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Abstract

A simple fixed frequency microwave reflectometer installed on the JET tokamak device is described. Data from the reflectometer are combined with data from other JET diagnostics to obtain the radial distribution of the electron density during the rise and decay phases of the plasma. The profiles are compared with those obtained using a conventional multichord transmission interferometer, and good agreement is obtained. The reflectometer is used to study movements of particular density layers due to MHD and sawtooth activity during the equilibrium phase of the plasma. The limitations of the device are discussed and some possible future developments outlined.

Introduction

The possibility of using beams of microwave radiation reflected from certain plasma density layers as a diagnostic of the electron density has been known for many years and used on a number of experiments. Fixed frequency microwaves were used on some small laboratory plasmas to obtain the peak electron density and profile shape parameters were fitted to the measurements /1,2,3/. Techniques using a narrow frequency modulation have provided information on bulk plasma movement in tokamaks /4,5/. An instrument swept over a broad frequency band has recently been used to measure part of the radial density distribution of the TFR plasma /6,7/. This work has shown the promise of microwave reflectometry as a diagnostic tool, but considerable scope for further development remains.

In this paper a simple fixed frequency microwave reflectometer used recently on the JET tokamak device is described. We show how by using data provided by the reflectometer, with data from other diagnostics standard on many tokamaks, it is possible to deduce the spatial profile of the electron density during the rise and decay phases of the plasma. The reflectometer is well suited to measuring the movement of particular density layers during MHD and sawtooth activity, and some examples of this are given. Finally, we discuss the limitations and possible future developments of this diagnostic technique.

Details of the JET tokamak are reported elsewhere /8/. The parameters of most importance during these reflectometry experiments are the horizontal minor radius a = 1.15 m, peak electron density $n_{e,max} \gtrsim 3.5 \times 10^{19}$ m^{-3} and the density rise time $\sim$ 4 seconds. The central magnetic field B_o was typically in the range 2.6 - 3.4 T.

Principle

The reflectometer used on JET is shown schematically in Figure 1. A wave of frequency F is launched in the ordinary mode ($\underline{E}//\underline{B}$) along the direction of the density gradient. Total reflection occurs where F equals the local plasma frequency. The electron density in this layer has the critical value $n_c = F^2(4\pi^2\varepsilon_o m_e/e^2) = F^2/80.6$ (MKS units).

This reflecting layer forms the second mirror of a simple microwave interferometer. A phase shift ϕ relative to the incident beam is experienced by the wave during propagation through, and reflection by, the plasma. The reflected wave is mixed with a reference beam of fixed path length. Changes in ϕ therefore produce N interference fringes where $N=\Delta\phi/2\pi$, which can be detected at the interferometer output.

For the conditions of interest a WKB solution of the wave equation can be used with a small correction near n_c, giving /9,10/

$$\phi = \frac{4\pi F}{c} \int_{R_c}^{R_{out}} \mu(R)\,dR - \frac{\pi}{2} \tag{1}$$

R_{out} and R_c are the major radii of the plasma edge and reflecting layer respectively, and $\mu(R) = (1 - n_e(R)/n_c)^{\frac{1}{2}}$ is the local refractive index. $n_e(R)$ is the local electron density. In interpreting reflectometer data it is convenient to define a mean refractive index

$$\bar{\mu} = \frac{1}{R_{out} - R_c} \int_{R_c}^{R_{out}} \mu(R)\,dR$$

Equation (1) can then be written

$$\phi = \frac{4\pi F}{c}\, \bar{\mu}\, (R_c)\, [R_{out} - R_c] - \frac{\pi}{2} \tag{2}$$

During a period of density change the position R_c moves, and the fixed frequency reflectometer in effect scans a portion of the density profile. If $\bar{\mu}$ can be estimated, it is possible to deduce this movement from the measured $\Delta\phi$.

Taking density profiles of the general form

$$n_e\,(r) = n_{eo}\,\left(1 - \left(\frac{r}{a}\right)^{\alpha}\right)$$

where n_{eo} is the central density, r is the minor radius and a is the plasma radius, we find $\bar{\mu}$ depends only weakly on the profile shape. Except in nearly flat profile regions, it lies in the range 0.5 to 0.66 for α in the range 1-10. A constant value $\bar{\mu} = 0.6 \equiv \bar{\mu}^*$ can be used to an accuracy of better than ±15%.

In any time interval t_1 - t we can then compute

$$|R_c(t) - R_c(t_1)| \equiv \Delta R_c(t) = \frac{c}{4\pi F\bar{\mu}^*} |\phi(t) - \phi(t_1)| \quad (3)$$

If the shape of the density profile remains constant during this interval, ie. only the amplitude is varying, the profile shape can be deduced in the region $R_c(t_1) \rightarrow R_c(t)$. Additional information on the mean density and plasma position is also necessary. On JET (and many other tokamaks) this is available from other diagnostics for each plasma pulse.

