JOINT EUROPEAN TORUS

JET–P(93)102

A.E. Costley, P. Cripwell, G. Vayakis

Measurement of Density Fluctuations by Correlation Reflectometry

Measurement of Density Fluctuations by Correlation Reflectometry

A.E. Costley, P. Cripwell[1], G. Vayakis

JET-Joint Undertaking, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]35 Spencer Road, Acton, London, W3 6DW.

Preprint of a paper to be submitted for publication in proceedings of
the workshop "Local Transport Studies in Fusion Plasmas"
Varenna, Italy, 30 August- 3 September 1993.
December 1993

ABSTRACT
The principles of correlation reflectometry are outlined and applications in the radial and toroidal directions on JET are described. The measurements show that fine-scale density perturbations exist in the plasma and that the size and movement of the perturbations depends on plasma conditions.

1. INTRODUCTION

Correlation reflectometry is a new and potentially powerful technique for determining some of the parameters which characterise density fluctuations in tokamak plasmas [1,2,3]. The technique has the potential to provide the correlation length and movement of the perturbations in specific directions (radial, toroidal and poloidal). The theory of the technique is still being developed; nevertheless there have been several applications with encouraging and intriguing results. In this paper, we outline the principles of the technique and present results obtained in two applications on JET.

2. SENSITIVITY TO DENSITY FLUCTUATIONS

In general, the fluctuations in the reflectometer signal are due to fluctuations in the electron density in the region of the reflecting layer and in the propagation path. They are also due to a range of fluctuation wavelengths. However, because of the properties of electromagnetic waves in plasmas, the signals can be highly localised and the integration over wave number is limited. These characteristics can be shown by simple arguments and calculations. We consider first the radial case.

2.1 Integration over k

We can treat the interaction between the waves and the plasma as a back-scattering problem; this means that the wave number of the fluctuations generating the scattering is given by the Bragg condition

$$k = 2k_{in} \sin\frac{\theta_s}{2} \tag{1}$$

where $k_{in} = 2\pi\mu / \lambda_0$ is the local wave number of the incident wave, λ_0 is the free space wavelength and θ_s is the scattering angle. Hence, for backward scattering $k = k_r = 2k_{in}$, so in the propagation region, where the refractive index $\mu \approx 1$,

$k_r \approx 2(2\pi/\lambda_0) \approx 2k_0$. In the reflection region, the refractive index tends to zero and the reflectometer becomes sensitive to longer wavelengths. Hence signals are integrated over the range

$$0 < k_r < 2k_0 \tag{2}$$

Typically, $\lambda_0 = 5\text{mm}$, so the wave number range is, $0 < k_r < 24\text{cm}^{-1}$.

2.2 Localisation

Studies of the localisation have been mainly numerical. Cripwell [3] used a 1-D approach and radially propagating Gaussian and other perturbations of correlation length l_c. The magnitude of the phase response increases with l_c (see figure 1). For $l_c > \lambda_0$, the phase response in the propagation region approaches the WKB solution. For the conditions of figure 1 with $l_c = \lambda_0/2$, 75% of the phase response is localised to within $\approx$5cm of the reflection layer. At least one study [4] has shown that the response becomes more localised when 2-D effects are taken into account.

In the poloidal and toroidal directions, the illuminated region (spot size) has to be taken into account. The size of the region will depend on the details of the antenna used. For fluctuation wavelengths larger than the spot size we expect the response to depend only on the amplitude of the perturbation and the local gradient of the flux surface. For fluctuation wavelengths shorter than the spot size, we expect more complicated behaviour, as the reflection layer begins to resemble a grating. For each instrument, the response can be predicted by detailed numerical simulation taking into account antenna geometry. In one calculation [4] the response of the instrument decreases when the fluctuation wavelength becomes smaller than the spot size.

