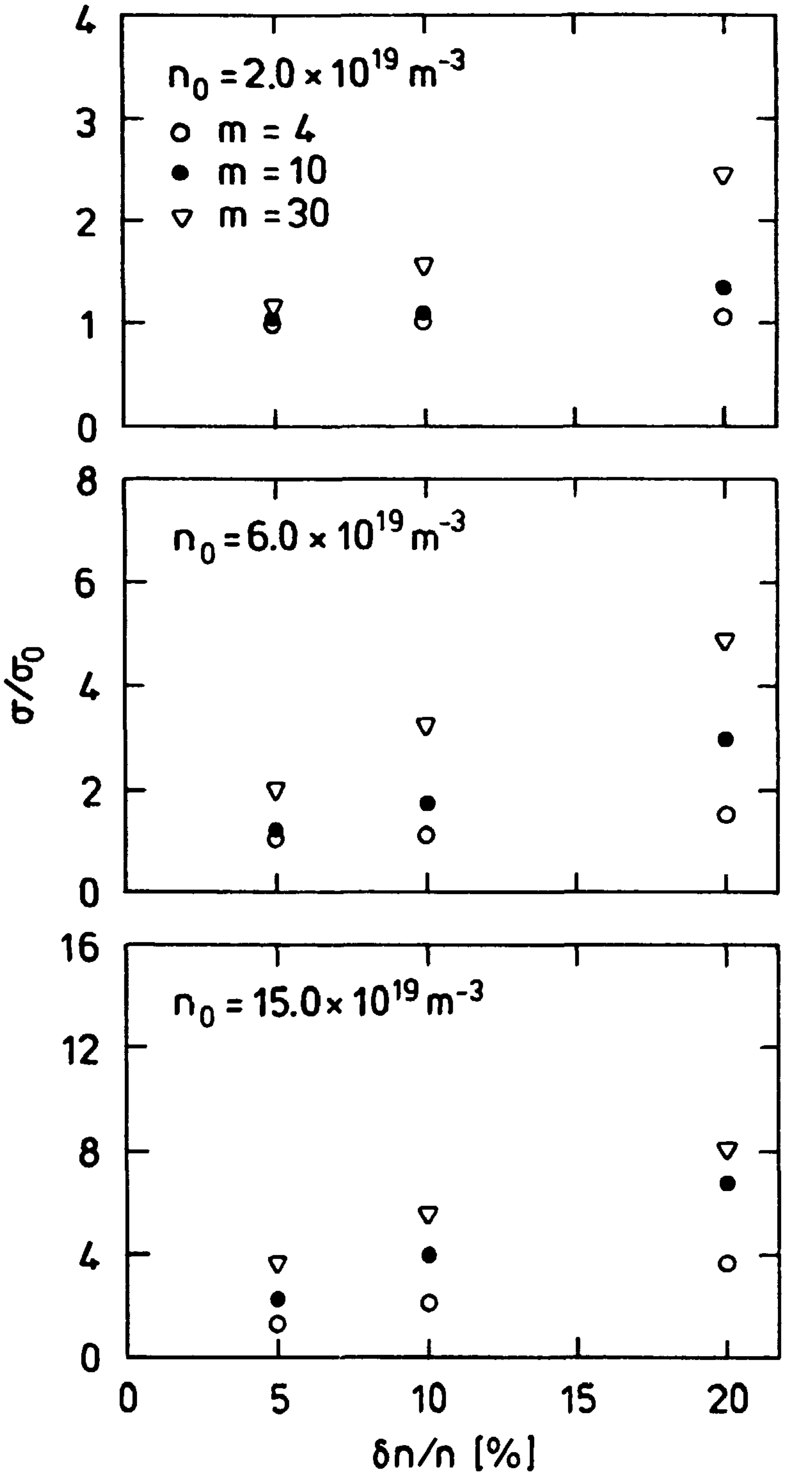

Figure 6: *Increase of beam width versus fluctuation level for three different values of the central density and three different values of the mode number. The data are taken from Table 1.*