Instrument

The source used for the reflectometer is a 100 mW Gunn oscillator, manually tunable in the range 29-38 GHz (Fig. 1). It can therefore follow layers with densities in the range 1.0 - 1.8 x 10^{19} m^{-3}, by selecting different frequencies between pulses. As electron cyclotron frequencies are above 50 GHz, electron cyclotron absorption effects are not important. At these frequencies the movement of the reflecting layer during density rise or fall produces typically 100 interference fringes at a rate between 1Hz and 100 Hz.

Shielding requirements for JET dictate that active components of diagnostics are located remote from the torus. Radiation from the source is therefore transmitted to the torus along $\sim$ 35 m of oversized S-band waveguide /11/. A single oversized antenna located at the horizontal midplane both launches and receives the microwave beam (see Fig. 1). Waves are launched with $\underset{\sim}{E}$ horizontal, parallel to the toroidal magnetic field and perpendicular to the weaker poloidal field due to the plasma current. There is therefore a component (<25%) in the extraordinary mode which under these conditions propagates through the plasma and is scattered from the inner wall. The vacuum interface is a 10 cm diameter crystal quartz window which is wedge shaped. Radiation reflected by the plasma is returned along the same transmission system. Partial reflections at the torus window and other components combine to form a net fixed reference beam, eliminating the need for a separate reference waveguide. A plastic beam divider mounted in the waveguide directs part of the reflected signal towards a sensitive liquid helium-cooled indium antimonide detector.

Signal to noise ratios of typically 50:1 are achieved in the measurement. Since the detector is sensitive to a wide range of frequencies, a low-pass scatter filter is included to reduce any electron cyclotron radiation received. An electrical bandwidth of 1 kHz and an ADC sampling rate of 2kHz were used throughout most pulses. A result obtained on a typical plasma pulse is shown in Fig. 2. The amplitude of the reflected signal S_R is not absolutely calibrated. Within a plasma pulse S_R varies as expected with the position of the reflecting layer.

Density Profile Analysis Procedure and Results

Density profile shapes have been deduced for many pulses having a monotonic density rise or fall period. We first check that the profile shape is not changing significantly during these periods by computing the ratio of the central density $n_e(0,t)$ to the mean density $\bar{n}_e(t)$ given by

$$\bar{n}_e(t) = \frac{1}{2b} \int_{-b}^{b} n_e(z,t)\, dz$$

Here n_e (0,t) is taken from the single point Thomson scattering diagnostic /12/, the integral of the density along a vertical line of sight is taken from a single channel microwave transmission interferometer operating at λ = 2mm /13/, and the plasma height b is derived from magnetic pick-up coils, full flux loops and saddle loops /14/. On many pulses we find $n_e(0,t)/\bar{n}_e(t)$ remains constant to within a few percent (Fig. 3), indicating that the profile shape remains a constant function of z/b.

The procedure to determine the profile shape is then as follows:

1. Interference fringes are counted from time t_1, approximately the time at which the maximum density n_m reaches the critical value (Fig. 4(a)). $\Delta\phi$ is thus known at a series of times t_n during the density rise period.

2. At each time t_n, we compute a normalised reflecting density defined as $n^*(t) = n_c/\bar{n}_e(t)$, using microwave interferometer data. This gives the relative height of the reflecting layer on the density profile (Fig. 4(b)).

3. The radial position of the reflecting layer is then computed using two iterations.

   In a first approximation $\bar{\mu}$ is assumed constant, as discussed above. We thus compute the movement of the reflecting layer ΔR_c using equation (3). A correction of typically 10cm is made for the slow movements of the bulk plasma, measured by magnetic diagnostics. Plotting $\Delta R_c(t_n)$ vs. $n^*(t_n)$ gives the shape of a portion of the density profile. Up to 90% of the radius is typically covered in a single pulse.

   The known plasma centre and edge positions are then used to estimate the position of the outer radius $R_{c,max}$ reached by the reflecting layer. Computation of ΔR_c is repeated starting at $R_{c,max}$ and progressing inwards towards smaller values of the major radius. Since $\bar{\mu}$ depends only on the density outside R_c, it is then computed at each interval. This second iteration gives a correction to the profile shape of typically 5-10%.

4. The normalised profile is multiplied by $\bar{n}_e(t)$ to obtain the absolute density profile for the times of interest.