3. CORRELATION REFLECTOMETRY

A correlation reflectometer uses two or more channels to probe different locations in the plasma. A simple form of a correlation reflectometer, probing along the radial direction, is shown in figure 2. For such a two-point instrument, the information available at fixed separation of the layers, Δx, is: (a) $G_1(\omega)$ and $G_2(\omega)$, the two auto-power spectra, (b) $G_{12}(\omega)$, the cross-power spectrum and (c) $\theta_{12}(\omega)$, the cross-phase spectrum. In the simplest case of a pure sinusoidal perturbation propagating radially with wave number k_r,

$$\theta_{12}(\omega) = k_r(\omega)\Delta x \tag{3}$$

For the case of turbulence, a measure of whether the two signals are correlated is the coherence function, $\gamma_{12}(\omega)$ defined by

$$\gamma_{12}^2(\omega) = \frac{|G_{12}(\omega)|^2}{G_1(\omega)G_2(\omega)} \tag{4}$$

For a given level of γ to be significant, it must exceed the minimum level, γ_r, that would be measured for purely uncorrelated signals recorded with the same bandwidth and sample time. For homogeneous turbulence standard measurement theory [5] gives, for the moments of k and k^2 over the wave number spectral density at each frequency

$$\bar{k}(\omega) = \frac{\theta_{12}(\omega)}{\Delta x} \tag{5}$$

$$\overline{k^2}(\omega) = \frac{2}{\Delta x^2}(1 - \gamma_{12}(\omega)) \tag{6}$$

provided that $k\Delta x < \pi/2$ for all wave numbers with significant power. In this way, a two-point measurement provides enough information to estimate the position of the peak and the width of the wave number spectral density, since $\sigma_k = \sqrt{\overline{k^2} - \bar{k}^2}$.

With measurements at two points, we may estimate the correlation length, l_c, by making reasonable assumptions about the shape of the spectrum. Without any such assumption the average phase and group velocities may still be calculated from

$$v_p = \frac{\omega}{\bar{k}} = \omega \frac{\Delta x}{\theta_{12}} \tag{7}$$

$$v_g = \frac{d\omega}{dk} = \frac{\Delta x}{d\theta_{12} / d\omega} \tag{8}$$

There is no difficulty with applying these results also in the toroidal or poloidal directions, although the response of the instrument must be considered. In particular the wave number spectrum estimates (5,6) will be modified if wavelengths shorter than the spot size of the instrument have significant amplitude.

4. MEASUREMENTS AT JET

4.1. Radial

The JET radial correlation reflectometer has four channels operating in the extraordinary mode (77.5, 76.0, 77.0 and 79GHz) through a single antenna system. For these frequencies, the typical corresponding interlayer distances are 4-40mm. The radial location of the cutoff layers varies in the range $\rho = 0.2 - 0.95$, depending on plasma conditions. Measurements are obtained in Ohmic, H-mode and L-mode conditions.

Under Ohmic conditions, the separation for which the coherence has decreased to $1/e$ (indicative of the correlation length), is less than 3mm (figure 3). The coherence level increases somewhat in H-mode, but is still very low (the $1/e$ length is $\approx 4\text{mm}$). The most dramatic results are in L-mode, where the coherence level increases with additional heating, the $1/e$ point exceeding the maximum separation of the instrument ($\approx 30\text{mm}$) for $P = 15\text{MW}$. Observations during one L-H transition show the coherence level decreasing as the H-mode is established.

In all cases, the phase is independent of frequency, suggesting that the perturbations do not propagate in the radial direction. This means that $\bar{k} = 0$ so that (6) reduces to

$$\sigma_k = \frac{1}{\Delta x}\sqrt{2(1 - \gamma_{12}(\omega))} \tag{9}$$

We can use this result, together with $l_c = \sqrt{2}/\sigma_k$, which is the relation between the wave number spread and the correlation length for a Gaussian turbulence

Table 1: *Wave number spread and corresponding radial correlation length for a Gaussian spectrum under Ohmic, H-Mode and L-Mode conditions.*

		$\sigma_k(\text{cm}^{-1})$	$l_c(\text{cm})$
Ohmic		3.8	0.4
H-mode		3.6	0.4
L-mode			
	4MW	2.2-3.1	0.6-0.44
	8MW	0.6-1.3	2.2-1.1
	15MW	0.35-0.7	4.1-2.0

spectrum, to estimate the wave number spread and corresponding correlation length under various conditions (table 1). For the limited data available this shows that the correlation length increases approximately linearly with additional heating power, with a baseline Ohmic level of $\approx$0.4cm (figure 4).