n_0	$\delta n/n$	m	σ_0	σ	σ/σ_0	
10^{19} m^{-3}	per cent		centimetre	centimetre		
2.0	5.0	4	1.81	1.82	1.01	
		10		1.93	1.06	
		30		2.57	1.42	
	10.0	4		1.89	1.04	
		10		2.26	1.25	
		30		3.92	2.17	
	20.0	4		2.12	1.17	
		10		3.24	1.79	
		30		6.41	3.54	
6.0	5.0	4	2.00	2.23	1.12	
		10		3.15	1.58	
		30		6.01	3.01	
	10.0	4		2.83	1.42	
		10		5.17	2.59	
		30		9.58	4.80	
	20.0	4		4.46	2.24	
		10		9.25	4.64	
		30		14.6	7.31	
15.0	5.0	4	2.80	5.48	1.96	
		10		10.8	3.86	
		30		16.2	5.79	‡
	10.0	4		9.79	3.50	
		10		18.9	6.75	
		30		23.9	8.54	
	20.0	4		18.9	6.75	
		10		32.3	11.5	
		30		35.9	12.8	

Table 2: *Scattering results for model 2. The row marked by the symbol ‡ indicates a parameter combination subject to a more detailed investigation.*

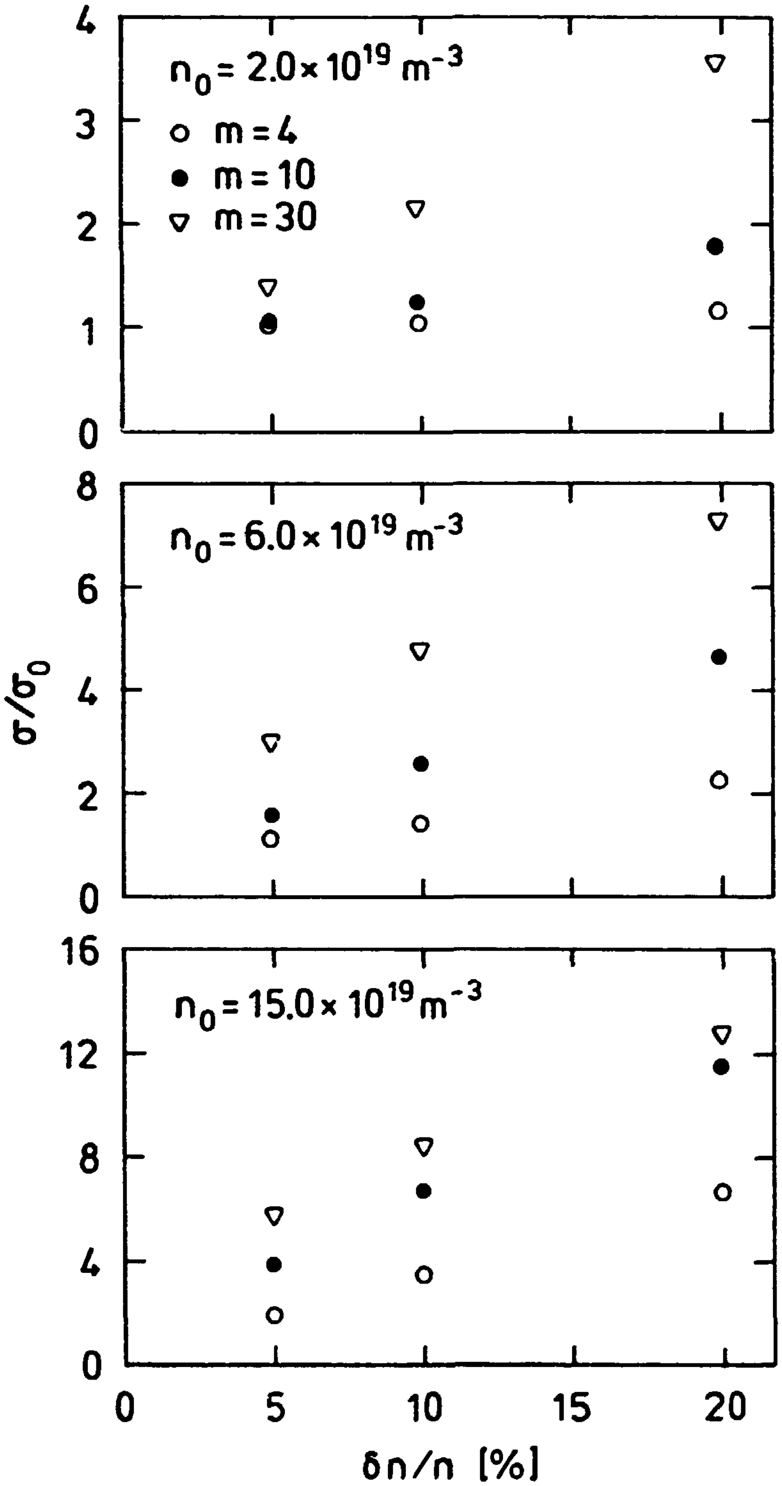

Figure 7: *Increase in beam width versus relative density fluctuation level for model 2.*