Figure 5 shows a typical profile derived from reflectometry data by this method. The uncertainty has been estimated by taking a range of possible $R_{c,max}$. A density profile produced by the multi-chord far infrared interferometer installed on JET /15/ is shown for comparison. In this pulse the shape of the density profile changed significantly between 1.5s and 2s, remaining nearly constant thereafter. Profiles obtained by the two methods during this later period are in good agreement.

Fluctuations

During a pulse flat top it is not possible to make density profile measurements with this simple fixed frequency device. However, movements of the critical density layer can be observed. For example, relatively fast phase excursions or "spikes" of about half a fringe in magnitude are clearly seen for some pulses.

Fig.6 shows a clear correlation between these spikes and sawtooth oscillations in the line of sight integrated density, as measured by the microwave interferometer. The reflecting layer in this case was in the outer half of the plasma radius.

The direction of the phase excursions can be deduced by comparing them with the phase change due to the slow basic movement of the reflecting layer. These slow fringes are caused by gradual changes in plasma density. During the density rise period this basic movement is away from the plasma centre. We find that the "spikes" retard the phase, indicating an inwards motion during the sawtooth rise, followed by a faster return to the mean position. In the density fall period, as in 6(b), the mean position moves slowly inward. The "spikes" now advance the phase, which again indicates an inwards motion during the sawtooth rise.

The measured phase is determined both by the position of the reflecting layer and by the refractive index in the propagation path. Simple numerical tests in which the density is varied by a small percentage over portions of the propagation path show the phase to be most sensitive to changes at and near the reflecting layer. We find that typically 75% of the maximum phase change is due to density changes in the 30% of the propagation path nearest R_{crit} (about 9cm for the example of Fig.6). The measurement is thus localised to this region.

The spikes observed in the case above are consistent with a uniform density variation of order 0.75%, which could be accounted for by a movement of R_{crit} by 5mm. There is considerable uncertainty since no profile measurement outside R_{crit} is available and the actual radial extent of the density perturbation is unknown. In future experiments planned on JET, this and other fluctuation phenomena will be investigated more thoroughly using a range of input frequencies.

Limitations

The greatest limitation of density profiles derived from fixed frequency reflectometry is their lack of time resolution. Since the slopes at different points are measured over a 2-4s measurement period, significant shape changes will obviously distort the derived profile. Comparing density data from Thomson scattering with the microwave transmission interferometer data provides a useful independent check. On pulses when this ratio was not constant unrealistic n_e profiles have resulted. For example, if the actual profile is highly peaked at the time $n_{eo} = n_c$ and then flattens, the derived profile will have an artifically steep central gradient.

A second limitation of the technique is that it does not measure directly the absolute position of the reflecting layer. The uncertainty in position is of particular importance when using the derived density profiles for calculating area or volume integrals. It can also lead to a small systematic error in $\bar{\mu}$, and therefore in the derived profile shape.

While these limitations are serious under some circumstances, this simple instrument can provide useful information for many purposes. Moreover, they can be reduced by launching several fixed frequencies simultaneously. A wider range of radii would then be probed during a given time interval. With suitable frequency separation techniques, a single oversized antenna would still be sufficient. This and other reflectometry techniques are currently being studied for future use on JET.

Conclusion

A simple fixed frequency reflectometer has been constructed using a single oversized waveguide channel. The system measures the movement of a particular density layer. Under some conditions, and by using data obtained from other diagnostics, the electron density profile on JET plasmas has been obtained during a period of density change. Good agreement is found with density profiles measured by far infrared multichord transmission interferometry.

The main advantages of fixed frequency reflectometry as a density profile diagnostic are the small machine access requirements and the simplicity of the instrument. There are, however, limits to the time and spatial resolution which under some circumstances are serious. These can be improved by using more probing frequencies and a multichannel system is presently being prepared.

Fluctuations correlated with sawtooth activity in the plasma centre have been observed with the instrument. As density information with this technique is relatively localised, it promises to be an important diagnostic tool for the study of such phenomena on JET.