4.2. Toroidal

The JET toroidal correlation reflectometer consists of two independent reflectometers, both operating at 29 (or 34) GHz in the ordinary mode ($n_e = 1 \text{ or } 1.4 \times 10^{19} \text{m}^{-3}$). These frequencies usually correspond to the plasma boundary ($\rho > 0.9$). The toroidal separation between the two antenna systems is 155mm.

Under ohmic conditions the coherence is at the random level. However, in the L-mode case, there is significant coherence, so that the toroidal velocity of the perturbations can be deduced using equation (8) and compared with the plasma toroidal rotation velocity, independently measured by the charge exchange diagnostic [6]. The result (figure 6) suggests that the measurements can be interpreted in terms of density perturbations moving with the plasma.

Using the average coherence from figure 5 and the method used to obtain the results of figure 4, we obtain the following correlation lengths:

	Ohmic	H-mode	L-mode
l_c(cm)	< 17	23	20

Alternatively, we can deduce the correlation length by assumming that the autocorrelation time of the fluctuations in the moving frame is much larger than their time of flight between the two detectors. In this case, l_c becomes equal to the product of the autocorrelation time in the laboratory frame, τ_c, and v_g. Taking an example from figure 7, $\tau_c = 16\mu\text{s}, v_g = 19\text{km/s} \rightarrow l_c = 30\text{cm}$ (We do not expect perfect agreement between the two methods because τ_c is not Gaussian).

The results from H-mode suggest that the perturbations are either moving toroidally at very high velocity (of order 300km/s) or poloidally. A poloidal correlation reflectometer is needed to resolve this issue.

5. NEW REFLECTOMETER FOR JET

A new correlation reflectometer is under construction at JET. The device uses a four antenna array and operates at 80 (or 105)GHz in the extraordinary mode. It can be configured for measurements in either the toroidal or poloidal direction. In addition, a two channel radial correlation reflectometer operating in the range 92-96GHz will share the same antenna system. In every case, the amplitude and phase of the reflected signal will be measured separately.

The poloidal and toroidal wave number response of the instrument is limited by the spot size and the separation (which implies significant overlap between channels, and hence low signal to noise for small wave numbers) to the range $1 < k < 25\text{m}^{-1}$. Both the upper and lower limit ultimately arise from access restrictions. In the radial direction, it is planned to reduce the frequency separation down to 5MHz, in order to resolve the instrument function. The radial coverage of the instrument will be $0.6 < \rho < 1.0$ depending on plasma conditions.

6. DISCUSSION

The measurements confirm that the fluctuations in the reflectometer signal are due mainly to density perturbations close to the reflecting layer, i.e. the information is highly localised. The low level of coherence measured at small radial separations with the radial correlation reflectometer under Ohmic conditions shows this. In fact, the localisation is better than expected on the basis of a 1-dimensional theory of correlation reflectometry (section 2). This is probably because, in practice, the finite size of the antenna pattern means that 2-dimensional effects become important. Work at modelling these effects is in progress [4,7] but not yet completed.

Perhaps the most important result from the point of view of energy and particle transport is that the measurements show that the density profile is 'structured' on a fine scale, and that this fine-scale structure moves with the bulk of the plasma. The density *gradient*, in particular has to vary substantially and non-monotonically with major radius. The radial scale of these structures is small under Ohmic and H-mode conditions, but grows larger on application of additional heating.

7. CONCLUSIONS

Correlation reflectometry is a potentially powerful technique for diagnosing density fluctuations. It can provide the correlation length and the movement of the fluctuations in the plasma core and edge with good spatial resolution. The theory of the technique is not yet fully developed: further modelling is required, especially of 2-dimensional effects. Experiments at JET have shown that fine-scale density structures exist in the plasma. Under L-mode conditions they have a radial correlation length l_c typically of order a few cm, which increases with beam power. Under Ohmic and H-mode conditions $l_c \leq 5\text{mm}$. The perturbations do not propagate radially but appear to rotate with the plasma. Under H-mode conditions the structures appear to move toroidally at very high velocity (of order 300km/s), or poloidally. A poloidal correlation reflectometer is needed to resolve this issue. Probably the most important result for energy and particle transport is that the measurements show that the gradient of the electron density varies substantially on a fine scale (cm or less) and is a non-monotonic function of major radius. A new correlation reflectometer is being constructed for JET which will enable measurements to be made separately in the radial, toroidal and poloidal directions, with improved sensitivity.