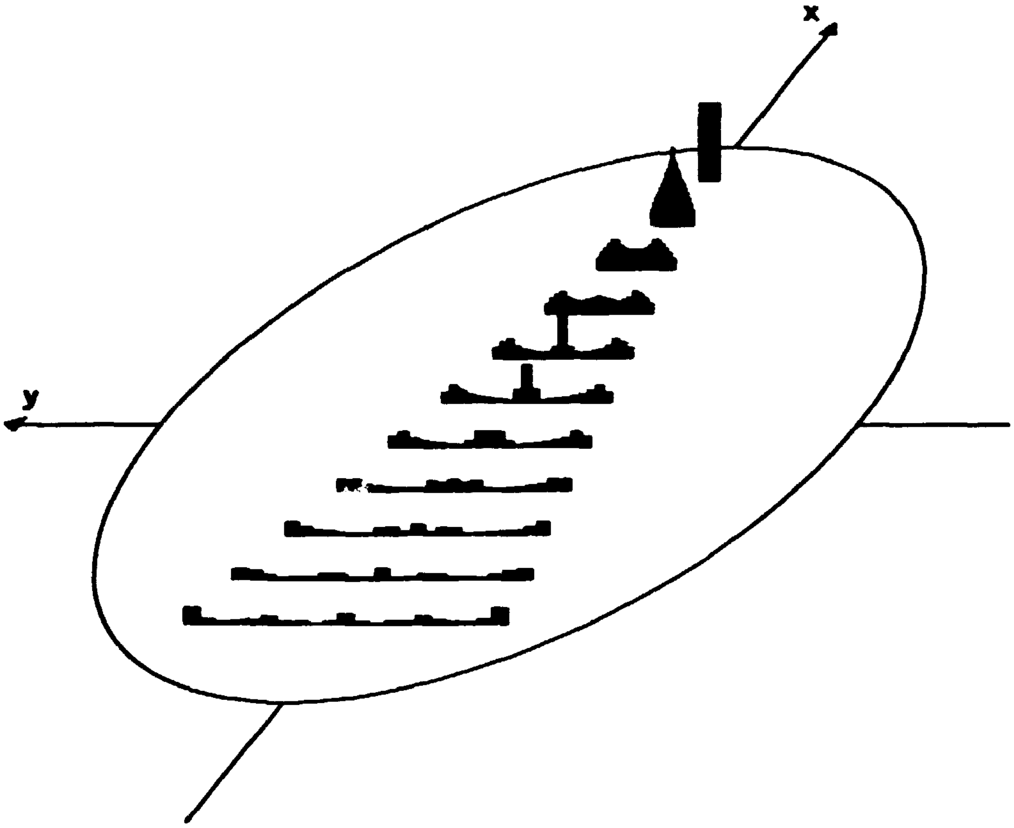

Figure 8: *Evolution of probability distribution of rays for model 2.* $n_0 = 15.0 \cdot 10^{19}$ m^{-3}, $\delta n/n = 5$ *per cent,* $m = 30$ *and* $N = 11$.

From Figure 8 it is evident that the shape of the beam changes significantly near the entrance point. From initially being rectangular, the shape of the distribution undergoes a series of changes, and it appears almost triangular in form at a certain point. These changes can also be observed in Figure 9 where the variation of K indicates a change in the shape of the distribution around $x = 90$ cm.

Finally, in Figure 10 we show the variation of σ and K for the same choice of parameters as in Figure 9, but with the simple representation for the antenna radiation pattern depicted in Figure 1b. Here the number of plasma realisations is 50. We note that also for plasma model 2 there is an extremely good agreement in the behaviour of σ for the two different antenna representations. This result justifies the usage of the simple antenna representation for plasma model 2 as well.