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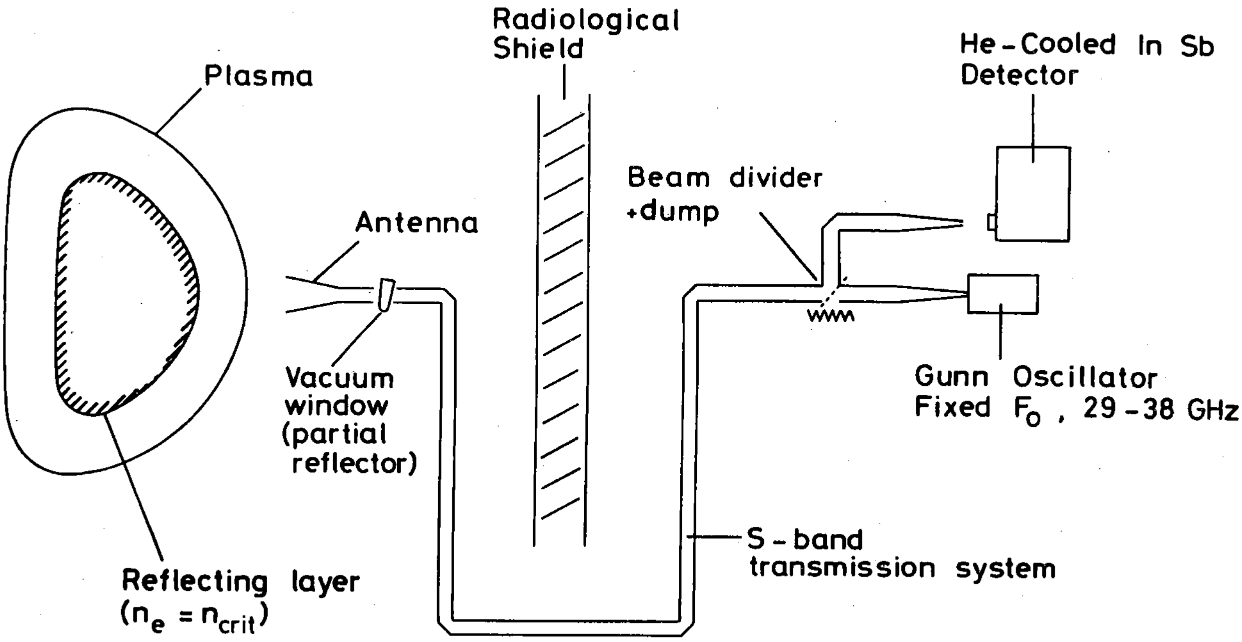

Fig. 1 Schematic of the JET reflectometry instrument. The actual transmission system is over 35m in length and includes 7 E-plane and 5 H-plane bends.

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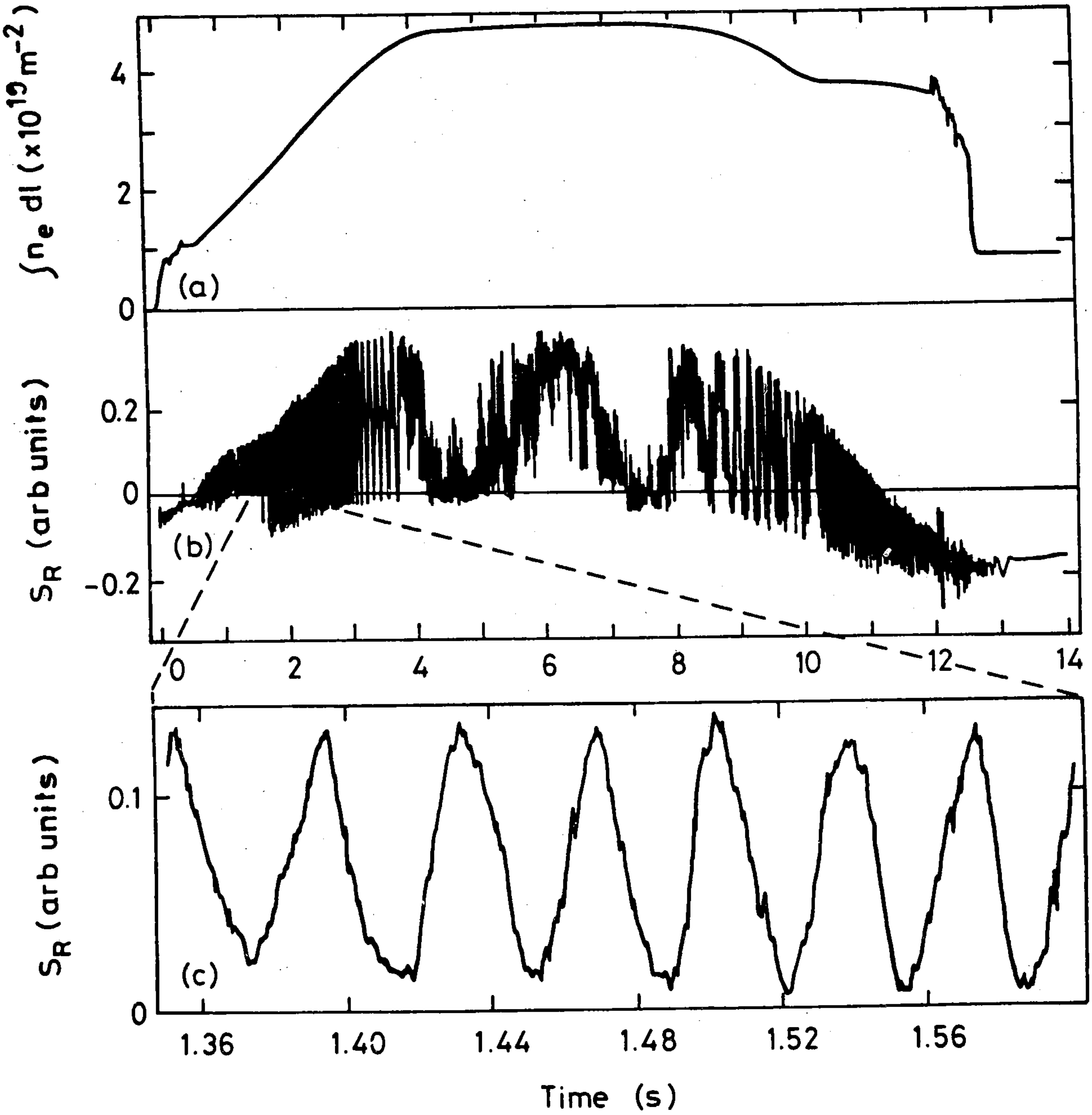