REFERENCES:

[1] P.Cripwell, A.E.Costley and A.E.Hubbard, *Proc. 16th Eur. Conf. on Cont. Fusion and Plasma Physics 1989*, vol **13B**, part 1 (1989), p.75

[2] A.E.Costley, P.Cripwell, R.Prentice and A.C.C.Sips, *Rev. Sci. Instrum.* **61** (1990) p.2823

[3] P. Cripwell, *'Extraordinary Mode Reflectometry at JET'*, Ph.D. Thesis, University of London (1992)

[4] J.H. Irby, S. Horne, I.H. Hutchinson and P.C. Stek, *Plasma Phys. Control. Fusion* **35** (1993) , p.601

[5] N. Iwama, Y. Ohba and T. Tsukishima, *J. Appl. Phys.* **50** (1979) p.3197

[6] P. Cripwell, A.E. Costley and T. Fukuda, *Proceedings IAEA Technical Committee meeting on Microwave Reflectometry for Fusion Plasma Diagnostics* (IAEA, Vienna 1992), p.168.

[7] E. Holzhauer and G. Rohrbach, *ibid.*, p 89.

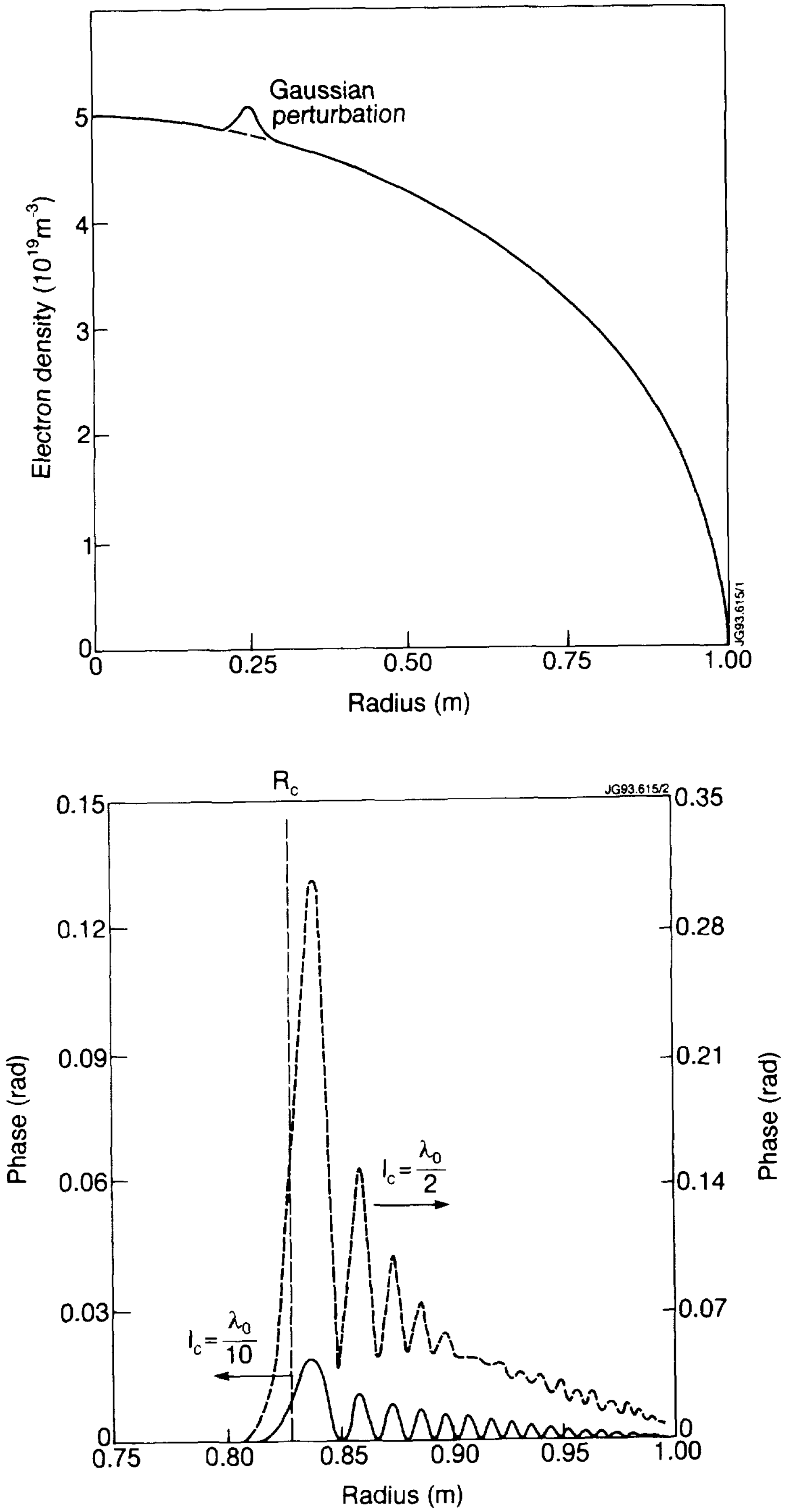

Figure 1: Gaussian perturbation of correlation length l_c (top) and the phase response of an O-mode reflectometer for each location of the perturbation for $l_c = 0.1\lambda_0$ and $l_c = 0.5\lambda_0$ (bottom). The perturbation amplitude is $\tilde{n}/n \approx 1\%$.

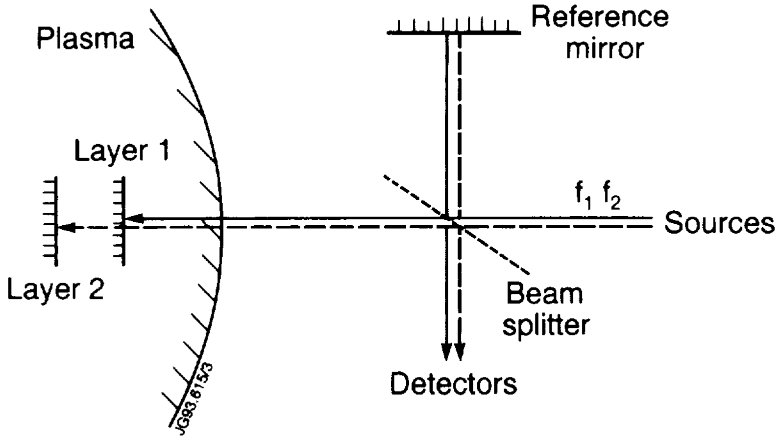

Figure 2: A two-channel reflectometer. The two channels share a radial view, but are tuned to slightly different frequencies.