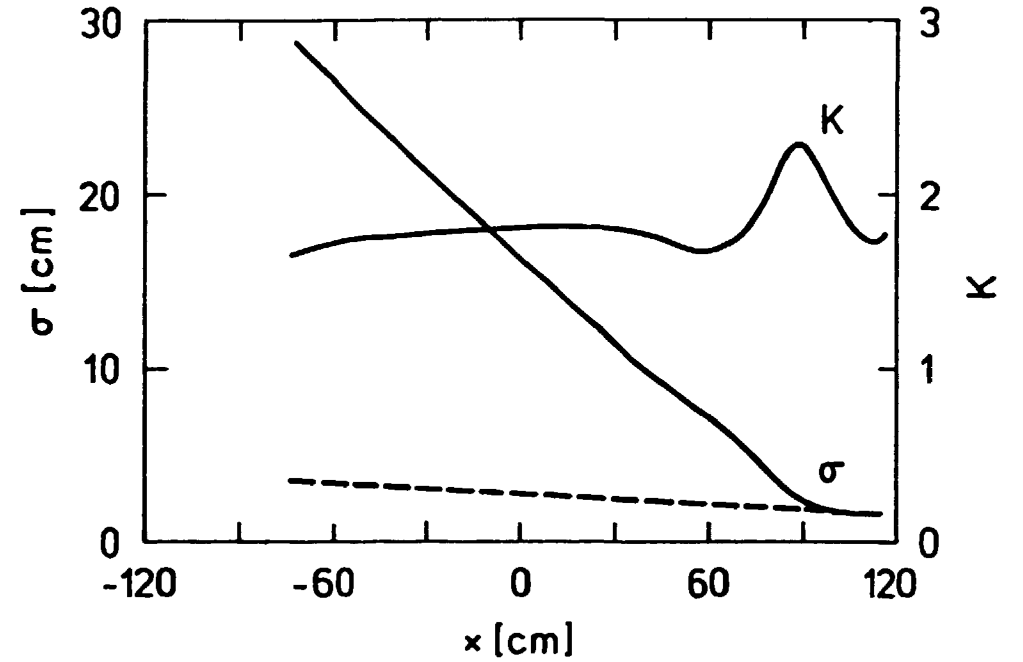

Figure 9: *Variation of σ and K along the reference direction. Parameters are the same as in the previous figure.*

4 CONCLUSIONS

From the results presented in the previous section it is clear that random density fluctuations can have a profound effect on a microwave beam propagating in the JET plasma. Especially for high values of the central density ($\simeq 15.0 \cdot 10^{19}$ m^{-3}) one can expect a substantial broadening of the incoming wave beam. In this regime a beam width in the centre of the plasma several times that of the width of the beam at the entrance point can be expected. This is true even even for a moderate density fluctuation level ($\simeq$ 5 per cent at the edge of the plasma column) as long as the azimuthal mode number for the density fluctuations is sufficiently high (approximately 10).

We would like to point out that in this work a series of assumptions have been made regarding the description of the plasma equilibrium. The assumptions concern the description of the unperturbed plasma density as well as the model for the density fluctuations. First of all, we have assumed that the plasma cross section is circular, and the wave propagation has been restricted to the poloidal plane. The JET plasma is however D-shaped, and the proposed α-particle diagnostic will launch a wave beam making a small angle ($\simeq 10°$) with the toroidal field. Furthermore, only a single viewing direction has been investigated, although the proposed diagnostic will allow for a range of viewing directions. Secondly, the analytical expression for the density fluctuations in this work is clearly simplified. Instead of fluctuations characterised by a single azimuthal mode number, an even more re-