Fig. 2 Typical signals during a plama pulse. (a) Line integrated density from the microwave transmission interferometer operating at $\lambda = 2$mm. (b) Signal from the reflectometer detector (the apparent DC droop is due to the lower frequency limit of the detector amplifier (1 Hz)). (c) Expansion of the reflectometer signal during the density rise phase.

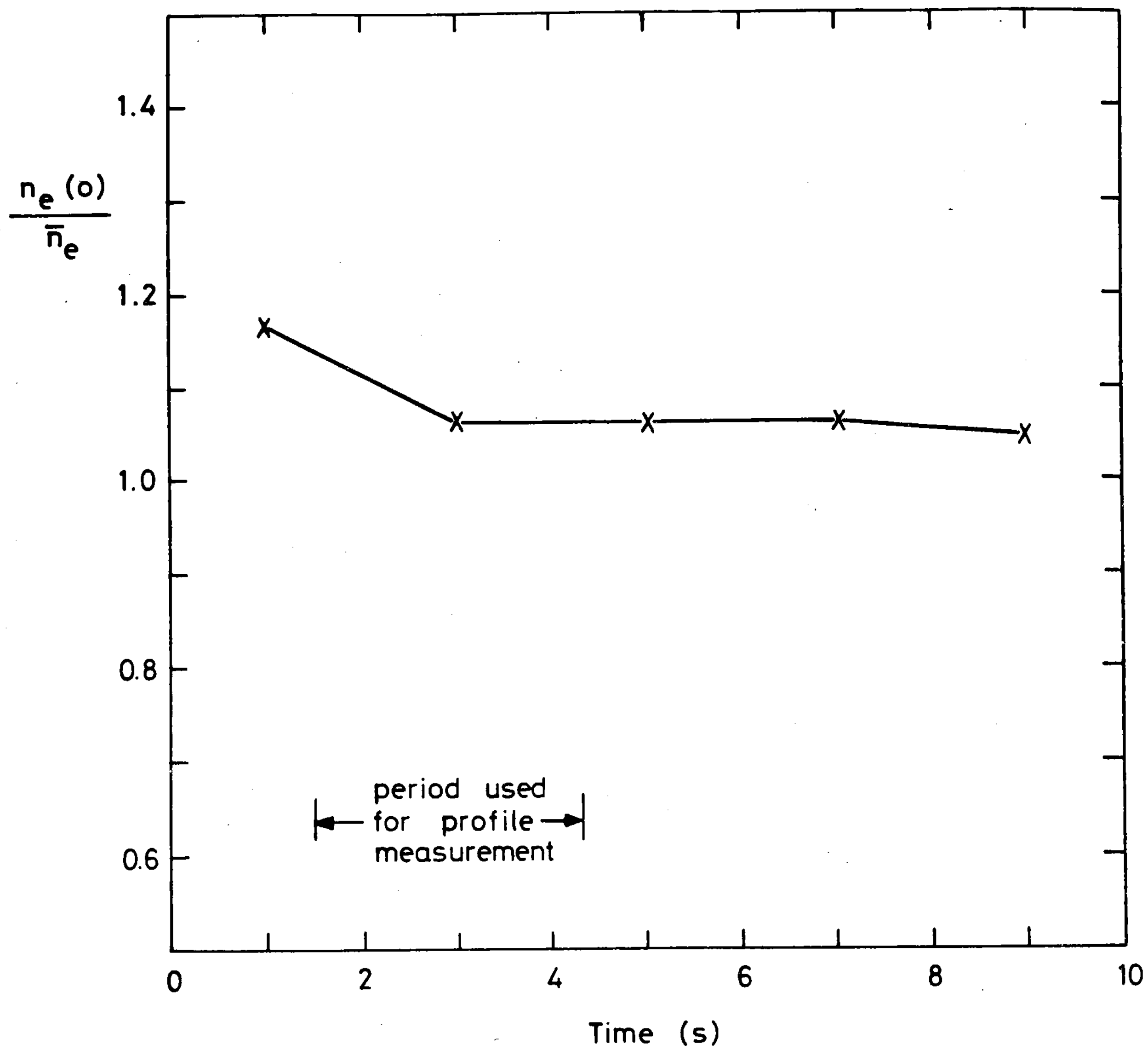