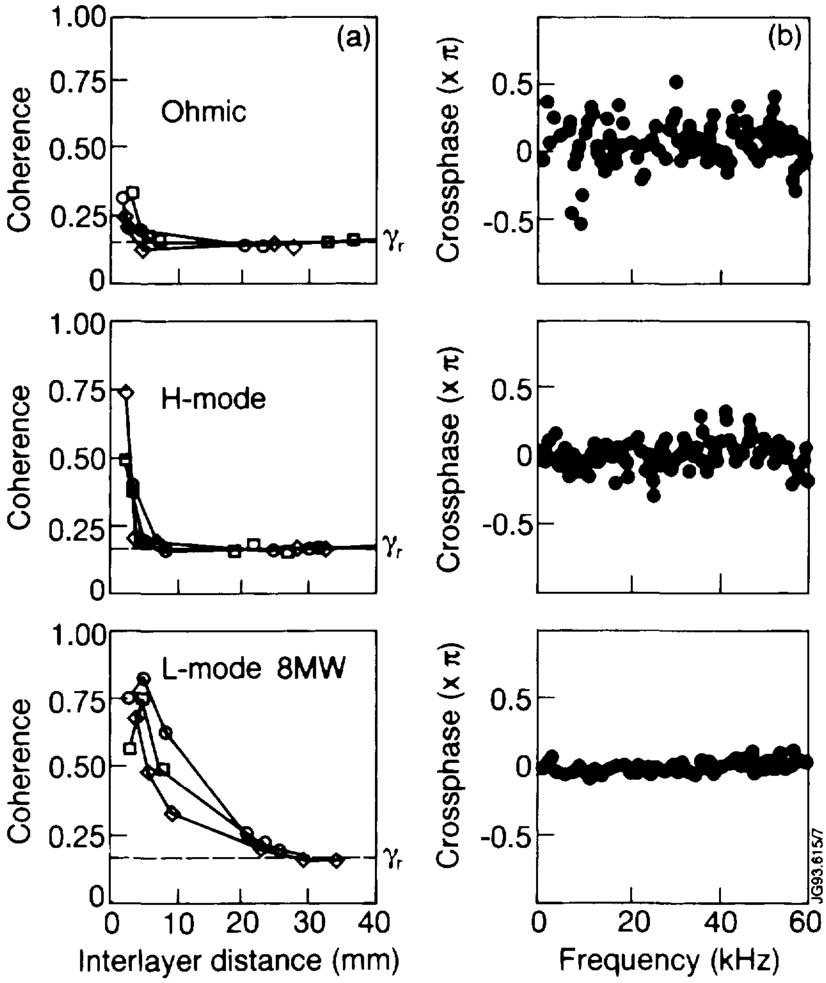

Figure 3: (a) Coherence against interlayer distance and (b) cross-phase against frequency. Ohmic: □, $\rho=0.3$; ×, $\rho=0.55$; ○, $\rho=0.9$; phase for $\gamma=0.35$. H-mode: □, $\rho=0.6$; ×, $\rho=0.8$; ○, $\rho=0.9$; phase for $\gamma=0.48$. L-mode: □, $\rho=0.4$; ×, $\rho=0.6$; ○, $\rho=0.9$; phase for $\gamma=0.71$.