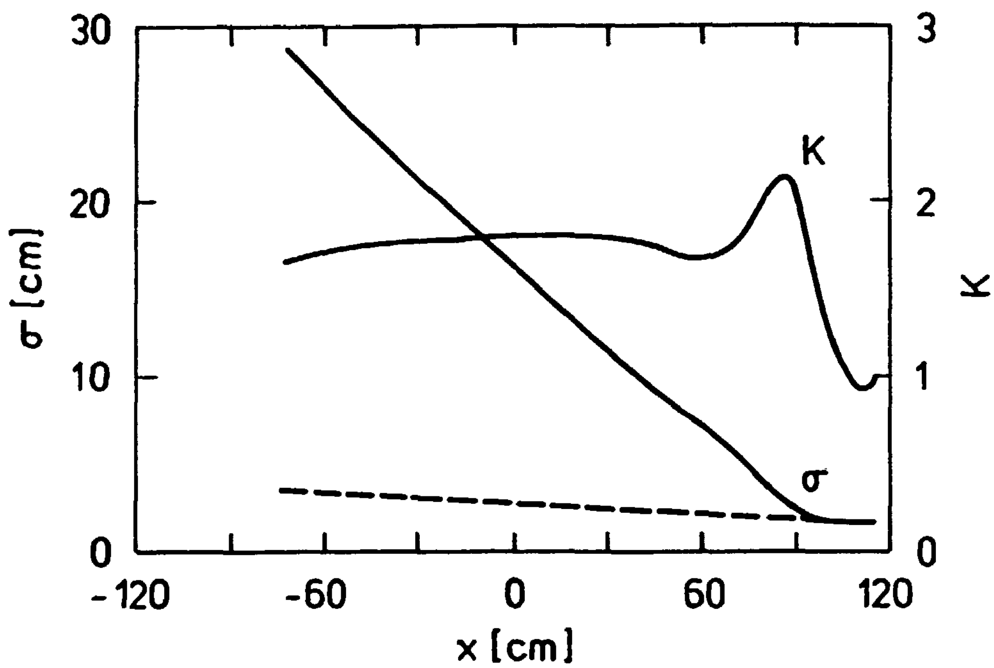

Figure 10: *Variation of σ and K along the reference direction for the simple antenna representation; otherwise the parameters are the same as in the previous figure.*

alistic description can be obtained by considering a full spectrum of waves with different mode numbers (including a wave spectrum with radial mode numbers) as in HANSEN *et al.* (1988). Another characteristic of the density fluctuations is the radial dependence of the relative density fluctuation level. In the present work only one form has been considered for the radial dependence, namely a $(r/a)^2$ variation of $\delta n/n$. A different variation might very well modify the results somewhat, but according to our knowledge no detailed investigations have yet been made of the radial distribution of density fluctuations in tokamaks. Although our model is plausible it is not experimentally confirmed.

In addition to the density fluctuations, the radial variation of the unperturbed density itself has an impact of the beam broadening. This is demonstrated in the previous section where the beam width in the centre of the plasma is found to be approximately 1.5 times greater for the density model with a flat top than for the one with a smooth rounded profile.

Obviously a lot of assumptions have been made, and the results presented in this work should therefore be interpreted with some caution. In spite of the limitations in our analysis, the calculations nevertheless clearly demonstrate that the propagation of waves with ordinary polarisation in JET may be seriously affected by random density fluctuations in certain parameter regimes.

Further investigations are needed in order to obtain a complete understanding of the implications random density fluctuations have on the JET α-particle diagnostic. In such investigations all of the above-mentioned considerations regarding the description of the plasma equilibrium will have to be kept in mind. A full three dimensional analysis will be particularly relevant. Also a more general model for the fluctuations in plasma parameters have to be obtained.

We would finally like to point out that random density fluctuations may be important for the other JET diagnostics using millimetre waves (ECE, microwave reflectometry and transmission interferometry). In the present work, however, special attention has been given to the proposed fast ion and α-particle diagnostic.

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Title and author(s) POSSIBLE INFLUENCE OF EDGE DENSITY FLUCTUATIONS ON THE PROPOSED FAST ION AND ALPHA PARTICLE DIAGNOSTIC FOR JET F.R. Hansen, J.P. Lynov, P. Michelsen and H.L. Pécseli	**Date** September 1988 **Department or group** Physics **Groups own registration number(s)** **Project/contract no.**
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Abstract (Max. 2000 char.)

Abstract. The influence of random density fluctuations in a tokamak on the propagation of electromagnetic waves polarised in the ordinary mode is studied numerically. The study is of direct relevance for a proposed fast ion and α-particle diagnostic for JET relying on collective scattering of intense millimetre waves. The wave propagation is studied in the limit of geometrical optics by a ray-tracing code. For overall parameters specified by the contract, it is found that even low levels of relative density fluctuations may lead to a substantial broadening of an incoming wave beam. This effect is particularly pronounced for high values of the central plasma density. The wave beam broadening due to density fluctuations could lead to a degradation in the performance of the proposed diagnostic by limiting its spatial resolution.

Descriptors

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