Fig. 3 Ratio of central electron density from Thomson scattering to line average density from the microwave transmission interferometer during a plasma pulse (arbitrary scale). Note that the ratio varies by less than 10% during the period used for the reflectometer profile measurement, indicating a nearly constant profile shape.

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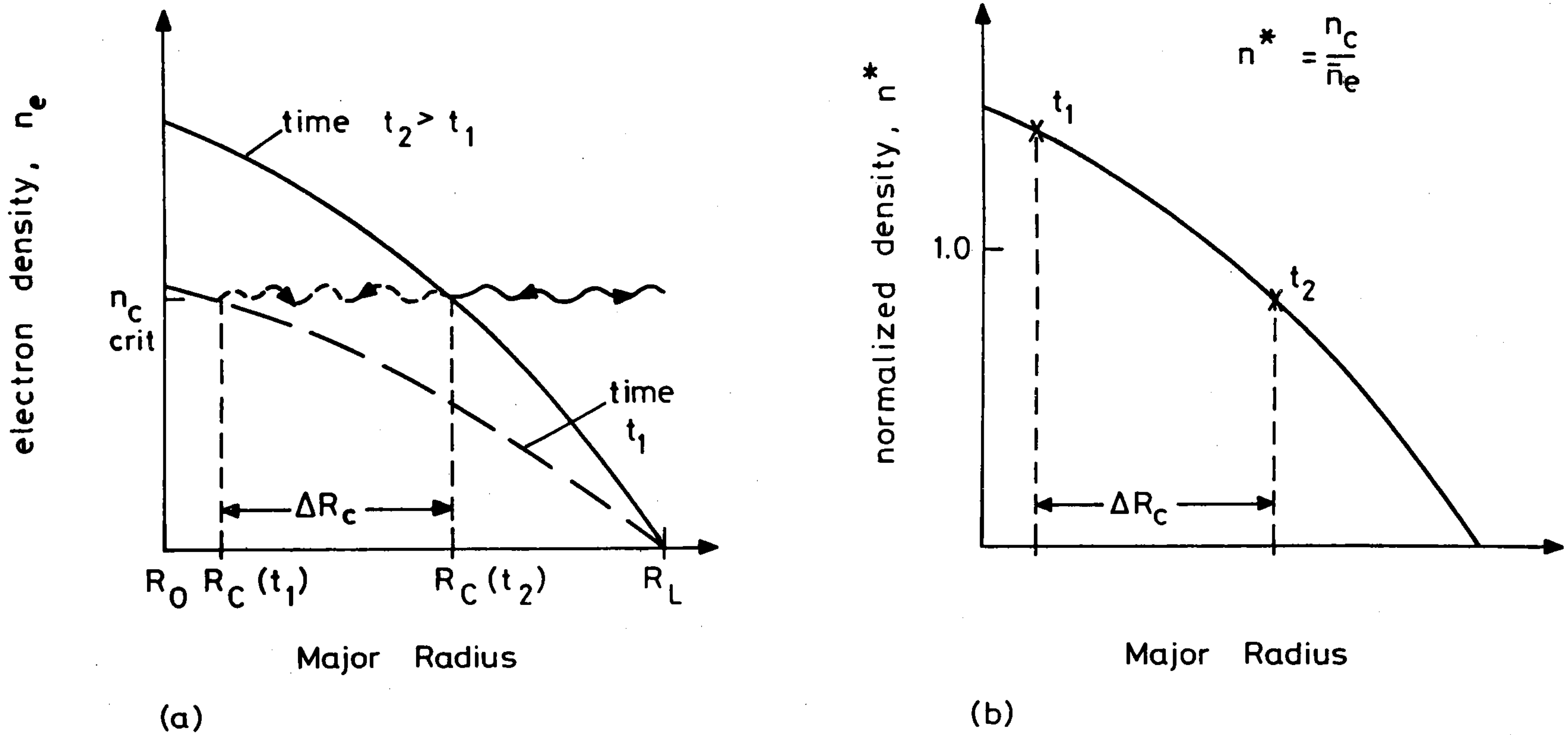