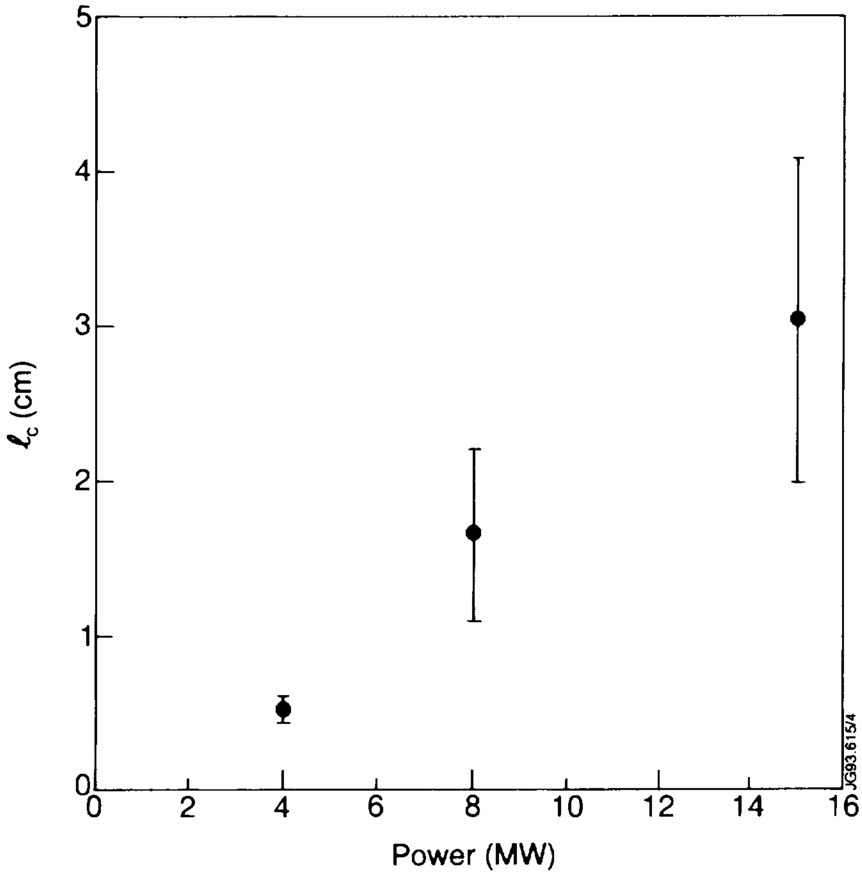

Figure 4: Correlation length against additional heating power

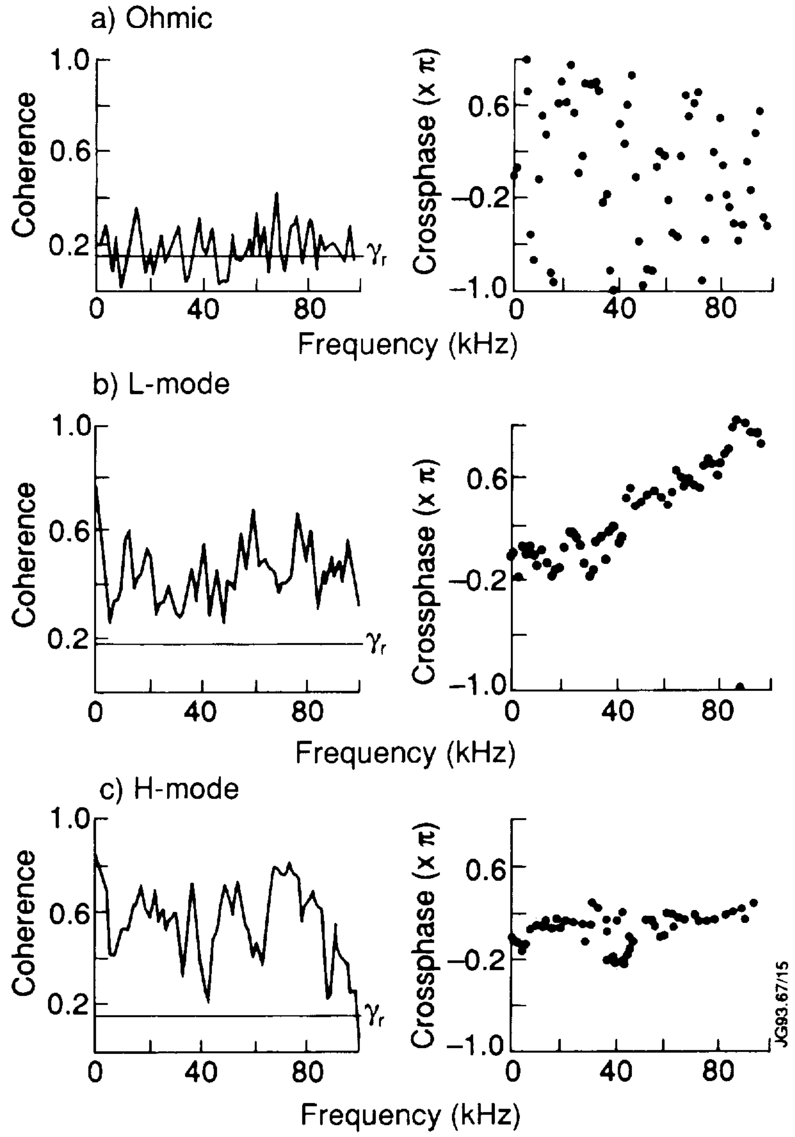

Figure 5: Results (coherence and phase against frequency) from the two channel toroidal correlation reflectometer.