Fig. 4 Derivation of the electron density profile during the rise period.
(a) Outward radial movement of the reflecting layer.
(b) Derived points on the density profile (normalised to the line average density $\bar{n}_e$)

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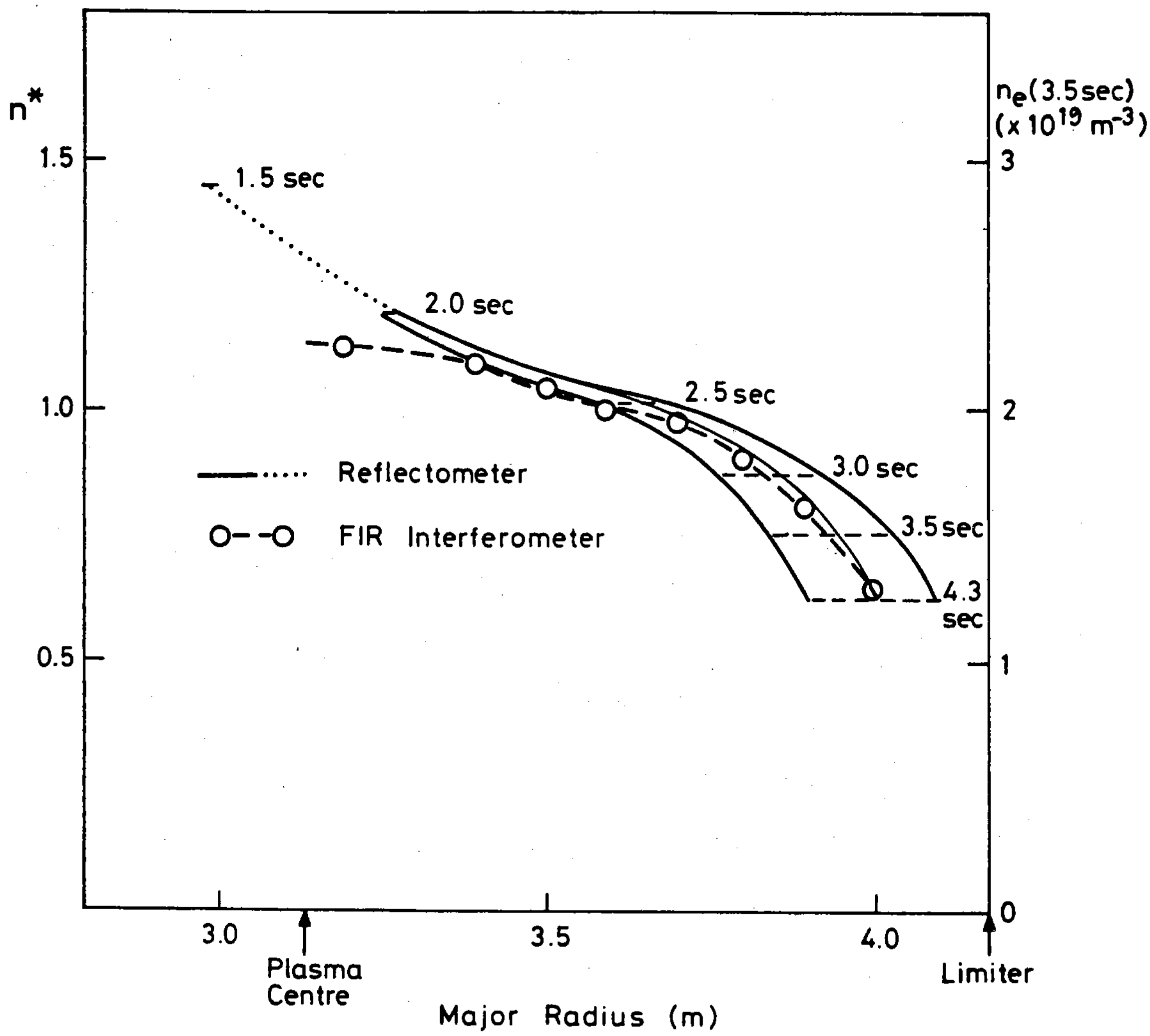

Fig. 5 Density profile derived from reflectometry for JET pulse 3886. The three solid curves were obtained by starting the second iteration from different outer positions, and represent the uncertainty in the profile shape. A profile measured by the multichord far infrared interferometer at 3.5 s is shown for comparison (dashed curve). On this pulse the profile shape was changing before 2.0 s making reflectometer analysis invalid (dotted portion).

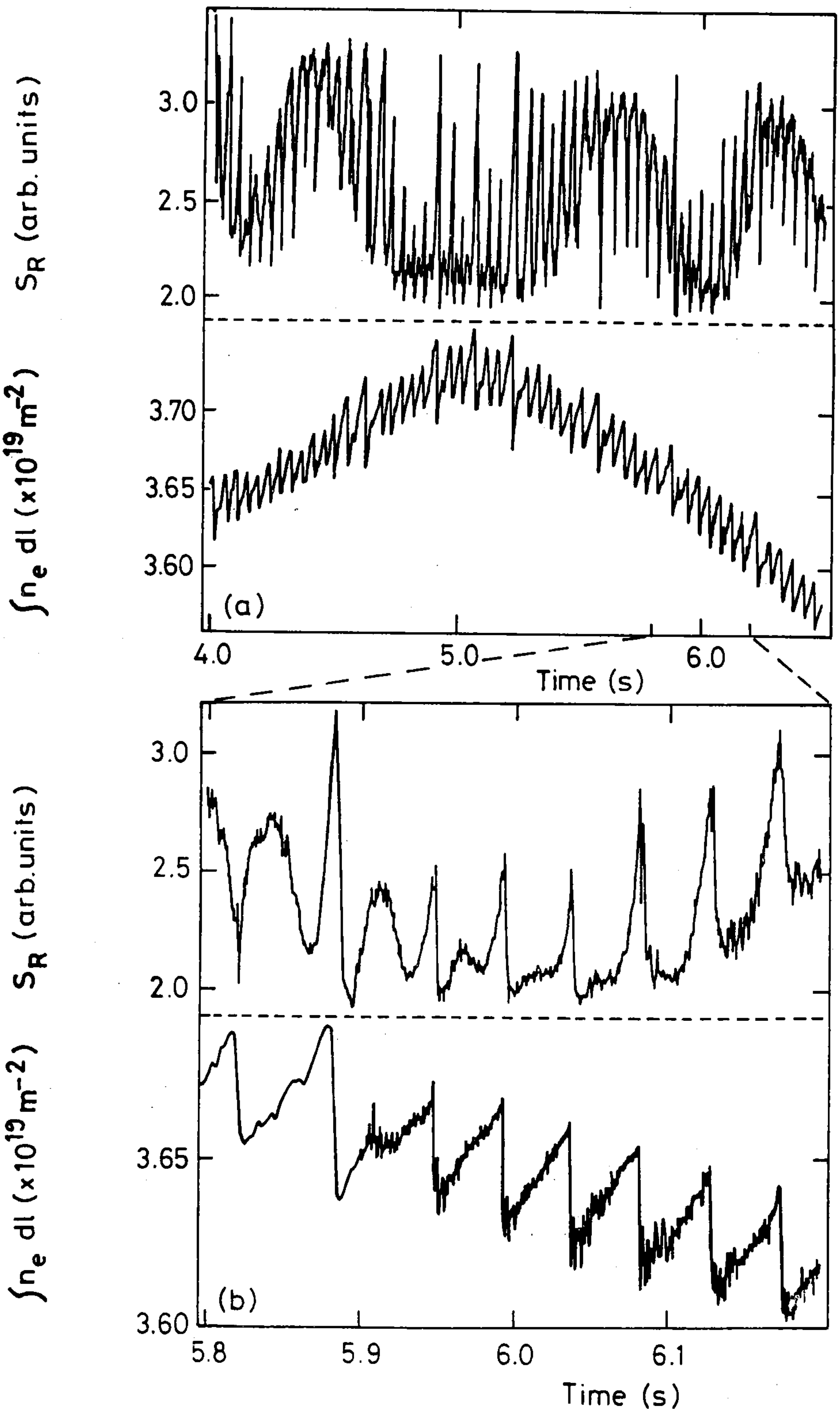

Fig. 6 Reflectometer phase changes correlated with density sawtooth oscillations.

(a) Reflectometer signal (top trace) and density line integral from the microwave transmission interferometer, during the peak density period. Slow (~2Hz) reflectometer fringes indicate bulk movement of the reflecting layer.

(b) Expansion of signals during the period 5.8–6.2s, showing sawtooth oscillations. (The apparent increase in noise on the interferometer data is due to a change in the sampling rate).