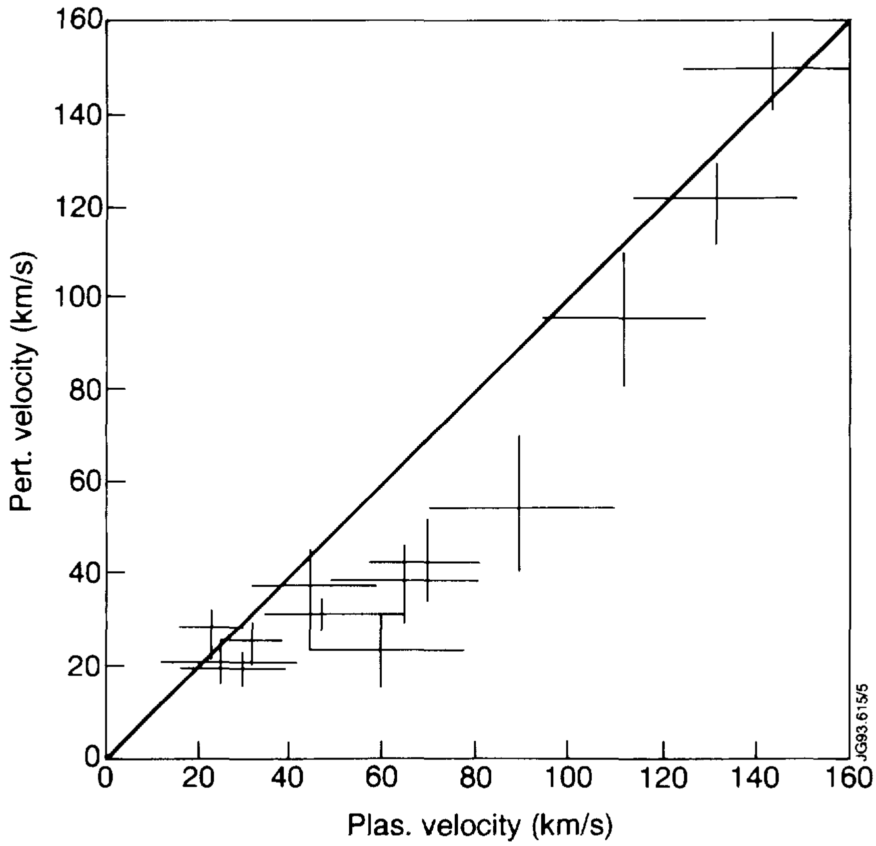

Figure 6: Comparison between the measured toroidal velocity of the perturbations and the toroidal velocity of the plasma measured with the CX diagnostic.

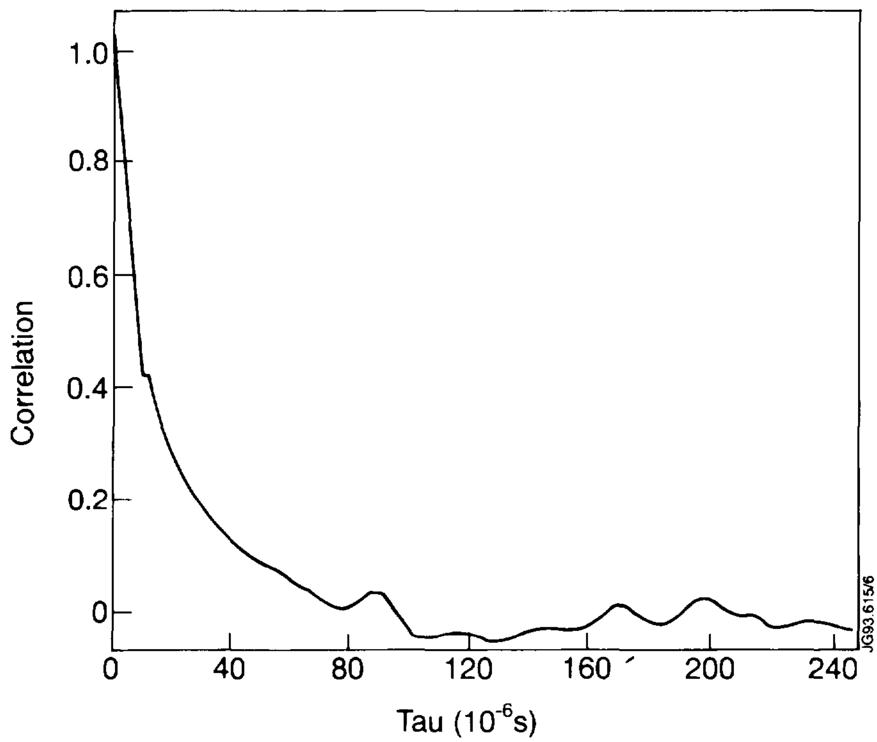

Figure 7: The autocorrelation function for reflectometer data taken under L-mode conditions. The toroidal velocity of the perturbations is 19km/s.